

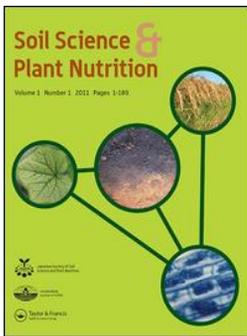
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Sulphur nutrition: An important factor for the quality of wheat and rapeseed

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Key words: *Brassica napus* L., breadmaking quality, glucosinolates, nitrogen, sulphur, *Triticum aestivum* L.

Abstract

The incidence of sulphur (S) deficiency has increased in many crops in the U.K. and other European countries in the last 10 years. Apart from the effects on yield, the S nutrition of a crop often has a strong influence on the quality of the produce. We have shown that S fertilisation significantly improved breadmaking quality of field-grown wheat (*Triticum aestivum* L.) in the U.K. with the loaf volumes of the same variety grown at different sites correlating better with the concentrations of grain S than grain N. Sulphur also increased gel protein content of flour, but decreased its elastic strength. In contrast, application of S fertilisers to oilseed rape (*Brassica napus* L.) can lead to increased glucosinolate concentrations in the seed which exceed the limit for the meal to be used in animal feeds. Results from 29 field experiments showed that the glucosinolate concentration of rapeseed was usually higher when grown at the S-sufficient than the S-deficient sites. However, the addition of S fertiliser increased the glucosinolate concentration much more under S-deficient than under S-sufficient conditions. Furthermore, there was a strong interaction between N and S on seed glucosinolates. Increasing N decreased the glucosinolate concentration when S was deficient, but increased the glucosinolate concentration when S was applied. The need to maintain a balanced N and S supply for both yield and quality is stressed.

Introduction

Sulphur is an essential nutrient for all plants and animals, because it is a constituent of essential compounds such as cysteine, methionine, several coenzymes (e.g. biotin, coenzyme A, thiamine pyrophosphate and lipoic acid), thioredoxins and sulpholipids. There are many other S-containing compounds in plants which are not essential, but may be involved in defence mechanisms against herbivores, pests and pathogens, or contribute to the special taste and odour of food plants (Bennett and Wallsgrove, 1994; Ernst, 1993; Fenwick et al., 1983).

The S requirement of most plants is in the same order as that of phosphorus, making it a major nutrient. The need for S fertilisers depends on the balance between inputs and losses by leaching and other pathways of removal from agricultural systems. In the past, uncontrolled inputs of S from atmospheric deposition often exceeded the amounts required by crops in Europe, thus, S deficiency was

rare. Due to the concerns about the effects of 'acid rain' on natural ecosystems which exist on poorly buffered soils and catchments, steps have been taken to reduce the emissions of sulphur dioxide, both in Europe and other parts of the world. For example, total emissions of sulphur dioxide in the U.K. decreased from 6.4 million tonnes in 1970 to 2.9 million tonnes in 1995 (DoE, 1995). Some other European countries achieved even more drastic decreases during the same period (McGrath et al., 1996). These changes have resulted in increased incidence of S deficiency in arable crops (McGrath and Zhao, 1995; McGrath et al., 1996).

Field experiments have shown that oilseed rape is one of the crops most susceptible to S shortage, and responds well to S fertilisation in many areas in the U.K. (McGrath and Zhao, 1996; McGrath et al., 1996). Although cereal crops require considerably less S than oilseed rape, yield responses to S have also been obtained (McGrath et al., 1996; Withers et al., 1995).

Apart from the effects on yield, the S nutrition of a crop often has a strong influence on the quality of the produce, because of its essential role in the synthesis of amino acids, proteins and some secondary metabolites. Quality requirements are determined mainly by the end use of the product. Because these requirements vary widely, the effects of S can be either positive or negative. A sufficient S supply to crops is important for good nutritional quality of grain legumes and good processing quality of wheat (Randall and Wrigley, 1986). An excessive S supply can lower the quality of rapeseed meal as animal feed by increasing the glucosinolate concentration. In contrast, an increased glucosinolate level in *Brassica* vegetables can be considered as positive, because of the enhanced flavour (Fenwick et al., 1983). We present in this paper our recent research results concerning the effects of S nutrition on the breadmaking quality of wheat and glucosinolate concentration of rapeseed.

Materials and methods

Experiments with wheat

Field experiments were conducted at four sites (Bridgets, Borders, Raynham and Woburn) in 1995, using a variety of breadmaking wheat (*Triticum aestivum* L., cv. Hereward). Treatments consisted of two rates of N (180 and 230 kg ha⁻¹) and three rates of S (0, 20 and 100 kg ha⁻¹), and were replicated three times in a randomised block design. Nitrogen was applied as ammonium nitrate, and S as gypsum (18% S). At maturity, crops were harvested and grain samples collected for the determination of chemical composition and breadmaking quality. The concentration of N in grain was determined using LECO CNS Analyzer. Grain protein content was calculated from the N concentration by multiplying by a factor of 5.7. For the determination of S, grain samples were digested with a mixture of HNO₃ and HClO₄, followed by measurement of S in solutions using inductively coupled plasma (Zhao et al., 1994b). Grain samples were milled and separated into white flour and bran. The gel protein content of flour and the elastic modulus were determined (Pritchard, 1993). White flour was used to bake bread using the standard method of Chorleywood Bread Process.

Experiments with oilseed rape

A total of 29 field experiments were conducted in the growing seasons of 1990-93, using low glucosinolate varieties of oilseed rape (*Brassica napus* L., cvs. Falcon, Bristol, Cobra and Libravo).

Experimental designs varied, but there were two treatments common in all experiments, i.e. 0 and 50 kg ha⁻¹ of S (applied as gypsum). Significant yield responses were obtained at 9 sites, and these were grouped as S-deficient sites. The other 20 sites were grouped as S-sufficient sites. Seed glucosinolate concentration was determined by X-ray fluorescence (Schnug and Haneklaus, 1988). Data for the two common treatments are presented in the paper.

A field experiment was carried out at a S-deficient site in the Scottish Borders in 1990 to study the interactions between N and S on seed glucosinolate concentration, using *Brassica napus* L., cv. Cobra. The treatments consisted of factorial combinations of three N rates (0, 150 and 300 kg ha⁻¹) and three S rates (0, 50 and 100 kg ha⁻¹). All treatments were replicated 4 times in a randomised block design. Nitrogen was applied as ammonium nitrate and S as potassium sulphate, both in early spring. Potassium chloride was applied to the S0 and S50 treatments to give the same amount of K as in the S100 treatment. Seed samples were collected at crop maturity for the determination of glucosinolates by X-ray fluorescence (Schnug and Haneklaus, 1988) and protein-S (Zhao et al., 1997).

Results and discussion

Effects of S on breadmaking quality of wheat

A wide range of food products are made from wheat flour, including various types of breads, noodles, pasta and biscuits. Wheat gluten is largely responsible for the functional properties of dough which are exploited in all these end uses. Wheat gluten is unusual in that it exhibits rheological properties of elasticity and extensibility (viscosity). A precise balance of these two properties is important for the breadmaking quality: excessive elasticity would limit the expansion of bread, whereas insufficient elasticity would fail to retain the carbon dioxide released by yeast (Shewry et al., 1995). Wheat gluten consists of a complex mixture of polypeptides, which can be separated into monomeric α -, γ - and ω -gliadins, and polymeric HMW and LMW subunits of glutenins. The α - and γ -gliadins and LMW subunits of glutenin are rich in S, with about 2-3 mol % cysteine, whereas ω -gliadin is poor in S, containing no cysteine (Shewry et al., 1994). The HMW subunits of glutenin have an intermediate level of cysteine, varying from about 0.5-1.5 mol %. Although the HMW subunits of glutenin account for only 6-10% of the gluten proteins, they are particularly important in determining elasticity (Shewry et al., 1995). In

Table 1. Effects of S on grain N:S ratio, contents of flour protein and gel protein fraction, and loaf volume

S applied (kg ha ⁻¹)	Grain N : S ratio	Flour protein (%) (based on 86%DM)	Gel protein (g FW/5g flour)	Loaf volume (ml)
0	17.9	11.1	9.9	1394
20	15.8	11.0	11.7	1428
100	14.7	11.1	11.5	1443
LSD (<i>p</i> < 0.05)	0.52	0.31	0.42	16.3

contrast, extensibility is generally associated with gliadins. It is generally believed that the interchange between the thiol and disulphide groups within the network of gluten proteins plays a key role in maintaining a good balance between elasticity and extensibility (Fullington et al., 1987).

Several studies, conducted mainly in Australia, have shown a pronounced effect of S deficiency on the composition of gluten proteins in wheat (see review by Randall and Wrigley, 1986). In general, S deficiency decreases the relative proportions of the S-rich α - and γ -gliadins and LMW subunits of glutenins, but increases those of the S-poor ω -gliadin and low S HMW subunits of glutenins. As a result of these compositional changes, the extensibility of dough is decreased by S deficiency, whereas the resistance to stretching (elasticity) is increased. Dough extensibility has been shown to correlate positively with flour S over a wide concentration range (0.8–1.7 mg S g⁻¹) (Moss et al., 1983). In these studies, the effect of S on loaf volume, which is the most important overall quality criterion, was less consistent (Moss et al., 1983; Randall and Wrigley, 1986)

Recently, we have investigated the quality responses of breadmaking wheat to S under field conditions in England, where S deficiency in cereals has only recently developed (McGrath et al., 1996). Table 1 shows mean results from field experiments conducted at 4 different sites in England. In the control treatment, grain N:S ratio was above 17, which is generally regarded as the critical value for grain yield and quality (Randall and Wrigley, 1986). Application of S decreased the ratio significantly. The total concentration of protein in flour was not affected by S. However, the fresh weight of gel protein, which consists principally of glutenins (Pritchard and Brock, 1994), was increased significantly by S. Loaf volume increased by 34 and 50 ml in response to applications of 20 and 100 kg S ha⁻¹, respectively.

Applications of S consistently decreased the elastic strength, whereas an extra application of 50 kg N ha⁻¹ increased it (Fig. 1). These results agree

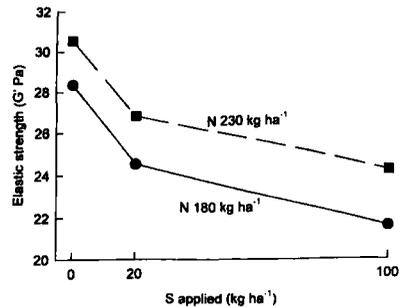


Fig. 1. Effects of N and S supply on the elastic strength of gel protein. Means of 4 experiments conducted in 1995 using the wheat variety Hereward.

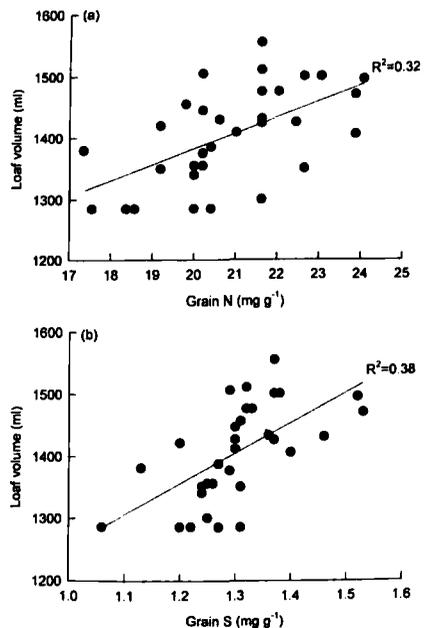


Fig. 2. Relationships between loaf volume and the concentrations of grain N (a) and grain S (b). All samples were of the wheat variety Hereward.

with previous reports concerning the effect of S on resistance to stretching of dough. (Moss et al., 1983; Randall and Wrigley, 1986). The contrasting effects N and S on the elasticity further indicate the importance of a balanced N and S supply for breadmaking quality.

Grain protein concentration is widely used by the milling industry to determine whether to pay a premium price for breadmaking wheat. In 1993, 32 wheat grain samples of the variety Hereward were collected from different sites in England. Loaf

volume was determined and related to both grain N and S concentrations (Fig. 2). Grain N concentration accounted for only 32% of the variation in loaf volume. The correlation between loaf volume and grain S concentration was closer, with a R^2 of 38%. A similar correlation with S was also found in other breadmaking varieties (data not shown). These results suggest that the concentration of S in grain is an indication of protein quantity and, to certain extent, protein quality, whereas grain N only reflects the content of protein.

Although much progress has been made in unravelling the composition and properties of the gluten protein complex, our understanding of the relationship between gluten structure and breadmaking performance is still far from complete. Rapid progress is also being made in manipulating the seed protein composition of wheat by transgenic techniques in order to explore and improve quality (Shewry et al., 1995). Transgenic wheat with an altered storage protein composition will facilitate investigations of the effects of environmental factors, particularly the supplies of N and S, on breadmaking quality.

Effects of S on the concentrations of glucosinolates in rapeseed

Glucosinolates are a group of secondary metabolites containing a β -thioglucose, a sulphonated oxime moiety and a side chain. About 100 glucosinolates have been identified, varying in the side chain (Fenwick et al., 1983; Poulton and Møller, 1993). The side chains are derived from amino acids, with the alkenyl group being synthesised from methionine, the indolyl group from tryptophan, and the aromatic group from phenylalanine. Glucosinolates are found mainly, but not exclusively, in crucifers, including oilseed rape (*Brassica napus*).

Intact glucosinolates are not toxic, but their breakdown products (thiocyanates, isothiocyanates and nitriles) are goitrogenic, anti-nutritional and toxic to animals (Chew, 1988; Fenwick et al., 1983). Inclusion of rapeseed meal in animal feeds is severely limited by the presence of high concentrations of glucosinolates. More recently, research interest has focused on the potential mutagenic, carcinogenic and anti-carcinogenic properties of the breakdown products from the glucosinolates found in the *Brassica* vegetables (Jongen, 1996).

Over the past two decades, considerable progress has been made in the breeding of low glucosinolate

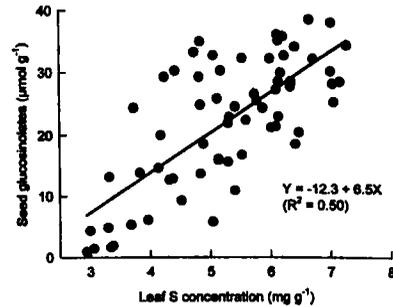


Fig. 3. Relationship between seed glucosinolate concentration and leaf S concentration at the flowering stage of oilseed rape.

oilseed rape, to improve the acceptability of rapeseed meal and meet increasingly stringent requirements from the processing industry. These genotypes contain only 10-20% of the normal concentrations of glucosinolates in the seed recorded in the older genotypes. Although genotypic differences between varieties are clear, environmental factors also exert large influences on the final concentrations of glucosinolates in the seeds (Milford and Evans, 1991). In particular, the effects of S and N nutrition are most noticeable (Bilsborrow et al., 1993; Mailer 1989; Withers and O'Donnell, 1994; Zhao et al., 1993a; 1994). This is not surprising, since each glucosinolate molecule contains two or three atoms of S, and amino acids are the precursors of glucosinolate biosynthesis.

A close relationship between plant S status and seed glucosinolate concentration can be seen in Fig. 3. In a survey of 68 oilseed rape crops of low glucosinolate varieties grown in 1990 in Northern England and Southeast Scotland, where S supply is generally low, approximately 50% of the variation of seed glucosinolates could be accounted for by the concentration of total S in leaves at the early flowering stage. This indicates that natural variation in the S supply to crops is a key factor affecting the final concentration of glucosinolates in rapeseed.

Oilseed rape crops have a high demand for S, with approximately 16 kg of S required to produce 1 tonne of seeds containing 91% dry matter (McGrath et al., 1996; Zhao et al., 1993b). Sulphur deficiency is now common place in this crop in the U.K., and increasingly, S fertiliser is required to maintain maximum yield production. The effects of applying S fertilisers on the glucosinolate concentrations in the seed are variable. Although the concentrations of glucosinolates are usually higher at the high S than at the low sites, addition of S fertiliser tends to

Table 2. Effects of S on the concentration ($\mu\text{mol g}^{-1}$) of glucosinolates in rapeseed at S-sufficient and S-deficient sites

S applied (kg ha ⁻¹)	S-sufficient sites (20)	S-deficient sites (9)
0	15.2	9.7
50	17.1	19.8

increase glucosinolates much more under S-deficient than under S-sufficient conditions (Withers and O'Donnell, 1994; Zhao et al., 1993a). Table 2 shows that, on average, an application of 50 kg S ha⁻¹ increased seed glucosinolate concentration by only 2 $\mu\text{mol g}^{-1}$ at the S-sufficient sites, but by 10 $\mu\text{mol g}^{-1}$ at the S-deficient sites. In some cases, application of S increased the concentration of glucosinolates beyond the current EU threshold of 18 $\mu\text{mol g}^{-1}$ which prohibits farmer-saved seeds from being sown. The greater responses obtained at the low S sites can be explained by an increased S uptake capacity as a result of S deficiency (Clarkson et al., 1993). For example, Hawkesford et al. (1993) found that the sulphate uptake capacity of roots increased from 150 nmol g⁻¹ (fresh weight) h⁻¹ in S-sufficient oilseed rape plants to 2300 nmol g⁻¹ (fresh weight) h⁻¹ in mildly S-starved plants.

Under S-sufficient conditions, increasing N supply was found to increase the concentration of glucosinolates in the seed (Bilsborrow et al., 1993). Under S-deficient conditions, however, increasing N supply resulted in a decrease in glucosinolate concentration (Zhao et al., 1993a). Fig. 4a shows the interactive effects of N and S on the glucosinolate concentration at a S-deficient site. The distribution of S in proteins and glucosinolates in the seeds was clearly affected by the N and S balance (Fig. 4b). When S was limiting (S0), most S was incorporated into proteins and less was available for the synthesis of glucosinolates. Increasing the N supply decreased the proportion of the seed S bound in glucosinolates from 26 to 15%. When S was added (S50 and S100), however, increasing the N supply increased both protein-S and glucosinolate-S, maintaining the proportion of glucosinolate-S at about 30% of the total S in the seeds.

Not only the total concentration, but also the relative proportions of the individual glucosinolates in rapeseed were influenced by the S supply (Withers and O'Donnell, 1994; Zhao et al., 1994a). The alkenyl glucosinolates, which are the predominant group found in rapeseed, were more sensitive to the S supply than the indolyl glucosinolates. Increasing S supply increased the

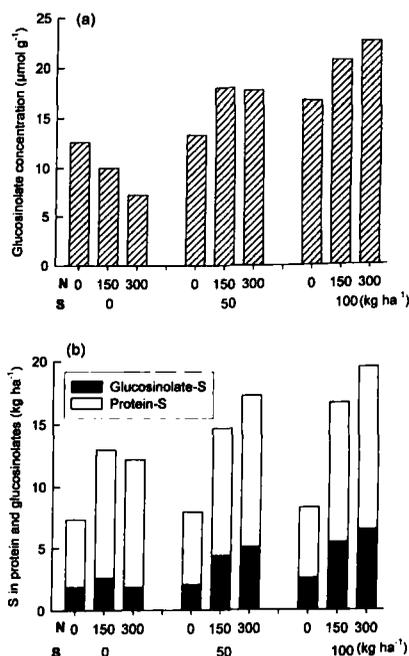


Fig. 4. Effects of N and S on the concentration of glucosinolates in the seeds of oilseed rape at a S-deficient site (a); and distribution of S in glucosinolates and proteins (b).

proportion of the alkenyl glucosinolates at the expense of the indolyl glucosinolates. The differences probably occurred because the alkenyl glucosinolates are derived from methionine, whereas the indolyls are derived from tryptophan. Some evidence suggests that the breakdown products from alkenyl glucosinolates are particularly harmful to animals (Vermorel et al., 1986).

The benefits of applying S fertiliser on seed yield and the potentially adverse effect on the quality of rapeseed meal are difficult to reconcile, but applying more S than required by oilseed rape crop for maximum yield must be avoided.

Glucosinolates in vegetative tissues are believed to be involved in plant defence against pests and diseases (Bennett and Wallsgrove, 1994). Limiting S availability may therefore have an impact on plant health. However, the low glucosinolate varieties of oilseed rape have not been shown to be more susceptible to diseases, because their vegetative tissues contain a similar level of glucosinolates to the high glucosinolate varieties (Mithen, 1992).

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