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Sensitivity of agricultural crops to tropospheric ozone: a review of Indian researches

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Abstract Tropospheric ozone (O_3) is a long-range transboundary secondary air pollutant, causing significant damage to agricultural crops worldwide. There are substantial spatial variations in O_3 concentration in different areas of India due to seasonal and geographical variations. The Indo-Gangetic Plain (IGP) region is one of the most crop productive and air-polluted regions in India. The concentration of tropospheric O_3 over the IGP is increasing by 6–7.2% per decade. The annual trend of increase is 0.4 ± 0.25% year^{-1} over the Northeastern IGP. High O_3 concentrations were reported during the summer, while they were at their minimum during the monsoon months. To explore future potential impacts of O_3 on major crop plants, the responses of different crops grown under ambient and elevated O_3 concentrations were compared. The studies clearly showed that O_3 is an important stress factor, negatively affecting the yield of crops. In this review, we have discussed yield losses in agricultural crops due to rising O_3 pollution and variations in O_3 sensitivity among cultivars and species. The use of ethylene diurea (EDU) as a research tool in assessing the losses in yield under ambient and elevated O_3 levels also discussed. Besides, an overview of interactive effects of O_3 and nitrogen on crop productivity has been included. Several recommendations are made for future research and policy development on rising concentration of O_3 in India.

Keywords Tropospheric O_3 · Crop sensitivity · Yield · Interactive effects · Antioxidants · Photosynthates

Introduction

Ground-level ozone (O_3) is a secondary, short-lived air pollutant (Parrish et al., 2012; Proietti et al., 2021) formed by the photochemical oxidation of NOx in the presence of precursor gases such as carbon monoxide, methane, and volatile organic compounds (Simpson et al., 2015). Ozone is a strong oxidant molecule and plays a crucial role in tropospheric chemistry by controlling the oxidation processes (Kunchala et al., 2021). The lifetime of tropospheric O_3 varies between ~ 5 and 30 days, which depends on season and altitude, for instance, the lifetime of O_3 is longer in winter season and upper troposphere and vice versa (Parrish et al.,

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2012). Similarly, concentrations of O_3 are high in tropical and subtropical regions as it is naturally appropriate environment (low humidity, high temperature, and high light intensity) for O_3 formation (Eghdami et al., 2022; Ziemke et al., 2019).

Tropospheric O_3 is a third leading greenhouse gas in terms of radiative forcing (Mickley et al., 2001), which affects climate change (IPCC, 2013) and is considered the most harmful air pollutant for crops, vegetation (Mills et al., 2018b; Sharps et al., 2021; Yadav et al., 2021a), biodiversity (Agathokleous et al., 2020) and ecological systems (Liu et al., 2021). Despite the implementation of air quality legislative standards to control the precursor's emissions worldwide (Sicard et al., 2016; Simon et al., 2015), current O_3 concentrations are still high and can suppress agricultural/horticultural productivity in many countries around the world (Cailleret et al., 2018; Mills et al., 2018a; Proietti et al., 2021). The O_3 pollution level has begun to decline mostly in developed countries in North America and Europe, but it continues to rise in rapidly developing countries like China, India, and Brazil (Kunchala et al., 2021; Mills et al., 2018a; Turnock et al., 2018). A report of China suggested a trend of 0.4 ppb per year increase of O_3 over East Asia (Chang et al., 2017). Similarly, a 30% O_3 increase was observed from 2013 (47.5 ppb) to 2019 (61.8 ppb) at 243 Chinese monitoring sites (Lu et al., 2019; Yuan et al., 2021).

In India, a study by Lal et al. (2012) assessed the pattern of O_3 concentration changes over the northeastern Indo-Gangetic plains (IGP) region and reported the largest escalation of 6–7.2% per decade with $0.4 \pm 0.25\%$ per year, which shows the severity of O_3 risk over the IGP region compared to global O_3 pollution rise. The spatiotemporal variabilities in O_3 concentration over different parts of India have been investigated by many researchers and ascribed to seasonal and geographical variations, which are further correlated with meteorology (Girach et al., 2017; Nair et al., 2018; Singh & Agrawal, 2017). The pattern of O_3 concentration shows 40–60 ppb (higher) range during the pre-monsoon/summer season and 15–20 ppb (lower) range during the monsoon months over the northern, western, and peninsular regions of India (Kunchala et al., 2021). The high O_3 concentration over the IGP region of India is now a major concern as it is posing a threat to agricultural productivity (Mukherjee et al., 2020; Singh & Agrawal, 2017).

The severity of O_3 impact on plants is attributed to the amount of uptake and its reaction ability with cellular components to generate reactive oxygen species (ROS) (Sicard et al., 2020; Yadav et al., 2019). The O_3 nearby the plant enters leaves through the stomata during gaseous exchange, reaches apoplast quickly and reacts to produce ROS such as superoxide, hydrogen peroxide, hydroxyl radical, and singlet oxygen (Janku et al., 2019). The O_3-induced ROS further reacts with plant cell organelles and then initiate's damage at the molecular, biochemical, and physiological levels and accelerates leaf senescence, resulting in a reduction of crop yield. In defense response, O_3 exposed plants start additional production of enzymatic and non-enzymatic antioxidants, which play a decisive role in maintaining cellular redox balance by detoxifying the extra ROS molecules (Severino et al., 2007; Yadav et al., 2019). The typical effect of O_3 on sensitive plants induced by long-term exposure is early senescence of leaves as a consequence of reduction in photosynthate accumulation in plants and alteration in partitioning of photoassimilates between defense and yield products (Emberson et al., 2018; Yadav et al., 2020a, b). The sensitive plant species show specific O_3 injury symptoms, which can be visualized in the form of chlorotic spotting (stipples), mottling, bronzing (red to brown minute spots) and eventually leading to foliar necrotic lesions (interveinal stipple on the adaxial side) (Feng et al., 2014; Hayes et al., 2007; Ladd et al., 2011; Sicard et al., 2021). A typical pattern of O_3 injury symptoms is mostly localized on the upper leaf surface (Nali & Lorenzini, 2021). The O_3 injury symptoms under ambient conditions are reported in North and South America, Europe, Asia, Australia, and Africa, which suggests that the current situation of O_3 concentration is above its phytotoxic threshold across the world (Krupa et al., 2001; Marco et al., 2020).

The damaging effect of O_3 on plants has been extensively studied using a series of indices, mainly divided into O_3 exposure-based indices such as AOT40 (accumulated ozone over a threshold value of 40 ppb), M12 (12 h mean O_3 concentration), M7 (7 h mean O_3 concentration), and O_3 flux-based indices such as POD_YIAM (phytotoxic ozone dose above a threshold flux of Y nmol m^{-2} s^{-1}, parameterized for integrated assessment modelling), and POD_YSPEC (species-specific phytotoxic ozone dose above a threshold flux of Y nmol m^{-2} s^{-1}) (CLRTAP, 2017;

Mills et al., 2018a, b, c; Yadav et al., 2021a). The O_3 flux-based indices are relatively complex to obtain, as they consider parameters such as leaf area index, stomatal conductance, weather condition, vapour pressure deficit, soil moisture, phenology, and vegetation characteristics of a plant (Pleijel et al., 2021). Whereas, O_3 exposure-based indices are quite straightforward and require only data of O_3 measurements nearby the plants (Yadav et al., 2021a). Studies conducted on the basis of flux-effect relationships (POD vs yield) and exposure-yield relationships (AOT40 vs yield) suggested that the stomatal O_3 flux-based indices provide a more accurate assessment of O_3 risk compared to exposure-based indices (Anav et al., 2016; Proietti et al., 2021). Usually, O_3 sensitive plants exhibit high stomatal O_3 uptake in leaves, which results in visible symptoms on leaves. The O_3 symptoms are more severe in older leaves than the younger ones due to the higher accumulation of stomatal O_3 flux into leaves, leading to premature leaf abscission (Sharps et al., 2021). Visible foliar damage to O_3 may have economic consequences for crop production and quality (Zhao et al., 2011, 2018).

Keeping these facts in mind, the main focus of this review is to provide complete information on crop's sensitivity to O_3 at the most fertile and O_3 polluted IGP region of India based on recent observational methods and studies. For securing the productivity of crops in such a scenario, an interactive mechanism of O_3 and nitrogen on plant performance and several future prospects are also discussed.

Indices for evaluating sensitivity of crops to O_3

Stomatal O_3 uptake (phytotoxic O_3 dose: POD)

Recent researches on crop response function against O_3 are shifting from exposure (based on O_3 concentration: AOT40) to stomatal flux (based on phytotoxic O_3 uptake) approach, since it provides physiologically more robust information of O_3 risk assessment (Paoletti et al., 2019; Pleijel et al., 2021). At present, phytotoxic ozone dose (POD) represents a strong improvement over AOT40 index. The strength of POD approach is highlighted in the development and application of models used for O_3 risk assessment of crops in different regions of the world (Feng et al., 2018; Harmens et al., 2018; Wu et al., 2016; Yadav et al., 2021a). The O_3 risk assessment and variability in different crop's sensitivity are well described in the Convention on Long-Range Transboundary Air Pollution (CLRTAP, 2017). Sensitivity to O_3 varied with crop species due to the differences in uptake potential of O_3 (Sharps et al., 2021). In addition, stomatal conductance of leaves is greatly influenced by environmental variables such as photosynthetically active radiation, temperature, and air humidity which create dissimilarities in stomatal O_3 uptake among crops, species, cultivars, and even plants of the same variety due to the variability in accumulation of POD (Hayes et al., 2019a; Paoletti et al., 2019; Yadav et al., 2021a). Pleijel et al. (2021) have observed that the variations in O_3 sensitivity were slightly larger in inter-cultivar than the intra-cultivar with the same input data of POD_6 for European wheat. And so also, some important genetic changes among the crop cultivars associated with genotypic differences are responsible for the variations in O_3 sensitivity in wheat (Feng et al., 2016) and rice (Ashrafuzzaman et al., 2017; Frei et al., 2012).

Recently, Yadav et al. (2021a) have observed O_3 flux-response based modeled approach to identify the critical levels and species-specific O_3 sensitivity of four wheat cultivars under Indian climatic conditions using DO_3SE model (Deposition of Ozone for Stomatal Exchange: a stomatal flux based model used for assessing O_3 risk in crops and tree species) (Table 1). Their study documents that the critical point of accumulation of POD_6 was 0.284 mmol O_3 m^{-2} for early sown cultivars and 0.393 mmol O_3 m^{-2} for late sown cultivars, which are responsible for 5% yield losses. This suggests that early sown cultivars are more sensitive to O_3 as the critical condition comes at lower accumulation of POD_6 than late sown cultivars. Besides, a significant negative linear flux-effect relationship is also assisted in identifying the sensitivity level of wheat cultivars in future O_3 situations by the slope coefficient comparison and allows quantitative rating of the sensitivity (Harmens et al., 2018; Pleijel et al., 2014; Wu et al., 2016; Yadav et al., 2021a).

Visible foliar injury

The O_3-injury assessment is an easy, convincing, and reliable method to determine the sensitiveness of a species because the severity of pollutants may differ with different (sensitive/resistant) genotypes (Nali

Table 1 Sensitivity of agricultural crops to tropospheric O_3 in IGP region

Crops/ cultivars/species	Characteristics	Less sensitive to O_3	More sensitive to O_3	Cause of sensitivity	References
Triticum aestivum L PBW 343 and M 533	Intra-species (among cultivar)	M 533	PBW 343	Larger leaf area and high stomatal conductance	Rai & Agrawal, 2014
Triticum aestivum L. PBW 343 *Triticum durum* L HD 2936	Intra-species (among variety)	HD 2936	PBW 343	Greater reduction in photosynthetic rate, stomatal conductance, growth and yield	Tomer et al., 2015
Triticum aestivum L. HD 2987, DBW 50, DBW 77, PBW 550, HD 2967, NIAW 34, HD 3059, PBW 502, HUW 213, HUW 251, HUW12, Kundan, HUW 55, and Kharchiya 65	Intra-species (among cultivar)	HUW12, Kundan, HUW 55, and Kharchiya 65	HD 2987, DBW 50, DBW 77, and PBW 550	Leaf injury, decrement in growth parameters and physiological characteristics	Singh et al., 2018b
Triticum aestivum L HD2967 and Sonalika	Intra-species (among cultivar)	HD 2967	Sonalika	Early senescence response, more allocation of resource toward maintenance of physiological conditions and yield reduction	Pandey et al., 2018
Triticum aestivum L HUW468 and HD3086 (early sown cultivars), HUW234 and HD3118 (late sown cultivars)	Early sown and late sown cultivars	Late sown cultivars (HUW234 and HD3118)	Early sown cultivars (HUW468 and HD3086)	Induction of non-enzymatic antioxidants, longer life span and post-anthesis growth period, high stomatal conductance and lower critical level of POD_6SPEC	Yadav et al., 2019, 2021a
Triticum aestivum L HD 2967	Shifting crop calendar	Timely sown cultivar	Late sown cultivar (delayed sowing by 20 days)	Higher accumulation of AOT 40 O_3 during reproductive stage, more yield reduction	Ghosh et al., 2020
Triticum aestivum L HD 2987, PBW 502 and Kharchiya 65	Old and Modern cultivars	Kharchiya 65 (Old cultivar)	HD 2987 (modern cultivar)	More oxidative stress led to enhancement in antioxidative enzymes consequently greater yield losses	Fatima et al., 2018
Triticum aestivum L HUW234 and HD3118	Old and Modern cultivars	HUW234 (Old cultivar)	HD3118 (modern cultivar)	High stomatal conductance, reductions in photosynthetic rate, photosynthetic nitrogen use efficiency and grain yield	Yadav et al., 2020a

Table 1 (continued)

Crops/ cultivars/species	Characteristics	Less sensitive to O_3	More sensitive to O_3	Cause of sensitivity	References
Triticum aestivum L HUW-37 and K-9107	Tall and dwarf cultivars	K-9107(tall)	HUW-37 (dwarf)	Greater reductions in grain yield and quality due to lesser translocation of photoassimilates towards reproductive structure	Mishra et al., 2013
Oryza sativa L Malviya dhan 36 and Shivani	Intra-species (among cultivar)	Malviya dhan 36	Shivani	More utilization of photoassimilates towards defense than translocation to reproductive parts	Sarkar et al., 2015
Oryza sativa L MDU6, TRY(R)2, ASD16, ASD18, ADT43, MDU5, ADT37, ADT(R)45, TPS5, Anna(R)4, PMK(R)3, ADT(R)48, CO51, CO47, and ADT36	Intra-species (among cultivar)	CO51, CO47, and ADT36	MDU6, TRY(R)2 and ASD16	Decreased photosynthetic traits, altered antioxidant metabolism and increased spikelet sterility	Ramya et al., 2021
Zea mays L Buland and Prakash	Intra-species (among cultivar)	Buland	Prakash	Greater reduction in yield parameters	Singh et al., 2018a
Zea mays L DHM117 (normal maize) and HQPM-1 (high quality protein maize)	High quality protein maize and normal maize	HQPM-1 (high quality protein maize)	DHM117(normal maize)	Carbohydrate content, kernel nutritional quality and yield reduced	Singh et al., 2019
Zea mays L HQPM-1 (high quality protein) and PMH-1 (normal)	High quality protein maize and normal maize	HQPM-1 (high quality protein)	PMH-1 (normal maize)	Higher reduction in carbohydrate content and grain yield	Yadav et al., 2021c

& Lorenzini, 2021). It is also helpful to detect areas of high potential risk (Feng et al., 2014; Sicard et al., 2021). Visible symptoms of O_3 are very easy to understand by representatives of the media, policymakers, and non-scientists. After exposure to ambient air containing phytotoxic O_3, plants start to change their metabolism, which eventually leads to the formation of visible injury (Krupa et al., 2001). Booker et al. (2009) reported that the visible foliar O_3 symptoms in a sensitive (18%) grape variety were more than in a resistant variety (6%) under ambient O_3 condition. The visible injury appears after the O_3 uptake through stomata reaches a threshold (CLRTAP, 2017). Fernandes and Moura (2021) assessed visible O_3 injury development related to PODy in *Astronium graveolens* Jacq. and confirmed the symptoms by using structural markers attributed to oxidative burst and hypersensitive responses. European programs such as EU/ECE International Co-operative Program (ICP-Forests and ICP-Vegetation) and North American programs such as Forest Health Monitoring Program have incorporated the visible injury assessment records of forest plants, crops, and semi-natural vegetation across Europe and the USA to easily identify the O_3 sensitive species in natural field conditions (Feng et al., 2014; Hayes et al., 2007). Some other past reviews have ranked plant species sensitivity to O_3 according to O_3-induced visible injury (Gerosa et al., 2003; Hoshika et al., 2018; Vanderheyden et al., 2001).

Despite O_3 being an important air pollutant in India, visible injury assessment is not attempted throughout the country. Under the exposure of ambient + 30 ppb O_3, Singh et al. (2018b) observed interveinal chlorotic and necrotic foliar spots in tested 14 Indian wheat cultivars and categorized them into sensitive, moderately sensitive, and tolerant cultivars on the basis of severity of foliar injury. A study on two mung bean (*Vigna radiata* L.) cultivars, HUM-2 and HUM-6, exposed to elevated O_3 also depicted the foliar injury in the form of interveinal chlorosis on adaxial portion of leaves. High foliar injury in HUM-2 as compared to HUM-6 was found to be related with greater production of ROS and little investment of antioxidant defense machinery (Mishra & Agrawal, 2015). Further, the percentage of injury symptoms on leaves was found to be matched with the yield losses in different cultivars. Chaudhary and Agrawal (2013) also observed foliar O_3 injury in 6 clover (*Trifolium alexandrinum* L.) cultivars under elevated O_3 conditions and found that the magnitude of O_3 injury symptoms directly corresponded with sensitivity of different cultivars. Wardan and Bundel were found the most sensitive cultivars to O_3, showing severe visible O_3 injury symptoms. The JHB-146 cultivar was intermediately sensitive with moderate injury symptoms, while Fahli, Saidi, and Mescavi cultivars were ranked under slightly O_3 sensitive category due to least injury symptoms.

Cumulative stress response index

Variations in O_3 sensitivity among the genotypes of wheat depend on changes in antioxidant defense capacity (Feng et al., 2016). Stress-response related parameters such as accessory pigments, ROS-scavenging metabolites/enzymes production rate (antioxidant), photosynthetic rate, and photoassimilates were measured individually and the percentage changes in each parameter were aggregated and the values were arranged in an order for the ranking of cultivar's sensitivity to O_3 (Singh et al., 2018b). Cumulative stress response index (CSRI) can be used as an important tool to assess the sensitivity of O_3 based on antioxidant defense response of plants (Fatima et al., 2019). Singh et al. (2018b) calculated CSRI for 14 Indian wheat cultivars and categorized them into sensitive, intermediately sensitive, and tolerant cultivars (Table 1). Yadav et al. (2019) demonstrated that the O_3 sensitivity of wheat cultivars was also attributed to detoxification of O_3-induced ROS levels by enzymatic and non-enzymatic antioxidants. The possible energy allocation trade-off between antioxidative defense and photosynthate's accumulation under elevated O_3 levels was cultivar-specific response that influenced cultivar's productivity (Table 1). Fatima et al. (2018) also suggested that defense mechanism of each wheat cultivar against O_3 was different and thus the sensitivity varied. Their study observed that high O_3-induced oxidative stress up regulated the enzymatic antioxidants and phenylpropanoid pathway in modern wheat cultivar (HD2987: O_3 sensitive cultivar). However, in PBW502 (intermediately O_3 sensitive cultivar), enzymatic and non-enzymatic antioxidants were enhanced, while in old cultivar (Kharchiya65: O_3 tolerant cultivar), only induction of non-enzymatic antioxidants occurred to combat O_3 stress.

Variations in crop species sensitivity to O_3

According to the existing information on crop sensitivity to O_3, differences in O_3 sensitivity are considerably larger for global data sets that reflect local and regional variations in O_3 sensitivity. In other words, sensitivity to O_3 of same crop species may change across different continents, including tropical, subtropical, and temperate crop-growing regions. However, the sensitivity of crops to O_3 is not much explored in every region of the world, only few countries are working such as Europe, China, the USA, India, and Japan. Some recent reports (Hayes et al., 2019b; Sharps et al., 2021) also provide information on African tropical crop responses to O_3, particularly wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.), finger millet (*Eleusine coracana* L.), pearl millet (*Pennisetum glaucum* L.), and common bean (*Phaseolus vulgaris* L.). All these crops have shown visible O_3 effect on leaves. The accelerated leaf senescence in African wheat cultivars was a main symptom of high O_3 exposure (Sharps et al., 2021).

Wheat cultivar's sensitivity to O_3 has increased progressively over time due to selective breeding plans for enhancing stomatal conductance and yield (Biswas et al., 2008; Pleijel et al., 2006; Yadav et al., 2020a). Moreover, variations in O_3 sensitivity of cultivars of a single species used in different continents might be due to the changed selection criteria in different locations, possibly because of suitability in a particular climate. Asian (India, China) wheat and rice cultivars are more sensitive than cultivars of the USA and Europe (Emberson et al., 2009). However, almost nothing is known about the sensitivity of staple African crops to O_3 (Harmens et al., 2019). Thus, it is suggested that critical levels of O_3 for tropical crops are needed using stomatal O_3 flux to take environmental conditions into account to fully quantify the risk to food production (Sharps et al., 2021). Likewise, sensitivity to O_3 may differ among distinct crop species. For instance, the average annual global yield losses due to stomatal O_3 uptake during 2010–2012 were 4.4, 6.1 and 7.1% for rice, maize and wheat, respectively (Mills et al., 2018c). In recent decades, many studies on agricultural crops over the IGP region have shown the differential sensitivity among cultivars and species and also identified the main causes of O_3 sensitivity which are compiled in Table 1.

Losses in productivity due to tropospheric O_3

The prevalent occurrence of high O_3 concentration is accelerating the loss of crop and vegetable productivity in the predominating fertile agricultural regions of India (Mukherjee et al., 2020; Oksanen et al., 2013). Investigations of crop yield losses due to prevailing high O_3 concentration in the IGP region have been attempted by many researchers with different approaches such as exposure-based experiments (Fatima et al., 2019; Ghosh et al., 2020; Yadav et al., 2020a), observation based studies (Kumari et al., 2020; Sinha et al., 2015) and O_3 flux-based and model-based approaches (Fischer, 2019; Sharma et al., 2019; Yadav et al., 2021a) which are given in Table 2.

Exposure-based study

A study in the Delhi NCR region found reductions in rice yield by 6.3% using AOT40 index and 23% by total AOTX (AOT40, AOT30, AOT25, AOT20, AOT15, AOT10, AOT5, and AOT0), while only 2% at M7 index (Saxena et al., 2020). The study also indicated that among all the indices, AOT 40 is the most suitable index for evaluating the impact of O_3 on rice in Indian climate. Ramya et al. (2021) estimated the responses of fifteen rice cultivars at a mean 50 ppb O_3 for 30 days, and found average reductions of 0.62% in test weight of 1000 seed and 23.83% in straw weight compared to control (Table 2). This finding further revealed intra-species variability in responses of rice cultivars to elevated O_3 stress. At ambient O_3 concentration, rice cultivar NDR 97 exhibited more reduction in grain yield compared to Saurabh 950. However, more decrement in test weight suggested that number of grains was enhanced but weight of grains decreased (Rai et al., 2010). Two rice cultivars, Shivani and Malviya dhan 36 treated at elevated O_3 (ambient + 20 ppb), showed yield reductions by 45 and 39%, respectively (Sarkar & Agrawal, 2012). More reduction in yield of Shivani was ascribed to greater utilization of photoassimilates in alleviating the harmful effects of O_3 rather than investment in reproduction (Sarkar et al., 2015) (Table 2). Similarly, Surabhi et al. (2020) reported Pusa Basmati-1, a cultivar of rice, to be more susceptible due to greater yield loss than Sarjoo-52 cultivar under ambient O_3 exposure.

Table 2 Variations in yield losses of crops and vegetables in India

Type of study	Crops/vegetables	Method	Duration of study (year)	Ozone concentration	Reduction in yield	Reference
Exposure based	*Triticum aestivum* L HUW-37 (dwarf) and K-9107 (tall)	Open top chambers	2010–11 and 2011–12	Ambient + 10 ppb	37–39% (2010–11) and 40.8% (2011–12) in dwarf while 12.8% (2010–11) and 14% (2011–12) in tall cultivar	Mishra et al., 2013
	Triticum aestivum L. (PBW 343) and *Triticum durum* L. (HD 2936)	Open top chambers	2008–09 and 2009–10	Ambient + 30 ppb	15% (2008–09) and 19% (2009–10) in PBW 343 while 9% (2008–09) and 13% (2009–10) in HD 2936	Tomer et al., 2015
	Triticum aestivum L (14 cultivars)	Open top chambers	Dec 2014– Mar 2015	Ambient + 30 ppb	10–31%; maximum reduction in HD 28 and least in Kharchiya 65	Singh et al., 2018b
	Triticum aestivum L. HD 2987, PBW 502 and Kharchiya 65	Open top chambers	Dec 2014– Mar 2015	Ambient + 30 ppb	12.9% in Kharchiya 65, 27.1% in PBW 502 and 42.2% in HD 2987	Fatima et al., 2018
	Triticum aestivum L. HD2967 and Sonalika	Open top chambers	Nov 2016– Mar 2017	Ambient + 20 ppb	10.2% in HD 2967 and 18% in Sonalika	Pandey et al., 2018
	Triticum aestivum L. HUW468 and HD3086 (early sown), HUW234 and HD3118 (late sown)	Open top chambers	Nov 2016– Mar 2017	Ambient + 20 ppb	24.3% in HUW468, 21.7% in HD3086, 18% in HUW234 and 18.8% in HD3118	Yadav et al., 2019
	Triticum aestivum L. HUW234 (Old cultivar) and HD3118 (modern cultivar)	Open top chambers	Dec 2015–Mar 2016	Ambient + 20 ppb	22.1% in HUW 234 and 23.8% in HD3118	Yadav et al., 2020a
	Triticum aestivum L. HD 2967	Open top chambers	Nov 2016- Apr 2017	Ambient + 20 ppb	45.3% in late sown while 16.2% in timely sown condition	Ghosh et al., 2020
	Triticum aestivum L. HD 2967	FACE	Nov 2016– Apr 2017	Ambient + 70 ppb	9.2%	Mina et al., 2021

Table 2 (continued)

Type of study	Crops/vegetables	Method	Duration of study (year)	Ozone concentration	Reduction in yield	Reference
	Triticum aestivum L. HUW468 and HD3086 (early sown cultivars), HUW234 and HD3118 (late sown cultivars)	Open top chambers	Nov 2016– Mar 2017 and Nov–2017–Mar 2018	Ambient + 20 ppb	30.5% in HUW468 and HD3086 and 23.1% in HUW234 and HD3118	Yadav et al., 2021a
	Oryza sativa L Malviya dhan 36 and Shivani	Open top chambers	Jun–Sep 2007	Ambient + 20 ppb	43% in shivani and in Malviya dhan 36 by 36.6%	Sarkar et al., 2015
	Oryza sativa L 15 cultivars	Open top chambers	Jan–May 2019	50 ppb	0.62% in test weight and straw weight by 23.83%	Ramya et al., 2021
	Zea mays L Buland and Prakash	Open top chambers	Sep–Dec 2013	Ambient + 30 ppb	9.8% in Buland and by 16.2% in Prakash	Singh et al., 2018a
	Zea mays L DHM117 (normal) than HQPM-1 (high quality protein)	Open top chambers	Dec 2012– Apr 2013	Ambient + 15 ppb, 30 ppb	Weight of kernels by 10.2% and 14.8% in DHM117 and 7.8% and 11.2% in HQPM-1 at ambient + 15 ppb and ambient + 30 ppb respectively	Singh et al., 2019
	Zea mays L HQPM-1 (high quality protein) and PMH-1 (normal)	FACE	Jul–Oct 2016 and Jul–Oct 2017	70 ppb (target O_3)	9.5% and 8.6% in HQPM-1 and 9.9% and 10.5% in PMH-1 in 2016 and 2017 respectively	Yadav et al., 2021c
	Glycine max L PK472 and Bragg	Open top chambers		70 and 100 ppb	20% (70 ppb) and 33.6% (100 ppb) in PK473 and 12% (70 ppb) and 30% (100 ppb) in Bragg	Singh et al., 2010a
	Brassica juncea L. Pusa Tarak	Open top chambers	2009–2010 2010–2011	ambient + 25–35 ppb O_3	35.9% in first year and by 35.9% in second year	Singh et al., 2013

Table 2 (continued)

Type of study	Crops/vegetables	Method	Duration of study (year)	Ozone concentration	Reduction in yield	Reference
	Brassica campestris L. Sanjukta and Vardan	Open top chambers	Nov 2010–Mar 2011	Ambient + 10 ppb	12.5% in test weight in Sanjukta and by 33.4% in Vardan	Tripathi & Agrawal, 2012
	Vigna radiata L HUM-1, HUM-2, HUM-6, HUM-23, HUM-24 and HUM-26	Open top chambers	Apr 2010–Jun 2010 and Apr 2011–Jun 2011	Ambient + 10 ppb O_3	9.8–15.4%	Chaudhary & Agrawal, 2015
	Solanum tuberosum L Kufri Swarna, Kufri Jyothi, Kufri Giridhari and Kufri Himalini	Open top chambers	Jan 2011–Apr 2013	Ambient O_3	4.56 – 25.5%	Suganthy & Udayasoorian, 2020
	Solanum tuberosum L. Kufri chandramukhi	Open top chambers	Nov 2010– Feb 2011	Ambient + 20 ppb	64.4%	Kumari & Agrawal, 2014
	Solanum lycopersicon L. Pusa ruby	Closed top exposure chambers	May–Aug 2002	75 and 150 ppb	54% after 45 days of treatment of 75 ppb O_3 and 73% at 150 ppb O_3	Mina et al., 2010
	Beta vulgaris L. allgreen	Open top Chambers	Dec 2008–Jan 2009	Ambient + 20 ppb	25%	Kumari et al., 2013
	Amaranthus hypochondriacus L 40 cultivars	FACE	Oct 2018–Feb 2019	Ambient + 30 ppb	7.8–94.9%	Yadav et al., 2020b
Observation based study	*Triticum aestivum L and Oryza sativa L*	AOT 40 index estimating the RYL	1997–2004		7.5% in winter and 22.7% in pre monsoon for wheat while 1.8% in winter and 5.5% in pre-monsoon for rice	Ghude et al., 2008
	Triticum aestivum L and *Oryza sativa* L	AOT 40 index estimating the RYL	2002–2007		21.79% in wheat 5% in rice	Debaje, 2014
	Triticum aestivum L *Oryza sativa* L. and *Zea mays* L	M7 index	2011–2013		27–41% in wheat 21–26% in rice 3–5% in maize	Sinha et al., 2015
	Triticum aestivum L and *Oryza sativa* L	AOT 40 index estimating the RYL	2011–2014		15% wheat 6.3% rice	Lal et al., 2017

Table 2 (continued)

Type of study	Crops/vegetables	Method	Duration of study (year)	Ozone concentration	Reduction in yield	Reference
	Triticum aestivum L and *Oryza sativa* L	AOT 40 index estimating the RYL	2010–2015		15% in wheat 7.5% in rice	Kumari et al., 2020
Model based simulation study	*Triticum aestivum* L	MOZART-2 global model	2000		9–30%	Avnery et al., 2011
	Triticum aestivum L and *Oryza sativa* L	WRF-Chem model	2005		3.5% in wheat 2.1% in rice	Ghude et al., 2014
	Triticum aestivum L	EMEP MSC-W, chemical transport model	2010–2012		22% (AOT 40), 20% (M7), 12% (POD_3)	Mills et al., 2018b
	Triticum aestivum L and *Oryza sativa* L	WRF-Chem model	2014–2015		21% in wheat 6% in rice	Sharma et al., 2019
	Triticum aestivum L	Chemical transport models	2008–2010		39%	Schauberger et al., 2019

In India, yield reductions in wheat due to surface O_3 ranged from 11 to 20.7% (Mukherjee et al., 2020). Recently, Mina et al. (2021) reported reductions in grain yield by 9.2% and biomass by 11% in wheat cultivar HD 2967 under elevated O_3 (ambient + 70 ppb) using FACE (free-air concentration enrichment). Elevated O_3 (ambient + 20 ppb) exposure led to decline in grain weight by 27.3% and harvest index by 16.8%, in HD2967 cultivar of wheat compared to ambient O_3 using open top chambers (Ghosh et al., 2021) (Table 2).

At identical O_3 concentrations, the variability in crop yield losses was reported mainly due to the distinct sensitivity of cultivars to O_3 (Rai et al., 2010; Singh et al., 2018b; Yadav et al., 2019). Modern and old wheat cultivars showed distinct variations in yield and quality parameters under elevated O_3, where modern high yielding cultivar was found more susceptible to O_3 compared to old low yielding cultivar (Yadav et al., 2020a). Furthermore, fourteen Indian wheat cultivars based on grain yield response under elevated O_3 depicted that early released cultivars (before year 2000) were less sensitive compared to newly released cultivars (Singh et al., 2018b) (Table 2). Wheat cultivars (Kharchiya 65-O_3 tolerant; PBW-intermediately sensitive and HD 2987-O_3 sensitive) selected from study of Singh et al. (2018b) were further examined for the impact of elevated O_3 on yield attributes. Losses in test weight by 12.9% in Kharchiya 65, 27.1% in PBW and 42.2% in HD 2987 were observed (Fatima et al., 2018). Similarly, Mishra et al. (2013) observed reductions in grain weight plant^{-1} in both dwarf (HUW-37) and tall (K-9107) cultivars of wheat under elevated O_3 (ambient + 10 ppb) (Table 2). However, dwarf cultivar having better yield was found to be more susceptible to O_3 compared to tall cultivar having lower yield potential. The shifting of crop calendar to bypass the peak concentration of O_3 exposure to wheat was not effective, as delay in sowing time by 20 days decreased grain yield by 45.3% compared to timely sowing, which had only a 16.2% reduction (Ghosh et al., 2020).

In maize cultivars, elevated O_3 (70 ppb) reduced the grain weight cob^{-1} in HQPM-1 by 5.8% and in PMH-1 by 11.3% compared to those at ambient concentration (Yadav et al., 2021c). Kernel weight m^{-2} and 1000 kernel weight declined more in DHM117 (normal maize) than HQPM-1 (quality protein maize) under exposure of elevated O_3, suggesting greater susceptibility of DHM117 (Singh et al., 2019). The greater reduction in yield of DHM117 was contributed due to more depletion of carbohydrate content than HQPM-1 (Table 2).

Two soybean cultivars, PK472 and Bragg, were assessed for their response under elevated O_3 and yield reduction was 20% and 33.6% in newly developed variety (PK472) while old variety (Bragg) showed reduction of 12% and 30% under 70 and 100 ppb O_3 treatment, respectively (Singh et al., 2010a). Some other economically important crops of IGP also showed sensitivity under prevailing O_3 stress. Singh et al. (2013) reported decrement in seed yield ranging between 22.7 and 26.2% under elevated O_3 in Pusa Tarak cultivar of mustard (*Brassica juncea* L.). In an analysis on elevated O_3 exposure and yield response of six mung bean cultivars, Chaudhary and Agrawal (2015) found that weight of seeds was reduced maximally in HUM-1 by 15.4% and minimally in HUM-23 by 9.8% (Table 2). Recently, an O_3-FACE experiment based study also recorded losses in yield and harvest index of Chickpea (*Cicer arietinum* L.), a pulse crop by 21.9% and 36.10%, respectively at 60 ppb O_3 concentration (Singh et al., 2021).

Horticultural crops are essential food as they provide necessary nutrients, minerals, and vitamins to human beings. India is ranked second in terms of horticultural crop production (Rais & Sheoran, 2015). Suganthy and Udayasoorian (2020) assessed the impact of elevated concentration of surface O_3 at high altitude of Western Ghat on ten potato (*Solanum tuberosum* L.) cultivars at tuber initiation stage. The reduction in yield ranged from 4.56 to 25.5% with Kufri Surya to be moderately resistant to O_3 with highest yield (Table 2). Both ambient and elevated levels of O_3 detrimentally affected the yield of Kufri chandramukhi cultivar of potato owing to declines in weight and number of tubers (sizes > 35 mm) (Kumari & Agrawal, 2014). A study on tomato (*Solanum lycopersicum* L.) depicted that elevated O_3 caused maximum reduction in yield during late vegetative phase (45 days old plant) than early vegetative and fruiting phases (Mina et al., 2010). Among leafy green vegetables, Palak (*Beta vulgaris* L.) is largely grown in suburban regions of India due to its high content of iron and folic acid and found to be extremely susceptible to O_3 (Tiwari et al., 2010). Response of Palak to O_3 was studied by Kumari et al. (2013) and 25% loss in yield was recorded (Table 2). Recently, Yadav et al. (2020b) screened forty *Amaranthus hypochondriacus* L. cultivars under FACE facility. Cultivars IC-5569 (91.4%) and IC-4200 (94.9%) showed very high decline in yield, while IC-5527 (7.8%) exhibited lowest yield loss.

Observation-based studies

An investigation of effects of surface O_3 concentrations in Delhi revealed relative yield loss (RYL) of 7.5%, 5.4%, and 1.8% in the winter season and 22.7%, 16.3%, and 5.5% in the pre-monsoon season for wheat, soybean, and rice, respectively over a 7-year period (1997–2004) (Ghude et al., 2008). Another observation-based evaluation of 17 sites from India between 2011 and 2014 reported 4.2 to 15% annual yield loss in wheat and 0.3 to 6.3% in rice due to tropospheric O_3 (Lal et al., 2017). Based on in situ O_3 measurements for 2-year period (2011–2013) in Punjab and Haryana region of India reported that yield losses in wheat ranged between 27 and 41%, maize between 3 and 5%, and rice between 21 and 26% (Sinha et al., 2015). A recent study by Feng et al. (2022) has reported the RYL of 33%, 9%, and 23% for wheat, maize, and rice, respectively in China which is ~ US $63 billion in terms of annual economic loss.

A detailed analysis of O_3 exposure based yield losses in the IGP region from 2010 to 2015 revealed losses of 1–5% at M7 (7-h mean O_3 concentration) and 6–15% at AOT40 in wheat, and 0.3–0.7% at M7 and 7.2–7.5% at AOT40 in rice (Kumari et al., 2020). The RYL ranged from 10–34% for wheat, and 7–10% for rice based on AOT40, while under M7, RYL for wheat ranged from 3 to 11% and for rice from 0.7 to 4% (Kumari et al., 2021). Osborne et al. (2016) gathered O_3 exposure yield related data (1998–2014) of 49 soybean cultivars from around the world at M7 of 55 ppb and discovered that Indian cultivars (which lost yield by 38%) are more susceptible to O_3 than cultivars from China and the USA.

Model-based studies

A study by Van Dingenen et al. (2009) assessed the impact of tropospheric O_3 on crops using global-scale modelling and predicted the annual yield loss for wheat ranging between 13 and 28% and for rice between 6 and 8% in India. Weather Research and

Table 3 Yield response of ozone exposed plants upon EDU treatment

Crop species	Cultivar	EDU Dose (ppm)	Duration (application interval in days)	Parameter	Response (% increase in yield)	Reference
Triticum aestivum L. (Wheat)	HD 2329	500	7	Weight of grain plant^{-1}	22	Agrawal et al., 2004
	HUW 234				27	
	HUW 468				36.3	
	Malviya 234	150	10	Weight of seeds plant^{-1}	24.8	Tiwari et al., 2005
		300			66.9	
		450			66.8	
	Malviya 533				18.8	
					19.1	
					20.5	
	HUW468	400	12	Weight of seeds plant^{-1}	25.8	Singh et al., 2009b
	HUW510				20.5	
	HUW234				11.2	
	Sonalika				10.2	
	PBW243				1.9	
	HD 2987	400	10	Weight of grains plant^{-1}	32.9	Fatima et al., 2019
	PBW 502				13.3	
	Kharchiya 65				8.8	
	WR544	300	10	Harvest index	37.4	Mina et al., 2021
Oryza sativa L. (Rice)	18 cultivars Banthra site Lucknow site	300	15	Weight of grains plant^{-1}	25 48	Pandey et al., 2015
	Sarjoo-52	200	7	Weight of grains plant^{-1}	8.9	Surabhi et al., 2020
				Harvest index	17.8	
	PB-1				25	
					44	
Zea mays L. (Maize)	Buland	$200+AO_3$	10	Weight of kernels plant^{-1}	4.8	Singh et al., 2018a
		$200+EO_3$			7.3	
	Prakash				11.8	
					14	
	SHM3031	50	7	1000 weight of seeds	20	Gupta et al., 2020
		200			14.2	
	PEHM5				15.15	
					17	
Glycine max L. (Soybean)	PUSA 9712	$400+AO_3$	10	Weight of seed plant^{-1}	29.8	Singh & Agrawal, 2011a
		$400+EO_3$			33	
	PUSA 9814				28.2	
					29.0	
	JS 335	400	10	Weight of seed plant^{-1}	26.7	Rai et al., 2015
Brassica compestris L. (Mustard)	Kranti	200	7	Weight of seeds plant^{-1}	7	Pandey et al., 2014
		400			17	
	Peela Sona				59	
					34	
Arachis hypogaea L. (Groundnut)	GG-20	500	12	Weight of seeds plant^{-1}	47.8	Chaudhary & Rathore, 2020
				Harvest index	23.7	

Table 3 (continued)

Crop species	Cultivar	EDU Dose (ppm)	Duration (application interval in days)	Parameter	Response (% increase in yield)	Reference
Mung Bean (*Vigna radiata* L.)	Malviya Jyoti	500	7	Weight of seeds plant^{-1}	32.2	Agrawal et al., 2005
	Malviya Janpriya	400	10	Weight of seeds plant^{-1}	32.2	Singh et al., 2010b
Vigna mungo L.	Barkha Shekhar	400	10	Weight of seeds plant^{-1}	36.4 35.6	Singh et al., 2010c
	Azad-1 BHU-1	400	10	Weight of seeds plant^{-1}	44.4 40.9	Singh & Agrawal, 2011b

Forecasting model coupled with Chemistry (WRF-Chem model) estimated 3.5 ± 0.8% losses in wheat and 2.1 ± 0.8 losses in rice, with maximum losses occurring in central and north India (Ghude et al., 2014). Recently, Sharma et al. (2019) reanalyzed the yield loss in India using the WRF-Chem model and found 21% and 6% yield losses in wheat and rice, respectively, which are considerably higher than previous studies (Table 2). An analysis of 2-year data based on O_3-flux model on four Indian wheat cultivars depicted that the loss in grain yield was higher (23.9% ± 1.35) in early sown cultivars compared to late sown cultivars (11.5% ± 0.37) under ambient + 20 ppb O_3 (Yadav et al., 2021a).

EDU as a research tool in estimating the yield losses against O_3

Ethylene diurea (EDU; [N-(2–2-oxo-1-imidazolidinyl) ethyl]-N-phenyl urea) is a well-known antiozonant research tool that was first described by Carnahan et al. (1978). Due to its phytoprotective responses, it is widely used for screening the cultivar's specific sensitivity, and assessing losses in yield under ambient and elevated O_3 conditions (Singh et al., 2015b). Application of EDU as control in comparison to ambient O_3 is beneficial for adequate monitoring of effects of ambient O_3 on agricultural crops in rural areas of India with electricity limitations (Manning et al., 2011; Tiwari et al., 2005). In India, several experiments using EDU as protectant to O_3 have been investigated for determining the variability among cultivars in terms of improvement in yield such as for wheat (Singh et al., 2009b), rice (Pandey et al., 2015), mustard (Pandey et al., 2014), and soybean (Singh & Agrawal, 2011a) (Table 3).

Recently, Mina et al. (2021) assessed the responses of thermotolerant wheat cv. WR544 to O_3 by applying 300 ppm EDU and found that harvest index was higher in EDU treated plants (37.4%) as compared to non-treated plant. Another study on three wheat cultivars by Fatima et al. (2019) found that EDU treatment (300 ppm) increased yield of HD 2987 (O_3 sensitive) by 32.9%, PBW 502 (intermediately sensitive) by 13.3%, and Kharchiya 65 (O_3 tolerant) by 8.8% (Table 3). Similarly in two rice cultivars, PB-1 (O_3 sensitive) showed about 25% increase in seed weight plant^{-1} in EDU treated plants than Sarjoo-52 (O_3 tolerant) which showed lower increment of 8.9% (Surabhi et al., 2020). Application of 50 and 200 ppm EDU on two maize cultivars showed protection by enhancing anti-oxidative defence machinery, ultimately greater yield in SHM3031 (sensitive variety) as compared to PEHM5 (tolerant variety) in response to high O_3 concentration (Gupta et al., 2020). A similar finding was also observed for the maize cultivars Buland and Prakash with 200 ppm EDU doses under ambient and elevated O_3 (Singh et al., 2018a).

The exact mode of action of phytoprotection provided by EDU against O_3 induced damage has remained unclear till now. An expected mechanism has been ascribed to its capability to induce enzymatic and non-enzymatic antioxidants which detoxify ROS (Pandey et al., 2015; Singh et al., 2018a). Agathokleous (2017) in its review gave another view of perception towards the phytoprotective mechanism of EDU by showing hormetic (means activating plant defense at a low stress dose) responses against ambient and elevated O_3 stress. There are several evidences that showed hormesis in a plant species by using low doses of abiotic agents like O_3 or specific chemicals such as EDU (Agathokleous & Kitao, 2018; Agathokleous et al., 2019; Calabrese & Blain, 2011). The EDU mediated hormetic responses were measured in various endpoints such as growth, physiology, reproduction, and productivity (Agathokleous & Kitao, 2018; Agathokleous et al., 2019). Dose response study manifested that treatment of EDU (0–800 mg·L^{-1}) induced hormesis in radish (*Rapahanus sativus* L.) plant (by stimulating fresh weight of cotyledons and dry weight of root) placed in nonfiltered air receiving ≈25 ppb O_3 concentration, and the maximum stimulation was recorded at 300 mg L^{-1} (Agathokleous, 2017; Kostka-Rick & Manning, 1993). Another experiment with carrot (*Daucus carota* L.) grown in ambient O_3 concentration on treatment with EDU (0–450 mg L^{-1}) mediated hormetic responses in terms of growth and nutritional aspect, and the highest immensity of positive response was recorded at 150 mg L^{-1} (Tiwari & Agrawal, 2010). Earlier, an EDU-mediated hormetic response has also been reported in wheat (Archambault et al., 2002). Further, it is shown that conditioning may be an important aspect of hormesis and O_3 may activate

Table 4 Responses of plants tropospheric O_3 under N fertilization

Crops/vegetables	Ozone concentration	Nitrogen dose	Effects on yield/quality	References
Brassica campestris L Kranti	Ambient O_3(41.65–54.2 ppb), 12 h mean	1.5 times RNPK, RNPK	Reductions in seed yield by 16.4% and oil content by 13.1% at RNPK, while insignificant differences at 1.5 times RNPK	Singh et al., 2009a
Brassica campestris L Vardan and Aashirwad	Ambient O_3 (27.7 and 59.04 ppb), 12 h mean	1.5 times RNPK, RNPK	Reductions in seed yield by 7.1% and oil content by 11.15% in Vardan and in Aashirwaad by 19.3% in seed yield and 12.8% in oil content at RNPK. No significant differences at 1.5 RNPK	Singh et al., 2012
Triticum aestivum L HUW 510 and LOK-1	Ambient O_3 (10.3 to 110 ppb), 12 h mean	1.5 times RNPK, RNPK	Reduction in yield by 16.2% at RNPK but no significant difference at 1.5 RNPK in LOK-1, while in HUW 510 no significant changes at both N doses	Singh et al., 2015a
Triticum aestivum L. HD2967 and Sonalika	Ambient O_3 (52.4 ppb) + 20 ppb, 8 h mean	RN, 1.5 times RN (high N)	Reduction in grain yield by 18% at RN and no improvement at high N (19%) while insignificant differences in HD2967	Pandey et al., 2018
Zea mays L Malviya hybrid-2 and HHM-1	Ambient O_3 (50.50 ppb), 8 h mean	RNPK, 1.5 times RNPK and 2 times RNPK	Increase in weight of kernels cob^{-1} by 38.5, 103 and 104% in Malviya hybrid-2 respectively at RNPK, 1.5 RNPK and 2RNPK and by 27.5, 58.6 and 58.8% in HHM-1 respectively	Gautam et al., 2020
Cymopsis tetragonoloba L PUSA-N and S-151	Ambient O_3 (56 ppb), 8 h mean	RNPK, 1.5 times RNPK and 2 times RNPK	Antioxidative defense machinery more strengthened in PUSA-N than S-151 at 1.5 RNPK 2 RNPK did not provide extra advantage	Gupta & Tiwari, 2020
Beta vulgaris L Allgreen	Ambient O_3 (42.60 ppb), 8 h mean	RNPK, 1.5 times RNPK	Increment in yield by 58.12% at RNPK and by 71.2% at 1.5 RNPK	Sahoo & Tiwari, 2021

conditioning in plant defense strategy (Sandermann et al., 1998). Preconditioning of tomato calli with 100, 200, or 300 ppb O_3 for 7 days (30 min d^{-1}) induced resistance in regenerated plantlets towards O_3 exposure (200 ppb, 2 h) by altering the antioxidant potential (Nagendra-Prasad et al., 2008). Similarly, Li et al. (2017) also showed such response in bean (*Phaseolus vulgaris* L.) plants on pre-treatment of O_3 (≈200 ppb for 30 min), which prevented against more extensive exposure to O_3 (600 ppb for 30 min).

Nitrogen fertilization in alleviating the impact of tropospheric O_3 on crops and vegetables

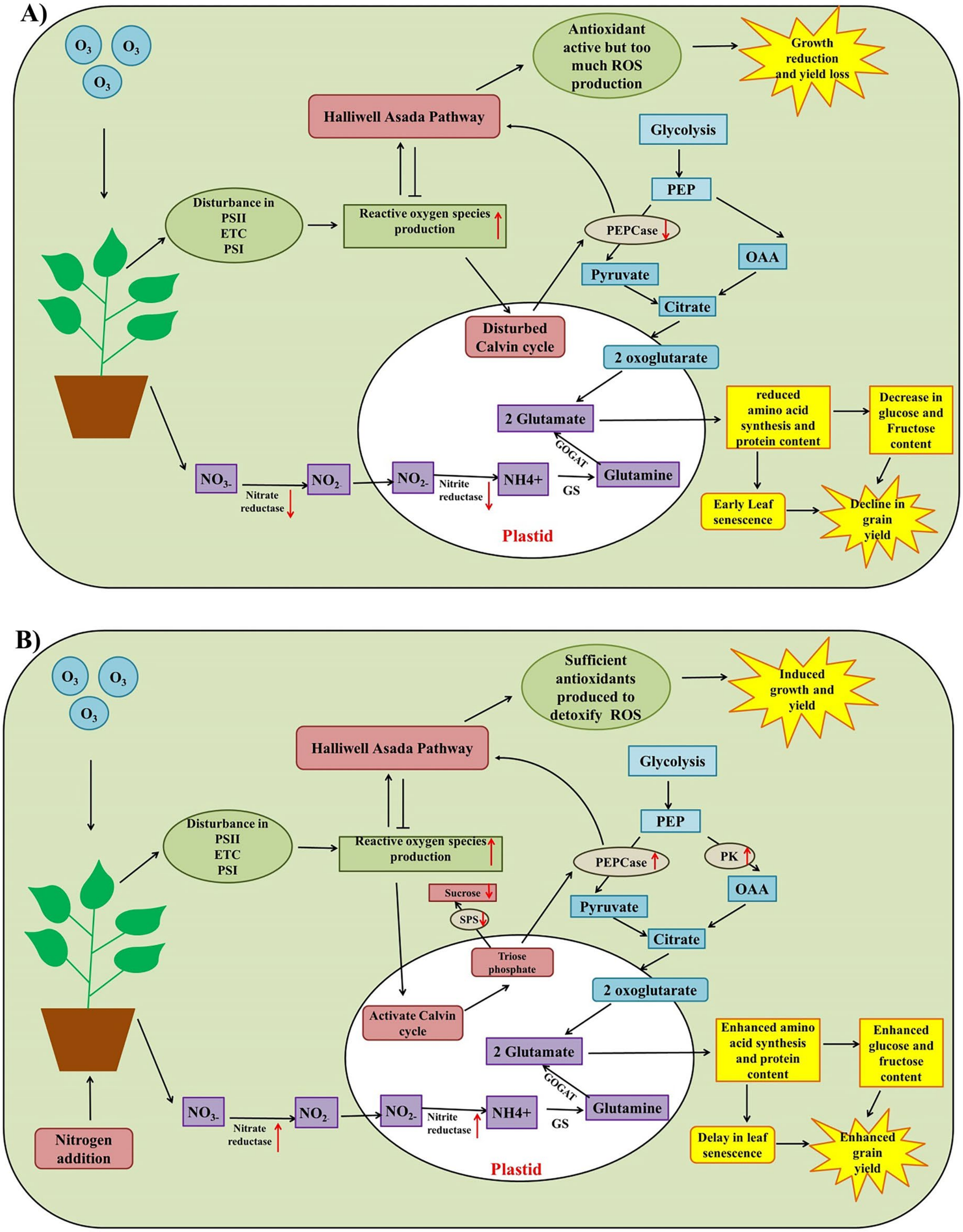
Inorganic nitrogen (N) fertilizers are widely used to increase grain production (Akhtar et al., 2020). There have been a lot of studies done on the connection between elevated O_3 and nitrogen management, but the obtained results were variable (Feng et al., 2019). Singh et al. (2015a) found an antagonistic response where a high dose of N mitigated the negative response of O_3 stress on wheat plants. At recommended NPK (RNPK), mustard cultivars Vardan and Aashirwad, which were grown in non-filtered chambers (NFCs) receiving ambient O_3, had significant drops in their micronutrient, protein, and seed oil contents. But at 1.5-times the RNPK, they did not have significant changes (Singh et al., 2012). In a study on interactive effects of different concentrations of N and elevated O_3 on wheat cultivars, HD2967 and Sonalika showed differential responses (Pandey et al., 2018). In Sonalika, treatment with a high dose of N did not alleviate the O_3 phytotoxicity in relation to yield, while HD2967 showed alleviation (Pandey et al., 2018).

Another study by Singh et al. (2015a) with LOK-1 and HUW 510 cultivars of wheat depicted that ambient O_3 negatively affected the N acquisition, which increased the demand of N in sensitive cultivar LOK-1 and hence increase in yield was recorded at 1.5-times recommended N dose (Table 4). However, HUW 510, being less sensitive, showed an increase in yield under ambient O_3 at recommended N. Similarly, Gautam et al. (2020) found that 1.5-times recommended dose of N was sufficient to relieve the negative impact of ambient O_3 on maize cultivars (Malviya hybrid-2 and HHM-1) by enhancing crop productivity, while 2-times recommended dose of N did not provide any additional benefit to plant metabolism compared to 1.5 times N dose (Table 4). Further, differences in allocation strategies during developmental phases led to greater increment in yield of Malviya hybrid-2 than HHM-1. Under ambient O_3 conditions, N amendments (in the form of NPK) induced antioxidant defense machinery in a more competent manner in tolerant cultivar (PUSA-N) of Cluster bean (*Cymopsis tetragonoloba* L.) compared to sensitive cultivar (S-151), which showed decline in stomatal conductance as an avoidance strategy (Gupta & Tiwari, 2020). An experiment on Palak (*Beta vulgaris* L.) also found that adding nitrogen to the soil helped to lessen the effects of O_3 stress by changing the plant's antioxidative properties (Sahoo & Tiwari, 2021).

The possible mechanism of alleviation of O_3 toxicity under N supplementation relies on positive impact of N on photochemical processes followed by increased carbon assimilation rate. This type of reaction could be linked to the expenditure of available N in protein, which may enhance the photosynthetic ability (Singh et al., 2015a). The proteins are important factors for defense machinery and, hence, N addition alleviates O_3 phytotoxicity (Yendrek et al., 2013). Insufficient N fertilization restricts the photosynthetic N use efficiency, which declines the grain yield. However, optimum N addition enhances the grain yield (Singh et al., 2015a).

The beneficial role of nitrogen on performance of plants exposed to O_3 can also be assigned to upregulation of enzyme activities of Halliwell-Asada pathway (APX, ASA, and DHA) under nitrogen implementation (Fig. 1B; Gupta & Tiwari, 2020; Pandey et al., 2018). Elevated O_3 exposure led to decline in seed protein in soybean, which is correlated with a detrimental reaction to nitrogen fixation (Broberg et al., 2020). It is also shown in rice that elevated O_3

Fig. 1 Schematic representation illustrating **A)** the impact of elevated O_3 on nitrogen metabolism and yield reduction, and **B)** role of nitrogen addition in combating harmful effect of tropospheric O_3 on plants. Nitrogen addition scavenges O_3 induced reactive oxygen species by upregulating antioxidative and Halliwell-Asada pathway enzymes. Contrarily, nitrogen addition mediated the carbon pool partitioning away from sucrose synthesis by deactivating SPS and being assisted towards amino acid synthesis by activating PEPcase. GS, glutamine synthetase; GOGAT, glutamine oxoglutarate aminotransferase; SPS, sucrose phosphate synthase; PEPcase, phosphoenolpyruvate carboxylase; PK, pyruvate kinase; PEP, phosphoenolpyruvate, OAA, oxaloacetic acid. Pointed arrow end represents induction and blunt end represents inhibition. Enhancements in parameters are shown by ↑ and reduction by ↓ ▸


A)
O_3
O_3
O_3
Antioxidant active but too much ROS production
Growth reduction and yield loss
Halliwell Asada Pathway
Glycolysis
PEP
Disturbance in PSII ETC PSI
Reactive oxygen species production
PEPCase
OAA
Pyruvate
Citrate
Disturbed Calvin cycle
2 oxoglutarate
2 Glutamate
reduced amino acid synthesis and protein content
Decrease in glucose and Fructose content
GOGAT
NO_{3-}
Nitrate reductase
NO_{2-}
NO_{2-}
Nitrite reductase
NH4+
GS
Glutamine
Early Leaf senescence
Decline in grain yield
Plastid
B)
O_3
O_3
O_3
Sufficient antioxidants produced to detoxify ROS
Induced growth and yield
Halliwell Asada Pathway
Glycolysis
PEP
Disturbance in PSII ETC PSI
Reactive oxygen species production
PEPCase
PK
OAA
Sucrose
SPS
Pyruvate
Citrate
Triose phosphate
2 oxoglutarate
Activate Calvin cycle
2 Glutamate
Enhanced amino acid synthesis and protein content
Enhanced glucose and fructose content
GOGAT
NO_{3-}
Nitrate reductase
NO_{2-}
NO_{2-}
Nitrite reductase
NH4+
GS
Glutamine
Delay in leaf senescence
Enhanced grain yield
Nitrogen addition
Plastid

treatment declines the nitrate reductase (NR) activity, NH_4^+-N and NO_3^--N contents (Fig. 1A; Huang et al., 2012). So, implementation of N may trigger N metabolism and may alter the allocation of N towards structural proteins and photosynthesis (Liu et al., 2018). Under O_3 stress, application of high dose of nitrogen delayed the leaf senescence process by conserving high protein content (Pandey et al., 2018).

It is observed that the biosynthetic pathways of sucrose and amino acids compete for energy and carbon skeleton (Champigny & Foyer, 1992). A study on effect of nitrate on wheat seedlings showed an inverse response between the rate of sucrose formation and the assimilation rate of NO_3^- (Van Quy et al., 1991). The two key enzymes, sucrose phosphate synthase (SPS) and phosphoenolpyruvate carboxylase (PEPcase), are responsible for carbon assimilation partitioning, and are modified by protein phosphorylation under nitrogen addition. But the reactions of both the enzymes show the opposite trend. Application of nitrogen reduces the content of PEP and activates PEPcase in leaves, which is linked to increased carbon flux towards amino acids (Fig. 1B). Accordingly, decrement in SPS activity restricts the synthesis of sucrose in leaves, suggesting that SPS plays a major role in flux of carbon towards sucrose (Champigny & Foyer, 1992). Although, in our understanding, there are very few studies indicating mechanism of carbon partitioning in crops and vegetables, which needs to be explored in future to assess the exact mechanism of nitrogen supplementation in alleviating O_3 stress.

Conclusions and future prospects

The present compilations of data on Indian agricultural crops clearly highlight the crop's sensitivity to present and future levels of O_3, experiencing significant yield losses. Ozone pollution is worsening and heavily impacting the crop's productivity, thus posing a threat to food security in near future. Cumulative stress response index, phytotoxic O_3 dose, and foliar injury are some important tools for estimating the sensitivity of crops against O_3 stress. The studies clearly indicate that wheat is the most sensitive crop to O_3 and hence showed greater loss in yield than rice. Maize is found to be less sensitive to O_3 in IGP region under present O_3 scenario. The sequence of susceptibility of major crops is wheat $^>$ mustard > rice > maize in IGP region. Under high O_3 concentration, Ethylenediurea (EDU), an O_3-protectant, is beneficial to evaluate crop yield losses in remote areas where electricity and infrastructures are limited. Implementation of N fertilizers (1.5 times the recommended NPK) effectively ameliorated the loss in grain yield under ambient and elevated O_3 by activating antioxidative pathway.

Taking into consideration the vulnerability of economically important crops and vegetables in India to elevated surface O_3 concentration, mitigation perspective should be taken to reduce emission of O_3 precursors. In European Union and United States of America, various strategies and implementation plans such as European Crop Loss Assessment Network (EUCLAN) and National Crop Loss Assessment Network (NCLAN) program were initiated and implemented, which effectively led to decline in O_3 concentrations. Such network programs are needed in India to assess the countrywide yield losses. Ozone biomonitoring and assessment programs may also include O_3-sensitive common biomonitors such as clover NC-S, snap bean genotype S156, and tobacco cultivar Bel-W3 to recognize air quality and climatic conditions in a specific region. Recently, some biomonitoring concepts such as O_3-Gardens of ICP Vegetation and the O_3-Bioindicator Garden Project of NASA were introduced for creating gardens having O_3 sensitive and resistant varieties of plants and raising public awareness of the threats posed by tropospheric O_3 across the region. Such awareness programs must be initiated by other countries at local and large scale.

In India, one of the biggest issues is the inadequate monitoring setup in rural areas that should be strengthened to provide accurate data regarding O_3 concentration. The accessibility of EDU chemical should be promoted in rural areas for cost-effective short-term O_3 biomonitoring and also for identifying indicator plant species against ambient O_3 in natural habitat.

Solar radiation, drought, temperature, and CO_2 are major factors that directly or indirectly modulate the effects of elevated O_3 on plants. These interactions need detailed analyses under various cropping pattern in the future. Therefore, O_3-flux-based metrics should be considered over the exposure-based metrics by the researchers for precise O_3 risk assessment and flux-response functions. The impact of elevated O_3 on plants differs with the addition of nitrogen as a fertilizer. Therefore, more studies on responses of crops and vegetables after implementation of an appropriate dose of nitrogen under O_3 stress should be promoted to understand the exact mechanism of plants. Use of beneficial agricultural practices in ameliorating the negative impact of tropospheric O_3 on productivity of crops could be worked out in future.

It is evident that to reduce yield losses, O_3 tolerant cultivars should be encouraged in future to withstand O_3 stress condition. Therefore, different cultivars of crops and unexplored cultivars need to be screened for their tolerance and sensitivity to O_3. Biotechnological tools and conventional breeding approaches are required to produce O_3 tolerant cultivars by modifying antioxidant defense pathways, stress regulated genes, and signaling pathways, which may be beneficial to restrict yield losses due to elevated O_3 in future.

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References

Agathokleous, E. (2017). Perspectives for elucidating the ethylenediurea (EDU) mode of action for protection against O_3 phytotoxicity. *Ecotoxicology and Environmental Safety, 142*, 530–537. https://doi.org/10.1016/j.ecoenv.2017.04.057

Agathokleous, E., Belz, R. G., Calatayud, V., De Marco, A., Hoshika, Y., Kitao, M., Saitanis, C. J., Sicard, P., Paoletti, E., & Calabrese, E. J. (2019). Predicting the effect of ozone on vegetation via linear non-threshold (LNT), threshold and hormetic dose-response models. *Science of the Total Environment, 649*, 61–74. https://doi.org/10.1016/j.scitotenv.2018.08.264

Agathokleous, E., Feng, Z., Oksanen, E., Sicard, P., Wang, Q., Saitanis, C. J., et al. (2020). Ozone affects plant, insect, and soil microbial communities: A threat to terrestrial ecosystems and biodiversity. *Science Advances*, *6*(33), eabc1176. https://doi.org/10.1126/sciadv.abc1176

Agathokleous, E., & Kitao, M. (2018). Ethylenediurea induces hormesis in plants. *Dose-Response, 16*(2), 1559325818765280.

Agrawal, S. B., Singh, A., & Rathore, D. (2004). Assessing the effects of ambient air pollution on growth, biochemical and yield characteristics of three cultivars of wheat (*Triticum aestivum* L.) with ethylenediurea and ascorbic acid. *Journal of Plant Biology, 31*, 165–172.

Agrawal, S. B., Singh, A., & Rathore, D. (2005). Role of ethylene diurea (EDU) in assessing impact of ozone on *Vigna radiata* L. plants in a suburban area of Allahabad (India). *Chemosphere*, *61*(2), 218–228. https://doi.org/10.1016/J.CHEMOSPHERE.2005.01.087

Akhtar, K., Wang, W., Ren, G., Khan, A., Enguang, N., Khan, A., et al. (2020). Straw mulching with inorganic nitrogen fertilizer reduces soil CO_2 and N_2O emissions and improves wheat yield. *Science of the Total Environment, 741*, 140488.

Anav, A., De Marco, A., Proietti, C., Alessandri, A., Dell'Aquila, A., Cionni, I., et al. (2016). Comparing concentration-based (AOT40) and stomatal uptake (PODY) metrics for ozone risk assessment to European forests. *Global Change Biology, 22*(4), 1608–1627. https://doi.org/10.1111/gcb.13138

Archambault, D. J. P., Li, X., & Vegreville A. (2002). Evaluation of the anti-oxidant ethylene diurea (EDU) as a protectant against ozone effects on crops (field Trials). *Alberta Environment*. Retrieved May 1, 2022, from https://open.alberta.ca/dataset/25689be1-b4df-4ae7-a76e

Ashrafuzzaman, M., Lubna, F. A., Holtkamp, F., Manning, W. J., Kraska, T., & Frei, M. (2017). Diagnosing ozone stress and differential tolerance in rice (*Oryza sativa* L.) with ethylenediurea (EDU). *Environmental Pollution, 230*, 339–350. https://doi.org/10.1016/j.envpol.2017.06.055

Avnery, S., Mauzerall, D. L., Liu, J., & Horowitz, L. W. (2011). Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmospheric Environment, 45*(13), 2284–2296. https://doi.org/10.1016/J.ATMOSENV.2010.11.045

Biswas, D. K., Xu, H., Li, Y. G., Sun, J. Z., Wang, X. Z., Han, X. G., & Jiang, G. M. (2008). Genotypic differences in leaf biochemical, physiological and growth responses to ozone in 20 winter wheat cultivars released over the past 60 years. *Global Change Biology, 14*(1), 46–59. https://doi.org/10.1111/j.1365-2486.2007.01477.x

Booker, F., Muntifering, R., Mcgrath, M., Burkey, K., Decoteau, D., Fiscus, E., et al. (2009, April). The ozone component of global change: Potential effects on agricultural and horticultural plant yield, product quality and interactions with invasive species. *Journal of Integrative Plant Biology*. John

Wiley & Sons, Ltd. https://doi.org/10.1111/j.1744-7909.2008.00805.x

Broberg, M., Daun, S., & Pleijel, H. (2020). Ozone induced loss of seed protein accumulation is larger in soybean than in wheat and rice. *Agronomy, 10*(3), 357. https://doi.org/10.3390/agronomy10030357

Cailleret, M., Ferretti, M., Gessler, A., Rigling, A., & Schaub, M. (2018). Ozone effects on European forest growth—Towards an integrative approach. *Journal of Ecology, 106*(4), 1377–1389. https://doi.org/10.1111/1365-2745.12941

Calabrese, E. J., & Blain, R. B. (2011). The hormesis database: The occurrence of hormetic dose responses in the toxicological literature. *Regulatory Toxicology and Pharmacology, 61*(1), 73–81. https://doi.org/10.1016/j.yrtph.2011.06.003

Carnahan, J., Jenner, E., & Wat, E. (1978). Prevention of ozone injury to plants by a new protectant chemical. *Phytopathology*, *68*, 1225–1229. Retrieved April 29, 2022, from https://www.apsnet.org/publications/phytopathology/backissues/Documents/1978Articles/Phyto68n08_1225.PDF

Champigny, M., & Foyer, C. (1992). Nitrate activation of cytosolic protein kinases diverts photosynthetic carbon from sucrose to amino acid biosynthesis: Basis for a new concept. *Plant Physiology, 100*(1), 7–12.

Chang, K. L., Petropavlovskikh, I., Cooper, O. R., Schultz, M. G., & Wang, T. (2017). Regional trend analysis of surface ozone observations from monitoring networks in eastern North America, Europe and East Asia. *Elementa, 5*, 50. https://doi.org/10.1525/elementa.243

Chaudhary, I. J., & Rathore, D. (2020). Relative effectiveness of ethylenediurea, phenyl urea, ascorbic acid and urea in preventing groundnut (*Arachis hypogaea* L) crop from ground level ozone. *Environmental Technology & Innovation, 19*, 100963. https://doi.org/10.1016/J.ETI.2020.100963

Chaudhary, N., & Agrawal, S. B. (2013). Intraspecific responses of six Indian clover cultivars under ambient and elevated levels of ozone. *Environmental Science and Pollution Research, 20*(8), 5318–5329. https://doi.org/10.1007/s11356-013-1517-0

Chaudhary, N., & Agrawal, S. B. (2015). The role of elevated ozone on growth, yield and seed quality amongst six cultivars of mung bean. *Ecotoxicology and Environmental Safety, 111*, 286–294. https://doi.org/10.1016/J.ECOENV.2014.09.018

CLRTAP (Convention on Long-Range Transboundary Air Pollution). (2017). Mapping critical levels for vegetation. Manual on Methodologies and Criteria for Modelling and Mapping Critical Loads and Levels and Air Pollution Effects, Risks and Trends. Chapter 3 Mapping critical levels for vegetation. (Vol. 2017).

Debaje, S. B. (2014). Estimated crop yield losses due to surface ozone exposure and economic damage in India Science. *Environmental and Pollution Research, 21*(12), 7329–7338. https://doi.org/10.1007/S11356-014-2657-6/TABLES/5

Eghdami, H., Werner, W., Büker, P., & Sicard, P. (2022). Assessment of ozone risk to Central European forests: Time series indicates perennial exceedance of ozone critical levels. *Environmental Research, 203*, 111798. https://doi.org/10.1016/j.envres.2021.111798

Emberson, L. D., Büker, P., Ashmore, M. R., Mills, G., Jackson, L. S., Agrawal, M., et al. (2009). A comparison of North American and Asian exposure-response data for ozone effects on crop yields. *Atmospheric Environment, 43*(12), 1945–1953. https://doi.org/10.1016/j.atmosenv.2009.01.005

Emberson, L. D., Pleijel, H., Ainsworth, E. A., van den Berg, M., Ren, W., Osborne, S., et al. (2018). Ozone effects on crops and consideration in crop models. *European Journal of Agronomy, 100*, 19–34. https://doi.org/10.1016/j.eja.2018.06.002

Fatima, A., Singh, A. A., Mukherjee, A., Agrawal, M., & Agrawal, S. B. (2018). Variability in defence mechanism operating in three wheat cultivars having different levels of sensitivity against elevated ozone. *Environmental and Experimental Botany, 155*, 66–78. https://doi.org/10.1016/j.envexpbot.2018.06.015

Fatima, A., Singh, A. A., Mukherjee, A., Dolker, T., Agrawal, M., & Agrawal, S. B. (2019). Assessment of ozone sensitivity in three wheat cultivars using ethylenediurea. *Plants, 8*(4). https://doi.org/10.3390/plants8040080

Feng, Z., Calatayud, V., Zhu, J., & Kobayashi, K. (2018). Ozone exposure and flux-based response relationships with photosynthesis of winter wheat under fully open air condition. *Science of the Total Environment, 619–620*, 1538–1544. https://doi.org/10.1016/j.scitotenv.2017.10.089

Feng, Z., Shang, B., Li, Z., Calatayud, V., & Agathokleous, E. (2019). Ozone will remain a threat for plants independently of nitrogen load. *Functional Ecology, 33*(10), 1854–1870. https://doi.org/10.1111/1365-2435.13422

Feng, Z., Sun, J., Wan, W., Hu, E., & Calatayud, V. (2014). Evidence of widespread ozone-induced visible injury on plants in Beijing, China. *Environmental Pollution, 193*, 296–301. https://doi.org/10.1016/j.envpol.2014.06.004

Feng, Z., Wang, L., Pleijel, H., Zhu, J., & Kobayashi, K. (2016). Differential effects of ozone on photosynthesis of winter wheat among cultivars depend on antioxidative enzymes rather than stomatal conductance. *Science of the Total Environment, 572*, 404–411. https://doi.org/10.1016/j.scitotenv.2016.08.083

Feng, Z., Xu, Y., Kobayashi, K., Dai, L., Zhang, T., Agathokleous, E., et al. (2022). Ozone pollution threatens the production of major staple crops in East Asia. *Nature Food 2022 3:1*, *3*(1), 47–56. https://doi.org/10.1038/s43016-021-00422-6

Fernandes, F. F., & Moura, B. B. (2021). Foliage visible injury in the tropical tree species, Astronium graveolens is strictly related to phytotoxic ozone dose (PODy). *Environmental Science and Pollution Research, 28*(31), 41726–41735. https://doi.org/10.1007/s11356-021-13682-3

Fischer, T. (2019). Wheat yield losses in India due to ozone and aerosol pollution and their alleviation: A critical review. *Outlook on Agriculture, 48*(3), 181–189. https://doi.org/10.1177/0030727019868484

Frei, M., Kohno, Y., Tietze, S., Jekle, M., Hussein, M. A., Becker, T., & Becker, K. (2012). The response of rice grain quality to ozone exposure during growth depends on ozone level and genotype. *Environmental Pollution, 163*, 199–206. https://doi.org/10.1016/j.envpol.2011.12.039

Gautam, A., Gupta, G., & Tiwari, S. (2020). Management of ozone stress through nutrient amendments: Role of biomass allocation in sustaining yield in selected maize cultivars. *Journal of Scientific Research*, *65*(3).

Gerosa, G., Marzuoli, R., Bussotti, F., Pancrazi, M., & Ballarin-Denti, A. (2003). Ozone sensitivity of Fagus sylvatica and

Fraxinus excelsior young trees in relation to leaf structure and foliar ozone uptake. *In Environmental Pollution, 125*, 91–98. https://doi.org/10.1016/S0269-7491(03)00094-0

Ghosh, A, Agrawal, M., & Agrawal, S. (2021). Examining the effectiveness of biomass-derived biochar for the amelioration of tropospheric ozone-induced phytotoxicity in the Indian wheat cultivar HD 2967. *Journal of Hazardous Material*, 408, 124968. Retrieved November 7, 2021, from https://www.sciencedirect.com/science/article/pii/S0304389420329599

Ghosh, A., Pandey, A. K., Agrawal, M., & Agrawal, S. B. (2020). Assessment of growth, physiological, and yield attributes of wheat cultivar HD 2967 under elevated ozone exposure adopting timely and delayed sowing conditions. *Environmental Science and Pollution Research, 27*(14), 17205–17220. https://doi.org/10.1007/S11356-020-08325-Y

Ghude, S. D., Jain, S. L., Arya, B. C., Beig, G., Ahammed, Y. N., Kumar, A., & Tyagi, B. (2008). Ozone in ambient air at a tropical megacity, Delhi: Characteristics, trends and cumulative ozone exposure indices. *Journal of Atmospheric Chemistry, 60*(3), 237–252. https://doi.org/10.1007/S10874-009-9119-4/FIGURES/7

Ghude, S. D., Jena, C., Chate, D. M., Beig, G., Pfister, G. G., Kumar, R., & Ramanathan, V. (2014). Reductions in India's crop yield due to ozone. *Geophysical Research Letters, 41*(15), 5685–5691. https://doi.org/10.1002/2014GL060930

Girach, I. A., Ojha, N., Nair, P. R., Pozzer, A., Tiwari, Y. K., Ravi Kumar, K., & Lelieveld, J. (2017). Variations in O_3, CO, and CH_4 over the Bay of Bengal during the summer monsoon season: Shipborne measurements and model simulations. *Atmospheric Chemistry and Physics, 17*(1), 257–275. https://doi.org/10.5194/acp-17-257-2017

Gupta, G., & Tiwari, S. (2020). Role of antioxidant pool in management of ozone stress through soil nitrogen amendments in two cultivars of a tropical legume. *Functional Plant Biology, 48*(4), 371–385. https://www.publish.csiro.au/FP/FP20159

Gupta, S. K., Sharma, M., Majumder, B., Maurya, V. K., Deeba, F., Zhang, J. L., & Pandey, V. (2020). Effects of ethylenediurea (EDU) on regulatory proteins in two maize (*Zea mays* L.) varieties under high tropospheric ozone phytotoxicity. *Plant Physiology and Biochemistry, 154*, 675–688. https://doi.org/10.1016/J.PLAPHY.2020.05.037

Harmens, H., Hayes, F., Mills, G., Sharps, K., Osborne, S., & Pleijel, H. (2018). Wheat yield responses to stomatal uptake of ozone: Peak vs rising background ozone conditions. *Atmospheric Environment, 173*, 1–5. https://doi.org/10.1016/j.atmosenv.2017.10.059

Harmens, H., Hayes, F., Sharps, K., Radbourne, A., & Mills, G. (2019). Can reduced irrigation mitigate ozone impacts on an ozone-sensitive african wheat variety? *Plants, 8*(7). https://doi.org/10.3390/plants8070220

Hayes, F., Lloyd, B., Mills, G., Jones, L., Dore, A. J., Carnell, E., et al. (2019a). Impact of long-term nitrogen deposition on the response of dune grassland ecosystems to elevated summer ozone. *Environmental Pollution, 253*(2), 821–830. https://doi.org/10.1016/j.envpol.2019.07.088

Hayes, F., Mills, G., Harmens, H., & Norris, D. (2007). Evidence of widespread ozone damage to vegetation in Europe (1990–2006). ICP Vegetation Programme Coordination Centre, CEH, Bangor, UK.

Hayes, F., Sharps, K., Harmens, H., Roberts, I., & Mills, G. (2019b). Tropospheric ozone pollution reduces the yield of African crops. *Journal of Agronomy and Crop Science*, (October), 1–15. https://doi.org/10.1111/jac.12376

Hoshika, Y., Carrari, E., Zhang, L., Carriero, G., Pignatelli, S., Fasano, G., et al. (2018). Testing a ratio of photosynthesis to O_3 uptake as an index for assessing O_3-induced foliar visible injury in poplar trees. *Environmental Science and Pollution Research, 25*(9), 8113–8124. https://doi.org/10.1007/s11356-017-9475-6

Huang, Y. Z., Sui, L. H., Wang, W., Geng, C. M., & Yin, B. H. (2012). Visible injury and nitrogen metabolism of rice leaves under ozone stress, and effect on sugar and protein contents in grain. *Atmospheric Environment, 62*, 433–440. https://doi.org/10.1016/j.atmosenv.2012.09.002

IPCC. (2013). In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on.

Janku, M., Luhová, L., & Petrivalský, M. (2019). On the origin and fate of reactive oxygen species in plant cell compartments. *Antioxidants*. https://doi.org/10.3390/antiox8040105

Kostka-Rick., R, & Manning, W.J. (1993). Dose-response studies with ethylenediurea (EDU) and radish. *Environmental Pollution, 79*, 249–260. https://doi.org/10.1016/0269-7491(93)90097-8

Krupa, S., McGrath, M. T., Andersen, C. P., Booker, F. L., Burkey, K. O., Chappelka, A. H., et al. (2001). *February)*. Plant Disease. American Phytopathological Society. https://doi.org/10.1094/PDIS.2001.85.1.4

Kumari, S, & Agrawal, M. (2014). Growth, yield and quality attributes of a tropical potato variety (*Solanum tuberosum* L. cv Kufri chandramukhi) under ambient and elevated carbon dioxide and ozone and their interactions. *Ecotoxicology and Environmental Safety, 101*(1), 146–156. https://doi.org/10.1016/J.ECOENV.2013.12.021

Kumari, S., Agrawal, M., & Tiwari, S. (2013). Impact of elevated CO_2 and elevated O_3 on *Beta vulgaris* L.: pigments, metabolites, antioxidants, growth and yield. *Environmental Pollution, 174*, 279–288. https://doi.org/10.1016/j.envpol.2012.11.021

Kumari, S, Lakhani, A., & Kumari, K.M. (2020). First observation-based study on surface O_3 trend in Indo-Gangetic Plain: Assessment of its impact on crop yield. *Chemosphere, 255*, 126972. Retrieved November 29, 2021, from https://www.sciencedirect.com/science/article/pii/S0045653520311656

Kumari, S., Verma, N., Lakhani, A., & Kumari, K. M. (2021). Impact of increasing ozone on agricultural crop yields. in urban air quality monitoring, modelling and human exposure assessment (pp. 211–223). Springer, Singapore. https://doi.org/10.1007/978-981-15-5511-4_15

Kunchala, R. K., Singh, B. B., Krishna, K. R., Attada, R., Seelanki, V., & Kumar, K. N. (2021). Assessment of spatiotemporal variability and rising trends of surface ozone over India. https://doi.org/10.21203/rs.3.rs-562605/v1

Ladd, I., Skelly, J., Pippin, M., & Fishman, J. (2011). Ozone-induced foliar injury field guide. Langley Research Center, Hampton: National Aeronautics and Space Administration, Publication NP-2011.

Lal, D. M., Ghude, S. D., Patil, S. D., Kulkarni, S. H., Jena, C., Tiwari, S., & Srivastava, M. K. (2012). Tropospheric ozone and aerosol long-term trends over the Indo-Gangetic Plain (IGP), India. *Atmospheric Research, 116*, 82–92. https://doi.org/10.1016/j.atmosres.2012.02.014

Lal, S., Venkataramani, S., Naja, M., Kuniyal, J. C., Mandal, T. K., Bhuyan, P. K., et al. (2017). Loss of crop yields in India due to surface ozone: An estimation based on a network of observations. *Environmental Science and Pollution Research, 24*(26), 20972–20981. https://doi.org/10.1007/S11356-017-9729-3/TABLES/4

Li, S., Harley, P. C., & Niinemets, U. (2017). Ozone-induced foliar damage and release of stress volatiles is highly dependent on stomatal openness and priming by low-level ozone exposure in *Phaseolus vulgaris*. *Plant, Cell and Environment*. https://doi.org/10.1111/pce.13003

Liu, N., Wang, J., Guo, Q., Wu, S., Rao, X., Cai, X., & Lin, Z. (2018). Alterations in leaf nitrogen metabolism indicated the structural changes of subtropical forest by canopy addition of nitrogen. Retrieved November 15, 2021, from *Ecotoxicology and Environmental Safety, 160*, 134–143. https://www.sciencedirect.com/science/article/pii/S0147651318304160

Liu, Z., Pan, Y., Song, T., Hu, B., Wang, L., & Wang, Y. (2021). Eddy covariance measurements of ozone flux above and below a southern subtropical forest canopy. *Science of the Total Environment, 791*, 1–9. https://doi.org/10.1016/j.scitotenv.2021.148338

Lu, X., Zhang, L., & Shen, L. (2019). Meteorology and climate influences on tropospheric ozone: A review of natural sources, chemistry, and transport patterns. *Current Pollution Reports, 5*(4), 238–260. https://doi.org/10.1007/s40726-019-00118-3

Manning, W. J., Paoletti, E., Sandermann, H., & Ernst, D. (2011). Ethylenediurea (EDU): A research tool for assessment and verification of the effects of ground level ozone on plants under natural conditions. *Environmental Pollution, 159*(12), 3283–3293. https://doi.org/10.1016/J.ENVPOL.2011.07.005

Marco, A. De, Anav, A., Sicard, P., Feng, Z., & Paoletti, E. (2020). High spatial resolution ozone risk-assessment for Asian forests. *Environmental Research Letters, 15*(10). https://doi.org/10.1088/1748-9326/abb501

Mickley, L. J., Jacob, D. J., & Rind, D. (2001). Uncertainty in preindustrial abundance of tropospheric ozone: Implications for radiative forcing calculations. *Journal of Geophysical Research Atmospheres, 106*(D4), 3389–3399. https://doi.org/10.1029/2000JD900594

Mills, G., Pleijel, H., Malley, C. S., Sinha, B., Cooper, O. R., Schultz, M. G., et al. (2018a). Tropospheric ozone assessment report: Present-day tropospheric ozone distribution and trends relevant to vegetation. *Elementa, 6*(1). https://doi.org/10.1525/elementa.302

Mills, G., Sharps, K., Simpson, D., Pleijel, H., Broberg, M., Uddling, J., et al. (2018b). Ozone pollution will compromise efforts to increase global wheat production. *Global Change Biology, 24*(8), 3560–3574. https://doi.org/10.1111/gcb.14157

Mills, G., Sharps, K., Simpson, D., Pleijel, H., Frei, M., Burkey, K., et al. (2018c). Closing the global ozone yield gap: Quantification and cobenefits for multistress tolerance. *Global Change Biology, 24*(10), 4869–4893. https://doi.org/10.1111/gcb.14381

Mina, U., Kandpal, A., Bhatia, A., Ghude, S., Bisht, D. S., & Kumar, P. (2021). Wheat cultivar growth, biochemical, physiological and yield attributes response to combined exposure to tropospheric ozone, particulate matter deposition and ascorbic acid application. *Bulletin of Environmental Contamination and Toxicology, 107*(5), 938–945. https://doi.org/10.1007/S00128-021-03373-7/TABLES/6

Mina, U., Kumar, P., & Varshney, C. (2010). Effect of ozone exposure on growth, yield and isoprene emission from tomato (*Lycopersicon esculentum* L.) plants. *Vegetable Crops Research Bulletin, 72*(1), 35–48. https://doi.org/10.2478/v10032-010-0004-0

Mishra, A. K., & Agrawal, S. B. (2015). Biochemical and physiological characteristics of tropical mung bean (*Vigna radiata* L.) cultivars against chronic ozone stress: An insight to cultivar-specific response. *Protoplasma*, *252*(3), 797–811. https://doi.org/10.1007/S00709-014-0717-X

Mishra, A. K., Rai, R., & Agrawal, S. B. (2013). Differential response of dwarf and tall tropical wheat cultivars to elevated ozone with and without carbon dioxide enrichment: Growth, yield and grain quality. *Field Crops Research, 145*, 21–32. https://doi.org/10.1016/J.FCR.2013.02.007

Mukherjee, A., Singh Yadav, D., Agrawal, S. B., & Agrawal, M. (2020). Ozone a persistent challenge to food security in India: Current status and policy implications. *Current Opinion in Environmental Science & Health, 19*, 100220. https://doi.org/10.1016/j.coesh.2020.10.008

Nagendra-Prasad, D., Sudhakar, N., Murugesan, K., & Mohan, N. (2008). Pre-exposure of calli to ozone promotes tolerance of regenerated *Lycopersicon esculentum* cv. PKM1 plantlets against acute ozone stress. *Journal of Plant Physiology, 165*, 1288–1299.

Nair, P. R., Ajayakumar, R. S., David, L. M., Girach, I. A., & Mottungan, K. (2018). Decadal changes in surface ozone at the tropical station Thiruvananthapuram (8.542° N, 76.858° E), India: Effects of anthropogenic activities and meteorological variability. *Environmental Science and Pollution Research, 25*(15), 14827–14843. https://doi.org/10.1007/s11356-018-1695-x

Nali, C., & Lorenzini, G. (2021). Biological monitoring of ozone pollution with vascular plants. In S. B. Agrawal, M. Agrawal, & A. Singh (Eds.), *Tropospheric ozone: A hazard for vegetation and human health* (pp. 142–170). Cambridge Scholars Publishing.

Oksanen, E., Pandey, V., Pandey, A. K., Keski-Saari, S., Kontunen-Soppela, S., & Sharma, C. (2013). Impacts of increasing ozone on Indian plants. *Environmental Pollution, 177*, 189–200. https://doi.org/10.1016/j.envpol.2013.02.010

Osborne, S., Mills, G., Hayes, F., Ainsworth, E., Buker, P., & Emberson, L. (2016). Has the sensitivity of soybean cultivars to ozone pollution increased with time? An analysis of published dose–response data. *Global Change Biology, 22*(9), 3097–3111. https://doi.org/10.1111/gcb.13318

Pandey, A. K., Ghosh, A., Agrawal, M., & Agrawal, S. B. (2018). Effect of elevated ozone and varying levels of soil nitrogen in two wheat (*Triticum aestivum* L.) cultivars: Growth, gas-exchange, antioxidant status, grain yield and quality. *Ecotoxicology and Environmental Safety, 158*, 59–68. https://doi.org/10.1016/j.ecoenv.2018.04.014

Pandey, A. K., Majumder, B., Keski-Saari, S., Kontunen-Soppela, S., Mishra, A., Sahu, N., et al. (2015). Searching for common responsive parameters for ozone tolerance in 18 rice cultivars in India: Results from ethylenediurea studies. *Science of the Total Environment, 532*, 230–238. https://doi.org/10.1016/J.SCITOTENV.2015.05.040

Pandey, A. K., Majumder, B., Keski-Saari, S., Kontunen-Soppela, S., Pandey, V., & Oksanen, E. (2014). Differences in responses of two mustard cultivars to ethylenediurea (EDU) at high ambient ozone concentrations in India. *Agriculture, Ecosystems & Environment, 196*, 158–166. https://doi.org/10.1016/J.AGEE.2014.07.003

Paoletti, E., Alivernini, A., Anav, A., Badea, O., Carrari, E., Chivulescu, S., et al. (2019). Toward stomatal–flux based forest protection against ozone: The MOTTLES approach. *Science of the Total Environment, 691*, 516–527. https://doi.org/10.1016/j.scitotenv.2019.06.525

Parrish, D. D., Law, K. S., Staehelin, J., Derwent, R., Cooper, O. R., Tanimoto, H., et al. (2012). Long-term changes in lower tropospheric baseline ozone concentrations at northern mid-latitudes. *Atmospheric Chemistry and Physics, 12*(23), 11485–11504. https://doi.org/10.5194/acp-12-11485-2012

Pleijel, H., Danielsson, H., Simpson, D., & Mills, G. (2014). Have ozone effects on carbon sequestration been overestimated? A new biomass response function for wheat. *Biogeosciences, 11*(16), 4521–4528. https://doi.org/10.5194/bg-11-4521-2014

Pleijel, H., Eriksen, A. B., Danielsson, H., Bondesson, N., & Selldén, G. (2006). Differential ozone sensitivity in an old and a modern Swedish wheat cultivar - Grain yield and quality, leaf chlorophyll and stomatal conductance. *Environmental and Experimental Botany, 56*(1), 63–71. https://doi.org/10.1016/j.envexpbot.2005.01.004

Pleijel, H, Danielsson, H., & Broberg, M. C. (2021). Benefits of the phytotoxic ozone dose (POD) index in dose-response functions for wheat yield loss. *Atmospheric Environment, 268*(April 2021), 118797. https://doi.org/10.1016/j.atmosenv.2021.118797

Proietti, C., Fornasier, M. F., Sicard, P., Anav, A., Paoletti, E., & De Marco, A. (2021). Trends in tropospheric ozone concentrations and forest impact metrics in Europe over the time period 2000–2014. *Journal of Forestry Research, 32*(2), 543–551. https://doi.org/10.1007/s11676-020-01226-3

Rai, R., & Agrawal, M. (2014). Assessment of competitive ability of two Indian wheat cultivars under ambient O_3 at different developmental stages. *Environmental Science and Pollution Research, 21*(2), 1039–1053. https://doi.org/10.1016/j.envpol.2005.02.008

Rai, R., Agrawal, M., & Agrawal, S. B. (2010). Threat to food security under current levels of ground level ozone: A case study for Indian cultivars of rice. *Atmospheric Environment, 44*(34), 4272–4282. https://doi.org/10.1016/J.ATMOSENV.2010.06.022

Rai, R., Agrawal, M., Choudhary, K. K., Agrawal, S. B., Emberson, L., & Büker, P. (2015). Application of ethylene diurea (EDU) in assessing the response of a tropical soybean cultivar to ambient O3: Nitrogen metabolism, antioxidants, reproductive development and yield. *Ecotoxicology and Environmental Safety, 112*, 29–38. https://doi.org/10.1016/J.ECOENV.2014.10.031

Rais, M., & Sheoran, A. (2015). Scope of supply chain management in fruits and vegetables in India. *Journal of Food Processing and Technology, 6*(3).

Ramya, A., Dhevagi, P., Priyatharshini, S., Saraswathi, R., Avudainayagam, S., & Venkataramani, S. (2021). Response of rice (*Oryza sativa* L.) cultivars to elevated ozone stress. *Environmental Monitoring and Assessment, 193*(12), 1–18.

Sahoo, A., & Tiwari, S. (2021). Role of soil nitrogen amendments in management of ozone stress in plants: A study of the mechanistic approach. *Journal of Emerging Technologies and Innovative Rsearch, 8*(9). https://doi.org/10.1729/Journal.28175

Sarkar, A., & Agrawal, S. B. (2012). Evaluating the response of two high yielding Indian rice cultivars against ambient and elevated levels of ozone by using open top chambers. *Journal of Environmental Management, 95*, S19–S24. https://doi.org/10.1016/J.JENVMAN.2011.06.049

Sarkar, A., Singh, A. A., Agrawal, S. B., Ahmad, A., & Rai, S. P. (2015). Cultivar specific variations in antioxidative defense system, genome and proteome of two tropical rice cultivars against ambient and elevated ozone. *Ecotoxicology and Environmental Safety, 115*, 101–111. https://doi.org/10.1016/J.ECOENV.2015.02.010

Sandermann, H., Jr., Ernst, D., Heller, W., & Langebartels, C. (1998). Ozone: An abiotic elicitor of plant defence reactions. *Trends in Plant Science, 3*(2), 47–50.

Saxena, P., Chakraborty, M., Sonwani, S., Saxena, P., Chakraborty, M., & Sonwani, S. (2020). Phytotoxic effects of surface ozone exposure on rice crop—A case study of tropical megacity of India. *Journal of Geoscience and Environment Protection, 8*(5), 322–334. https://doi.org/10.4236/GEP.2020.85020

Schauberger, B., Rolinski, S., Schaphoff, S., & Muller, C. (2019). Global historical soybean and wheat yield loss estimates from ozone pollution considering water and temperature as modifying effects. Retrieved October 28, 2021, from *Agricultural and Forest Meteorology, 265*, 1–15. https://www.sciencedirect.com/science/article/pii/S0168192318303502

Severino, J. F., Stich, K., & Soja, G. (2007). Ozone stress and antioxidant substances in *Trifolium repens* and *Centaurea jacea* leaves. *Environmental Pollution, 146*(3), 707–714. https://doi.org/10.1016/j.envpol.2006.04.006

Sharma, A., Ojha, N., Pozzer, A., Beig, G., & Gunthe, S. S. (2019). Revisiting the crop yield loss in India attributable to ozone. *Atmospheric Environment: X, 1*, 100008. Retrieved October 26, 2021, from https://www.sciencedirect.com/science/article/pii/S2590162119300115

Sharps, K., Hayes, F., Harmens, H., & Mills, G. (2021). Ozone-induced effects on leaves in African crop species. *Environmental Pollution, 268*, 115789. https://doi.org/10.1016/j.envpol.2020.115789

Sicard, P., De Marco, A., Carrari, E., Dalstein-Richier, L., Hoshika, Y., Badea, O., et al. (2020). Epidemiological derivation of flux-based critical levels for visible ozone injury in European forests. *Journal of Forestry Research, 31*(5), 1509–1519. https://doi.org/10.1007/s11676-020-01191-x

Sicard, P., Hoshika, Y., Carrari, Elisa, De Marco, A., Paoletti, E., Carrari, E., et al. (2021). Testing visible ozone injury within a light exposed sampling site as a proxy for ozone risk assessment for European forests. *Journal of Forestry Research, 1*, 3. https://doi.org/10.1007/s11676-021-01327-7

Sicard, P., Serra, R., & Rossello, P. (2016). Spatiotemporal trends in ground-level ozone concentrations and metrics in France over the time period 1999–2012. *Environmental Research, 149*, 122–144. https://doi.org/10.1016/j.envres.2016.05.014

Simon, H., Reff, A., Wells, B., Xing, J., & Frank, N. (2015). Ozone trends across the United States over a period of decreasing NOx and VOC emissions. *Environmental Science and Technology, 49*(1), 186–195. https://doi.org/10.1021/es504514z

Simpson, W. R., Brown, S. S., Saiz-Lopez, A., Thornton, J. A., & Von Glasow, R. (2015, *May*). Sources, cycling, and impacts. Chemical Reviews. American Chemical Society. https://doi.org/10.1021/cr5006638

Singh, A. A., & Agrawal, S. B. (2017). Tropospheric ozone pollution in India: Effects on crop yield and product quality. *Environmental Science and Pollution Research, 24*(5), 4367–4382. https://doi.org/10.1007/s11356-016-8178-8

Singh, A. A., Agrawal, S. B., Shahi, J. P., & Agrawal, M. (2019). Yield and kernel nutritional quality in normal maize and quality protein maize cultivars exposed to ozone. *Journal of the Science of Food and Agriculture, 99*(5), 2205–2214. https://doi.org/10.1002/JSFA.9414

Singh, A. A., Chaurasia, M., Gupta, V., Agrawal, M., & Agrawal, S. B. (2018a). Responses of Zea mays L. cultivars 'Buland' and 'Prakash' to an antiozonant ethylene diurea grown under ambient and elevated levels of ozone. *Acta Physiologiae Plantarum, 40*(5), 1–15. https://doi.org/10.1007/S11738-018-2666-Z/FIGURES/5

Singh, A. A., Fatima, A., Mishra, A. K., Chaudhary, N., Mukherjee, A., Agrawal, M., & Agrawal, S. B. (2018b). Assessment of ozone toxicity among 14 Indian wheat cultivars under field conditions: growth and productivity. *Environmental Monitoring and Assessment, 190*(4). https://doi.org/10.1007/S10661-018-6563-0

Singh, A. A., Singh, S., Agrawal, M., & Agrawal, S. B. (2015a). Assessment of ethylene diurea-induced protection in plants against ozone phytotoxicity. *Reviews of Environmental Contamination and Toxicology, 233*, 129–184. https://doi.org/10.1007/978-3-319-10479-9_4

Singh, E., Tiwari, S., & Agrawal, M. (2010a). Variability in antioxidant and metabolite levels, growth and yield of two soybean varieties: An assessment of anticipated yield losses under projected elevation of ozone. *Agriculture, Ecosystems & Environment, 135*(3), 168–177. https://doi.org/10.1016/J.AGEE.2009.09.004

Singh, P., Agrawal, M., Agrawal, S. B., Singh, S., & Singh, A. (2015b). Genotypic differences in utilization of nutrients in wheat under ambient ozone concentrations: Growth, biomass and yield. *Agriculture, Ecosystems & Environment, 199*, 26–33. Retrieved November 25, 2021, from https://www.sciencedirect.com/science/article/pii/S0167880914003818

Singh, P., Agrawal, M., & Agrawal, S. B. (2009a). Evaluation of physiological, growth and yield responses of a tropical oil crop (*Brassica campestris* L. var. Kranti) under ambient ozone pollution at varying NPK levels. *Environmental Pollution, 157*(3), 871–880. https://doi.org/10.1016/J.ENVPOL.2008.11.008

Singh, P., Singh, S., Agrawal, S. B., & Agrawal, M. (2012). Assessment of the interactive effects of ambient O_3 and NPK levels on two tropical mustard varieties (*Brassica campestris* L.) using open-top chambers. *Environmental Monitoring and Assessment, 184*(10), 5863–5874.

Singh, R., Mukherjee, J., Sehgal, V. K., Krishnan, P., Das, D. K., Dhakar, R. K., & Bhatia, A. (2021). Interactive effect of elevated tropospheric ozone and carbon dioxide on radiation utilisation, growth and yield of chickpea (*Cicer arietinum* L.). *International Journal of Biometeorology, 65*(11), 1939–1952. https://doi.org/10.1007/s00484-021-02150-9

Singh, S., Bhatia, A., Tomer, R., Kumar, V., Singh, B., & Singh, S. D. (2013). Synergistic action of tropospheric ozone and carbon dioxide on yield and nutritional quality of Indian mustard (*Brassica juncea* (L.) Czern.). *Environmental Monitoring and Assessment, 185*(8), 6517–6529. https://doi.org/10.1007/s10661-012-3043-9

Singh, S., & Agrawal, S. B. (2011a). Cultivar-specific response of soybean (*Glycine max* L.) to ambient and elevated concentrations of ozone under open top chambers. *Water, Air, and Soil Pollution*, *217*(1–4), 283–302. https://doi.org/10.1007/S11270-010-0586-7/FIGURES/12

Singh, S., & Agrawal, S. B. (2011b). Ambient ozone and two black gram cultivars: An assessment of amelioration by the use of ethylenediurea. *Acta Physiologiae Plantarum, 33*(6), 2399–2411. https://doi.org/10.1007/S11738-011-0781-1/FIGURES/5

Singh, S., Agrawal, S. B., & Agrawal, M. (2009b). Differential protection of ethylenediurea (EDU) against ambient ozone for five cultivars of tropical wheat. *Environmental Pollution, 157*(8–9), 2359–2367. https://doi.org/10.1016/J.ENVPOL.2009.03.029

Singh, S., Agrawal, S. B., Singh, P., & Agrawal, M. (2010b). Screening three cultivars of *Vigna mungo* L. against ozone by application of ethylenediurea (EDU). *Ecotoxicology and Environmental Safety*, *73*(7), 1765–1775. https://doi.org/10.1016/J.ECOENV.2010.05.001

Singh, S., Agrawal, M., Agrawal, S. B., Emberson, L., & Büker, P. (2010c). Use of ethylenediurea for assessing the impact of ozone on mung bean plants at a rural site in a dry tropical region of India. *International Journal of Environment and Waste Management, 5*(1–2), 125–139. https://doi.org/10.1504/IJEWM.2010.029697

Sinha, B., Singh Sangwan, K., Maurya, Y., Kumar, V., Sarkar, K., Chandra, B., & Sinha, V. (2015). Assessment of crop yield losses in Punjab and Haryana using 2 years of continuous in situ ozone measurements. *Atmospheric Chemistry and Physics, 15*(16), 9555–9576. Retrieved November 30, 2021, from https://acp.copernicus.org/articles/15/9555/2015/

Suganthy, V. S., & Udayasoorian, C. (2020). Ambient and elevated ozone (O_3) impacts on potato genotypes (*Solanum Tuberosum*.L) over a high altitude Western Ghats location in Southern India. *Plant archives, 20*(2), 1367–1373.

Surabhi, S., Gupta, S. K., Pande, V., & Pandey, V. (2020). Individual and combined effects of ethylenediurea (EDU) and elevated carbon dioxide (ECO_2), on two rice (*Oryza sativa* L.)

cultivars under ambient ozone. *Environmental Advances, 2*, 100025. https://doi.org/10.1016/J.ENVADV.2020.100025

Tiwari, S., & Agrawal, M. (2010). Effectiveness of different EDU concentrations in ameliorating ozone stress in carrot plants. *Ecotoxicology and Environmental Safety, 73*(5), 1018–1027. https://doi.org/10.1016/j.ecoenv.2010.03.008

Tiwari, S., Agrawal, M., & Manning, W. J. (2005). Assessing the impact of ambient ozone on growth and productivity of two cultivars of wheat in India using three rates of application of ethylenediurea (EDU). *Environmental Pollution, 138*(1), 153–160. https://doi.org/10.1016/J.ENVPOL.2005.02.008

Tiwari, S., Agrawal, M., & Marshall, F. M. (2010). Seasonal variations in adaptational strategies of *Beta vulgaris* L. plants in response to ambient air pollution: Biomass allocation, yield and nutritional quality. *Tropical Ecology, 51*(2), 353–363. Retrieved November 10, 2021, from www.tropecol.com

Tomer, R., Bhatia, A., Kumar, V., Kumar, A., Singh, R., Singh, B., & Singh, S. D. (2015). Impact of elevated ozone on growth, yield and nutritional quality of two wheat species in Northern India. *Aerosol and Air Quality Research, 15*(1), 329–340. https://doi.org/10.4209/AAQR.2013.12.0354

Tripathi, R., & Agrawal, S. B. (2012). Effects of ambient and elevated level of ozone on Brassica campestris L. with special reference to yield and oil quality parameters. *Ecotoxicology and Environmental Safety, 85*, 1–12. https://doi.org/10.1016/J.ECOENV.2012.08.012

Turnock, S. T., Wild, O., Dentener, F. J., Davila, Y., Emmons, L. K., Flemming, J., et al. (2018). The impact of future emission policies on tropospheric ozone using a parameterised approach. *Atmospheric Chemistry and Physics, 18*(12), 8953–8978. https://doi.org/10.5194/acp-18-8953-2018

Van Dingenen, R., Dentener, F. J., Raes, F., Krol, M. C., Emberson, L., & Cofala, J. (2009). The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment, 43*(3), 604–618. https://doi.org/10.1016/J.ATMOSENV.2008.10.033

Van Quy, L., Lamaze, T., & Champigny, M. L. (1991). Short-term effects of nitrate on sucrose synthesis in wheat leaves. *Planta, 185*(1), 53–57. https://doi.org/10.1007/BF00194514

Vanderheyden, D., Skelly, J., Innes, J., Hug, C., Zhang, J., Landolt, W., & Bleuler, P. (2001). Ozone exposure thresholds and foliar injury on forest plants in Switzerland. *Environmental Pollution, 111*(2), 321–331. https://doi.org/10.1016/S0269-7491(00)00060-9

Wu, R., Zheng, Y., & Hu, C. (2016). Evaluation of the chronic effects of ozone on biomass loss of winter wheat based on ozone flux-response relationship with dynamical flux thresholds. *Atmospheric Environment, 142*, 93–103. https://doi.org/10.1016/j.atmosenv.2016.07.025

Yadav, A., Bhatia, A., Yadav, S., Singh, A., Tomer, R., Harit, R., et al. (2021a). Growth, yield and quality of maize under ozone and carbon dioxide interaction in North West India. *Aerosol and Air Quality Research, 21*(2). https://doi.org/10.4209/aaqr.2020.05.0194

Yadav, D. S., Agrawal, S. B., & Agrawal, M. (2021b). Ozone flux-effect relationship for early and late sown Indian wheat cultivars : Growth, biomass, and yield. *Field Crops Research, 263*(December 2020), 108076. https://doi.org/10.1016/j.fcr.2021.108076

Yadav, D. S., Jaiswal, B., Agrawal, S. B., & Agrawal, M. (2021c). Diurnal variations in physiological characteristics, photoassimilates, and total ascorbate in early and late sown Indian wheat cultivars under exposure to elevated ozone. *Atmosphere, 12*, 1568. https://doi.org/10.3390/atmos12121568

Yadav, D. S., Mishra, A. K., Rai, R., Chaudhary, N., Mukherjee, A., Agrawal, S. B., & Agrawal, M. (2020a). Responses of an old and a modern Indian wheat cultivar to future O_3 level: Physiological, yield and grain quality parameters. *Environmental Pollution, 259*. https://doi.org/10.1016/J.ENVPOL.2020.113939

Yadav, D. S., Rai, R., Mishra, A. K., Chaudhary, N., Mukherjee, A., Agrawal, S. B., & Agrawal, M. (2019). ROS production and its detoxification in early and late sown cultivars of wheat under future O_3 concentration. *Science of the Total Environment, 659*, 200–210. https://doi.org/10.1016/j.scitotenv.2018.12.352

Yadav, P., Mina, U., & Bhatia, A. (2020b). Screening of forty Indian *Amaranthus hypochondriacus* cultivars for tolerance and susceptibility to tropospheric ozone stress. *Nucleus, 63*(3), 281–291. https://doi.org/10.1007/s13237-020-00335-y

Yendrek, C., Leisner, C., & Ainsworth, E. (2013). Chronic ozone exacerbates the reduction in photosynthesis and acceleration of senescence caused by limited N availability in *Nicotiana sylvestris*. *Global Change Biology, 19*(10), 3155–3166. https://doi.org/10.1111/gcb.12237

Yuan, X., Feng, Z., Hu, C., Zhang, K., Qu, L., & Paoletti, E. (2021). Effects of elevated ozone on the emission of volatile isoprenoids from flowers and leaves of rose (Rosa sp.) varieties. *Environmental Pollution, 291*(April), 118141. https://doi.org/10.1016/j.envpol.2021.118141

Zhao, H., Zheng, Y., & Wu, X. (2018). Assessment of yield and economic losses for wheat and rice due to ground-level O3 exposure in the Yangtze River Delta, China. *Atmospheric Environment, 191*, 241–248. https://doi.org/10.1016/j.atmosenv.2018.08.019

Zhao, Y., Bell, J. N. B., Wahid, A., & Power, S. A. (2011). Inter- and intra-specific differences in the response of Chinese leafy vegetables to ozone. *Water, Air, and Soil Pollution, 216*(1–4), 451–462. https://doi.org/10.1007/s11270-010-0544-4

Ziemke, J. R., Oman, L. D., Strode, S. A., Douglass, A. R., Olsen, M. A., McPeters, R. D., et al. (2019). Trends in global tropospheric ozone inferred from a composite record of TOMS/OMI/MLS/OMPS satellite measurements and the MERRA-2 GMI simulation. *Atmospheric Chemistry and Physics, 19*(5), 3257–3269. https://doi.org/10.5194/acp-19-3257-2019