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SULPHUR AS A FERTILISER COMPONENT DETERMINING CROP YIELD AND QUALITY

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Abstract

The aim of this paper was to review 100 years of Polish studies on sulphur fertilisation and its effects on the growth and development of plants, the chemical composition and impact of sulphur compounds on the health of plants, and its fungicidal activity. In the reviewed studies sulphur deficiency generally delayed vegetative growth, caused the dying out of the growth cone, yellow discolouration of the generative and vegetative organs and delayed maturation. Observations of plants have demonstrated that sulphur is essential for normal photosynthetic functions. Plants suffering from a lack or shortage of sulphur had pale green or yellowish, narrow, short and small leaves, and a smaller than normal root system, which was associated with reduced chlorophyll synthesis. The availability of sulphur was found to enatil an improved uptake of nitrogen by plants, thus affecting their quality and optimising the N:S ratio. Fertilisation with sulphur increased the total content of sulphur and sulphates in plants. Findings from studies on the effect of sulphur on the content of macroelements in tested plants are inconclusive. Sulphur used in excess disturbed the ionic balance in plants and indirectly affected the intensity and level of uptake of other nutrients. The results of studies investigating the impact of sulphur on changes in the content of heavy metals were ambiguous and demonstrated either synergistic or antagonistic interactions. Generally, sulphur fertilisation increased the content of *glucosinolates* in plants and improved their nutritional value. Most studies also showed that sulphur fertilisation improved the disease resistance of plants. Some studies have also demonstrated an increased content of glucosinolates in plants fertilised with sulphur, which stimulated natural resistance to fungal infections.

Keywords: sulphur; crop quality; macroelements; microelements; organic compounds.

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INTRODUCTION

Oczapowski (1819) wrote that sulphur is “familiar to all. It is a brittle substance, yellow, with a specific taste and odour…Sulphur is often found in the plant and animal kingdom.” Godlewski and Jentys (1903) found that “shortage of just a single nutrient in soil causes some delay in plant development.” Researchers have observed that “the supply of sulphates to tubers is adjusted closely to the plant’s needs, and the excess of this nutrient is not accumulated in tubers.” Rejman (1965) found that “the agricultural literature on sulphur is abundant, but tackles too many different problems considered separately, which often results in insufficiently precise and repetitive analysis of a given issue.” Today, the significant role of sulphur in the improvement of crop yield and quality in many areas is undebatable, although until recently this element has been considered as a factor degrading the environment.

The aim of this paper is to review findings from studies on sulphur carried out in Poland, investigating sulphur impact on the vegetative and generative development of plants, their chemical composition and resistance to diseases.

EFFECTS OF SULPHUR ON PLANT GROWTH AND DEVELOPMENT

In the mid-1950s, Strzemski (1965) reported that “…predictions concerning potential shortages of sulphur in soil (particularly in light soil) are supported by relatively limited analytical data and biological symptoms.” The researcher pointed out the disorders of the fruiting process in legumes. Sulphur deficiency in soil was manifested by the poor formation of seeds in peas, vetch, clover, and even the limited distribution of tuberous pea (*Lathyrus tuberosus vel bulbosus*), a weed preferring soil rich in sulphur

Koter and Grzesiuk (1966) carried out an experiment with a starvation dose of sulphur (2.5 mg S pot^{-1}) and demonstrated its negative effect on the growth of plants fertilised with high doses of nitrogen. Plant growth was clearly inhibited, and leaves were thick, rigid and purple. Increased doses of sulphur resulted in the luxurious growth of plants, and their morphology indicated normal metabolism. The significant impact of sulphur on vegetative and generative development was confirmed in studies carried out by Uziak and Szymańska (1969), who found delayed plant maturation due to sulphur deficiency. Observations of plants have demonstrated that sulphur is essential for normal photosynthetic functions. Plants suffering from a lack or shortage of sulphur had pale green or yellowish, narrow, short and small leaves, and a smaller than normal root system, which was associated with reduced chlorophyll synthesis (Nowotny-Mieczyńska 1965). Koter and Benedycka (1984) found that an increasing deficit of sulphur in soil resulted in a decreased content of magnesium, and thus a limited synthesis of chlorophylls in the cultivated radish. MURKOWSKI (1999) observed that the chlorophyll content in leaves of oilseed rape plants fertilised with small doses of nitrogen in the form of ammonium nitrate was lower than in plants fertilised mainly with ammonium sulphate, which may indicate a positive impact of sulphate ions.

GOŹLIŃSKI (1965) found that sulphur deficiency in oilseed rape was manifested as late as on day 17 from seedling emergence. This confirmed previous observations of the visual symptoms caused by sulphur deficiency resulting in the inhibited growth of oilseed rape that failed to form flower buds. Mustard plants grown on experimental plots without sulphur fertilisation were shorter, and produced finer and lighter seeds. GOŹLIŃSKI (1965) also recorded differences in the susceptibility of mustard and oat plants to sulphur shortage, both at the initial stage of development and during further periods of growth. In studies by NURZYŃSKI (1974), plants fertilised with potassium sulphate were vivid green when compared to plants fertilised with potassium chloride. Tomato plants fertilised with potassium sulphate formed smaller fruits, and their harvest was delayed by about 12 days in comparison to plants fertilised with potassium chloride. While SEIDLER (1975) concluded that the addition of sulphur in all tested plants accelerated the generative phase, increased the number of formed flowers and heads, and shortened the growing period, which was particularly clear in mustard plants.

KOTER and BENEDYCKA (1984) fertilised experimental plants with potassium chloride and found that sulphur shortage caused the dying out of the growth cones. Xenomorphy and succulence were observed in these plants, indicating an excessive accumulation of chlorides. Additionally, plants had typical symptoms of sulphur shortage, such as a pale green or yellow colour of the youngest leaves. Similar findings on the visual effects of sulphur shortage were reported by SCHNUG et al. (2003), JAKUBUS (2006) and BARCZAK (2010).

WIELEBSKI (2006) found that the used doses of sulphur poorly differentiated the appearance of oilseed rape plants before harvest, such as plant height, number of branches and lodging, but stressed that they had the strongest effect on the number of pods per unit area and the number of pods per plant. However, the analysis of results from 3-year-long studies demonstrated lack of significant correlation between these morphological features of plants and sulphur doses (WIELEBSKI 2006). This was confirmed by KLIKOCKA and ĆWIKŁA (2008), who fertilised spring triticale with sulphur and found no significant differences between the analysed components of yield. Nevertheless, their study revealed a positive effect of sulphur on the number of heads per m^2 and an increased number of kernels per head. Fertilisation with sulphur also improved other features important for oilseed rape wintering, such as the diameter of the root collar, observed by WIELEBSKI (2012) as well. A positive but weather-dependent effect of sulphur application before sowing on the morphology of wintering plants and their survival was also found in a 3-year-long study carried out by JANKOWSKI et al. (2008*a*).

CHANGES IN THE ELEMENTAL COMPOSITION OF PLANTS

A number of experiments have demonstrated that sulphur fertilisation significantly changes the chemical composition of crops. The availability of sulphur determines the efficient use of nitrogen by plants and consequently affects plant composition and quality (Krauze, Bowszys 2000, Wielebski, Muśnicki 1998*a*, Podleśna 2003). Nitrogen content in tested plants is significantly modified by the content of sulphur in soil available to plants. Koter and Grzesiuk (1966) demonstrated that fertilisation with calcium sulphate increased the content of protein nitrogen, which indicated better uptake of nitrogen by red clover. The total nitrogen content in plants also increased. Lack of sulphur did not inhibit nitrogen uptake by plants, and it was accumulated in non-protein compounds (Koter, Grzesiuk 1966). Similar findings were made by Uziak, Szymańska (1969), Goźliński (1970*a*), Uziak and Szymańska (1987), who, having applied increasing doses of sulphur in the form of potassium sulphate, achieved an increase in the content of protein nitrogen in harvested crops. Sulphur starvation limited the accumulation of protein nitrogen in crops, but increased the content of asparagine, glutamine and aspartic acid in leaves. The researchers indicated that legume plants could bind large amounts of nitrogen if the level of supplied sulphur is sufficient. The most important impact of sulphur on plant growth is observed for plants growing on soils rich in bioavailable nitrogen. Sulphur deficiency results in inhibited photosynthesis, and this is reflected in an increased content of non-protein nitrogen. In plants suffering from severe sulphur starvation this form of nitrogen accounted for up to 70% of the total nitrogen content, while in plants sufficiently supplied with sulphur protein nitrogen dominated. This indicates the important role of sulphur in protein synthesis (Grzesiuk 1965). Lack of sulphur results in a limited bioassimilation of nitrogen, promoting an increase in the concentration of nitrate nitrogen and organic non-protein nitrogen (Koter, Benedycka 1984). A study carried out by Pyś, Pucek (1993*a*, *c*) revealed that fodder rye, oats, wheat and barley grown near sulphur landfill sites contained a high proportion of protein nitrogen to total nitrogen, suggesting the high nutritional value of crops. The mean total nitrogen content was 1.13-1.73% d.m. for rye, 1.15-2.05% d.m. for wheat, and 1.83-2.36% d.m. for barley. The use of sulphur for plant fertilisation generally promotes an increase in the total nitrogen content, as indicated by Koter and Grzesiuk (1966), Seidler (1975), Uziak and Szymańska (1987), Koter and Benedycka (1984), Wielebski and Muśnicki (1998*b*), Barczak, Nowak (2010), Wielebski (2011).

Sulphur fertilisation enhances the content of exogenous amino acids, in particular the component containing amino acids: methionine, cysteine and cystine dimer being cysteine (Horodyski, Krzywińska 1979). This was confirmed in studies by Barczak (2010), who found that sulphur fertilisation, in comparison to non-fertilised controls, usually caused a significant increase in the content of most amino acids in proteins, as well as the indicators of protein biological value, i.e. chemical store index (CS) and essential amino acids index (EAA). Sulphur fertilisation significantly increased the indices of protein nutritional value (net protein uptake – NPU, biological value – BV and protein efficiency ratio – PER) of spring barley kernels. The analysis of index values demonstrated the leading role of sulphur in maintaining a positive nitrogen balance in experimental animals, improving the efficiency of animal feeding.

Sulphur fertilisation induces changes in the content of total sulphur and sulphates in plants. Generally, it increases the content of total sulphur, organic sulphur and sulphates (Koter, Grzesiuk 1966, Babuchowski 1971, Uziak, Szymańska 1979, Benedycka 1983, Uziak, Szymańska 1987, Krauze, Bowszys 2000, Podleśna 2004, Barczak, Nowak 2015). Plants grown under conditions of low sulphur supply without sulphur fertilisation contain low amounts of total sulphur and trace levels of sulphates. A negligible content of inorganic sulfur in this case is a good indicator of sulphur starvation in plants (Grzesiuk 1965). Sulphur supplementation has a positive effect on crop quality by increasing the content of organic sulphur compounds. At good levels of sulphur supply to plants, the share of sulphates in different vegetative organs may reach 50-80% of its total level, but its large share has no longer any positive or negative effects on plant growth. When the supply of sulphur was insufficient, the content of total sulphur decreased to about 0.1% in straw and to 0.05-0.07% in stems. Under conditions of sulphur shortage, the intensity of its uptake by roots and transport to aerial parts were much higher than in sufficiently nourished plants (Goźliński 1965).

Seidler (1975) observed a clearly antagonistic interaction between chlorine and sulphur. In all experiments, an addition of chlorine caused a reduction in the content and uptake of sulphur by plants, indicating the inhibitory effect of chlorine on sulphur uptake. The content of sulphur in protein, and thus the amount of deficient sulphur-containing amino acids, evidently increased when plants were fertilised with potassium sulphate (Benedycka 1983). Interestingly, fodder plants grown in extreme conditions created by the proximity of sulphur landfill sites contained no harmful (toxic) levels of sulphur, both in terms of plant physiology and suitability for animal feeding (Pyś, Pucek 1993*b*). Krauze and Bowszys (2001) in a 3-year-long study on cv. Star spring barley found that sulphur fertilisation, either before sowing or during oilseed rape growth, improved the supply of plants with this element and significantly increased sulphur content and uptake in kernels. Similar findings were made by Kulczycki (2003), Klikocka et al. (2003), Brodowska and Kaczor (2003), Skwierawska et al. (2008) and Szulc et al. (2014).

The analysis of investigated indices of sulphur supply to plants (total sulphur content and total content of sulphur and sulfates, their ratio and the N:S ratio) demonstrated that the index values significantly depended on sulphur doses. The low share of sulphates in the total sulphur and the high content of protein nitrogen in total nitrogen indicate an exceptionally high efficiency of sulphur in protein synthesis (Barczak 2010).

Sulphur metabolism in plants is determined by an appropriate N:S ratio. In the vegetative organs of all crop species the N:S ratio is similar in proteins (about 15:1), and the total ratio of these elements is 12:1. Sulphur deficit results in the accumulation of non-protein nitrogen compounds that affect the increase in the N:S ratio above the level characteristic for proteins (Jakubus 2006). Comparable results were achieved by Benedycka (1983), Pyś and Pucek (1993*b*) and Kulczycki (2003). The N:S ratio is a very sensitive indicator of sulphur supply to plants (Boreczek 2001, Jakubus 2006, Potarzycki, Grzebisz 2007, Grzebisz, Przygocka-Cyna 2007). Disorders in plant growth resulting from sulphur shortage are manifested by the reduced biological value of crops. Fertilisation of plants with sulphur has a positive effect on the reduction of N:S ratios. In general, lower N:S ratios, adequate for the biological value, are found in luxurious and highly productive plants (Uziak et al. 1982, Grygierzec et al. 2015).

The content of sulphur in soil may indirectly affect the intensity and level of uptake of other nutrients. This is an important problem in agriculture, as it eventually shapes plant quality. Koter and Grzesiuk (1966) found an increased content of total phosphorus after sulphur fertilisation only in red clover. Grzesiuk (1965) reported that plants suffering from a severe sulphur shortage contain higher levels of total phosphorus. Under conditions of sulphur shortage, the accumulation of phosphorus and nitrogen is mainly attributed to the inhibited synthesis of organic matter. On the other hand, a reduction in the content of phosphorus in oilseed rape grown on soil rich in bioavailable sulphur was most likely associated with the antagonistic interaction between sulfates and phosphates (Koter, Grzesiuk 1966).

No significant impact of sulphur on the content of phosphorus in sunflower and serradella has been found. However, sulphur had a positive effect on the Ca:P ratio (Uziak, Szymańska 1987). In a study on kale carried out by Nurzyński (1974) the use of sulphates caused an increase in the content of total phosphorus, and a decrease in the content of potassium, calcium and magnesium in plants. Sulphur fertilisation reduced the content of phosphorus in lupin seeds as compared to a non-fertilised control (Barczak et al. 2014). Studies by Skwierawska et al. (2008) revealed that phosphorus content in plants was not significantly correlated with the used doses and types of sulphur. Podleśna (2004) demonstrated that treatment with sulphur increased the content of Ca and Mg in oilseed rape organs. Skwierawska et al. (2006) showed some decrease of total magnesium content in cabbage and juvenile plants of spring barley.

The content of P and K in plants treated with sulphur reduced at the stage of rapeseed flowering, but no significant differences were found between plant material harvested at later stages from experimental and control plots. Greater accumulation of nitrogen, sulphur, potassium, calcium and magnesium was found in mature plants fertilised with sulphur (Podleśna 2004).

Interesting observations have been made on the effects of different forms of sulphur on changes in the content of heavy metals in soil and yields of tested pollution indicator plants. Biogeochemical cycles are usually characterised by some regularity, but because of human economic activity may be incomplete and acyclic due to a deficit or excessive supply of certain compounds. The solubility of trace metals is often presented as a function of soil pH. Sulphur fertilisation usually decreases soil pH, but simultaneously it increases the concentrations of nutrients available to plants, such as Zn, Cu and Mn (Kabata-Pendias, Pendias 1992).

The increase in sulphur content in soil is associated with an increase in the levels of manganese, and sometimes aluminium in plants. No regular unidirectional changes in the content of these elements were found caused by increased concentrations of sulphur in soil (Gądor, Motowicka-Terelak 1986). Similar findings were made by Pyś and Pucek (1993*c*), who investigated crops grown near sulphur landfill sites. The levels of manganese and iron increased in the tested plants, but the molybdenum content decreased after the experimental supplementation of potassium sulphate (Nurzyński 1974). Terelak et al. (1996) found that soil contamination with sulphur increased the bioavailability and accumulation of Cd and Pb in crops. Sulphur fertilisation to some extent influenced the increase and uptake of selenium by alfalfa, and increasing doses caused a reduction in the content and uptake of selenium (Patorczyk-Pytlik et al. 2009). Changes in the content of zinc and manganese in plants after supplementation with sulphur varied depending on plant species and organ, as indicated by Jankowski et al. (2014*a*). Sulphur fertilisation increased the content of Zn and Mn in root debris, and significantly decreased the content of Mn in white mustard straw Jankowski et al. (2014*b*).

The results of studies investigating the impact of sulphur on changes in the content of heavy metals are ambiguous and demonstrate either synergistic or antagonistic interactions. In order to verify and consolidate knowledge on this subject, further studies are necessary, both on soils with a natural content of heavy metals and artificially contaminated soils, and the simultaneous monitoring of crops.

CHANGES IN THE CONTENT OF ORGANIC COMPOUNDS

By influencing nitrogen metabolism, sulphur determines both crop yield and yield quality (Krauze, Bowszys 2000, Podleśna 2003). Sulphur fertilisation modifies fat content in experimental plants.

Findings from investigations on the effect of sulphur on the content and quality of fats in plants are inconclusive. For example, Goźliński (1970*b*) reported an increase in the content of fat in mustard seeds after fertilisation with sulphur. Similar findings were made by Barczak et al. (2013) in their experimental study on the narrow-leaved lupin, while Babuchowski (1971) concluded that supplemental fertilisation with sulphur only decreased fat content in seeds and increased oil pH. Considering unsaturated fatty acids, the most significant changes were found for erucic acid, whose content increased during seed ripening. On the other hand, the content of saturated fatty acid (palmitic acid) decreased significantly. Sulphur fertilisation decreased the content of fat and increased the content of protein in seeds (Wielebski 2011). No effects of sulphur fertilisation on the amount of fat in oilseed rape seeds were found (Krauze, Bowszys 2001). This was also confirmed in studies by Wielebski and Wójtowicz (2004), who found no significant modifications in the content of fat and protein in seeds after spring fertilisation with nitrogen and sulphur.

The nutritional value of fat is mainly determined by the content of unsaturated fatty acids (UFA). Fertilisation of spring oilseed rape with sulphur improves the nutritional value of fat through a significant increase in UFA ($C_{18:2}$ and $C_{18:3}$). Wierzbowska et al. (2012) found that sulphur supplementation increased the content of linoleic acid ($C_{18:2}$), but decreased the content of oleic acid ($C_{18:1}$) in oil pressed from milk thistle seeds. Wielebski (2011) applied sulphur and did not find any significant changes in the levels of seven major fatty acids in oil, or any significant correlation between nitrogen and sulphur in modifying the content and yield of fat, protein or share of fatty acids in oil pressed from investigated oilseed rape varieties.

Many researchers have emphasised the effect of sulphur fertilisation on the content of glucosinolates in seeds, which determines the suitability and value of oilseed rape meal feed. Studies demonstrated that excessive fertilisation with sulphur increased the content of glucosinolates (Horodyski, Krzywińska 1979, Wielebski, Muśnicki 1998*b*, Wielebski 2011).

Glucosinolates help to prevent *cancer* as they are precursors of compounds with potential anticancer activity and exhibit antiviral, antifungal and antibacterial activity on many human pathogens. It is believed that foods containing glucosinolates have functional and health-promoting properties (Sosińska, Obiedziński 2007). Glucosinolates contribute to plant defence against herbivores, pathogens and insects, and thus are also termed natural pesticides (Gaj, Klikocka 2011).

Different conclusions have been made on the content of glucosinolates in oilseed rape. For example, supplemental fertilisation with sulphur decreased the nutritional value of rapeseed. Babuchowski (1971), in an experiment with high doses of sulphur fertilisers, found that sulphur excess had a negative effect on the processing value of winter oilseed rape seeds and oil, and deteriorated the quality of fodder meal. Sulphur is an important component of glucosinolates, and therefore the amount of S available to plants significantly affects the level of these substances (Wielebski, Muśnicki 1998*a*). Seeds from oilseed rape fertilised with boron and sulphur had a significantly increased content of L-5 *vinyloxazolidinetion*, a compound of goitergenic activity causing functional and morphological changes in the thyroid. Isothiocyanates prevent the uptake of iodine from the blood, and a slow loss of this element accumulated earlier in the thyroid gland. The toxic effect of L-5 vinyloxazolidinetion is mainly attributed to the inhibited tyrosine iodination, which results in the formation of goiter in cattle and sheep, swine and poultry (Koter et al. 1976). Barczak (2010) found that the use of sulphur was the only factor determining and modifying the content of secondary metabolites (glucosinolates and fatty acids) in white mustard seeds. Sulphur caused a greater increase in the content of alkene forms of glucosinolates than in their total level. Considering other identified secondary metabolites the application of sulphur had the strongest impact on the increase in the content of sinalbin and linoleic acid. Shortage of sulphur in fertilisers limited the synthesis of thioglycosides and other organic thiocompounds in black radish plants (Koter, Benedycka 1984).

Sulphur supply to plants demonstrably affected the quantity and composition of glucosinolates accumulated in seeds. Increasing doses of sulphur had the strongest impact on the content of progoitrin, followed by gluconapin and glucobrassicanapin. Treatment of two oilseed rape varieties with increasing doses of sulphur increased the share of alkene glucosinolates, but decreased that of the indole fraction. The content of glucosinolates in seeds of both varieties was strongly correlated with the content of sulphur in the youngest leaves of plants at an early flowering stage. Sulphur fertilisation slightly decreased the accumulation of fat and protein in seeds without changing their energy value, and caused a minor improvement in the share of pure protein in the total protein (Wielebski 1997, Wielebski, Muśnicki 1998*a*,*b*, Wielebski, Wójtowicz 2003, 2004).

EFFECT OF SULPHUR ON PLANT HEALTH AND DISEASE RESISTANCE

The use of elemental sulphur for disease and pest control was discovered between the late 18^{th} and early 19^{th} century. Sulphur paste or powder suspensions have been widely used to control powdery mildew on fruit trees and vegetables. Foliar application of elemental sulphur demonstrated that it is also effective in controlling rust and powdery mildew in cereals, and can successfully eliminate *Erisiphe graminis* and *Streoptomyces scabies*. The fungicidal efficiency of sulphur results from its direct influence on pathogens or the activity of sulphur reduction products (Gaj, Klikocka 2011).

Researchers investigating the beneficial effects of sulphur fertilisation have started to pay attention to its efficiency in limiting infectious diseases of crops, particularly in *Brassicaceae* and oily plants containing glucosinolates. Glucosinolates are a wide group of bioactive compounds and provide natural protection for plants against pathogenic microorganisms and herbivores. Being biodegradable substances, glucosinolates can be used as biofumigants to control pests, especially in crops for consumption (Piekarska et al. 2010). Alliin, a substance containing sulphur and found in garlic and onion, is another compound with antibacterial and fungicidal properties. The enzyme alliinase converts alliin into allicin (diallyl sulfide), having bactericidal activity (Marska, Wróbel 2000). Studies on the adjuvant use of sulphur in plant protection, prevention of fungal diseases and infestation of crops have provided ambiguous and conflicting results.

For example, the protective effects of sulphur were reported by Miazga et al. (1985), who fumigated cereal crops with sulphur dioxide, and its reaction products with ammonia. The researchers found a clear reduction in the infestation of cereals by *Puccinia graminis* and *Erisiphe graminis*. Jędryczka et al. (2002) reported that sulphur in mineral fertilisers had a protective effect in controlling *Alternaria brassicae*, *Blumeria graminis DC* on oilseed rape leaves. Some studies have also demonstrated an increased content of glucosinolates in plants fertilised with sulphur, which stimulated natural resistance to fungal infections. Podleśna et al. (2005), Podleśna (2005) reported that sulphur fertilisation did not provide full protection for oilseed rape against fungal diseases but still significantly reduced their severity. Moreover, less downy mildew was observed on spring oilseed rape fertilised with sulphur. However, Sadowski et al. (2002) found no correlation between sulphur fertilisation and occurrence of powdery mildew. Foliar feeding of spring oilseed rape with sulphur can to some extent limit the occurrence of powdery mildew and sclerotinia rot (Sadowski et al. 2005).

Sulphur used as soil fertiliser increased the total content of glucosinolates, including their alkene forms, and reduced seed infection with *A. brassicae* by 11.6%. A negative correlation was found between the level of alkene glucosinolates (progoitrin, gluconapin and glucobrassicanapin) in seeds and plant infection with *A. brassicae* (Figas et al. 2008). Szulc et al. (2009) tested fertilisation rates of nitrogen (0, 30, 60, 90, 120,150 kg ha^{-1}) and elemental sulfur (0, 20,40 kg ha^{-1}) and found no differences in damage caused by frit fly (*Oscinella frit* L.) and the European corn borer (*Ostrinia nubilalis)*. Elemental sulphur used in different doses had no impact on the number of plants with symptoms of common smut or fusariosis. Kurowski and Jankowski (2003*a*) found no significant effect of sulphur fertilisation on the development of diseases in white mustard and red mustard. Sulphur fertilisation was only associated with a slightly lower infection of experimental plants with pathogens and selected diseases (Kurowski, Jankowski 2003*b*). Studies on the effect of sulphur on the health of roots in winter wheat also provided inconclusive results (Majchrzak et al. 2010).

CONCLUSIONS

As early as in 1956 Strzemski wrote that "(...) attributing sulphur only an intermediate role in improving the yield of crops is without any doubt a certain exaggeration." The activity of sulphur in plants is multidirectional due to its high impact on nitrogen metabolism. This can be considered in three aspects: direct impact on yield and its quality, increased resistance to pathogens and environmental impact. Sulphur shortage reduces the photosynthetic performance and the synthesis of carbohydrates and proteins. Currently, it can be said without any exaggeration that sulphur significantly affects many aspects of crop quality, including vegetative and generative development, modification of plants' chemical composition, and it has protective activity and the multifunctional role of sulphur, ranging "from nutrition to protection". Problems related to sulphur in various aspects are still vital and, by offering space for exploration, have invariably attracted the attention of creative researchers representing different scientific approaches.

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