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Effect of sulphur dioxide (SO_2) enrichment on growth attributes and its biochemical basis in tomato (*Solanum lycopersicum* L.)

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Abstract

Sulphur dioxide (SO_2), belongs to a group of highly reactive gaseous pollutants "oxides of sulphur," that are emitted into the air upon fossil fuel burning and other sulphur-containing discharges from the industry. SO_2 is known to cause damage to plantations and crops by adversely affecting the productivity and the quality of the economic produce. We hypothesized that there exists an inter and intra-species variation with respect to the SO_2 response, which can be exploited. To improve the SO_2 tolerance of crop plants an experiment was, thus, conducted with three varieties of tomato (*Solanum lycoperscium*), var. H-414, H-445, and H-226, developed by IARI, New Delhi to assess their SO_2 response in terms of the growth, yield and biochemical attributes under the ambient (~7 to 25µg SO_2 m^{-3}) and enriched SO_2 (ambient SO_2 + ~10 to 15µg SO_2 m^{-3}). An assessment of crop utilization of SO_2-S as a nutrient source suggests that the variety H-445 was the most potent, H-414 slightly able to absorb and H-226 was the least efficient. The SO_2-mediated damage was observed to increase gradually following the ESO_2 exposure duration in the var. H-414 as against the response in var. H-445 which showed a higher initial ESO_2 damage at 0 DAE but later showed a greater recovery from 0 to 14 DAE. The SO_2 enrichment of the air environment under tomato cultivation was also found to contribute towards the plant's S-requirement in variety H-445, which promoted its vegetative growth even under the stressful environment. Besides genetic variation in SO_2 tolerance in tomatoes, the results also indicate greater adaptability and tolerance in var. H-445 to an elevated SO_2 stress when compared to the other experimental tomato cultivars. Identification of air pollutant tolerant cultivars across crops may help protect the productivity and quality of the major dietary crops, which are likely to be threatened by climate change in the near future.

Key words: Air pollution, climate change, genetic variability, SO_2 enrichment, tomato

Introduction

Deteriorating air quality is a major concern and a risk for human health worldwide. Its adverse impact on crop productivity and quality is also reported (Dong and Wang, 2023), besides its amplifying adversity when tied along with the climate change scenario (Agathokleous *et al.*, 2023). The quantum of air pollutants or the air quality, in principle, is measured in terms of the National Air Quality Index (NAQI), based on the following criteria air pollutants, which include carbon monoxide, lead, ground-level ozone, Particulate Matter (PM 2.5 and PM 10), nitrogen dioxide and Sulphur dioxide. A rapidly depleting air quality index (AQI) owing to an increasing level of the criteria air pollutants is expected to cause a serious dent in the crop yield and the food security of a developing country like India (Kumar, 2023).

Air pollutants can negatively impact crop yield depending on the emission pattern, atmospheric transport, leaf uptake, and the plant's ability to defend itself biochemically (Devrajani *et al.,* 2020). Air pollutants can have negative effects based not only on concentration but also on duration and combination of pollutants. The air pollutants spread to a larger area more quickly than the pollutants in the soil and water. Air pollutants can significantly impact the physiology and biochemistry of plants. While some pollutants may promote growth and enhance yields by modifying physiological and morphological processes, the majority are harmful, negatively affecting crop yields and quality (Shrestha et al., 2022). It is beyond doubt that air pollutants cause a decline in the yield of the food crop, which is crucial for crops that provide food and nutritional security. Air pollution is likely to cause a significant reduction in the yield of rice and wheat crops—by up to 50%—both directly and indirectly, particularly in developing nations such as India (Pandya *et al.,* 2022). Research also shows a negative effect of increased SO_2 concentrations in the air on photosynthesis and transport in rice plants (Rai and Agrawal, 2012) and the reduction in biomass accumulation and seed quality of mung bean (Agrawal *et al.,* 2006).

In urban industrial areas, sulphur dioxide and nitrogen dioxide are regarded as the major primary pollutants responsible for causing plant damage. Sulphur dioxide, a gaseous criteria air pollutant can impact crop growth, yield, and quality adversely depending upon the crop tolerance, which is governed by the capacity of the foliage to absorb the gaseous pollutants and detoxify them and/or dispose of the excess load (Rai *et al.*, 2011). According to CPCB, SO_2 levels vary in rural and urban divide with a national mean of 2 to 23 µg SO_2 m^{-3}, which goes up to 60 to 125 µg m^{-3} in the industrial regions. On average the SO_2 levels >50 are considered high and those >75 µg m^{-3} are regarded as critical. In nature, the SO_2, once emitted, is transferred from the atmosphere to surfaces by diffusion (both dry and wet deposition) at variable rates that are strongly influenced by meteorological conditions. While, in the atmosphere, SO_2 is also transformed to SO_4^{2-} which gets deposited on foliar and other surfaces by Brownian motion (dry deposition) and by precipitation (wet deposition). Any observed foliar injury or changes in plant growth and productivity due to SO_2 exposures is essentially the result of dry/wet deposition (Hardacre *et al.*, 2021).

The effects of SO_2 on a plant system are both direct and indirect. The direct effects include loss of chlorophyll or bleaching of the photosynthetically active surfaces due to an increased opening of the stomata leading to a rapid loss of water and/or an unregulated exchange of gases from the crop cover, consequently causing a reduction in crop productivity and quality (Dhupper *et al.*, 2019). The exposure becomes threatening when the concentration of SO_2 and the sulphite derivatives reaches levels higher than the plants' detoxification capacity. Plants may also benefit from SO_2 exposure given that it can contribute to the plants' S- nutrition, and result in enhanced crop productivity, especially in plants growing in sulphur-deficient soils. Wide variation in plant response to SO_2 may exist at the genetic and the species level (Brychkova *et al.*, 2007). The importance of sulphur as an essential macronutrient that is required for optimum growth and development is well known. It is a structural component of protein disulphide bonds, amino acids, vitamins, and cofactors. Since most of the sulphur in soil is present in organic matter, and not accessible to the plants, in the event of an elevated SO_2 condition, prevailing during the crop growth, plants may utilize the gaseous S form SO_2 to fulfill their S-nutrition requirement (Aulakh, 2003). SO_2 also consistently lowers the root-shoot ratio (RSR) (Jones and Mansfield, 1982). Crop yield reduction of 10-50% in response to SO_2 concentration in the range of 75 to 139 µg m^{-3} has been reported (Burney and Ramanathan, 2014). A critical analysis of the available literature reveals a gap in the understanding of the effect of SO_2 on crop plants and its underlying regulatory mechanisms, particularly when SO_2 can also serve as a source of sulphur (S as sulphate, SO_4^{2-}) nutrition and thereby can influence the quality of the produce under a high SO_2 air environment.

The effects of elevated SO_2 on plant growth and development are poorly understood. We hypothesized that an intra-species variability exists in tomatoes in respect of the SO_2 conversion into sulphate, which is then utilized to meet the S-demand. Experiments were, therefore, conducted to determine the tolerance limit of three genetically diverse varieties of tomato and the extent of adaptability to varying levels of SO_2 stress.

Materials and methods

Experimental setup and planting material: An experiment was conducted during winter of the year 2022 in the research farms of IARI, Pusa Campus, New Delhi in the situated between latitude 28° 38' 23" N and longitude 77 ° 09' 27" E at an altitude of 228.61 m above mean sea level (MSL), under the sub-temperate and sub-arid climatic condition. Twenty-one-day-old nursery seedlings of three varieties of hybrid tomato (*Solanum lycoperscium*), *viz*., H-414, H-445, and H-226 were procured from the Division of Vegetable Science, ICAR- Indian Agricultural Research Institute, New Delhi, and were grown in field plots of 9 m^2 size in three replicates. The physico-chemical characteristics of field soil were analyzed before the commencement of the experiment and were as follows: pH 7.9, EC 0.5 dS/m, organic carbon (OC) 0.4%, available N-content of 260 kg/ha, available phosphorus of 37.5 kg/ha, available potassium of 290 kg/ha, available sulphur content of 15 mg/kg, available Zn 2.5 mg/kg, available Fe 60 mg/kg, available Mn 18 mg/kg and available Cu 0.8 mg/kg. Recommended row-to-row and plant-to-plant spacing for tomatoes besides the other routine agronomic practices were followed. Tomato seedlings following transplanting were further acclimatized to the field conditions for another 21 days, before exposing them to varying levels of SO_2 stress.

SO_2 stress under field conditions was created by performing a specific chemical reaction in specially designed chambers laid over the field-grown tomato crop. For this, sodium bisulphite ($NaHSO_3$) was made to react with concentrated hydrochloric acid (HCl) in a petri dish to release sulphur dioxide in a specially designed air-tight PVC enclosure (2 x 1 x 1 m) for exposing field-grown tomato plants to the variable concentration of SO_2, which were ensured by using different quantities of sodium bisulphite. The total duration of SO_2 exposure was 1 hour each day (11 am-12 pm), after which the chambers were removed and plants were allowed to grow under a natural air environment. The SO_2 exposure was practiced for seven continuous days at the following levels: (a) ambient (~7 to 25 µg SO_2 m^{-3}, control, C); (b) ambient + ~ 10 to 15 µg SO_2 m^{-3}, experimental, E). Plant samples were collected at the end of the seven-day SO2 exposure cycle *i.e.*, at zero- day after exposure (0 DAE) and at the 7th and 14th day after exposure (7 and 14 DAE, respectively) post the SO_2 exposure. At each of the sampling stages, plants were harvested, processed, and analyzed for different morphological and biochemical attributes as per the following details.

Shoot and root characteristics: Shoot biomass, root biomass, root-shoot ratio (RSR), and root surface area were recorded under the ambient and elevated SO_2 conditions at 0 DAE, 7 DAE, and 14 DAE). Shoot and root biomass was recorded by separating the freshly harvested plants into the shoot and the root tissues and drying them in an open-air oven maintained at 80^{0}C for a few days until complete dryness was achieved. The respective tissue biomass was expressed as g dw $plant^{-1}$. Root surface area was recorded using a root area meter (Biovis PSM root scanner, Expert Vision Labs Pvt Limited, Mumbai) and expressed as cm^2 $plant^{-1}$.

Leaf characteristics: Leaf attributes were measured in terms of leaf number, total surface area, and necrotic surface area at various sampling stages *i.e.*, at 0, 7, and 14 DAE. The number of leaves in each plant was physically counted and their surface area was determined using a leaf area meter (Biovis PSM leaf area meter, Expert Vision Labs Pvt Limited, Mumbai). The total leaf area, taken as the mean of three treatment replicates, was expressed as cm^2 $plant^{-1}$. For the same leaves, the total necrotic leaf surface area, as affected by the SO_2 exposure, was also marked using the leaf area meter as per the details mentioned above.

Leaf chlorophyll content of the tomato plants upon SO_2 enrichment when compared to ambient SO_2 conditions, was measured using the dimethyl sulphoxide (DMSO) method of Hiscox and Israelstam (1979). The absorbance was measured at 645 and 663 nm and total chlorophyll was calculated using the formula given by Arnon (1949), and expressed as (mg g^{-1} fw).

$$\text{Total chlorophyll} = \frac{20.2\ (A_{645}) + 8.02\ (A_{663})^{*}\ V}{W}$$

Where, V = Final extract volume and, W = Weight of tissue extracted.

Leaf sulphate (SO_4^{2-}) sulphur content of tomato plants exposed to the ambient air and SO_2 enriched air environment was estimated following the turbidimetric method (Tabatabai and Bremner, 1970), for which the dried plant tissue samples were ground, and ~500 mg of the powdered sample was subjected to wet di-acid digestion (9:4 part of nitric acid and perchloric acid, respectively) overnight before heating them on a hot plate at 300-350°C until the appearance of the colorless white fumes. The flasks containing a clear solution were air-cooled and the contents were diluted to 50 mL with deionized water and filtered for sulphur estimation. A known volume of the final aliquot was processed with barium chloride dehydrates, gum acacia solution, salt buffer solution, and 6N hydrochloric acid (1:1) following the protocol of Tabatabai and Bremner (1970), and the absorbance was read at 420 nm using a UV-Vis spectrophotometer (Motras Scientific Instruments Pvt Limited, New Delhi). S-concentration and S-content in the tissues were measured against the S-standard curve prepared in a range of 0-10 mg S L^{-1} and expressed as µg S g^{-1} dw and µg S $plant^{-1}$, respectively.

Statistical analysis: The dataset for all the experimental observations taken in triplicates were collated and their mean averages were calculated. The data was subjected to one-way ANOVA and the significance between the observed variations was reflected as the critical difference (cd at a 5% level of significance).

Results and discussion

Effect of elevated SO_2 on growth attributes: Intra-species variation in the growth response of the tomato varieties under the ambient and the elevated level of the SO_2 in the air environment was measured in terms of the shoot biomass, root biomass, root-shoot ratio (RSR), and root surface area at 0, 7 and 14 DAE stages. Tomato var. H-414 showed a continuous decline in the shoot biomass (2 to 32%) over two weeks (between 0 to 14 DAE) following an elevated SO_2 exposure. On the other hand, var. H-445, which showed a severe immediate decline of 35% in shoot biomass at 0 DAE, recouped from the SO_2 stress and recovered its growth in the following period from 0 to 14 DAE and was also able to effectively utilize the SO_2-sulphur for propelling its growth as evident from a 21% increase in shoot biomass under the elevated SO_2 than the ambient control. The variety H-226 showed an immediate decline of ~13% following a week of the elevated SO_2 exposure but showed recovery at later stages of observation, as evident from the observed 8.09 and 1.39 % decline in the shoot mass between the SO_2 stressed and unstressed plants at 7 and 14 DAE stages, respectively (Table 1).

Table 1. Effect of SO_2 enrichment (ESO_2, ambient SO_2 + 10 to 15 µg/m^3) on the shoot biomass (g dw plant $^{-1}$) in three varieties of tomato (H414, H226 and H445) at 0, 7 and 14 days after SO_2 exposure (DAE), when compared with the ambient air SO_2 level (Control, ~7 to 25 µg/m^3). The difference in shoot biomass, at each of the sampling stages under the elevated to control SO_2 treatment is reflected as % change

Variety	Sample	0 DA.E	7 DAE	14 DAE
H414	Control	14.1	22.7	38.5
	ESO_2	13.8	20.4	26.2
	% Change	-2.13	-10.13	-31.95
H226	Control	9.3	17.3	21.6
	ESO_2	8.1	15.9	21.3
	% Change	-12.9	-8.09	-1.39
H445	Control	19.1	22.5	28.8
	ESO_2	12.4	18.1	34.9
	% Change	-35.08	-19.78	21.18

In respect of the root response of tomato varieties to an elevated SO_2 stress, the var. H-414 showed an insignificant SO_2 phytotoxicity at the 0 DAE stage but showed an increasing toxicity response at later stages from 7 to 14 DAE (Table 2)

Table 2. Effect of SO_2 enrichment (ESO_2, ambient SO_2 + 10 to 15 µg/m^3) on the root biomass (g dw plant $^{-1}$) in three varieties of tomato (H414, H226 and H445) at 0, 7 and 14 days after SO_2 exposure (DAE), when compared with the ambient air SO_2 level (Control, ~7 to 25 µg/m^3). The difference in shoot biomass, at each of the sampling stages under the elevated to control SO_2 treatment is reflected as % change

Variety	Sample	0 DAE	7 DAE	14 DAE
H414	Control	1.833	3.405	5.39
	ESO_2	1.932	3.264	4.454
	% Change	5.40%	-4.14%	-17.37%
H226	Control	1.488	3.114	3.888
	ESO_2	1.377	3.021	3.621
	% Change	-7.46%	-2.99%	-6.87%
H445	Control	3.438	4.275	6.048
	ESO_2	2.852	3.971	6.631
	% Change	-17.04%	-7.11%	9.64%

A general decline in the root biomass as observed following the SO_2 exposure, was in sync with the observed decline in the shoot biomass across the experimental tomato varieties and may be attributed to an indirect effect of roots on the leaf water relations *viz*-a-*viz*., stomatal function which may consequently alter the gas exchange attributes *viz*., carboxylation or carbon fixation efficiency and the C- partitioning between the shoot and the root tissues to impact the overall plant growth. On the other hand, var H-445 showed a steady decline in root growth upon elevated SO_2 exposure at 0 DAE (-17.04 %), with a rapid recovery of root growth at the later stages of observation *i.e.*, -7.11 and +9.64 % at 7 and 14 DAE, respectively. Tomato var. H-226 showed SO_2 sensitivity for the root growth characteristics. The root-to-shoot ratio (RSR), in general, declined over time in the variety H-445, meaning that the toxicity effect of SO_2 exposure is more prominent in the shoot than in the root tissue. The other two varieties maintained more or less a similar RSR under the elevated and ambient SO_2 exposure conditions (Table 3).

Table 3. Effect of SO_2 enrichment (ESO_2; Ambient + 10-15 ug/m^3) on root-to-shoot ratio measured at 0, 7 and 14 days after SO_2 exposure (DAE)

Variety	Sample	0 DAE	7 DAE	14 DAE
H414	Control	0.13	0.15	0.14
	ESO_2	0.14	0.16	0.17
	% Change	7.69%	6.67%	21.43%
H226	Control	0.16	0.18	0.18
	ESO_2	0.17	0.19	0.17
	% Change	6.25%	5.56%	-5.56%
H445	Control	0.18	0.19	0.21
	ESO_2	0.23	0.22	0.19
	% Change	27.78%	15.79%	-9.52%

When compared over days after the SO_2 exposure, between ambient and elevated treatments, the RSR, in general, increased between 0 to 14 DAE only for var. H-414 indicates better adaptability in this cultivar to fight an elevated SO_2 stress. The root surface area (RSA), in general, was significantly inhibited across the three experimental tomato varieties at the 0 DAE stage when compared to the ambient SO_2 control. However, at later stages *i.e.*, 7 and 14 DAE the root surface area increased across varieties more so under elevated than ambient SO_2 conditions. The least RSA variation between the ambient and the elevated SO_2 treatments at 14 DAE was evidenced for var. H-445 followed by H-226 and H-414. The results revealed that tomato var. H-414 is most sensitive to elevated SO_2 exposure as it showed the least recovery for both root and shoot biomass from 0 to 14 DAE stage while var. H-445 was tolerant and var. H-226 showed an intermediate tolerance to elevated SO_2, as evident from their respective plant mass recoveries from 0 to 14 DAE following the ESO_2 exposure. Padhi (2013) recorded a greater decline in shoot than root dry matter accumulation in tomato in response to elevated SO_2 conditions. Sharma and Sharma (2014) showed that even brief exposure to high sulphur dioxide concentration is sufficient to cause leaf necrosis and significantly inhibit the shoot biomass.

Table 4. Effect of SO_2 enrichment (ESO_2; Ambient + 10-15 ug/m3) on Root Surface Area (mm^2 per plant) measured at 0, 7 and 14 days after SO_2 exposure (DAE)

Variety	Sample	0 DAE	7 DAE	14 DAE
H414	Control	185	290	304
	ESO_2	99	209	16200%
	% Change	-46.49	-27.93	-4671%
H226	Control	123	197	23500%
	ESO_2	89	158	186
	% Change	-27.64	-19.8	-20.85
H445	Control	176	281	506
	ESO_2	121	188	432
	% Change	-31.25	-33.1	-14.62

Effect of elevated SO_2 on the leaf attributes: The impact of an elevated SO_2 exposure on tomato varieties was observed in terms of the leaf number, leaf surface area, necrotic leaf area, necrotic-to-fresh leaf area ratio, leaf chlorophyll content, and leaf sulphur content. The data suggests that the variety H-414 of Tomato is highly sensitive to elevated sulphur dioxide and responds by shedding of the leaves with no recovery over 0 to 14 DAE (Table 5).

Table 5. Effect of SO_2 enrichment (ESO_2; Ambient + 10 to 15 ug/m3) on the number of leaves per plant measured at 0, 7, and 14 days after SO_2 exposure (DAE)

Variety	Sample	0 DAE	7 DAE	14 DAE
H414	Control	139	222	480
	ESO_2	132	183	28500%
	% Change	-5.04	-17.57	-4063%
H226	Control	108	143	25600%
	ESO_2	97	136	253
	% Change	-10.19	-4.89	-1.17
H445	Control	171	254	324
	ESO_2	84	191	343
	% Change	-50.87	-24.8	5.86

While the difference in number of leaves between the control group and experimental group was only 5.04%, it increased to 40.63% on the 14 days after exposure. A similar effect was seen in the leaf area, wherein the difference between the ambient and elevated SO_2 treatment increased from 5.26 % to 44.75% over 14 DAE (Table 6).

Table 6. Effect of SO_2 enrichment (ESO_2; Ambient + 10-15 ug/m3) on leaf surface area (cm^2 per plant) measured at 0, 7 and 14 days after SO_2 exposure (DAE)

Variety	Sample	0 DAE	7 DAE	14 DAE
H414	Control	722.5	1248.3	2282.4
	ESO_2	684.5	99740%	1261.1
	% Change	-5.26	-2009%	-44.75
H226	Control	591.2	77260%	1127.7
	ESO_2	498.4	721.3	1117.2
	% Change	-15.69	-6.63	-0.93
H445	Control	885	1185.1	1535.8
	ESO_2	457	853.6	1564.1
	% Change	-48.36	-27.97	1.84

The response was in contrast to that observed for var. H-445 which showed the least number of leaves at 0 DAE in elevated than ambient SO_2 treatment but thereafter showed a significant recovery in growth and the percent ESO_2 inhibition between the two groups was reduced to 24.8 at 7 DAE and recovered further to come at par with the unstressed control (+5.86) at 14 DAE. A similar recovery was also observed in terms of the leaf surface area for the var. H-445 while var. H226 exhibited an intermediate response. The observed increase in leaf area across varieties was caused by the appearance of new leaves, which were maximally formed in var. H-445. Total leaf necrotic area (%) upon SO_2 stress, on the other hand, did not differ significantly between the tomato varieties, and all the tomato varieties showed a decline in the necrotic leaf area from 0 to 14 DAE (Table 7).

Table 7. Effect of SO_2 enrichment (ESO_2; Ambient + 10-15 ug/m^3) on necrotic leaf area (in %) measured at 0, 7 and 14 days after SO_2 exposure (DAE)

Variety	Sample	0 DAE	7 DAE	14 DAE
H414	Control	8.94	7.08	6.92
	ESO_2	20.58	16.51	13.38
	% Change	11.64	9.43	6.46
H226	Control	9.56	8.13	7.55
	ESO_2	21.53	17.22	15.84
	% Change	11.97	9.09	8.29
H445	Control	7.04	7.96	6.83
	ESO_2	18.83	15.64	12.43
	% Change	11.79	7.68	5.6

The results suggest that the growth of variety H-414 is largely impacted by elevated levels of SO_2 pollution Further, a decline in the necrotic to fresh leaf area was observed across the tomato varieties, which suggests an initiation of a recovery phase however, the rate of recovery varied significantly among the experimental varieties and was maximum for var. H-445 (Table 8). Additionally, a measure of the leaf chlorophyll in SO_2-stressed and unstressed control leaves of the three experimental tomato varieties showed a major limitation in var. H-414, which showed a mean decline of 50% between the control and ESO_2 treatments when averaged over 0, 7, and 14 DAE stages (Table 9). On

Table 8. Effect of SO_2 enrichment (ESO_2; Ambient + 10-15 ug/m^3) on necrotic-to-fresh leaf area ratio measured at 0, 7 and 14 days after SO_2 exposure (DAE)

Variety	Sample	0 DAE	7 DAE	14 DAE
H414	Control	0.098	0.076	0.074
	ESO_2	0.259	0.198	0.154
H226	Control	0.106	0.088	0.082
	ESO_2	0.274	0.208	0.188
H445	Control	0.076	0.086	0.073
	ESO_2	0.232	0.185	0.142

Table 9. Effect of SO_2 enrichment (ESO_2; Ambient + 10-15 ug/m^3) on total chlorophyll (in mg/g fw) measured at 0, 7 and 14 days after SO_2 exposure (DAE); BE: before enrichment

Variety	Sample	BE	0 DAE	7 DAE	14 DAE
H414	Control	1.419	1.693	2.195	2.769
	ESO_2	NA	0.821	0.818	1.446
	% Change		-51.5	-62.76	-47.77
H226	Control	1.419	1.346	1.537	1.823
	ESO_2	NA	1.217	1.416	1.675
	% Change		-9.57	-7.86	-8.11
H445	Control		1.169	1.676	1.981

the other hand, Var. H-445 and H-226 continued to maintain a relatively higher leaf chlorophyll at all stages of measurement following the ESO_2 treatment when compared with the ambient SO_2 control. A better recovery under the ESO_2 condition in var. H-445 when compared with other experimental varieties, may be related to a higher capacity and efficiency of the variety to convert SO_2 into sulphate and utilize the same as a major source of mineral sulphur under the contaminated air environment in comparison to the other tomato varieties *viz*., H-414 and H-226. The above hypothesis was confirmed by measurement of leaf suphur content under the ambient and ESO_2 condition (Table 10), which showed a significantly higher content of leaf sulphur in H445 *i.e.*, +12.25 % under the ESO_2 than the ambient SO_2 control at 0 DAE which increased further to +27.34 % at the 14 DAE stage. At the same stage (14 DAE) var. H-414 and H-226 showed a decline in the leaf sulphur content by 8.19 and 6.09 % due to ESO_2 when compared with ambient SO_2 control treatment (Table 10).

Table 10. Effect of SO2 enrichment (ESO_2; Ambient + 10-15 ug/m3) on leaf sulphur (in mg/g dw) measured at 0, 7 and 14 days after SO2 exposure (DAE); BE: before enrichment

Variety	Sample	BE	0 DAE	7 DAE	14 DAE
H414	Control	5.475	9.83	14.29	12.94
	ESO_2	NA	11.48	14.1	11.88
	% Change		16.78	-1.33	-8.19
H226	Control	12.64	13.43	14.06	15.19
	ESO_2	NA	12.64	13.43	14.06
	% Change		-5.89	-4.48	-6.09
H445	Control	12.26	11.59	11.48	11.96
	ESO_2	NA	13.01	12.83	15.23
	% Change		12.25	11.76	27.34

Various studies have revealed a drastic decline in leaf chlorophyll with an increase in SO_2 contamination in the air environment. The observed decline in chlorophyll content may be attributed to the harmful effect of ESO_2 on the chloroplast machinery, which becomes more apparent with an increased duration of SO_2 exposure. The highest mean chlorophyll damage was observed in the variety H-414 over the three weeks (~48 %) including the 7-day SO^2 exposure period. The variety H-445, on the other hand, showed the least ESO_2 damage at -4.3%. This shows that the elevated SO_2 interferes the most with the metabolic and physiological processes in the H-414, and the least in the variety H-445, thus, indicating, respectively their ESO_2 susceptible and tolerant characteristics. Further, an increase in sulphur content in the leaf tissues upon exposure to an elevated SO_2 level may be attributed to plants' incapacity to metabolize and convert the excessively absorbed SO_2 into sulphate, which is mainly partitioned into vacuoles to maintain a relatively lower S-concentration in the cytosol. If not partitioned into the vacuoles, the excessive cytosolic SO_2^{4-} level can prevent photosynthesis without necessarily causing the death of cells. Photosynthesis is not inhibited at sub-threshold doses because the sulphite is oxidized to the non-toxic sulphate as quickly as it is absorbed via the epidermal or stomatal cells. The SO_2 level below the survival threatening thresholds can cause a decline in leaf photosynthesis, early senescence, an unthrifty appearance, inhibited growth, and yield without showing any discernible symptoms. Swain and Padhi (2015) observed an SO_2-induced decline in leaf chlorophyll ranging from 39 to 65 %, which depended on the period of fumigation of sulphur dioxide. Marie and Ormrod (1984) in an experiment with tomato plants also noted a significant increase in the total sulphur content of the leaf tissue when exposed to an elevated SO_2 concentration.

The results indicate that the variety H-445 is the most competent to uptake sulphur from the polluted air environment and utilize the same as source of mineral sulphur to propel its growth during the winter months (October-onwards) in the Northern India, as the period is challenged by immense smog and deterioration of the air quality. Another interesting observation of the study pertains to the fact that the SO_2-mediated damage in H-414 increases gradually after the SO_2 exposure period in contrast to var. H-445 which showed a higher initial ESO_2 damage at 0 DAE but showed a greater recovery in the following period from 0 to 14 DAE. This may indicate a greater adaptability and tolerance of the var. H-445 to an elevated SO_2 stress when compared to the other experimental tomato cultivars. Tomato var. H-445 appears to possess a relatively greater inherent ability to utilize the bisulphite and sulphite ions deposited in its leaves during the period of ESO_2 exposure. Expression of acute and/or chronic SO_2 symptoms was observed to vary at the genus, species, variety or cultivar, provenance, and population levels (Singh *et al*., 2012). Olszyk and Tingey (1985) reported that the damage-causing potential of SO_2 is a manifestation of a sequence of chemical and physical occurrences that start with the entry of sulphur dioxide into plants and continue with disturbance and balance before concluding with damage to the leaves or impacting the plant growth. Further, as is also reported in the present study the plants may also benefit from SO_2 exposure and utilize it for the plants' S-nutrition, to record enhanced crop productivity, especially in plants growing in sulphur-deficient soils (Singh *et al*., 2012).

The study clearly shows that there exists a genetic variability within the crop species in respect of ESO_2 tolerance. An elevated SO_2 exposure during the late winter months or in industrially polluted regions may cause physiological and metabolic damage to crop plants. The extent of this damage may be acute or chronic depending upon the SO2 concentration and the duration of exposure. The study clearly shows that a genetic variability for SO2 tolerance exists in tomato and that the tomato var. H-445 is better suited for cultivation in the Rabi season in Northern India, which witnesses a deteriorated air quality over a prolonged period from October to December each year owing to rampant burning of the paddy residue. The study further, highlights that the greater adaptability of the variety H-445 to tolerate an elevated SO_2 concentration in the air environment originates from its extremely superlative ability to utilize SO_2 to meet the mineral S-requirement of the tomato plant, in comparison to the other experimental tomato varieties. It is, thus, important to deduce the inter and intra-species variation in air pollutant (pollution) tolerance across the dietary important crops, whose productivity is likely to be challenged under the climate change scenario.

Author Contribution Statement: Anshul Gupta and Bhupinder Singh conceived the presented idea. Anshul Gupta developed the theory, carried out the field work and performed the computations. Bhupinder Singh and Renu Dhupper verified the analytical methods. All authors discussed the results and contributed to the final manuscript.

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