Environ Sci Pollut Res (2017) 24:4367–4382
DOI 10.1007/s11356-016-8178-8

REVIEW ARTICLE

Tropospheric ozone pollution in India: effects on crop yield and product quality

Aditya Abha Singh[1] **· S. B. Agrawal**[1]

Received: 18 September 2016 / Accepted: 28 November 2016 /

Abstract Ozone (O_3) in troposphere is the most critical secondary air pollutant, and being phytotoxic causes substantial losses to agricultural productivity. Its increasing concentration in India particularly in Indo-Gangetic plains is an issue of major concern as it is posing a threat to agriculture. In view of the issue of rising surface level of O_3 in India, the aim of this compilation is to present the past and the prevailing concentrations of O_3 and its important precursor (oxides of nitrogen) over the Indian region. The resulting magnitude of reductions in crop productivity as well as alteration in the quality of the product attributable to tropospheric O_3 has also been taken up. Studies in relation to yield measurements have been conducted predominantly in open top chambers (OTCs) and also assessed by using antiozonant ethylene diurea (EDU). There is a substantial spatial difference in O_3 distribution at different places displaying variable O_3 concentrations due to seasonal and geographical variations. This review further recognizes the major information lacuna and also highlights future perspectives to get the grips with rising trend of ground level O_3 pollution and also to formulate the policies to check the emissions of O_3 precursors in India.

Keywords Crop productivity · Ethylene diurea · India · Oxides of nitrogen · Ozone · Quality · Yield

Responsible editor: Philippe Garrigues

✉ S. B. Agrawal
sbagrawal56@gmail.com

Aditya Abha Singh
abha2512.singh@gmail.com

[1] Laboratory of Air Pollution and Global Climate Change, Department of Botany, Institute of Science, Banaras Hindu University, Varanasi 221005, India

Introduction

During the last few decades, tropospheric ozone (O_3) has become one of the widest spread toxic pollutants around the globe (IPCC 2007; Booker et al. 2009) with negative impact on humans, animals, and plants (Cho et al. 2011). Though being a toxicant at ground level, O_3 in upper troposphere plays a role in controlling the atmospheric chemistry due to its influential role in the heat balance of atmosphere leading to climate change (Khemani et al. 1995). Ozone in upper troposphere plays a major role in greenhouse effect, as 1 Dobson unit increase in O_3 produces a temperature increase of about 0.02 K (Ahammed et al. 2006). Being a secondary pollutant in troposphere, O_3 is formed by a chain of photochemical reactions involving its various precursors such as methane (CH_4), carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) in the presence of bright sunlight (Collins et al. 1997). Having a considerable share from industrial emissions and other anthropogenic activities, transport sector also contributes significantly to emissions of O_3 precursors leading to O_3 formation in urban areas. Apart from being a pollutant of concern in cities and metropolitans, ground level O_3 is also a problem in rural areas. Due to long-distance transport, though being located hundreds or thousands miles away from the original source, remote rural areas experience high concentrations of O_3, where majority of land areas are dedicated to agricultural practices (Prather et al. 2003; Agrawal et al. 2003). Two mechanisms have been proposed for its higher levels in rural environment. Firstly, the direct transport of O_3 from urban areas, and secondly, the transport of its precursors like NO_x, VOCs, CO, CH_4, and nonmethane hydrocarbons followed by in situ photochemical O_3 production (Naja and Lal 2002). Another source of O_3 in troposphere is through transport from stratosphere (Forster et al. 2007), but its contribution to O_3 built up is relatively low.

Background concentrations of ground-level O_3 has risen from an estimated preindustrial concentration of 10 ppb to average summer concentrations varying from 30 to 50 ppb in mid-latitudes of the northern hemisphere and O_3 episodes reaching 100 ppb (Morgan et al. 2006). With current air quality legislation implemented worldwide, multimodal simulations for 2030 projected that global surface O_3 would increase by 1.5 ± 1.2 ppb on average, and for IPCC SRES A2 scenario, by 4.3 ± 2.2 ppb with the strongest increases in South Asia, Southeast Asia, and the Middle East (Gauss et al. 2007). According to Dentener et al. (2005), global photochemical models project that as per the current legislation of O_3 precursor emissions; parts of Asia will experience further significant increase in O_3 concentration up to 2030. Monitoring reports of O_3 in suburban and rural areas of Asia also showed that mean monthly O_3 concentration now commonly reach up to 50 ppb (EANET 2006).

Ozone gains entry inside the leaves through stomatal pores. Upon reaching the intercellular spaces, it rapidly generates reactive oxygen species (ROS) and also reacts with components of the leaf apoplast causing oxidative stress (Booker et al. 2009). As a result, antioxidant defense system is triggered which plays a decisive role of keeping ROS levels under control, thereby maintaining cellular redox balance. Thus, under O_3 stress, induced metabolic pathways, reduction in photosynthetic proteins, impaired reproductive development and accelerated senescence conclusively leads to decreased carbon assimilation and alterations in its partitioning resulting in lower accumulation of biomass in plants (McCrady and Andersen 2000), reductions in yield and modification in crop quality (Black et al. 2000; Singh et al. 2009a; Tripathi and Agrawal 2012; Sarkar et al. 2015). Previously, several studies have reported reduction in crop yield due to O_3 (Feng et al. 2009; Feng and Kobayashi 2009; Sawada and Kohno 2009; Rai et al. 2010; Sarkar and Agrawal 2010; Mishra et al. 2013; Singh et al. 2014). The relative regional yield loss in developing countries of East Asia (India, Pakistan, and Bangladesh) in year 2000 was 8–27% for wheat, 3–13% for soybean, and 3–8% for maize based on the M12 or AOT40 metrics used for O_3 exposure (Avnery et al. 2011). Van Dingenen et al. (2009) calculated that in the year 2000, an economic loss of nearly US$6.3–12.0 billion took place globally for four major crops (wheat, rice, maize, and soybean) out of which India and China shared 22 and 21%, respectively, of the total damage. Studies conducted at global level in relation to O_3 induced crop yield losses has also shown that relative yield loss (RYL) leading to economic cost losses (ECL) are highest in India followed by China (Van Dingenen et al. 2009; Avnery et al. 2011). Takigawa et al. (2009), in their global regional CTM-based analysis, estimated that yield reduction due to O_3 in spring wheat will increase by 7.4 and 7.7% in China and India, respectively, by the year 2020 as compared to 2002. A model-based study suggested that yield losses of 5–20% for important crops may be common in areas experiencing higher O_3 concentrations and concluded that Asian grown wheat and rice cultivars are more sensitive to O_3 than the cultivars of North America (Emberson et al. 2009).

India is one of the rapidly growing economies in the Asian region and large emissions from industries, automobiles, other anthropogenic activities and relatively high solar intensity provide most favorable conditions for the formation of surface O_3. Due to anthropogenic emissions, several chemical transport models have estimated large increases in O_3 production over the Indian region (Berntsen et al. 1996; Brasseur et al. 1998; Oksanen et al. 2013). India is an agriculture-based economy, and its 58% of the population relies on agriculture for livelihood. Agriculture in India is demographically the broadest economic sector, ranking worldwide second in its farm production (Ghude et al. 2014). Nearly 1.2 billion people of India depend largely on food produced within the country, and simultaneously, other African and Asian nations depend mostly on import of Indian rice (Burney and Ramanathan 2014). Since the yield losses caused due to O_3 pose a greater risk to food supply, the increasing O_3 pollution is one of the major threats for agriculture sector in India, being the home of one fifth hungry population of the world. According to the estimations of Van Dingenen et al. (2009), economic losses of four crops (wheat, rice, maize and soybean) were found to be largest in India ranging between US$3 to US$6 billion for the year 2000. According to different monitoring reports, throughout India, there is higher incidence of O_3 formation in the areas falling under agriculture production.

Thus, the aim of this compilation is to highlight the prevalence of O_3 and its concentrations over different locations of India and resulting magnitude of reductions in crop productivity as well as alterations in the quality of their product collated from the literature published. The present review could be beneficial in (a) adding knowledge about the prevailing O_3 concentrations in India and its direct correlation with the economic consequences of agriculture production losses that might be critical for food security, (b) to make and implement long-term policies to curb the emissions of O_3 precursors, and (c) to set standards in relation to O_3 for agriculture in India.

NO_x concentration in Indian region: a potent O_3 precursor

Microclimatic conditions and availability of O_3 precursors are the two prime factors responsible for O_3 formation. One of the most prominent O_3 precursors contributing to O_3 formation is oxides of nitrogen (NO_x). NO_x includes chiefly nitric oxide (NO) and nitrogen dioxide (NO_2). According to EPA (2007), tropospheric O_3 is formed by a series of reactions involving volatile organic compounds (VOCs) combined with NO_x in the presence of sunlight. NO_x molecules participate in competing O_3 creation and destruction reactions (Simon et al. 2014). A wavelength of 430 nm of sunlight breaks NO_2 into NO and O. The free oxygen atom then combines with oxygen molecule to form tropospheric O_3. VOCs play a prominent role in process by which "free radicals" convert NO into NO_2 and NO_2 then breaks again into NO and O leading to the continuation of this cycle (Ghazali et al. 2010). At low NO_x concentrations, O_3 production is limited by the availability of NO_x molecules, while at high NO_x concentrations, availability of other compounds limits O_3 production (Lin et al. 1988).

NO_x emissions have been increasing over Indian region due to rapid economic growth, uncontrolled use of fossil fuels in industries and extended transport sector. Records of ministry of surface transport in India had tabulated that the number of vehicles in the country was 21.3, 53, and 67 million in 1991, 2000, and 2003, respectively (Rai et al. 2011a), which has now been increased up to 159.4 million in 2012 (https://data.gov.in/catalog/total-number-registered-motor-vehicles). Lelieveld et al. (2001) reported that the formation of O_3 in India is predominantly controlled by NO_x, indicating a positive correlation between O_3 and NO_x concentration. Model studies have confirmed that the growing NO_x emissions in India account for the consistent increase in background O_3 levels over the past three decades (Horaginamani and Ravichandran 2010). Annual average NO_2 levels across India for the year 2007 depicted that the maximum emissions of NO_x were prevalent in north-eastern and west-eastern parts of India (Oksanen et al. 2013).

According to Garg et al. (2001), NO_x emissions over the Indian region were growing at an annual rate of 5.5% $year^{-1}$, while Streets et al. (2003) found an increase rate of 6.5% $year^{-1}$, displaying an increasing trend. Beig and Brasseur (2006) showed that maximum increase of NO_x concentration from 1991 to 2001 was about 0.5–1.5 ppb (20–50%). Air quality monitoring conducted by the Indian government organization Central Pollution Control Board (CPCB) in various cities had shown a dramatic increase in NO_x concentrations since 1990. For the year 2009, it has been reported that prevalence of NO_x concentrations was 4.3 to 42.9 ppb in various parts of the country with peak concentrations in metropolitan cities (Rai and Agrawal 2012). Lu and Streets (2012) found an increase of 70% in NO_x emissions from 1996 to 2010 from Indian public thermal power plants.

Lal et al. (2000) found that the diurnal and seasonal variations at Ahmadabad were affected by mutual effects of local emissions, boundary layer processes, and wind pattern. Horaginamani and Ravichandran (2010) monitored oxides of nitrogen in ambient air from August 2008 to January 2009 (24 h) at eight different sampling stations in Tiruchirappalli (Table 1). The concentrations ranged from 67.4 to 90.2 ppb exceeding the quality standards of CPCB at all sampling stations except at one site. Increasing concentrations of NO_x were also modeled by van der et al. (2008) and Ghude et al. (2008) showing an annual growth of 7.4 and 2.4% in Delhi and a larger region of North India, respectively, chiefly due to industrial growth and vehicular traffic load. Indo-Gangetic Plain (IGP) region is highly vulnerable to human induced pollutant emissions due to its conductive weather pattern. Beig and Ali (2006) used Model for Ozone Related Tracers (MOZART) which revealed maximum value of 7.5 ppb and minimum value of 0.4 ppbv over IGP while the distribution of NO_x over rest of the Indian landmass was in the range of 1.6–4.0 ppb (Beig and Ali 2006). Annual mean concentration of NO_2 ranged from 10.1 to 31.3 ppb in different zones of Varanasi city in 1990, while it varied from 16 to 155 ppb during 1999–2001 (Trivedi and Agrawal 2003; Rai and Agrawal 2012). Concentrations of NO_x/NO_2 in different cities of India are given in Table 1.

Ozone concentration in different regions of India

Being located in subtropical region, Indian subcontinent encounters fairly high O_3 concentrations. Representative O_3 concentrations at different monitoring stations in India are shown in Fig. 1. Global chemical transport models suggested that surface O_3 concentration could increase to a level 25–30 ppb in tropical India between years 2000 and 2100 (Prather et al. 2003). Debaje and Kakade (2009) monitored surface O_3 variability for the period 2001–2005 over western Maharashtra taking up five different sites. Seasonal variation of O_3 displayed a maximum concentration of 40–50 ppb in summer and winter season at the urban sites, and similar levels were observed at rural site in spite of less emission of precursors. While at a high altitude mountain site, comparatively less O_3 formation (30–40 ppb) was observed (Debaje and Kakade 2009). Monthly AOT40 as high as 36 ppmh were found between November to April 2003 over Pune (Roy et al. 2009). According to Tiwari and Peshin (1995), surface O_3 concentration at Pune during 1988–1991 had increased at a rate of 0.03% per year. At Ahmadabad, annual variation in average O_3 concentrations ranged from a least value of 12 ppb during August to the highest value of 30 ppb during November (Lal et al. 2000) (Fig. 1). Ahammed et al. (2006) have reported highest O_3 levels during the winter and summer and lowest during the monsoon at Anantpur. Similar patterns of seasonal variation of O_3 concentration have also been observed at another rural site Gadanki (Naja and Lal 2002). A relatively low O_3 was observed during monsoon (18.4 ± 3.5 ppbv) than summer, winter and post-monsoon season (monitoring period November 2009 to October 2010) at Kannur, a tropical site located in coastal region of India (Nishanth et al. 2012b). According to Beig and Brasseur (2006), the relatively low amount of O_3 and its precursors during monsoon compared

Table 1 Trend of NOx/NO_2 concentrations at different locations in India

City	Months/year/season	NO_x/NO_2 concentration (ppb)	Reference
Ahmadabad	1993–1996	5.0–75 (diurnal mean)	Lal et al. (2000)
Anantpur	2001–2003	3.9 ± 0.6 (annual average)	Ahammed et al. (2006)
New Delhi	January 1997–November 1998	32 ± 11–41.5 ± 35 (annual average)	Aneja et al. (2001)
Nagercoil	March 2007–February 2010	3.4–7.7 (monthly mean)	Elampari et al. (2013)
Tiruchirappalli (eight sites)	August 2008–January 2009	67.4–90.2 (24 h)	Horaginamani and Ravichandran (2010)
Varanasi (four sites)	Summer and winter of 1998–99 and 1999–2000	Summer—11.7–80.1 (monthly mean) Winter—28.0–47.4	Agrawal et al. (2003)
Varanasi	June 2005–October 2006	12.1–16.9 (monthly mean)	Rai and Agrawal (2008)
Varanasi	December 2004–March 2005	38.2–43.1 (monthly mean)	Rai et al. (2007)
Varanasi	December 2007–March 2008	4.5–6.9 (monthly mean)	Tripathi et al. (2011)

to other seasons is due to washout effects. Table 2 depicts the O_3 concentrations at different locations in India.

Apart from general emission sources, there are also episodic emissions from various social activities in India and one such important source is from fireworks set off during the festival days (Praseed et al. 2012a) which leads to sudden many fold increase in the O_3 precursors or O_3 itself. Apart from causing serious health hazards to humans, these increased O_3 concentrations leads to acute exposure of plants to O_3 stress. Praseed et al. (2012a) investigated the air quality of Kannur, India during "Vishu" a traditional festival during April 2010 and April 2011 and observed that the concentration of O_3 were doubled during that period while NO_2 increased by 2.5 times compared to the concentration on days taken as control. Yerramsetti et al. (2013) focused on the influence of "Diwali" festival fireworks emissions on surface O_3 and NO_x over the tropical urban region of Hyderabad during three consecutive years (2009–2011). A twofold to threefold increase was observed in the concentrations of O_3 and NO_x, during the festival phase compared to control days. Attri et al. (2001) reported significant increase in night time O_3 concentrations due to firecrackers burning during the festive period. Long-term trend (2005 to 2013) indicates that the annual average concentrations of both primary

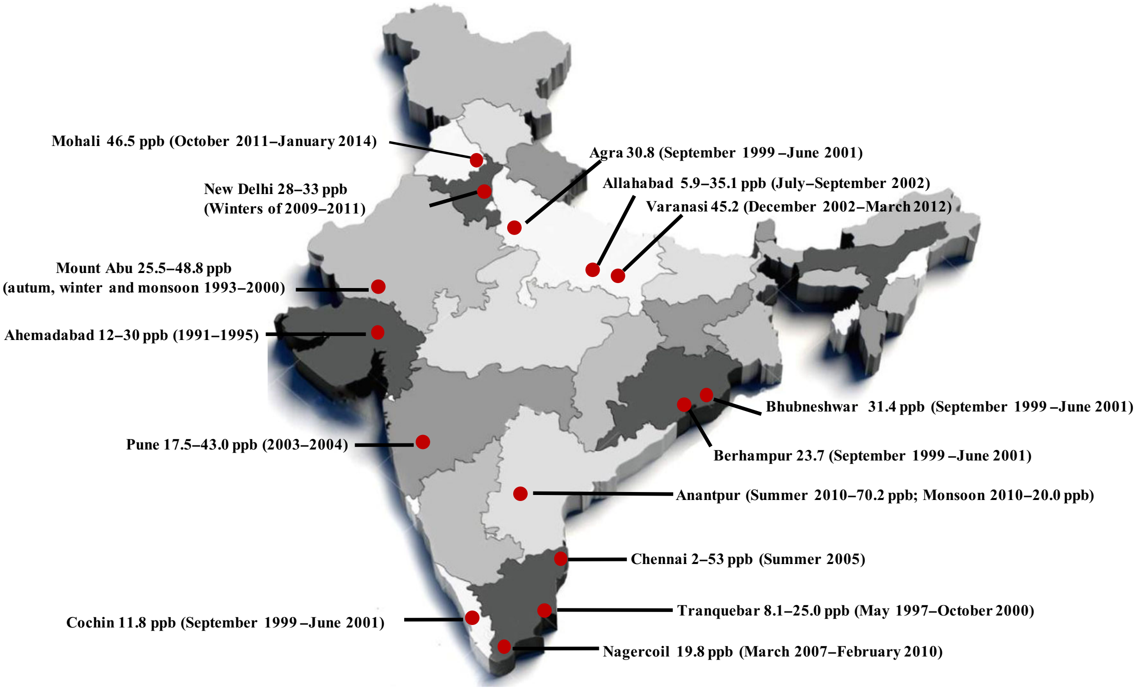

Fig. 1 Representative O_3 concentrations and monitoring duration at different monitoring stations in India. Data collected are based on the available published reports

Table 2 Trend of ozone concentration at different locations in India

City/state	Months/year/season	Ozone concentration (ppb)	Reference
Agra	September 1999–June 2001	30.8 (monthly median)	Carmichaei et al. (2003)
Bhubaneswar		31.4	
Berhrampur		23.7	
Cochin		11.8	
Allahabad	July–September 2002	5.9–35.1 (monthly mean)	Agrawal et al. (2005)
Anantapur	January 2002–December 2003	25–46 (annual average diurnal variation)	Reddy et al. (2008)
Anantapur	Summer 2010	70.2 ± 6.9 (seasonal mean)	Reddy et al. (2012)
	Monsoon 2010	20 ± 4.7	
Chandigarh	April 1984–December 1984	45.0 (average monthly mean)	Bhatnagar (1996)
	November 1990–March 1992	43.0	
Chennai (five sites)	Summer 2005	2–53 (hourly)	Pulikesi et al. (2006)
Delhi (four sites)	1989–1990	9.4–128.3 (diurnal mean)	Varshney and Aggarwal (1992)
Delhi (three sites)	March–June 1997	44.2–44.9 (average hourly)	Varshney and Rout (1998)
New Delhi	1997–2003	Summer—62–95 (monthly average) Autumn—50–82	Jain et al. (2005)
New Delhi	Winters of 2009–2011	2009–2010—28 (seasonal mean) 2010–2011—33	Singh et al. (2013)
Maharashtra (five sites)	2001–2005	40–50 (maximum seasonal variation)	Debaje and Kakade (2009)
Mohali	October 2011–January 2014	46.5 (M12)	Sinha et al. (2015)
Mount Abu	1993–2000	25.1 ± 9.4–48.8 ± 7.7 (monthly mean)	Naja et al. (2003)
Nagercoil	March 2007–February 2010	19.8 (annual average)	Elampari et al. (2013)
Pune	August 1991–July 1992	Monsoon—14.2 (seasonal mean) Summer—32.3	Khemani et al. (1995)
Pune	2003–2004	Monsoon 17.5 ± 3.3 (seasonal mean) Summer 43.0 ± 16.4	Beig et al. (2007)
Pune and Delhi	1990–1999	35–53 (seasonal maximum) 49.0–77.5	Ali et al. (2012)
Tranquebar	May 1997–October 2000	8.1–25.0 (monthly mean)	Debaje et al. (2003)
Varanasi	1989–1990	6.0–10.2 (24 h)	Pandey and Agrawal (1992)
Varanasi	March–June 1998	45.0–48.0 (monthly mean)	Agrawal et al. (2006)
Varanasi (six sites)	Winter 1998–1999	9.9–40.6 (seasonal mean)	Rajput and Agrawal (2005)
Varanasi	2002–2006	Rainy—24.0–43.8 (seasonal mean) Winter—28.5–44.2 Summer—45.1–62.3	Tiwari et al. (2008)
Varanasi	July–October 2005	32.8–44.0 (monthly mean)	Singh et al. (2009a)
Varanasi	December 2006–March 2007	41.6–54.2 (monthly mean)	Singh et al. (2009b)
Varanasi	December to March 2008–2010	46.1–56.4 (monthly mean)	Rai and Agrawal (2014)
Varanasi	December 2011–April 2012	46.3–67.9 (monthly mean)	Singh et al. (2014)

and secondary air pollutants have increased, exceeding the US National Ambient Air Quality Standards (NAAQS) limit, on the respective Diwali days (Saha et al. 2014).

The IGP region is an area of about 700,000 km^2 which is the most extensive continuous alluvial plain falling under the category of extensively farmed zones in the world (Beig and Ali 2006). High temperature, longer sunshine hours, low relative humidity, and wind pattern of IGP favor the formation of tropospheric O_3. Moreover, IGP is one of the most polluted regions of the world in terms of gases and aerosol loading which contributes to O_3 formation (Ramanathan and Ramana 2005; Ghude et al. 2011). The highest trend of increase (3–5.6%) per decade has been observed over the densely populated IGP region, while increasing trend of 1.2–2% per decade has been observed for southern regions of India (Lal et al. 2012). Mittal et al. (2007) have also reported about the prevalence of very high AOT 40 in the IGP compared to rest of the Indian regions depicting higher concentrations of O_3 in northern than the southern regions. A multifunction regression model was utilized by Lal et al. (2012) that estimated the O_3 trend from 1979 to 1992 over the Indian region and found a trend of 0.4 ± 0.4% annual increase over the north eastern IGP region.

Figure 2 shows the O_3 monitoring carried out at Varanasi situated at the northeastern IGPs for the two major crop seasons. In India, wheat is chiefly a rabi crop (December to March) while rice is a kharif crop (July to October). The data

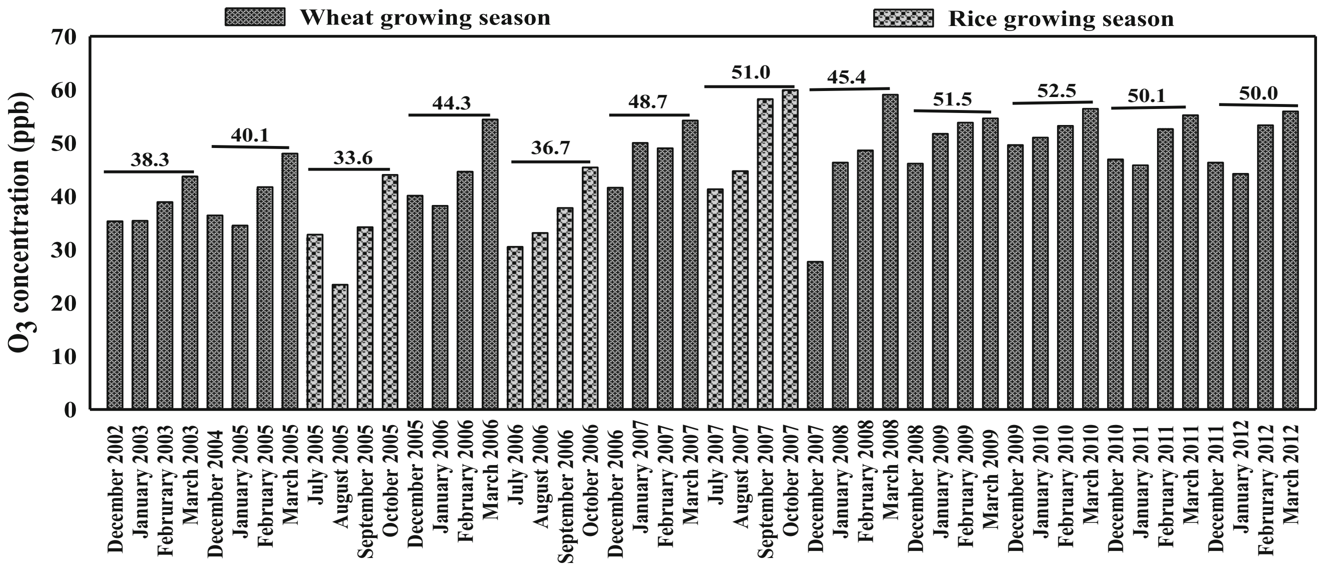

Fig. 2 Compilation of the O_3 monitoring data of a decade (2002–2012) carried out at Varanasi for the two major crop seasons (rabi—wheat-growing season; kharif—rice-growing season). Mean of the individual months are given along with the seasonal mean. Data collected are based on the available published reports

provided here represents the decadal variations in O_3 concentrations in both the crop-growing seasons from December 2002 to March 2012 (Fig. 2). For the kharif season, lowest seasonal mean (33.6 ppb) was in the year 2005 and highest concentration (51.0 ppb) was in the year 2007. For rabi season, seasonal mean varied from lowest value of 38.3 ppb in 2002–2003 to highest value of 52.5 ppb during 2009–2010. A general lower value has been observed in the kharif season which represents the monsoon in India while rabi crop growth season depicted higher values often exceeding 40 ppb. It is also evident that there were higher O_3 concentrations during the reproductive phase of the plant life in comparison to the vegetative phase in both the seasons. Different stages of reproductive development are sensitive to O_3 (Black et al. 2000) and the higher concentrations during reproductive phase perhaps may be a cause of yield reductions in IGPs by affecting different stages of reproductive development.

AOT40 is a concentration based critical levels for crops and is calculated as the mean hourly O_3 concentration accumulated over a threshold concentration of 40 ppb. According to the LRTAP Convention (1996), AOT40 of 3 ppmh accumulated over 3 months was considered to be critical above which O_3 can cause significant yield losses. Considering the significance of AOT40, Mills et al. (2007) also employed the crop response data to derive the O_3 dose and yield functions of 19 agricultural and horticultural crops. In Europe, AOT 40 is an exposure-response approach based on the linear decline in crop yield (Fuhrer et al. 1997). Other workers have also shown a close linear relationship between AOT40 and yield of crop plants (Sarkar and Agrawal 2010; Rai and Agrawal 2014; Singh et al. 2014). Rai and Agrawal (2014) showed reduction in yield of two wheat varieties (PBW 343 and M 533) at ambient O_3 and reported that linear regression between relative yield and AOT40 showed 6% yield loss at AOT40 of 3 ppmh for both the cultivars. AOT40 and yield response relationship indicated a linear decline in yield resulting from cumulative exposure of O_3 and relative yield of quality protein maize (HQPM1) and nonquality protein maize (DHM117) (Singh et al. 2014). A compilation of AOT40 values reported from different studies performed in Varanasi is provided in Table 3.

The burning of agricultural residues in the field particularly the rice and wheat straw is a very common agricultural practice in Northern India. This results in the emissions of VOC, CO, NO_x (0.47 Tg year^{-1}) which act as O_3 precursors and hence more photochemical production of O_3 in rural areas (Galanter et al. 2000; Oksanen et al. 2013). A considerable temporal and spatial variation in AOT 40 values has been observed across the Indian region, and its large parts show O_3 values above the AOT 40 threshold limit (3000 ppbh) for 3 months (Roy et al. 2009). Moreover, a large portion of India shows that the directive set by UNECE (UN Economic Commission for Europe) and WHO for the critical limit of AOT 40 exceeds every month (Roy et al. 2009). Such higher concentration of O_3 leads to marked reduction in the yield of various crops in India.

Yield losses in India

Debaje (2014) estimated the yield losses of two major crops (winter wheat and rabi rice) due to surface O_3 for the period 2002–2007. It was indicated that relative yield loss (RYL) of the mean total production per year was 5 to 11% (6–30%) for

Table 3 AOT values for ambient O_3 recorded at Varanasi during different crop growing seasons

Plant	AOT40 value (ppm h)	Monitoring duration per day (h)	Reference
Rice			
June to October 2005 and 2006	2.1	12	Rai et al. (2010)
June–September	11.2	12	Sarkar et al. (2015)
Wheat			
December–March	6.2	12	Rai et al. (2011b)
December 2007–March 2008	7.9	12	Sarkar and Agrawal (2010)
December 2008–March 2009	8.7	12	Sarkar and Agrawal (2010)
December 2009–March 2010	12.1	12	Rai and Agrawal (2014)
December 2010–March 2011	11.6	8	Singh et al. (2015a)
December 2011–March 2012	7.8	8	Mishra et al. (2013)
Maize			
December 2011–April 2012	8.4	10	Singh et al. (2014)
Mung bean			
April–June 2011	11.5	8	Chaudhary and Agrawal (2015)
April–June 2012	11.4	8	Chaudhary and Agrawal (2015)
Soybean			
July–October 2012	9.0	12	Rai et al. (2015)
Mustard			
November 2007–March 2008	7.9	12	Singh et al. (2012)
November 2010–March 2011	7.3	8	Tripathi and Agrawal (2012)

winter wheat and 3–6% (9–16%) for rabi rice using M7 (AOT40) index. Sinha et al. (2015) estimated the O_3 induced yield losses based on the AOT40 metrics for wheat, rice, cotton, and maize in Punjab. RYL ranged from 27 to 41% for wheat, 21–26% for rice, 9–11% for maize, and 47–58% for cotton. The IGP is one of the most fertile zones of Asia and is well suited for the cultivation of staple cereals and legumes and hence is called the bread basket of India (Burney and Ramanathan 2014). Major portion of the studies considering impact of O_3 on plant productivity in IGP have been carried out with rice and wheat which are largest and second largest cultivated crops in India. Few other economically important crops such as soybean, mung bean, and mustard have also been studied in detail. The majority of experimental work in natural field conditions has been carried out in Eastern parts of IGPs in rural and suburban regions of Varanasi, where climatic conditions favor the prevalence of high concentrations of ambient O_3. These studies have been performed mostly by using open top chambers (OTCs) and also by application of ethylene diurea (EDU) an antiozonant as a monitoring tool to evaluate the yield losses.

Rice is the staple crop of India as well as Southeast Asia providing 21% of the calorific needs of world's total population (Fitzgerald et al. 2009). Rice cultivars Saurabh 950 and NDR 97 showed 10.2 to 15.9% yield reduction under NFCs (ambient O_3) as compared to filtered chambers (FCs) during the years 2005–2006 (Rai and Agrawal 2008) (Table 4). Later, Rai et al. (2010) taking up similar rice cultivars reported that number of grains showed less reduction in NDR 97 than Saurabh 950 but more reduction in test weight were recorded in former than the later. Sarkar and Agrawal (2011) have reported 31–45% yield loss in two cultivars of rice Malviya dhan 36 and Shivani under elevated O_3 (Table 4).

Wheat is the second most important food crop of India contributing nearly one third of total grain production. India occupies the second position among all the wheat-producing countries with an annual production of 78.4 million tons (Singh et al. 2015a). Most of the investigations have been carried out with wheat under ambient or elevated levels of O_3. In these experiments, O_3 stress led to yield losses as a consequence of impaired gas exchange, increased loss of energy in defense activities (Ambasht and Agrawal 2003; Rai et al. 2007), reduced growth, accelerated senescence, and decline in viability of pollens and harvest index (Sarkar and Agrawal 2010; Mishra et al. 2013). Rajput and Agrawal (2005) reported yield loss ranging from 4.0 to 5.9% in cultivar HUW 468 at six different experimental sites (Table 4). A reduction of 20.7% was found in yield of M 234 cultivar of wheat grown in OTCs ventilated with ambient air (40.6 ppb O_3) as compared to filtered chambers (Rai et al. 2007). Sarkar and Agrawal (2010) found reductions of 11–46% in weight of grains (m^{-2}) at ambient and elevated O_3 compared to filtered

Table 4 Yield response of various agricultural crop plants to variable O_3 concentration

Species and cultivar/variety	Experimental setup	O_3 conc./other treatments	Yield parameter	Reductions in yield	Reference
Oryza sativa 'NDR 97' 'Saurabh 950'	Open top chamber	2005–23.4 ppb (12 h) 2006–45.5 ppb (12 h)	Weight of grains (g plant^{-1})	NDR 97—14.0% in the first year and 15.9% in the second year Saurabh—10.2% in the first year and 11.4% in the second year	Rai and Agrawal (2008)
Oryza sativa 'Malviya dhan36'	Open top chamber	NFCs (49.3 ppb) (12 h)	Weight of grains (g m^{-2})	15%	Sarkar and Agrawal (2011)
'Shivani'		NFC+ (NFC + 10 ppb)		27%	
		NFC++ (NFC + 20 ppb)		39%	
		NFCs (49.3 ppb) (12 h)		13%	
		NFC+ (NFC + 10 ppb)		31%	
		NFC++ (NFC + 20 ppb)		45%	
Triticum aestivum 'Malviya 234'	Open top chamber	70 ppb (4 h)/UV-B 7.1 kJ m^2	Weight of grains (g m^{-2})	8.6%	Ambasht and Agrawal (2003)
Triticum aestivum 'HD2329'	Pot study	9.7–58.5 ppb (6 h)	Weight of grains (g plant^{-1})	0.5–25.5%	Agrawal et al. (2003)
Triticum aestivum 'HUW 468'	Pot study	9.9–40.6 ppb (6 h)	Weight of seeds (g plant^{-1})	4.0–5.9%	Rajput and Agrawal (2005)
Triticum aestivum 'HUW-234'	Open top chamber	36.4–48 ppb (8 h)	Weight of grains (g plant^{-1})	20.7%	Rai et al. (2007)
Triticum aestivum 'HUW 510'	Open top chamber	NFCs (45.3 ppb) (12 h)	Weight of grains (g m^{-2})	20.0%	Sarkar and Agrawal (2010)
'Sonalika'		NFCLOs (NFCs + 10 ppb)		37.0%	
		NFCHOs (NFCs + 20 ppb)		46.0%	
		NFCs (45.3 ppb) (12 h)		11.0%	
		NFCLOs (NFCs + 10 ppb)		25.0%	
		NFCHOs (NFCs + 20 ppb)		38.5%	
Triticum aestivum 'HUW-37' 'K-9107'	Open top chamber	Ambient O_3 (48.5–52.7 ppb) (8 h) + 10 ppb elevated O_3	Weight of grains (g plant^{-1})	HUW-37—39% in the first year and 40.8% in the second year K-9107—12.8% in the first year and 14% in the second year	Mishra et al. (2013)
Triticum aestivum 'PBW 343' 'M 533'	Open top chamber	2008–2009–50.2 (M 12) 2009–2010–53.2 (M 12)	Weight of grains (g plant^{-1})	PBW 343—16.2% in the first year and 19% in the second year M 533—14.1% in the first year and 18.8% in the second year	Rai and Agrawal (2014)
Triticum aestivum 'LOK-1'	Open top chamber	58.2 (M 12)	Weight of grains (g plant^{-1})	7.3%	Singh et al. (2015a)
'HUW 510'				16.2%	
Zea mays 'HQPM1'	Open top chamber	Ambient O_3 (55.6 ppb) (10 h)	Weight of kernels (g plant^{-1})	4.0%	Singh et al. (2014)
'DHM117'		Ambient O_3 + 15 ppb		7.2%	
		Ambient O_3 + 30 ppb		10.1%	
		Ambient O_3 (55.6 ppb) (10 h)		5.5%	
		Ambient O_3 + 15 ppb		9.5%	
		Ambient O_3 + 30 ppb		13.8%	
Vigna radiata 'Malviya Jyoti'	Pot study	9.7–58.5 ppb (6 h)	Weight of seeds (g plant^{-1})	34.3–73.4%	Agrawal et al. (2003)
Vigna radiata 'Malviya Jyoti'	Pot study	9.7–58.5 ppb (6 h)	Weight of seeds (g plant^{-1})	22–79%	Agrawal et al. (2006)
Vigna radiata 'HUM 1'	Open top chamber	Ambient (64 ppb) (8 h)	Weight of seeds (g m^{-2})	15.4%	Chaudhary and Agrawal (2015)
'HUM 2'		+10 ppb elevated O_3		13.8%	
'HUM 6'				13.5%	
'HUM 24'				12.0%	
'HUM 26'				10.2%	
'HUM 23'				9.8%	
Glycine max 'PK472'	Open top chamber	70 ppb (4 h)	Weight of seeds (g plant^{-1})	20%	Singh et al. (2010a)
'Bragg'		100 ppb (4 h)		33.6%	
		70 ppb (4 h)		12%	

Table 4 (continued)

Species and cultivar/variety	Experimental setup	O_3 conc./other treatments	Yield parameter	Reductions in yield	Reference
		100 ppb (4 h)		30%	
Brassica campestris 'Pusa Jaikisan'	Pot study	9.7–58.5 ppb (6 h)	Weight of seeds (g plant^{-1})	5.9–25.2%	Agrawal et al. (2003)
Brassica campestris 'Aashirwad'	Open top chamber	29.7–59.0 ppb (12 h)	Weight of seeds (g plant^{-1})	19.3%	Singh et al. (2012)
'Vardan'				7%	
Brassica campestris 'Sanjukta'	Open top chamber	Ambient O_3 (49.4 ppb) (8 h) +10 ppb elevated O_3	Test weight and oil content	12.5 and 47%	Tripathi and Agrawal (2012)
'Vardan'				33.4 and 48.5%	
Brassica juncea 'Pusa Tarak (EJ-13)'	Open top chamber	2009–10–28 ppb (7 h) 2010–11–33 ppb (7 h)	Weight of seed (g m^{-2})	35.9% in the first year and 35.1% in the second year	Singh et al. (2013)
Linum usitatissimum 'Padmini'	Open top chamber	Ambient O_3 (50.3 ppb) (8 h) +10 ppb elevated O_3 UV-B—ambient +7.2 kJ m^{-2} day^{-1}	Weight of seeds plant^{-1} and oil content	Padmini—40.5 and 46.7%	Tripathi and Agrawal (2013)
'T-397'				T-397—42.8% and 42.5%	

chamber taken as control (Table 4). The dose-response analysis indicated 5.4% yield reduction at the European critical level of 3 ppmh (Sarkar and Agrawal 2010). Moreover, Mishra et al. (2013) also recognized reduction in weight of grains plant^{-1} of tall cultivar (K-9107) and dwarf cultivar (HUW-37) and found that dwarf cultivar with higher yield potential was more sensitive to O_3 than tall cultivar with lower yield potential (Table 4). A study was performed on maize cultivars differing in nutritional quality of the kernels; Singh et al. (2014) noticed 4–13.8% reduction in weight of kernels plant^{-1} for DHM117 and HQPM1 cultivars.

Other major economically important crops were also found to respond similarly under the prevailing O_3 stress at IGP. Ozone responses of *Vigna radiata* and *Brassica campestris* was reported by Agrawal et al. (2003). The species were grown within the urban fringes of Varanasi at four sites, and the respective yield reductions are provided in Table 4. In an investigation on air pollution and yield of mung bean plants, Agrawal et al. (2006) reported that weight of seed plant^{-1} was lowered by 22–79% depending on the concentration of pollutants at different sites of Varanasi as compared to the yield measured at reference site (Table 4). Ozone exposure of 70 and 100 ppb led to reductions in yield of *Glycine max* cultivars, and it was emphasized that the newly developed one (PK 472) was more O_3-sensitive compared to the older variety (Bragg) (Singh et al. 2010a) (Table 4). Responses of mustard (*B. campestris*) and linseed (*Linum usitatissimum*) to O_3 were studied by Tripathi and Agrawal (2012 and 2013), and reductions were detected in test weight of seeds and oil contents (Table 4). In the biomonitoring study with mung bean cultivars, reductions were found in yield, and the dose-response analysis indicated towards highest sensitivity for HUM-1 and least sensitivity for cultivar HUM-23 (Chaudhary and Agrawal 2015) (Table 4). Interaction between nutrients (NPK) availability and O_3 stress was investigated by Singh et al. (2015a and 2012) taking up wheat and mustard (Table 4). Yield losses due to ambient O_3 were detected at recommended NPK grown in NFC condition with respect to air filtration. Studies from other regions of India have also reported reductions in yield upon O_3 exposure. Bhatia et al. (2011) stated that the presence of higher O_3 (59.1–69.7 ppb) led to 11 to 12% decrease in the yield of rice. Singh et al. (2013) found a decrease of 8% in the number of siliqua plant^{-1} while weight of grains decreased by 35.9% at elevated O_3 (EO) as compared to nonfiltered air (NF) in *B. juncea*. Yield reductions of 14.3% in no. of grains cob^{-1} for NF treatment while a reduction of 23.3% was observed for EO (NF + 25–35 ppb O_3) as compared to controlled filtered (CF) treatment in maize (Bhatia et al. 2013).

Variations/differences in magnitude of yield reductions in different cultivars of the crops was found due to inherent plant characters (leaf area, stomatal conductance, etc.), differential allocation of photosynthates to reproductive organs and seed filling, foliar injury, impairment to reproductive structures, variable reductions in photosynthesis and stomatal conductance and different levels in induction of antioxidative defense system. Wheat cultivar PBW 343 with larger leaf area and high stomatal conductance was more sensitive to O_3 than M533 with comparatively smaller leaf area and low stomatal conductance (Rai and Agrawal 2014). Reproductive structure such as viable pollens and fertile florets per plant were affected more in cultivar Sonalika than HUW510, thus displaying greater reduction in yield (Sarkar and Agrawal 2010). Similarly in mustard, cultivar Sanjukta showing greater reduction in photosynthesis and reproductive structures manifested greater reductions in yield (Tripathi and Agrawal 2012). Higher reduction in number of ovules per capsule resulted in more loss in test weight in cultivar Padmini as compared to T-397 in linseed (Tripathi and Agrawal 2013). More foliar injury, reductions in green leaf area ratio and number of male flowers led to comparatively more yield loss in maize cultivar DHM117 than HQPM1 (Singh et al. 2014). Rai and Agrawal (2008) and Rai et al. (2010) suggested that rice cultivar NDR 97 utilized more photosynthate in maintaining metabolic machinery against O_3 stress resulting in less translocation of photosynthate to reproductive parts and therefore more yield loss compared to Saurabh 950. Chaudhary and Agrawal (2015) found that higher resistance in mung bean cultivars towards elevated O_3 correlated with higher induction of antioxidative enzymes. Similar result was obtained in soybean cultivars PK472 and Bragg by Singh et al. (2010a).

EDU as a research tool for the assessment of yield losses against ozone

EDU ([N-(2–2-oxo-1-imidazolidinyl) ethyl]-N-phenyl urea) is a chemical protectant against O_3 (Carnahan et al. 1978). The application of EDU as a “control” to ambient O_3 is useful to determine ambient O_3 effects in field grown plants, particularly in remote rural areas or developing regions where there are limited electricity supply and funding (Manning et al. 2011; Tiwari et al. 2005; Rai et al. 2015). It has been extensively used as research tool for O_3 injury, screening of cultivars as well as assessment of yield losses caused due to O_3 (Singh et al. 2015b). Studies using EDU as a chemical protectant to O_3 has been used in few studies in India to reveal differences among the cultivars (O_3 sensitive/tolerant) as detected for wheat (Singh et al. 2009c) and black gram (Singh et al. 2010c). EDU induced yield improvement on various agricultural crop plants grown under different O_3 doses are provided in Table 5. Recently, Rai et al. (2015) assessed the response of soybean to O_3 applying 400 ppm EDU as the soil drench and found that EDU was effective in preventing yield loss and provided protection to the growth of soybean plants.

Effects of ozone on nutritional quality

Apart from yield, nutritional quality of the agricultural products is also a major functional trait and a concern for society. It has been previously reported that O_3 exposure changes the composition of seed nutritional parameters and hence affects the product quality. Concentrations of starch, protein, P, N, Ca, Mg, and K decreased, while reducing and total soluble sugar increased in rice grains of cultivars NDR 97 and Saurabh 950 under ambient air exposure (NFCs) compared to FCs (Rai et al. 2010). Recently, Sarkar et al. (2015) found negative effects of O_3 on nutritional parameters of grains resulting in a decreased content of starch, protein and N with an increased pool of total soluble sugars and reducing sugars. Mishra et al. (2013) found that protein content in wheat grains decreased significantly by 18.8 and 15.3% in EO (NFC + 10 ppb O_3) in cultivars HUW-37 and K-9107, respectively, as compared to NFCs (ambient O_3). Reductions in total soluble sugars and starch content were also observed in both the cultivars grown under EO treatment as compared to NFCs.

Starch content and protein in the seeds of mung bean varied at different experimental sites (grown in peri-urban areas of Varanasi) with a trend showing that the sites having high O_3 concentration had lower starch and seed protein content (Agrawal et al. 2006). Chaudhary and Agrawal (2015) studied the role of O_3 in modifying the seed quality of six mung bean cultivars. Total soluble sugar and starch reduced along with protein and N. Lower Ca, Mg, and K contents were also observed in all the cultivars under elevated O_3 atmosphere. Singh et al. (2010c) exposed two black gram cultivars to O_3 and observed a decline in total amino acid and protein contents in the seeds.

Exposure of O_3 also changed the quantity as well as quality of oil in crop plants. Apart from reduction in protein content, oil content and fatty acid profile displayed variation in mustard seeds after O_3 exposure in test cultivars Sanjukta and Vardan (Tripathi and Agrawal 2012). Iodine and saponification values were increased with greater induction in Sanjukta as compared to Vardan. While saturated fatty acid (SFA) content was reduced after O_3 exposure; other constituents of fatty acid profile [monounsaturated fatty acid (MUFA), polyunsaturated fatty acid (PUFA), and omega 6 fatty acid] showed an enhancement (Tripathi and Agrawal 2012). The increase in PUFA and omega-6 fatty acid is not positive because high content of PUFA lowers the oxidative stability of oil leading to its lower suitability for frying purpose and increased chances of ulcerative colitis due to increased consumption of omega-6 fatty acid (Tripathi and Agrawal 2012). Significant decline in total sugar, N, and mineral nutrient (P, Ca, Mg, and Zn) of seeds were observed in the test cultivars (Padmini and T-397) of *L. usitatissimum* at elevated O_3 treatment (10 ppb above the ambient O_3)

Table 5 A summary of the effects of EDU application on various agricultural crop plants grown under ozone treatment

Species/cultivar	EDU concentration	O_3 concentration	Yield parameter	Yield increment	Reference
Oryza sativa	300 ppm	42 ppb (8 h)	Net grain weight plant^{-1} across 18 cultivars	25% (↑)	Pandey et al. (2015)
18 cultivars		46 ppb (8 h)		48% (↑)	
Banthra site					
Lucknow site					
Triticum aestivum	500 ppm	29.2 ppb (6 h)	Weight of grains (g m^{-2})	22% (↑)	Agrawal et al. (2004)
'HD 2329'				27% (↑)	
'HUW 234'				36.3% (↑)	
'HUW 468'					
Triticum aestivum	150 ppm	Often exceeding 40 ppb (8 h)	Weight of seeds (g plant^{-1})	24.8% (↑)	Tiwari et al. (2005)
'M 234'	300 ppm			66.9% (↑)	
'M 533'	450 ppm			66.8% (↑)	
	150 ppm			18.8% (↑)	
	300 ppm			19.1% (↑)	
	450 ppm			20.5% (↑)	
Triticum aestivum	400 ppm	34.2 to 54.2 ppb (8 h)	Weight of seeds (g m^{-1})	11.2% (↑)	Singh et al. (2009c)
'HUW234'				25.8% (↑)	
'HUW468'				20.5% (↑)	
'HUW510'				1.9% (↑)	
'PBW343'				10.2% (↑)	
'Sonalika'					
Vigna radiata 'Malviya Jyoti'	500 ppm	32.6 to 35.1 ppb (8 h)	Weight of seeds (g plant^{-1})	32.2% (↑)	Agrawal et al. (2005)
Vigna radiata	400 ppm	52.9 to 64.5 ppb (12 h)	Weight of seeds (g plant^{-1})	32.2% (↑)	Singh et al. (2010b)
'Malviya Janpriya'					
Vigna mungo	400 ppm	41.3 to 59.9 ppb (12 h)	Weight of seeds (g plant^{-1})	36.4% (↑)	Singh et al. (2010c)
'Barkha'				35.6% (↑)	
'Shekhar'					
Glycine max	400 ppm	NFCs (50.5 to 58.9)	Weight of seeds (g plant^{-1})	29.8% (↑)	Singh and Agrawal (2011)
'Pusa 9712'		NFCs + 20 ppb		33.0% (↑)	
'Pusa 9814'		NFCs (50.5 to 58.9)		28.2% (↑)	
		NFCs + 20 ppb		29.0% (↑)	
Glycine max	400 ppm	42 ppb (12 h)	Weight of seeds (g plant^{-1})	11.0%	Rai et al. (2015)
'JS 335'					
Brassica Campestris	200 ppm	58.4 ppb (8 h)	Weight of seeds (g plant^{-1})	7% (↑)	Pandey et al. (2014)
'Kranti'	400 ppm			17% (↑)	
'Peela sona'	200 ppm			59% (↑)	
	400 ppm			34% (↑)	

compared with ambient O_3 (NFC). Among the variables of oil quality, acid value and iodine value were enhanced significantly in both the cultivars; however, the saponification value was reduced. Enhancement of iodine value is an indicative of oil unsaturation and increased saponification value shows more number of carboxylic acid groups which is not good for human consumption and may have serious health implications (Tripathi and Agrawal 2013). Singh et al. (2013) reported that elevated O_3 (EO) significantly decreased the oil, mineral nutrients (Ca, Zn, Fe, Mg, S), and protein content in *B. campestris* compared to ambient O_3 (NF) which served as the control. Singh et al. (2010a), while investigating the effect of elevated O_3 on nutrient content in pods of *G. max* (cv. PK 472 and Bragg), found that K, P, and N content declined in pods in T_1 (70 ± 5 ppb O_3) and T_2 (100 ± 5 ppb O_3) plants of both the cultivars compared to the control.

Impact of nutrient (NPK) availability and O_3 and related alterations in seed qualitative traits were studied by Singh et al. (2009b). Reductions in nutrient elements, protein, and oil contents in seeds of mustard were recorded under NFCs (ambient O_3) at recommended NPK (RNPK) dose as compared to FCs. The percent reductions at RNPK were 12.5% for protein, 9% for N, 14% for P, 17% for Ca, 26.8% for Mg, 31% for K, and 34.8% for Zn, respectively, in seeds of plants grown in NFCs as compared to FCs (Singh et al. 2009b). In the similar type of setup, significant reductions were observed in protein, Mg, K, Zn, N, Ca, and oil contents in seeds of both the test cultivars (Vardan and Aashirvad) grown in NFCs and FCs at RNPK, but no significant changes were observed at 1.5 times recommended NPK (1.5 RNPK) (Singh et al. 2012). Genotypic differences between the two wheat cultivars (HUW 510 and LOK-1) based on the changes in grain quality on application of RNPK and 1.5 RNPK were studied by Singh et al. (2015a). Though total sugar content increased, starch accretion reduced in grains of both the cultivars in NFCs compared to FCs and the reductions were higher at RNPK than 1.5 times RNPK. P, N, and K were reduced at NFCs compared to FCs at RNPK as well as 1.5 RNPK but the magnitude of impact was less at 1.5 times RNPK.

Information lacuna, mitigation strategies, and future perspectives

India's population is growing at a faster rate and to feed a growing population, it will need to increase crop yield with sustainable intensification of agriculture. Simultaneously, the rising O_3 concentration in India is a threat to its crop productivity. Though there exists an appreciable literature on O_3-induced yield reductions for crop plants, information available are not enough considering the phytotoxicity of O_3. Most of the studies conducted so far in relation to O_3 stress are performed either in field conditions or by using OTCs. Free Air Concentration Enrichment (FACE) studies in India are still in its infancy. FACE provides more natural conditions for the plant growth and OTCs have their own limitations. Though the environment inside OTCs approaches that of the natural field but generally it is comparatively warmer, more humid, shaded, and has altered air movement (Kimball et al. 1997). Moreover, experiments carried out in OTCs often overestimate treatment effects on biomass production and yield (Long et al. 2005). The plant responses that have been tested are predominantly physiological and biochemical; therefore, there is a pressing need to expand these studies at gene/protein level to unveil the molecular mechanism behind O_3 toxicity.

In India, few more monitoring stations should be set up, which can monitor O_3 for long term to generate meaningful information. A more comprehensive surface O_3 monitoring network suggested by Ghude et al. (2014) can be employed to investigate the origins of pollution. Mitigation efforts for limiting the O_3 precursor's emissions (particularly NO_x) should effectively be implemented. Present air quality standards need to be validated and improved.

To quantify the impacts of O_3 on crop yield at national and regional scale, National Crop Loss Assessment Network (NCLAN) program in USA and European Crop Loss Assessment Network (EUCLAN) in Europe were conducted. Such programs at national level if promoted in India can generate a lot of important information regarding the crop losses occurring in India due to O_3 pollution and would be helpful in formulation of some policies to curb the emissions of O_3 precursors. Also, there is no set up of critical limit or dose-response relationships for Indian plants like those in Europe and North America (Wang and Mauzerall 2004; Emberson et al. 2009). So, more accurate determination of O_3 exposure and dose response relationship should be carried out to set up the critical limit for Indian plants.

Responses of plants to air pollutants vary with the supply of mineral nutrients such as NPK which is an eco-friendly solution (Singh et al. 2005). Therefore, application of suitable level of NPK should be promoted in the field. EDU is a useful research tool to estimate crop losses especially in high O_3 under field conditions where electricity and infrastructure are the limiting factors (Singh et al. 2015b). So, its accessibility should be promoted in rural areas as EDU can better reveal the differences among the cultivars (Oksanen et al. 2013) and hence help in screening of tolerant/resistant cultivars to find their suitability for cultivation in the areas having high concentrations of O_3.

It is noteworthy that to minimize the yield losses, future crop productivity may depend on utilization of O_3-tolerant cultivars or else developing O_3-resistant cultivars either through conventional breeding methods or by the utilization of recent biotechnological tools. Hence, there should be large scale screening of local cultivars for their O_3 sensitivity/tolerance taking economically important crop species as well as the unexplored species. Simultaneously, some early maturing varieties can be deployed which could face shorter growth period (Ghude et al. 2014) escaping from cumulative O_3 exposure that larger duration crops are forced to encounter. In the long-term scenario, farmers may select/more pollution resilient or tolerant cultivars to minimize the crop losses.

Conclusions

Ozone in troposphere is a serious problem of concern due to its phytotoxicity causing yield reductions in India. Emissions of NO_x, an important O_3 precursor, are increasing in India which is responsible for an escalation of O_3 concentration over Indian regions. Higher levels of O_3 during summer and winter seasons are experienced whereas lowest O_3 formation is noticed during monsoon. Such variations over India are mainly due to higher levels of precursors and the availability of ample solar radiation in winter and summer. A low O_3 during monsoon can be attributed to weather pattern as well as washing out of O_3 precursors. This seasonal variation in O_3 concentration also varies from region to region. A general tendency of high O_3 formation can be seen over IGPs as compared to other parts of India. Prevalence of high O_3 in India results in yield losses of economically important crops as well as affects their nutritional quality. So, in view of rising O_3 problem in India, some mitigation steps should be taken urgently for reducing the O_3 precursors, developing new O_3-

resistant varieties and by adopting recent agricultural management techniques to reduce the impact of O_3 on staple crops for ensuring food security.

Acknowledgements The authors are thankful to the Head of the Department of Botany, Coordinator CAS in Botany, FIST (DST), UPE (UGC) and ISLS (DBT) for all the laboratory facilities, and to the SERB (Department of Science and Technology), New Delhi, for providing financial support to the work.

References

Agrawal M, Singh B, Rajput M, Marshall F, Bell JNB (2003) Effect of air pollution on peri-urban agriculture: a case study. Environ Pollut 126: 323–329

Agrawal SB, 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. J Plant Biol 31:165–172

Agrawal SB, Singh A, Rathore D (2005) Role of ethylenediurea (EDU) in assessing impact of ozone on *Vigna radiata* L. plants in a suburban area of Allahabad (India). Chemosphere 61:218–228

Agrawal M, Singh B, Agrawal SB, Bell JNB, Marshall F (2006) The effect of air pollution on yield and quality of mung bean grown in peri-urban areas of Varanasi. Water Air Soil Pollut 169:239–254

Ahammed YN, Reddy RR, Gopal KR, Narasimhulu K, Baba Basha B, Reddy LSS, Rao TVR (2006) Seasonal variation of the surface ozone and its precursor gases during 2001–2003, measured at Anantapur (14.62°N), a semi-arid site in India. Atmos Res 80: 151–164

Ali K, Inamdar S, Beig G, Ghude S, Peshin S (2012) Surface ozone scenario at Pune and Delhi during the decade of 1990s. J Earth Syst Sci 121:373–383

Ambasht NK, Agrawal M (2003) Effects of enhanced UV-B radiation and tropospheric ozone on physiological and biochemical characteristics of field grown wheat. Biol Plantarum 47:625–628

Aneja VP, Agarwal A, Roelle PA, Phillips SB, Tong Q, Watkins N, Yablonsky R (2001) Measurement and analysis of criteria pollutants in New Delhi, India. Environ Int 27:35–42

Attri AK, Kumar U, Jain VK (2001) Microclimate: formation of O_3 by fireworks. Nature 41:1015

Avnery S, Mauzerall DL, Liu J, Horowitz LW (2011) Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. Atmos Environ 45:2284–2296

Beig G, Ali K (2006) Behavior of boundary layer ozone and its precursors over a great alluvial plain of the world: Indo–Gangetic plains. Geophys Res Lett 33

Beig G, Brasseur GP (2006) Influence of anthropogenic emissions on troposheric ozone and its precursors over the Indian tropical region during monsoon. Geophys Res Lett 33

Beig G, Ghude S, Jadha DB (2007) Simultaneous measurements of ozone and its precursors on a diurnal scale at a semi urban site in India. J Atmos Chem 57:239–253

Berntsen T, Isaksen IS, Wang WC, Liang XZ (1996) Impacts of increased anthropogenic emissions in Asia on tropospheric ozone and climate. Tellus B 48:13–32

Bhatia A, Ghosh A, Kumar V, Tomer R, Singh SD, Pathak H (2011) Effect of elevated tropospheric ozone on methane and nitrous oxide emission from rice soil in North India. Agric Ecosyst Environ 144: 21–28

Bhatia A, Kumar V, Kumar A, Tomer R, Singh B, Singh S (2013) Effect of elevated ozone and carbon dioxide interaction on growth and yield of maize. Maydica 51:291–298

Bhatnagar VS (1996) Chandigarh, the city beautiful: environmental profile of a modern Indian city. APH Publishing pp 77

Black VJ, Black CR, Roberts JA, Stewart CA (2000) Impact of ozone on the reproductive development of plants. New Phytol 147:421–447

Booker F, Muntifering R, McGrath M, Burkey K, Decoteau D, Fiscus E, Manning W, Sagar K, Chappelka A, Grantz D (2009) The ozone component of global change: potential effects on agricultural and horticultural plant yield, product quality and interactions with invasive species. J Integr Plant Biol 51:337–351

Brasseur GP, Hauglustaine DA, Walters S, Rasch PJ, Müller JF, Granier C, Tie XX (1998) MOZART, a global chemical transport model for ozone and related chemical tracers: 1. Model description. J Geophys Res: Atmospheres (1984–2012) 103:28265–28289

Burney J, Ramanathan V (2014) Recent climate and air pollution impacts on Indian agriculture. P Natl Acad Sci USA 111:16319–16324

Carmichaei GR, Ferm M, Thongboonchoo N, Woo JH, Chan LY, Murano K, Viet PH, Mossberg C, Bala R, Boonjawat J, Upatum P (2003) Measurements of sulfur dioxide, ozone and ammonia concentrations in Asia, Africa, and South America using passive samplers. Atmos Environ 37:1293–1308

Carnahan JE, Jenner EL, Wat EKW (1978) Prevention of ozone injury in plants by a new protective chemical. Phytopathol 68:1225–1229

Chaudhary N, Agrawal SB (2015) The role of elevated ozone on growth, yield and seed quality amongst six cultivars of mung bean. Ecotoxicol Environ Safe 111:286–294

Cho K, Tiwari S, Agrawal SB, Torres NL, Agrawal M, Sarkar A, Shibato J, Agrawal GK, Kubo A, Rakwal R (2011) Tropospheric ozone and plants: absorption, responses, and consequences. Rev Environ Contam T 212:61–111

IPCC Climate Change (2007) The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Collins WJ, Stevenson DS, Johnson CE, Derwent RG (1997) Tropospheric ozone in a global-scale three-dimensional Lagrangian model and its response to NO_x emission controls. J Atmos Chem 26:223–274

Convention LRTAP (1996) Manual on methodologies and criteria for mapping critical levels/loads and geographical areas where they are exceeded. In: Texte 71/96. Umweltbundesamt, Berlin, Germany

Debaje SB (2014) Estimated crop yield losses due to surface ozone exposure and economic damage in India. Environ Sci Pollut Res 21: 7329–7338

Debaje SB, Kakade AD (2009) Surface ozone variability over western Maharashtra, India. J Hazard Mater 161:686–700

Debaje SB, Jeyakumar SJ, Ganesan K, Jadhava DB, Seetaramayya P (2003) Surface ozone measurements at tropical rural coastal station Tranquebar, India. Atmos Environ 37:4911–4916

Dentener F, Stevenson D, Cofala J, Mechler R, Amamm M, Bergamaschi P, Raes F, Derwent R (2005) The impact of air pollutant and methane emission controls on tropospheric ozone and radiative forcing: CTM calculations for the period 1990-2030. Atmos Chem Phys 5:1731–1755

EANET (2006) Data report on acid deposition on east asia region 2005. Network centre of EANET, Japan. http://www.eanet.cc/. Accessed 16th Aug. 2015

Elampari K, Debaje SB, Jeyakumar SJ, Chithambarathanu T (2013) Measurements of ozone and its precursor nitrogen dioxide and crop yield losses due to cumulative ozone exposures over 40 ppb (AOT40) in rural coastal southern India. J Atmos Chem 70:357–371

Emberson LD, Buker P, Ashmore MR, Mills G, Jackson LS, Agrawal M, Atikuzzaman MD, Cinderby S, Engardt M, Jamir C, Kobayshi K, Oanh OTR, Quadir QF, Wahid A (2009) A comparison of north-

American and Asian exposure-response data for ozone effects on crop yields. Atmos Environ 43:1945–1953

Environmental protection agency (EPA) (2007) http://www.epa.gov. Accessed 9th Nov 2016

Feng Z, Kobayashi K (2009) Assessing the impacts of current and future concentrations of surface ozone on crop yield with meta-analysis. Atmos Environ 43:1510–1519

Feng Z, Kobayashi K, Wang X, Feng Z (2009) A meta-analysis of responses of wheat yield formation to elevated ozone concentration. Chinese Sci Bull 54:249–255

Fitzgerald MA, McCouch SR, Hall RD (2009) Not just a grain of rice: the quest for quality. Trends Plant Sci 14:133–139

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Fuhrer J, Skärby L, Ashmore MR (1997) Critical levels for ozone effects on vegetation in Europe. Environ Pollut 97:91–106

Galanter M, Levy H, Carmichael GR (2000) Impacts of biomass burning on tropospheric CO, NO_x, and O_3. J Geophys Res-Atmos 105: 6633–6653

Garg A, Shukla RP, Bhattacharya S, Dadhwal VK (2001) Sub-region (district) and sector level SO_2 and NO_x emissions for India: assessment of inventories and mitigation flexibility. Atmos Environ 35: 703–713

Gauss M, Ellingsen K, Isaksen ISA, Dentener FJ, Stevenson DS, Amann M, Cofala J (2007) Changes in nitrogen dioxide and ozone over Southeast and East Asia between year 2000 and 2030 with fixed meteorology source. Terres Atmos Ocean Sci 18:475–492

Ghazali NA, Ramli NA, Yahaya AS, Yusof NF, Sansuddin N, Al Madhoun WA (2010) Transformation of nitrogen dioxide into ozone and prediction of ozone concentrations using multiple linear regression techniques. Environ Monit Assess 165:475–489

Ghude SD, Jain SL, Arya BC, Beig G, Ahammed YN, Kumar A, Tyagi B (2008) Ozone in ambient air at a tropical megacity, Delhi: characteristics, trends and cumulative ozone exposure indices. J Atmos Chem 60:237–252

Ghude SD, Kulkarni SH, Kulkarni PS, Kanawade VP, Fadnavis S, Pokhrel S, Jena C, Beig G, Bortoli D (2011) Anomalous low tropospheric column ozone over eastern India during the severe drought event of monsoon 2002: a case study. Environ Sci Pollut Res 18: 1442–1455

Ghude SD, Jena C, Chate DM, Beig G, Pfister GG, Kumar R, Ramanathan V (2014) Reductions in India's crop yield due to ozone. Geophys Res Lett 41:5685–5691

Horaginamani MS, Ravichandran M (2010) Ambient air quality in an urban area and its effects on plants and human beings: a case study of Tiruchirappalli, India. Kathmandu Univ J Sci, Eng Technol 6:13–19

Jain SL, Arya BC, Kumar A, Ghude SD, Kulkarni PS (2005) Observational study of surface ozone at New Delhi, India. Int J Remote Sens 21:3515–3526

Khemani LT, Momin GA, Rao PSP, Vijaykumar R, Safai PD (1995) Study of surface ozone behaviour at urban and forest sites in India. Atmos Environ 29:2021–2024

Kimball BA, Pinter PJ, Wall GW, Garcia RL, LaMorte RL, Jak P, Frumau KF, Vugts HF (1997) Comparisons of responses of vegetation to elevated carbon dioxide in free-air and open-top chamber facilities. Advances in carbon dioxide effects research. (advances in carbo): 113–130

Lal S, Naja M, Subbaraya BH (2000) Seasonal variations in surface ozone and its precursors over an urban site in India. Atmos Environ 34:2713–2724

Lal DM, Ghude SD, Patil SD, Kulkarni SH, Jena C, Tiwari S, Srivastava MK (2012) Tropospheric ozone and aerosol long-term trends over the Indo-Gangetic Plain (IGP), India. Atmos Res 116:82–92

Lelieveld JO, Crutzen PJ, Ramanathan V, Andreae MO, Brenninkmeijer CAM, Campos T, Hansel A (2001) The Indian Ocean experiment: widespread air pollution from South and Southeast Asia. Science 291:1031–1036

Lin X, Trainer M, Liu SC (1988) On the nonlinearity of the tropospheric ozone production. J Geophys Res Atmos 93:15879–15888

Long SP, Ainsworth EA, Leakey AD, Morgan PB (2005) Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. Philos T R Soc B 360:2011–2020

Lu Z, Streets DG (2012) Increase in NO_x emissions from Indian thermal power plants during 1996−2010: unit-based inventories and multisatellite observations. Environ Sci Technol 46:7463–7470

Manning WJ, Paoletti E, Sandermann H Jr, Ernst D (2011) Ethylenediurea (EDU): a research tool, for assessment and verification of the effects of ground level ozone on plants under natural condition. Environ Pollut 159:3283–3293

McCrady JK, Andersen CP (2000) The effect of ozone on below-ground carbon allocation in wheat. Environ Pollut 107:465–472

Mills G, Buse A, Gimeno B, Bermejo V, Holland M, Emberson L, Pleijel H (2007) A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops. Atmos Environ 41:2630–2643

Mishra AK, Rai R, Agrawal SB (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 Crop Res 145:21–32

Mittal ML, Hess PG, Jain SL, Arya BC, Sharma C (2007) Surface ozone in the Indian region. Atmos Environ 41:6572–6584

Morgan PB, Mies TA, Bollero GA, Nelson RL, Long SP (2006) Season-long elevation of ozone concentration to projected 2050 levels under fully open-air conditions substantially decreases the growth and production of soybean. New Phytol 170:333–343

Naja M, Lal S (2002) Surface ozone and precursor gases at Gadanki (13.5 N, 79.2 E), a tropical rural site in India. J Geophys Res-Atmos (1984–2012), 107(D14), ACH-8

Naja M, Lal S, Chand D (2003) Diurnal and seasonal variabilities in surface ozone at a high altitude site Mt Abu (24.6°N, 72.7°E, 1680 m asl) in India. Atmos Environ 37:4205–4215

Nishanth T, Praseed KM, Rathnakaran K, Satheesh Kumar MK, Ravi Krishna R, Valsaraj KT (2012a) Atmospheric pollution in a semi-urban, coastal region in India following festival seasons. Atmos Environ 47:295–306

Nishanth T, Satheesh Kumar MK, Valsaraj KT (2012b) Variations in surface ozone and NO_x at Kannur: a tropical, coastal site in India. J Atmos Chem 69:101–126

Oksanen E, Pandey V, Pandey AK, Keski-Saari S, Kontunen-Soppela S, Sharma C (2013) Impacts of increasing ozone on Indian plants. Environ Pollut 177:189–200

Pandey J, Agrawal M (1992) Ozone: concentration variabilities in a seasonally dry tropical climate. Environ Int 18:515–520

Pandey AK, 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. Agric Ecosyst Environ 196:158–166

Pandey AK, Majumder B, Keski-Saari S, Kontunen-Soppela S, Mishra A, Sahu N, Pandey V, Oksanen E (2015) Searching for common responsive parameters for ozone tolerance in 18 rice cultivars in

India: results from ethylenediurea studies. Sci Total Environ 532: 230–238

Prather M, Gauss M, Berntsen T, Isaken I, Sundet J, Bey I, Brasseur G, Dentener F, Derwent R, Stevenson D, Grenfell L, Hauglustaine D, Horowitz L, Jacob D, Mickley L, Lawrence M, Kuhlmann RV, Muller JF, Pitari G, Rogers H, John-son M, Pyle J, Law K, Weele MV, Wild O (2003) Fresh air in the twenty-first century. Geophys Res Lett 30:72–74

Pulikesi M, Baskaralingam P, Rayudu VN, Elango D, Ramamurthi V, Sivanesan S (2006) Surface ozone measurements at urban coastal site Chennai, in India. J Hazard Mater B 137:1554–1559

Rai R, Agrawal M (2008) Evaluation of physiology and biochemical responses of two rice (*Oryza sativa* L.) cultivars to ambient air pollution using open top chambers at a rural site in India. Sci Total Environ 407:679–691

Rai R, Agrawal M (2012) Impact of tropospheric ozone on crop plants. P Natl A Sci India B 82:241–257

Rai R, Agrawal M (2014) Assessment of competitive ability of two Indian wheat cultivars under ambient O_3 at different developmental stages. Environ Sci Pollut Res 21:1039–1053

Rai R, Agrawal M, Agrawal SB (2007) Assessment of yield losses in tropical wheat using open top chambers. Atmos Environ 41:9543–9554

Rai R, Agrawal M, Agrawal SB (2010) Threat to food security under current levels of ground level ozone: a case study for Indian cultivars of rice. Atmos Environ 44:4272–4282

Rai R, Rajput M, Agrawal M, Agrawal SB (2011a) Gaseous air pollutants: a review on current and future trends of emissions and impact on agriculture. J Sci Res 55:77–102

Rai R, Agrawal M, Agrawal SB (2011b) Effects of ambient O_3 on wheat during reproductive development: gas exchange, photosynthetic pigments, chlorophyll fluorescence, and carbohydrates. Photosynthetica 49:285–294

Rai R, Agrawal M, Choudhary KK, Agrawal SB, Emberson L, Buker P (2015) Application of ethylene diurea (EDU) in assessing the response of a tropical soybean cultivar to ambient O_3: nitrogen metabolism, antioxidants, reproductive development and yield. Ecotox Environ Safe 112:29–38

Rajput M, Agrawal M (2005) Biomonitoring of air pollution in a seasonally dry tropical suburban area using wheat transplants. Environ Monit Assess 101:39–53

Ramanathan V, Ramana MV (2005) Persistent, widespread, and strongly absorbing haze over the Himalayan foothills and the Indo-Gangetic Plains. Pure Appl Geophys 162:1609–1626

Reddy RR, Gopal KR, Reddy LS, Narasimhulu K, Kumar KR, Ahammed YN, Reddy CVK (2008) Measurements of surface ozone at semi-arid site Anantapur (14.621°N, 77.651°E, 331 m asl) in India. J Atmos Chem 59:47–59

Reddy BS, Kumar KR, Balakrishnaiah G, Gopal KR, Reddy RR, Sivakumar V, Lingaswamy AP, Arafath SM, Umadevi K, Kumari SP, Ahammed YN (2012) Analysis of diurnal and seasonal behavior of surface ozone and its precursors (NO_x) at a semi-arid rural site in Southern India. Aerosol Air Qual Res 12:1081–1094

Roy SD, Beig G, Ghude SD (2009) Exposure-plant response of ambient ozone over the tropical Indian region. Atmos Chem Phys 9:5253–5260

Saha U, Talukdar S, Jana S, Maitra A (2014) Effects of air pollution on meteorological parameters during Deepawali festival over an Indian urban metropolis. Atmos Environ 98:530–539

Sarkar A, Agrawal SB (2010) Elevated ozone and two modern wheat cultivars: an assessment of dose dependent sensitivity with respect to growth, reproductive and yield parameters. Environ Exp Bot 69: 328–337

Sarkar A, Agrawal SB (2011) Evaluating the response of two high yielding Indian rice cultivars against ambient and elevated levels of ozone by using open top chambers. J Environ Manag 95:S19–S24

Sarkar A, Singh AA, Agrawal SB, Ahmad A, Rai SP (2015) Cultivar specific variations in antioxidative defense system, genome and proteome of two tropical rice cultivars against ambient and elevated ozone. Ecotox Environ Safe 115:101–111

Sawada H, Kohno Y (2009) Differential ozone sensitivity of rice cultivars as indicated by visible injury and grain yield. Plant Biol 11:70–75

Simon H, Reff A, Wells B, Xing J, Frank N (2014) Ozone trends across the United States over a period of decreasing NOx and VOC emissions. Environ Sci Technol 49:186–195

Singh S, Agrawal SB (2011) Cultivar-specific response of soybean (*Glycine max* L.) to ambient and elevated concentrations of ozone under open top chambers. Water Air Soil Pollut 217:283–302

Singh A, Agrawal SB, Rathore D (2005) Amelioration of Indian urban air pollution phytotoxicity in *Beta vulgaris* L. by modifying NPK nutrients. Environ Pollut 134:385–395

Singh P, Agrawal M, Agrawal SB (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. Environ Pollut 157:871–880

Singh E, Tiwari S, Agrawal M (2009b) Effects of elevated ozone on photosynthesis and stomatal conductance of two soybean varieties: a case study to assess impacts of one component of global climate change. Plant Biol 11:101–108

Singh S, Agrawal SB, Agrawal M (2009c) Differential protection of ethylenediurea against ambient ozone for five cultivars of tropical wheat. Environ Pollut 157:2359–2367

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. Agric Ecosyst Environ 135:168–177

Singh S, Agrawal M, Agrawal SB, Emberson L, Büker P (2010b) Use of ethylenediurea for assessing the impact of ozone on mung bean plants at a rural site in a dry tropical region of India. Int J Environ Waste Manag 5:125–139

Singh S, Agrawal SB, Singh P, Agrawal M (2010c) Screening three cultivars of *Vigna mungo* L. against ozone by application of ethylenediurea (EDU). Ecotoxicol Environ Safe 73:1765–1775

Singh P, Singh S, Agrawal SB, 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. Environ Monit Assess 184:5863–5874

Singh S, Bhatia A, Tomer R, Kumar V, Singh B, Singh SD (2013) Synergistic action of tropospheric ozone and carbon dioxide on yield and nutritional quality of Indian mustard (*Brassica juncea* (L.) Czern.). Environ Monit Assess 185:6517–6529

Singh AA, Agrawal SB, Shahi JP, Agrawal M (2014) Assessment of growth and yield losses in two *Zea mays* L. cultivars (quality protein maize and non quality protein maize) under projected levels of ozone. Environ Sci Pollut Res 21:2628–2641

Singh P, Agrawal M, Agrawal SB, Singh S, Singh A (2015a) Genotypic differences in utilization of nutrients in wheat under ambient ozone concentrations: growth, biomass and yield. Agric Ecosyst Environ 199:26–33

Singh AA, Singh S, Agrawal M, Agrawal SB (2015b) Assessment of ethylene diurea-induced protection in plants against ozone phytotoxicity. DM Whitacre (Ed) Rev Environ Contam T 233:129–184

Sinha B, Singh Sangwan K, Maurya Y, Kumar V, Sarkar C, Chandra BP, Sinha V (2015) Assessment of crop yield losses in Punjab and Haryana using two years of continuous in-situ ozone measurements. Atmos Chem Phys 15:2355–2404

Streets DG, Yarber KF, Woo JH, Carmichael GR (2003) Biomass burning in Asia: annual and seasonal estimates and atmospheric emissions. Global Biogeochem Cy 17

Takigawa M, Niwano M, Akimoto H, Takahashi M, Kobayashi K (2009) Projection of surface ozone over East Asia in 2020 65:161–166.

Tiwari VS, Peshin S (1995) A prominent maximum in surface ozone concentration during winter months at Pune (India). Mausam 46: 155–162

Tiwari S, Agrawal M, Manning WJ (2005) Assessing the effects of ambient ozone on growth and productivity of two cultivars of wheat in India using three rates of application of ethylenediurea (EDU). Environ Pollut 138:153–160

Tiwari S, Rai R, Agrawal M (2008) Annual and seasonal variations in tropospheric ozone concentrations around Varanasi. Int J Remote Sens 29:4499–4514

Tripathi R, Agrawal SB (2012) Effects of ambient and elevated level of ozone on *Brassica campestris* L. with special reference to yield and oil quality parameters. Ecotox Environ Safe 85:1–12

Tripathi R, Agrawal SB (2013) Interactive effect of supplemental ultraviolet-B and elevated ozone on seed yield and oil quality of two cultivars of linseed (*Linum usitatissimum* L.) carried out in open top chambers. J Sci Food Agric 93:1016–1025

Tripathi R, Sarkar A, Rai SP, Agrawal SB (2011) Supplemental ultraviolet-B and ozone: impact on antioxidants, proteome and genome of linseed (*Linum usitatissimum* L. cv. Padmini). Plant Biol 13:93–104

Trivedi S, Agrawal M (2003) Air quality status in Varanasi city. J Environ Stud Polic 6:75

van der ARJ, Eskes HJ, Boersma KF, Van Noije TP, Van Roozendael M, De Smedt I, Peters DH, Meijer EW (2008) Trends, seasonal variability and dominant NO_x source derived from a ten year record of NO_2 measured from space. J Geophys Res: Atmos 113 (D4)

Van Dingenen R, Dentener FJ, Frank R, Maurten CK, Emberson L, Cofala J (2009) The global impact of ozone on agricultural crop yields under current and future air quality legislation. Atmos Environ 43:604–618

Varshney CK, Aggarwal M (1992) Ozone pollution in the urban atmosphere of Delhi. Atmos Environ 26:291–294

Varshney CK, Rout C (1998) Ethylene diurea (EDU) protection against ozone injury in tomato plants at Delhi. B Environ Contam Tox 61: 188–193

Wang X, Mauzerall DL (2004) Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020. Atmos Environ 38:4383–4402

Yerramsetti VS, Sharma AR, Navlur NG, Rapolu V, Chitanya Dhulipala NSK, Sinha PR (2013) The impact assessment of Diwali fireworks emissions on the air quality of a tropical urban site, Hyderabad, India, during three consecutive years. Environ Monit Assess 185: 7309–7325