JOURNAL OF AGRICULTURE AND APPLIED BIOLOGY
2022, Vol. 3, No. 1, 40 - 49
http://dx.doi.org/10.11594/jaab.03.01.05
E-ISSN: 2723-5106

Review Article

Sulphur and particulate matter affecting on soil and underground plants

Haroon Ejaz[1]*, Eshrat Bibi[1], Waqas Ali[2], Ikhlaq Ahmad[3], Aamna Lashari[1], Hadia Faiz[1], Wajeeha Nazar[1]

[1]Department of Chemistry, Faculty of Science, Lahore Garrison University, Pakistan
[2]Department of Agronomy, Faculty of Agriculture, Agriculture University Faisalabad, Pakistan
[3]Department of Chemistry, Minhaj University, Lahore, Pakistan

Article history:
Submitted 01 September 2021
Accepted 16 March 2022
Published 13 April 2022

Keywords:
Accretion
Accumulation
Diversity
Implications
Inhibition
Reductase
Sulphoixides
Thiophene

**Corresponding author:*
E-mail:
haroonejaz4114@gmail.com

Abstract

Environmental problems were faced, and one of them is the accumulation of Sulphur and its compounds in the atmosphere and through the atmosphere, it accumulates in the soil and then the underground plants. In the atmosphere Sulphur it is present in the form of aerosols and acid precipitation. Volatile Sulphur compounds are released by the combustion of fossil fuels and volcanic eruption also produces Sulphur oxides. Deficiency of Sulphur produces paling of plants and denaturing of some enzymes that are then fulfilled by using the fertilizers of Sulphur. Soil also has an adverse effect when particulate matter or Sulphur aggregates in the plants and their physiological and biological development is retarded. Most of the industrial processes contain Sulphur compounds like thiol, thiophene, oxides of Sulphur etc. Structural and chemical mutation occurs when particulate substances induce into the plants and productivity and efficiency of that plant is reduced. The impact of acid rain in places with high quantities of mixed air pollutants has yet to be determined. Acid inputs appear to be affecting several techniques in field soils. These must be measured in terms of plant output. SO_2 enters the leaves via stomata and quickly dissolves in Apoplastic water, producing mostly Sulphite $(SO_3)^{-2}$, bisulphite (HSO^{-3}), and H+ ions. SO_2 phytotoxicity has been attributed to Sulphite and bisulphite ion interactions with different chemicals. If the quantities are not too high, most leaves can detoxify Sulphite and bisulphite by oxidizing them to less harmful Sulphate ions via a series of processes. SO_2 absorbed by foliage may undergo reduction conversion, including absorption into organic Sulphur compounds and release from the leaves as H_2S. The oxidizing or reducing route of SO_2 in plants is determined by plant species, soil Sulphur content, SO_2 amount and persistence, and plant growth conditions.

How to cite:
Ejaz, H., Bibi, E., Ali, W., Ahmad, I., Lashari, A., Faiz, H., & Nazar, W. (2022). Sulphur and particulate matter affecting on soil and underground plants. *Journal of Agriculture and Applied Biology, 3*(1): 40 - 49. doi: 10.11594/jaab.03.01.05

Introduction

The whole world is facing huge problems some economically, some socially, and some environmentally. These problems put long-lasting effects that are increasing day by day with the development of the world. One of the major environmental problems is air pollution which has adverse effects on humans and other living organisms. Particulate matter includes generally minute particles of metals, nitrates, sulphates, smoke, dust particles, soil, carbon oxides etc. these particles can be classified into two types: 1. Coarse particulate matter (10 μm) 2. Fine particulate matter (2.5μm) (Kim et al. 2015). Underground plants are generally affected by the fertility of the soil and the temperature at which they are grown then fertilizers are added to manipulate the soil fertility (Hamilton et al. 1998). Pollution is increasing rapidly, so it is important to measure the concentration (Kapitány et al. 2020).

Table 1. Global emission of particulate matter (Davidson et al., 2005)

Source	Natural (Tg year^{-1})		Human (Tg year^{-1})
Sulphate from biological gasses	130	Black Carbon	13
Volcanic Sulphate	40	Sulphate from SO_2	190
Biogenics (terpenes)	13-60	Organic carbon, biomass, fossil fuel burning	70
Nitrates	60	Volatile Organic compounds	10
Total	223-270	Total	283

There are different sources of particulate matter may be natural or anthropogenic sources. It is very difficult to verify or identify which source is producing coarse particulate matter and which one is producing fine particulate matter (McGrath & Zhao, 1995). These sources must be taken into account for their better understanding.

Then if the sources are identified then it is difficult to know the emission for example ammonia different emission in soil by fertilizers, livestock manure etc. It is different in different places. Mostly Sulphur is present in its organic form which is approximately 50 per cent (Williams & Steinbergs, 1959). The effect of various strategies on the concentration of organic compounds is also unknown for example chemical interaction of different oxides of nitrogen, Sulphur, and ammonia (Davidson et al., 2005). Sulphur is the inorganic compound belonging to the sixth group having the valence 2, 4, 6 in different compounds of Sulphur. Sulphur and its derivatives are present in the form of sulphates (inorganic form) and amino acids or protein synthesis (organic form) (Roy et al., 1970). During the fumigation period accretion of Sulphur in vegetation, occurrence, and application, the plant's capability of removing injury or wounds and it's not related with the average sulphation rates. The consequences of terrestrial moss-lichen carpet annihilation are also due to the accretion of Sulphur and its compounds (Case & Krouse, 1980). It is studied that out of 100% only 7% Sulphur is present inorganically while the rest of it is present in the organic form because mostly it is covalently attached with nitrogen where 59% is converted to hydrogen sulphide (Freney, 1961). DMS (dimethylsulphide) is significant in the environmental Sulphur cycle as it is used in the food industry as flavoring agent in beverages, wines, synthetic or canned food. This DMS is then is converted to hydrogen sulphide and its methylation is done by micro-organisms (Schäfer et al., 2010). Therefore, Sulphur has a different amount of concentrations from different sources.

The main purpose of this review is to study the effect of particulate matter and especially the effect of Sulphur and its compounds in soil. The plants' structure changes due to accretion of Sulphur and other particulate matter. These

changes may lead to biological changes, physiological changes and then environmental changes. Accumulation of particles also causes diseases that affect the growth and productivity of plants.

Sulphur as particulate matter and its sources

Normally, when coal and oil are burnt it produces Sulphur dioxide and Sulphur trioxide which react with elements in the atmosphere and produces sulphides and sulphates. It has been observed that air pollution is caused by the increase or decrease of the particulate matter present as the atmosphere constituent. Many health issues are seen especially respiratory disorders and cardiac diseases (Bircan, 2016). These diseases are increasing rapidly around the globe.

The gaseous Sulphur is readily present in the atmosphere when inhaled by living organisms it blocks the alveolar sacs and causes bronchial diseases. More exposure of the Sulphur oxides to the respiratory tract causes mechanical changes in the lungs (Frank, 1964). Sulphur and its compound usually are emitted by the vehicles or the fuel using the equipment. It can be in the form of sulphates, Sulphur oxides, sulphuric acid and different forms of aerosols that contaminates the air quality, affecting the environment and the living standards. The amount of Sulphur and its compounds in the environment is measured by its usage by the fuel (Turalioğlu, 2005). That is why emission of Sulphur by the fuel is very much important.

Table 2. Sulphur content of petroleum fuel and natural gas (Reddy & Venkataraman, 2002)

Fuel	Sulphur content (wt. %)
Petrol (gasoline)	0.2
High speed diesel oil (HSDO)	1.0
Low speed diesel oil (LSDO)	1.8
Fuel oil	4.0
Low Sulphur heavy stock (LHSS)	2.0
Kerosene	0.2
Liquefied petroleum gas (LPG)	0.02
Natural gas	0.00064

Volatile compounds of Sulphur are released by the burning of biomass, pre-industrialization, combustion of fossil fuels and some from petrochemicals, paper industry, oil spillage, municipal sewage industry and ore smelting. By burning of fossils and oil spillage mostly contains thiols and sulphides. The Paper and pulp industry forms organic Sulphur compounds. Most of the mercaptans, trisulphide and sulphites are produced by the waste of plants when converted to coke and coal. Emission of Sulphur usually in the atmosphere is in the form of Sulphur oxides which react with vapors present in the atmosphere forming sulphuric acid and then acid rain formation (Wardencki, 1988). This means that almost every industry involves the emission of Sulphur compounds.

Soil have different forms of Sulphur may be elemental Sulphur or sulphates that mineralize the soil and enhances the fertility of soil due to which plant growth is accomplished. This soil is having organic and inorganic forms of Sulphur and is treated with oxidizing agents or reducing agents and converted the sulphates to metallic sulphides or hydrogen sulphides and then dispose of it by diluting them it with acid-forming hydrogen sulphide gas (Little, 1957). Different processes are used to convert inorganic Sulphur to organic Sulphur by means of reduction by hydrogen iodide or other processes like mineralization and immobilization (McLaren et al., 1995). This leads highly toxic sulphur to less toxic one.

Sulfur Cycle

In rocks and salts or in marine sediments, the majority of the earth's sulphur is trapped. The atmosphere also contains sulphur. Through both natural and man-made sources, it penetrates our environment. Volcanic eruptions, microbiological activities, water evaporation, and decomposing organisms are all examples of natural resources. Sulphur dioxide (SO_2) and hydrogen sulphide (H_2S) gases are released on a large scale by industrial activities when sulphur enters the atmosphere through human activity.

With oxygen or other chemicals present in the environment, the sulphur dioxide reacts to form sulphur trioxide gas (SO_3), or to make sulphuric acid. Sulfuric acid can also be produced by the reaction of sulphur dioxide with water (H_2SO_4). Demethylsulphide, which plankton species release into the atmosphere, may also generate sulphuric acid.

Eventually, all of these particles will fall back to the ground, or they will react with rain and form acid deposition. The sulphur cycle will begin again once the particles are absorbed by plants and released back into the atmosphere (Goldhader, 1975). The sulphur cycle will begin again once the particles are absorbed by plants and released back into the atmosphere.

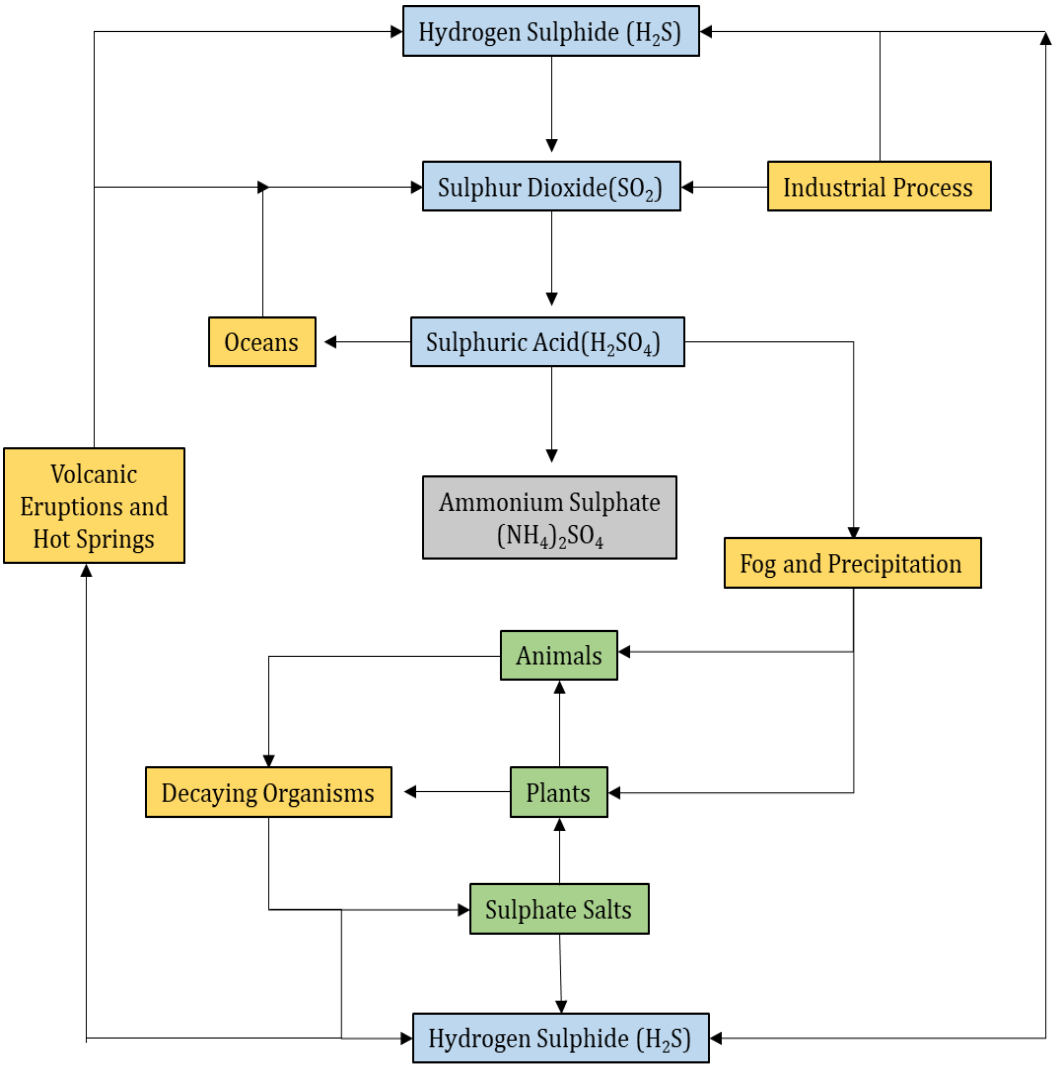

Figure 1. Sulphur cycle

Effect of sulphur on ground plants

Usually, Sulphur plays an important role in photosynthesis and the accumulation of dry mass in underground plants. Deficiency of Sulphur produces Cysteine Leucine and loss of Vitamin A so by the fertilization of Sulphur increases micronutrients like copper manganese zinc etc. and nutritive values (Singh et al., 2018). More production of Sulphur in plants increases the therapeutic potency of plants and shows antidiabetic potential due to reduction of glucose serum and enzyme serum (Nasim et al., 2009). Usually, the roots need Sulphur and nitrogen-rich soil so that it enhances its yield and quality (Thomas et al., 2003). Sulphur content affects the yield of the crops but it also affects the quality. The crops that do not have Sulphur, it is provided externally which increases their productivity and quality (Pedersen et al., 1998). All these effects of sulphur show that it is very important that sulphur amounts must be controlled.

The Sulphur is added to the soil by two types of deposition dry deposition of matter and wet deposition where controlled fumigation is done to prevent the Sulphur content (Last, 1982). *Allin* in garlic is metabolized by the *allinase* enzyme and prevent injuries. While the garlic once stored become old then *allicin* is present instead of *allin* (Tesfaye & Mengesha, 2015). Allicin can act synergistically with artificial fungicides.

Effects of plants towards the Sulphur concentration is different at different levels like those exposed directly to the atmosphere have more severe response than those who are indirectly exposed to Sulphur and its compounds (Legge & Krupa, 2002). Physiological and structural changes occur that alter the stomata of the leaves and their cuticle become upraised and the leaves are usually smaller in size (Elliott-Kingston et al., 2014).

Cellular structure is distorted due to the release of sulphoxides and the smell and taste is due to the release of the thiosulphinates. The presence of sulphur and its compound is due to its lability (Sobolewska et al., 2015). *Allicin* activity is related to the sulphydryl enzymes like reductase dehydrogenase (Lanzotti et al., 2013). The roots of the plants mostly contain thiophene in the form of terpenes and flavonoids that are used for oil synthesis (Bitew & Hymete, 2019).

Effect of oxides of sulphur

Sulphur oxides when low in concentration effects physiological responses and growth of plant but its optimum level is important for the high growth rate. When the Sulphur oxides exceed the optimum level it become toxic that causes decrease in productivity and growth rate. Sulphur oxide penetrates through leaves and form sulphites, bi sulphides and hydrogen ions that hinders the photosynthesis and sometimes the reactions occur that convert the sulphides and sulphites to less toxic Sulphur compounds and fertilizes the soil texture (Agrawal, 2003). Sulphur dioxide induces growth reduction in the well-watered plant as compared to water-stressed plants. In the growing season, the plant shows the progressive function to soil water stress when exposed to Sulphur oxide (Qifu & Murray, 1991).

The first source of Sulphur is soil and the second main source is from the atmosphere as Sulphur dioxide, phytotoxic produce adverse effects on the plant growth (Weigel et al., 1990). Sulphur dioxide produces two types of injuries mainly: acute and chronic injury. An acute injury is mostly visible at the petiole of broad leaves while the chronic injury is the decolourization of the leaves or chlorosis. This is all due to the acidification of terrestrial and aquatic systems because of the industrialization and modernization or development (Linzon, 1972). This is all due to the acidification of terrestrial and aquatic systems because of industrialization and modernization or development.

Table 3: Shows the exposure of sulphur oxide (Last, 1982)

SO_2 exposure (μgm^{-3})	
Possibly beneficial	<50
Beneficial in some instances Detrimental in other	50-100
Usually decreases growth	100-200
Significantly decreases growth within 1-3 months	200-400

Sulphur dioxide has a biochemical effect as a reducing and oxidizing agent by interfering in the carbon dioxide fixation cycle as SO^{3-} ion is competitive inhibition of ribulose diphosphate carboxylase and interfering in energy metabolism by inhibiting the mitochondrial ATP production by SO^{3-}. All such factors alter the structure of chloroplast and mitochondria. Metabolic systems are unable to cope with the Sulphur causing tissue disruption and bifacial intercostal necrosis (Malhotra & Hocking, 1976). Therefore, sulphur has enormous effects for humans and living organisms.

Loss of biodiversity

Sulphur in the form of Sulphides are phytotoxins that cause microbial reduction of sulphates in anaerobiosis. It is observed that sulphides are strong phytotoxins that affect the growth and ecology at the different organizational levels. Sulfate is sucked up by roots and spread into the plant, and transported through membranes by proton-sulfate co-transporters driven by a proton gradient (Geurts et al., 2009). Sulphite is oxidized to sulphates by the enzyme called sulphite oxidase. This is vertebral enzymes consuming cytochrome c causes neurological disorders in the same way it is present in the plants causes chlorosis (Brychkova et al., 2007). Some factors should be under consideration while providing Sulphur i.e. sowing of crops, deficiency of Sulphur on time, decreasing the use of phosphatic fertilizers so that sulphate ions from colloidal solution should be desorbed in less amount (Aulakh, 2003). This all shows that sulphur is affecting biodiversity.

Oil refinery produces Sulphur dioxide near populated areas where it reacts with other particles to form dilute sulphuric acid which in produces acid rain affecting the nearby buildings especially the corrosion of marbles of the building (Goyal & Singh, 1990). When more accumulation of Sulphur and its compounds occur it acidifies the soil for plant growth because of large exposure of soil to the particulate matter or excess use of fertilizers (Lochman & Fadrhonsova, 2004). Acidification of soil increases the pH unfavorable for the productivity of crops and hinders the yield (Karlsson et al., 2011). So, for better productivity of crops, sulphur amounts should be controlled.

Sulphur containing agrochemicals

Agrochemicals are usually called as pesticides or fertilizers to control; the pest attack or to enhance the crop yield. Sulphur compounds are mostly used as pesticides to control the powdery mildews leafspot, brown rot, downy mildew etc. Sulphonylureas herbicides are used mostly on major agronomy crops including sulfonyl sulfur attached with an ortho-substituted aryl or hetero aryl group (P) and the nitrogen in urea is bonded with the nitrogen and has the heterocyclic (Q) i.e. pyrimidinyl heterocycles. Sulphonamide herbicides along with carbamates to control the stubborn weeds usually used as Sodium and Potassium salts (Devendar & Yang, 2019). Sulphur containing compounds are also used as agrochemicals at a large scale, therefore, they also contribute to the increase in sulphur concentrations.

Table 4. The agrochemical effects as the content of soy seeds in various types of sulphur treatment % (Burkitbayev et al., 2021).

Treatment			
Powder Sulphur containing agrochemicals	Sulphur containing solution agrochemicals	Pasty Sulphur containing agrochemicals	Control
35.5±0.82	36.6±0.77	37.3±1.01	32.9±0.33

Effect of sulphur on human health that eat sulphur contaminated plants

Sulphur generally affects the metabolism reaction. In plants, Sulphur is present about 70% in the form of amino acids. Humans do not have Sulphur containing amino acids, its need usually fulfilled by the diet or nutrition obtained from outside the body (Prasad, 2014). The normal person inhales almost 8 ppm of Sulphur when having the mask on his face in 10 minutes while the person who works in the environment of Sulphur dioxide, it inhales more than 10 ppm of it and respiration becomes difficult for him (Amdur et al., 1953). Sulphur from industries in the form of Sulphur oxides and sulphuric acid are good combustion Sulphur while there are some oils that emit less Sulphur are used in kitchens for cooking purposes. Chemical reactions convert the Sulphur to different forms of pollution Sulphur dioxide is converted to sulphuric acid that affects rain or fertility of soil etc. (Ellison & Waller, 1978). That is why, sulphur amounts should be checked properly in the food items.

Effect of sulphur in biology

Sulphur plays a prehistoric environment for different biological processes like catalytic activities and structural functions. The elemental form of Sulphur is reduced to form hydrogen sulphide to give energy to the Desulphuromonas and archaea and when oxidized, provides energy to the Beggiatoa but when it splits during the process of photosynthesis form hydrogen for the green and purple Sulphur bacteria in plants. The Allium family generally form different compounds of Sulphur that affects human health when stored for a long time period. It is evident from some research that Sulphur compounds are beneficial against fungal and viral attacks. It controls the protein synthesis by modifying the tRNA and activity of enzymes by reducing the cell capacities of cells (Toohey & Cooper, 2014). Antimicrobial activity is due to the high content of Sulphur against pneumonia and sulphanilamides interrupt the manufacturing of folic acid (John-Dewole et al., 2012). The biological activities of thiophenes show mainly *in vitro effects* and they have also insecticidal, anti-fungal potential and anti-proliferative effects. Fatty acids having Sulphur in them are deduced from garlic which is used for the synthesis of palmitic acid and stearic acid (Dembitsky et al., 2007). In some wines manufactured by grapes Sulphur compounds, especially thiol are added for their flavor and to reduce the effect or odor of Sulphur metabolism by yeast is done (Rauhut, 2017). Therefore, the effects of sulphur in biology are also important.

How to reduce sulphur compounds in atmosphere?

Mostly the Sulphur is emitted in atmosphere by combustion process of fossil fuel. Coal combustion produces a large amount of Sulphur oxides and to reduce its production some additives are mixed with coal i.e. dry Wyoming Trona in powder or granular form (Cook & Maitland, 1974). Thermal power coal combustion is the largest contributor of Sulphur dioxide (Reddy & Venkataraman, 2002). To increase the efficiency of energy need in industry we should reduce the consumption of Sulphur dioxide or desulphurization is done (Yuan et al., 2013). Sulphur gives green color to the plant mostly in alfalfa in the form of sulphates and provided to the soil to leach it (Sahota 2006). The excess Sulphur is related to livestock and the Sulphur present in air to overcome it or to reduce the excess Sulphur, by lessening the sulphate leaching and by reducing the extra use of fertilizers (animal manure) which are considered to be the most efficient way of increased Sulphur in the atmosphere (Eriksen, 2009). When Sulphur is oxidized it becomes less toxic.

so the Sulphur is then oxidized by using bacteria that is chemolithotropic bacteria from thiobacillus genus (Vidyalakshmi et al., 2009). We should increase the use of carbonates so that the alkalinity of soil is increased and the acid produced from sulphates could be neutralized so the acidity of the soil is neutralized and the pH should be increased (Hussain et al., 2021; Nilsson, 1988). All these methods should be followed in order to control sulphur in the biosphere.

Conclusion

The second most important nutrient after nitrogen is Sulphur which is present in the form of oxides and sulphates that penetrates the soil through the stomatal openings and roots that enters the plant affecting the catalytic activity and enzymatic processes. The plants with underground bulb-like garlic, onion, etc. lack its productivity when more Sulphur is accumulated in their stem and storage for a large time will change the plant physiology. Mutation occurs that changes the structure of enzymes and amino acids as inhibitors due to which some diseases occur. It is not usual that Sulphur is accumulated every time it is sometimes deficient in the soil causing discolouration of plant or other diseases. When animals eat these plants in result, they also will catch some diseases. To reduce the particulate effect of Sulphur should use additives so that Sulphur is emitted in a less deleterious form. Soil leaching is done by using Sulphur fertilizers. Sulphur compounds are very toxic if present in excess inhibiting the activity of the enzyme and causing structural changes, especially in the structure of cytoplasm and membranes. The leaf cuticle becomes upraised and the cuticle becomes thin and may cause injury in underground plants. Alone Sulphur can do nothing, it works along with other nutrients in the soil and when in the atmosphere becomes more adverse for plants as well as other living organisms. Health effects are also observed on humans who ate Sulphur contaminant plants. The effects may be beneficial or adverse depending upon the concentration of its Sulphur content.

Acknowledgement

The assistance provided by Head of the department; Lahore Garrison University is highly appreciated. Furthermore, I would like to thank Head of the department, Agriculture Department, Agricultural University Faisalabad for his guidance.

Author's declaration and contribution

There are no conflicts of interests with this review article.

EB has done all the research work regarding reviewing. HE designed this study. WA carried out laboratory work and analysed data. All authors read and approved the final version of the manuscript.

References

Agrawal, M. (2003). Plant responses to atmospheric sulphur. In *Sulphur in plants* (pp. 279-293). Springer.

Amdur, M. O., Melvin Jr, W. W., & Drinker, P. (1953). Effects of inhalation of sulphur dioxide by man. *Lancet*, 758-759.CrossRef

Aulakh, M. (2003). Crop responses to sulphur nutrition. In *Sulphur in plants* (pp. 341-358). Springer.

Bircan, A. Effects of atmospheric sulphur dioxide and particulate matter concentrations on emergency room admissions due to asthma in Ankara. Direct Link.

Bitew, H., & Hymete, A. (2019). The genus Echinops: Phytochemistry and biological activities: A review. *Frontiers in Pharmacology*, *10*. CrossRef

Brychkova, G., Xia, Z., Yang, G., Yesbergenova, Z., Zhang, Z., Davydov, O., . . . Sagi, M. (2007). Sulfite oxidase protects plants against sulfur dioxide toxicity. *The Plant Journal*, *50*(4), 696-709. CrossRef

Burkitbayev, M., Bachilova, N., Kurmanbayeva, M., Tolenova, K., Yerezhepova, N., Zhumagul, M., . . . Demeu, G. (2021). Effect of sulfur-containing agrochemicals on growth, yield, and protein content of soybeans (Glycine max (L.) Merr). *Saudi Journal of Biological Sciences*, *28*(1), 891-900. CrossRef

Case, J., & Krouse, H. (1980). Variations in sulphur content and stable sulphur isotope composition of vegetation near a SO 2 source at Fox Creek, Alberta, Canada. *Oecologia*, *44*(2), 248-257. CrossRef

Cook, W., & Maitland, J. (1974). Method of reducing sulphur dioxide emissions from coal. In: Google Patents. Direct Link.

Davidson, C., Phalen, R., & Solomon, P. (2005). Airborne Particulate Matter and Human Health: A Review. *Aerosol Science and Technology*, *39*(8), 737-749. Direct Link.

Dembitsky, V., Abu-Lafi, S., & Hanus, L. (2007). Separation of sulfur-containing fatty acids from garlic, Allium sativum, using serially coupled capillary columns with consecutive nonpolar, semipolar, and polar stationary phases. *Acta Chromatographica*, *19*, 206. Direct Link.

Devendar, P., & Yang, G.-F. (2019). Sulfur-containing agrochemicals. In *Sulfur Chemistry* (pp. 35-78). Springer. CrossRef

Elliott-Kingston, C., Haworth, M., & McElwain, J. (2014). Damage structures in leaf epidermis and cuticle as an indicator of elevated atmospheric sulphur dioxide in early Mesozoic floras. *Review of Palaeobotany and Palynology*, *208*, 25-42. CrossRef

Ellison, J. M., & Waller, R. E. (1978). A review of sulphur oxides and particulate matter as air pollutants with particular reference to effects on health in the United Kingdom. *Environmental research*, *16*(1-3), 302-325. CrossRef

Eriksen, J. (2009). Soil sulfur cycling in temperate agricultural systems. *Advances in Agronomy*, *102*, 55-89. CrossRef

Frank, N. (1964). Studies on the effects of acute exposure to sulphur dioxide in human subjects. In: SAGE Publications. Direct Link.

Freney, J. (1961). Some observations on the nature of organic sulphur compounds in soil. *Australian Journal of Agricultural Research*, *12*(3), 424-432. CrossRef

Geurts, J. J., Sarneel, J. M., Willers, B. J., Roelofs, J. G., Verhoeven, J. T., & Lamers, L. P. (2009). Interacting effects of sulphate pollution, sulphide toxicity and eutrophication on vegetation development in fens: a mesocosm experiment. *Environmental Pollution*, *157*(7), 2072-2081. CrossRef

Goldhader, M. (1975). The sulfur cycles. *The sea*, *5*, 569-655. Direct Link.

Goyal, P., & Singh, M. (1990). The long-term concentration of sulphur dioxide at Taj Mahal due to the Mathura Refinery. *Atmospheric Environment. Part B. Urban Atmosphere*, *24*(3), 407-411.

Hamilton, B. K., Yoo, K. S., & Pike, L. M. (1998). Changes in pungency of onions by soil type, sulphur nutrition and bulb maturity. *Scientia Horticulturae*, *74*(4), 249-256. Direct Link.

Hawkesford, M. J., & De Kok, L. J. (2006). Managing sulphur metabolism in plants. *Plant, Cell & Environment*, *29*(3), 382-395. CrossRef

Hussain, S., Aslam, M. U., Javed, M., Zahra, M., Ejaz, H., Kubra, K.-a., & Mushtaq, I. (2021). Impact of Climatic Changes and Global Warming on Water Availability. *Anthropogenic Pollution*, *5*(2), 57-66. CrossRef

John-Dewole, O., Agunbiade, S., Alao, O., & Arojojoye, O. (2012). Phytochemical and antimicrobial studies of extract of the fruit of Xylopia aethiopica for medicinal importance. *Journal of Biotechnology and Pharmaceutical Research*, *3*(6), 118-122. Direct Link.

Kapitány, S., Nagy, D., Posta, J., & Béni, Á. (2020). Determination of atmospheric sulphur dioxide and sulphuric acid traces by indirect flame atomic absorption method. *Microchemical Journal*, 104853. CrossRef

Karlsson, G. P., Akselsson, C., Hellsten, S., & Karlsson, P. E. (2011). Reduced European emissions of S and N–effects on air concentrations, deposition and soil water chemistry in Swedish forests. *Environmental Pollution*, *159*(12), 3571-3582. CrossRef

Kim, K.-H., Kabir, E., & Kabir, S. (2015). A review on the human health impact of airborne particulate matter. *Environment international*, *74*, 136-143. CrossRef

Lanzotti, V., Bonanomi, G., & Scala, F. (2013). What makes Allium species effective against pathogenic microbes? *Phytochemistry reviews*, *12*(4), 751-772. CrossRef

Last, F. (1982). Effects of atmospheric sulphur compounds on natural and man-made terrestrial and aquatic ecosystems. *Agriculture and Environment*, *7*(3-4), 299-387. CrossRef

Legge, A., & Krupa, S. (2002). Effects of sulphur dioxide. *Air pollution and plant life*, *2*, 135-162. Direct Link.

Linzon, S. (1972). Effects of sulphur oxides on vegetation. *The Forestry Chronicle*, *48*(4), 182-186. CrossRef

Little, R. C. (1957). Sulphur in soils. II.—Determination of the total sulphur content of soil. *Journal of the Science of Food and Agriculture*, *8*(5), 271-279. CrossRef

Lochman, V., & Fadrhonsova, V. (2004). Development of air pollutant deposition, soil water chemistry and soil on Šerlich research plots, and water chemistry in a surface water source. CrossRef

Malhotra, S., & Hocking, D. (1976). Biochemical and cytological effects of sulphur dioxide on plant metabolism. *New phytologist*, *76*(2), 227-237. CrossRef

McGrath, S., & Zhao, F. (1995). A risk assessment of sulphur deficiency in cereals using soil and atmospheric deposition data. *Soil Use and Management*, *11*(3), 110-114. CrossRef

McLaren, R., Keer, J., & Swift, R. (1985). Sulphur transformations in soils using sulphur-35 labelling. *Soil biology and biochemistry*, *17*(1), 73-79. CrossRef

Nasim, S., Dhir, B., Samar, F., Rashmi, K., & Mujib, A. (2009). Sulphur treatment alters the therapeutic potency of alliin obtained from garlic leaf extract. *Food and chemical toxicology*, *47*(4), 888-892. CrossRef

Nilsson, J. (1988). Critical loads for sulphur and nitrogen. In *Air pollution and Ecosystems* (pp. 85-91). Springer. Direct Link.

Pedersen, C., Knudsen, L., & Schnug, E. (1998). Sulphur fertilisation. In *Sulphur in agroecosystems* (pp. 115-134). Springer. CrossRef

Prasad, R. (2014). Major sulphur compounds in plants and their role in human nutrition and health–An Overview. Proc Indian Natn Sci Acad, Direct Link.

Qifu, M., & Murray, F. (1991). Responses of potato plants to sulphur dioxide, water stress and their combination. *New phytologist*, *118*(1), 101-109. CrossRef

Rauhut, D. (2017). Usage and formation of sulphur compounds. In *Biology of Microorganisms on Grapes, in Must and in Wine* (pp. 255-291). Springer. CrossRef

Reddy, M. S., & Venkataraman, C. (2002). Inventory of aerosol and sulphur dioxide emissions from India: I—Fossil fuel combustion. *Atmospheric Environment*, *36*(4), 677-697. CrossRef

Roy, A. B., Roy, A. B., & Trudinger, P. (1970). *The biochemistry of inorganic compounds of sulphur*. Cambridge University Press. Direct Link.

Sahota, T. S. (2006). Importance of sulphur in crop production. *Northwest Sci*, *9*, 10-12. CrossRef

Schäfer, H., Myronova, N., & Boden, R. (2010). Microbial degradation of dimethylsulphide and related C1-sulphur compounds: organisms and pathways controlling fluxes of sulphur in the biosphere. *Journal of experimental botany*, *61*(2), 315-334. CrossRef

Singh, S., Sharma, M., Reddy, K., & Venkatesh, T. (2018). Integrated application of boron and sulphur to improve quality and economic yield in potato. *Journal of Environmental Biology*, *39*(2), 204-210. Direct Link.

Sobolewska, D., Podolak, I., & Makowska-Wąs, J. (2015). Allium ursinum: botanical, phytochemical and pharmacological overview. *Phytochemistry reviews*, *14*(1), 81-97. CrossRef

Tesfaye, A., & Mengesha, W. (2015). Traditional uses, phytochemistry and pharmacological properties of garlic (Allium Sativum) and its biological active compounds. *Int. J. Sci. Res. Eng. Technol*, *1*, 142-148. Direct Link.

Thomas, S., Hocking, T., & Bilsborrow, P. (2003). Effect of sulphur fertilisation on the growth and metabolism of sugar beet grown on soils of differing sulphur status. *Field Crops Research*, *83*(3), 223-235. CrossRef

Tingey, D. T., & Reinert, R. A. (1975). The effect of ozone and sulphur dioxide singly and in combination on plant growth. *Environmental Pollution (1970)*, *9*(2), 117-125. CrossRef

Toohey, J. I., & Cooper, A. J. (2014). Thiosulfoxide (sulfane) sulfur: new chemistry and new regulatory roles in biology. *Molecules*, *19*(8), 12789-12813. CrossRef

Turalioğlu, F. S. (2005). An assessment on variation of sulphur dioxide and particulate matter in Erzurum (Turkey). *Environmental Monitoring and Assessment*, *104*(1-3), 119-130. CrossRef

Vidyalakshmi, R., Paranthaman, R., & Bhakyaraj, R. (2009). Sulphur Oxidizing Bacteria and Pulse Nutrition- A Review. *World Journal of Agricultural Sciences*, *5*(3), 270-278. Direct Link.

Wardencki, W. (1998). Problems with the determination of environmental sulphur compounds by gas chromatography. *Journal of Chromatography A*, *793*(1), 1-19. CrossRef

Weigel, H., Adaros, G., & Jäger, H. (1990). Yield responses of different crop species to long-term fumigation with sulphur dioxide in open-top chambers. *Environmental Pollution*, *67*(1), 15-28. CrossRef

Williams, C., & Steinbergs, A. (1959). Soil sulphur fractions as chemical indices of available sulphur in some Australian soils. *Australian Journal of Agricultural Research*, *10*(3), 340-352. CrossRef

Yuan, X., Mi, M., Mu, R., & Zuo, J. (2013). Strategic route map of sulphur dioxide reduction in China. *Energy Policy*, *60*, 844-851. CrossRef