Abstract. Gaseous sulphur dioxide, particulate sulphates and sulphuric acid in wet deposition are the main anthropogenic sulphur species in the atmosphere. Atmospheric emissions of sulphur species result in an increase in acid deposition and tropospheric levels of sulphate aerosols. Anthropogenic emission of \( \text{SO}_2 \) showed a declining pattern in North America and Europe since 1980, however, emissions from South America, Africa and Asia are increasing dramatically. As sulphur is an essential element for plant growth, low concentrations of \( \text{SO}_2 \) have been shown to stimulate the growth and physiological responses, especially for plants growing in sulphur deficient soil, where \( \text{SO}_2 \) might be metabolised to fulfil the demand of sulphur as nutrient. However, the higher uptake of \( \text{SO}_2 \) turns toxic and has been reported to damage plants causing reduction in growth and productivity through interference with different physiological and metabolic processes. \( \text{SO}_2 \) gains entry into the leaves through stomata, and readily dissolves in the apoplastic water to produce mainly sulphite \( (\text{SO}_3^{2-}) \), bisulphite \( (\text{HSO}_3^-) \) and \( \text{H}^+ \) ions. The phytotoxicity due to \( \text{SO}_2 \) has been ascribed to the reactions of sulphite and bisulphite ions with various compounds. Most leaves have the capacity to detoxify sulphite and bisulphite by oxidising them to less toxic sulphate ions through a series of reactions, if the concentrations are not excessively high. The \( \text{SO}_2 \) absorbed on foliage may undergo into reductive conversion including assimilation into organic sulphur compounds and export from the leaves in the form of \( \text{H}_2\text{S} \). The oxidative or reductive pathway of \( \text{SO}_2 \) in plants depends on the plant species, soil sulphur content, concentration and duration of \( \text{SO}_2 \) exposure and developmental stage of plants.

1. INTRODUCTION

Atmospheric sulphur has always been present throughout the course of Earth’s history. Interest in this form has increased tremendously due to concern with environmental pollution, as sulphur pollution is one of the most recognized environmental problems throughout the world, which has generated general public concern also. Anthropogenic sources contribute a significant fraction of sulphur in the atmosphere since the beginning of the industrialization and urbanization. The main anthropogenic sulphur species released into the atmosphere are gaseous \( \text{SO}_2 \) and particulate sulphate. Locally high levels of \( \text{H}_2\text{S} \) may also be due to anthropogenic activity. The reduced sulphur compounds undergo oxidation in the atmosphere to form \( \text{SO}_2 \) which further undergo oxidation, primarily with hydroxyl radicals on the surface of particles, or in precipitation leading to formation of sulphate either in particles or in clouds and rain droplets. Gaseous \( \text{SO}_2 \) may also oxidized due to peroxylradical or ozone, or in the presence of metal catalysts. Rennenberg (1991) described that the contribution of atmospheric sulphur ranges from 38-89 Tg a\(^{-1}\) by marine environment and terrestrial ecosystems. The anthropogenic sulphur emissions are also in the same range, with a high degree of uncertainty. Fossil fuel combustion accounts for 80 to 85% of the total anthropogenic sulphur emission, with the remainder coming from additional sources such as certain metallurgical processes, petroleum refineries, coking of coal, manufacture of paper and pulp, other industrial processes and burning. The emission of sulphur from these sources is largely in the form of gaseous \( \text{SO}_2 \). \( \text{H}_2\text{S} \) is other
sulphurous form known to be phytotoxic (De Kok, 1990). H₂S emission and utilization has been dealt with by Lakkineni et al. (this book). The present review will be restricted to the consequences of SO₂ influx in plants.

2. PATTERN OF ATMOSPHERIC SULPHUR DEPOSITION

Before the industrial revolution, mean atmospheric S depositions were below 10 kg S ha⁻¹ a⁻¹, but from 1890 to 1980, S deposition increased steadily by 0.47 kg S ha⁻¹ a⁻¹ (Daemmgen et al., 1998) due to increased utilization of fossil fuels along with industrial and urban developments. Sulphur emissions in North America and Europe have shown an upward trend from the early part of the last century into the decade of the 1970, but thereafter a declining pattern was observed due to control measures on sulphur emission in the region (Iversen et al., 1989). The sulphur emission, which was estimated as 17 Tg a⁻¹ in 1970, went down to 12 Tg a⁻¹ in 1985 in North America. Similarly in Western Europe the sulphur emission of 26 Tg a⁻¹ was down to 21 Tg a⁻¹ in 1988 (Iversen et al., 1989). Arends et al. (1997) reported approximately 3% a⁻¹ decrease in summer sulphate concentration in Europe. However, emissions from Asia, South America and Africa are increasing dramatically. The future sulphur emissions estimated on the basis of per capita emission and population growth show increase of 6 times for South America, 7 times for Africa and 6.5 times for Asia (Galloway, 1989). On the basis of average emission density for sulphur (0.4 g m⁻² a⁻¹), the ratio of anthropogenic to natural emissions is of order unity or slightly greater on a global basis but at highly industrialized areas, with high average emission density, the ratio is approximately 10.

Global emissions of SO₂ are 294 mt a⁻¹, of which 160 mt are of anthropogenic origin (UNEP/GEMS, 1991). About 90% of SO₂ emission arise from Europe, North America, and Asia in Northern Hemisphere. The approximate 1980 regional apportionment of fossil fuel sulphur emission is estimated as 16% for China and Japan, 28% for USA and Canada, 34% for Europe, 15% for the remainder of Northern Hemisphere and 7% for Southern Hemisphere (Hameed and Dignon, 1988). Global anthropogenic emissions of SO₃ are predicted to rise by 30% beyond year 2000 upon present day rates due to forecasts of increased coal combustion (Wellburn, 1994).

Global anthropogenic emissions of SO₂ will range from 86 to 106.5 Tg a⁻¹ in 2010 and from 139 to 279.5 Tg a⁻¹ in the year 2100 for the protocol and no protocol scenarios, respectively (Alcamo et al., 1995). Based on the RAINS model, SO₂ emissions in India show an increase of 321% i.e. from 4.48 mt to 18.87 mt under the base scenario during the period 1990-2020 (Panwar, 1998). The percentage of SO₂ emissions from coal and oil are 49 and 29%, respectively in 1990 and would increase to 50 and 40% in 2020 due to increase in share of oil consumption in energy production. Though SO₂ emission from developed countries has been reduced significantly, SO₂ is still the most important atmospheric sulphur form affecting the vegetation.

3. RESPONSES OF PLANT TO SULPHUR DIOXIDE

SO₂ is a unique form of anthropogenic S as its low doses may have beneficial effects on plant productivity but increased uptake causes depressing effects on plant growth.