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Research Article

Assessment of Synergistic Impact of Ambient Surface Ozone and Fine Particulate Matter on Experimentally Grown Wheat Crop

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ABSTRACT The present study aims to understand how increasing surface ozone and fine particulate matter concentrations affect wheat crop productivity under ambient conditions. A pot experiment was conducted spanning over a period of 117 days starting from December 2016 to April 2017 at one of the receptor locations in Delhi characterized with high levels of surface ozone and fine particulate matter. The study site recorded highest concentrations of PM_1, $PM_{2.5}$, PM_{10} and surface ozone of 159±77 $\mu g\ m^{-3}$, 172±79 $\mu g\ m^{-3}$, 280±108 $\mu g\ m^{-3}$ and 335±18 $\mu g\ m^{-3}$, respectively during the crop cycle indicating the high levels of air pollutants at the site. The crops were treated with ascorbic acid under different experimental setups. A large number of growth, biochemical and yield parameters were evaluated at the vegetative, reproductive and grain formation stage of the crop cycle. Results indicated that the chlorophyll content and harvest yield of crops grown under ambient conditions were ~23% and ~14% lower than those of crops grown under controlled environment. Furthermore, a ~13%, 5%, 15% and 10% decline in root length, plant height, number of tillers and number of leaves was observed in crops that were exposed to only surface ozone in comparison to crops exposed to only fine particulate matter under vegetative stage, respectively. Relative water content, chlorophyll content and air pollution tolerance index observed ~56%, 23% and 61% decline with fully exposed setup in comparison control setup in the vegetative stage, while ~57%, 23% and 44% decline was observed in the reproductive stage. Experiments also suggested that surface ozone had a more pronounced influence on overall productivity of wheat crops in comparison to fine particulate matter.

KEY WORDS Surface ozone, Fine particulate matter, Wheat, Crop yield loss

1. INTRODUCTION

India being an agrarian country is the second largest producer of wheat across the world and holds a critical position in the worlds' food economy (Burney and Ramanathan, 2014). The Indo-Gangetic Plains (IGP) is one of the most fertile region which contributes to ~80% of the wheat and rice production of the country (Pathak *et al.*, 2011). However, of late IGP has been experiencing a declining trend in the overall productivity and yield of these crops which is sure to impact the food security of the country (Rai, 2016; Tiwari *et al.*, 2016). The increasing levels of air pollution in both urban and rural areas of the region have been identified as a one of the prominent reason for the loss in agricultural productivity in the IGP region (Kumar *et al.*, 2018; Rai, 2016; Burney and Ramanathan, 2014). In particular, surface ozone and fine particulate matter (FPM) i.e. PM_1, $PM_{2.5}$ and PM_{10} have emerged as prominent air pollutants prevalent in this area producing negative impacts on the overall growth patterns of the crops (Gurjar *et al.*, 2016; Ghude *et al.*, 2014). Surface ozone not only interferes in the gaseous exchange phenomenon in plants but also inflicts phytotoxic damage to plant tissues, thus, reducing the overall productivity of crops (Lombardozzi *et al.*, 2012; Wilkinson *et al.*, 2012). In contrast to surface ozone, FPM interferes with the productivity of crops by either decreasing the quantity and quality of solar radiation, i.e., by reducing the total shortwave light exposure to the plant by increased scattering or dust deposition on the crops (Mina *et al.*, 2018; Rai, 2016). The negative impacts of elevated levels of surface ozone and FPM on vegetation has been a cause of concern for the country since the last decade and is a prominent problem of urban agriculture (Shukla *et al.*, 2016; Monks *et al.*, 2015; Oksanen *et al.*, 2013). Surface ozone is being considered as a 'new age pollutant' for tropical and developing countries like India and has emerged as a major concern in highly polluted cities like Delhi (Sharma and Khare, 2017). Furthermore, it has been extensively highlighted in literature that the IGP reports higher concentration of surface ozone and its precursors in comparison to other parts of the country (Kumari *et al.*, 2020; Lal *et al.*, 2012; Roy *et al.*, 2008).

A large number of experimental studies have been conducted in past to estimate the impacts of surface ozone on wheat crops which have showed decline in morphological, biochemical and yield parameters of the crop (Hansen *et al.*, 2019; Kamal *et al.*, 2015; Tomer *et al.*, 2015; Chauhan, 2010). Forest trees and vegetation are also negatively impacted by elevated levels of surface ozone (Watanabe *et al.*, 2011; Yamaguchi *et al.*, 2011). A 5% to 11% relative yield loss in the mean total production per year for winter wheat and 3% to 6% loss for rabi rice has been reported for the time period of 2002 to 2007 in India due to exposure to surface ozone (Debaje, 2014). The relative losses in wheat and rice crops have seen an increase after 2007 as evident by the findings of a study conducted by Lal *et al.* (2017). The results of the study report a 4.2–15% loss in all India wheat production amounting to ~9 million tons, while a 0.3–6.3% loss in all India rice production amounting to ~2.6 million tons. Furthermore, in 2005, food needs of ~35% of the Indian population lying below poverty line could have been sufficed by the ozone induced damage to wheat and rice adding up to ~3.5 million tons and ~2.1 million tons, respectively. Similar loss of crop yields amounting to 27% to 41% of wheat yield loses have been reported by other studies like (Sinha *et al.*, 2015). In contrast to the massive amount of literature evaluating the impact of surface ozone on crop productivity, a limited number of studies have been conducted to assess the impact of FPM on the crops. Though, studies like (Mina *et al.*, 2018) reports a 7.5–14% reduction in the grain yield of PS-5 and PB-1509 rice varieties when exposed to elevated levels of FPM and (Sonkar *et al.*, 2019) reported a 23% decline northern hills zone of India.

Moreover, not many studies have been conducted in past that evaluates the synergistic impacts of surface ozone and FPM on wheat crop under ambient environment settings. Majority of the existing studies analyze the impacts of either surface ozone or SPM on the crop productivity in closed environments with elevated dose exposure to the plant, masking the impacts of other pollutants present during the growth cycle. Hence, ambient settings were chosen for the present study with an aim to assess the combined effect of surface ozone and FPM deposition on wheat crop.

2. MATERIALS AND METHODS

The overall methodological framework and the experimental design employed in the current study is shown in Fig. 1. The following section describes the methodological steps and characteristics of the experimental design.

2. 1 Experimental Site

The study was carried out at TERI School of Advanced Studies (TERI SAS) located in south western part of Delhi (28°32′89″N, 77°08′54″E) and considered as a receptor site due to predominant south western wind direction of the city (Sharma *et al.*, 2017). The site is characterized with increased levels of air pollutants, especially FPM and surface ozone owing to its geographic location and predominant wind direction, thus, making it a suitable site for replicating ambient conditions for an experiment. Moreover, the higher concentration of pollutants at this receptor site in post monsoon months (Agrawal *et*

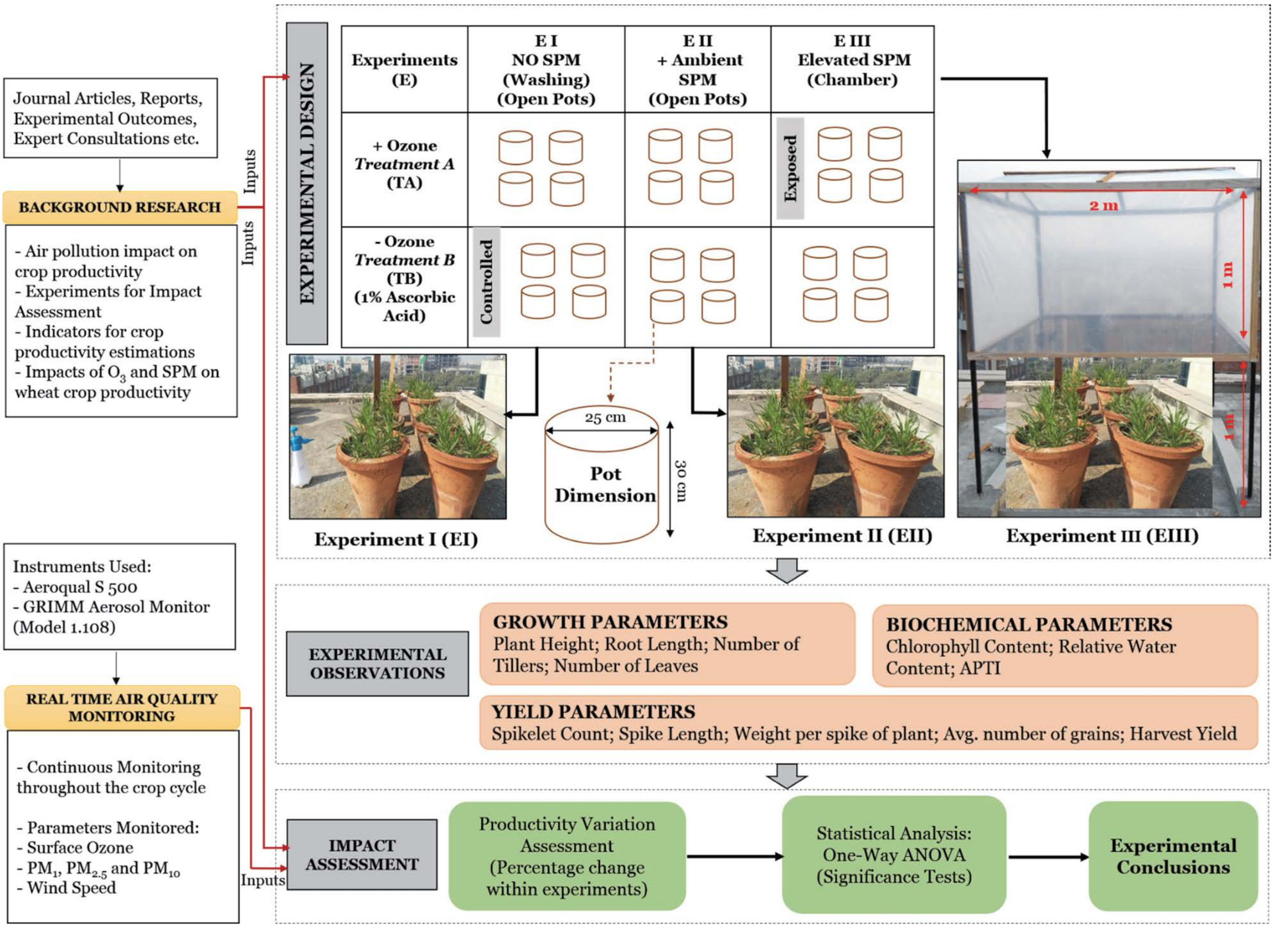

Fig. 1. Framework for assessment of impacts of air pollution on wheat crop productivity.

al., 2011) was also validated by conducting a background air quality monitoring before sowing of the crop which continued throughout the crop cycle.

2.2 Experimental Design and Setup

A pot experiment was carried out by growing HD2967 double dwarf wheat variety developed by Indian Agriculture Research Institute (IARI) known for high yield and resistance against the common diseases like yellow and brown rusts (Vaid *et al.*, 2017). The plant has average height of 101 cm with profuse tillering. The ears are medium dense and tapering in shape with white glumes. Its grains are amber, medium bold, hard and lustrous. This wheat variety is prominent in North Western Plain Zone (NWPZ) and North Eastern Plains Zone (NEPZ) of Indian subcontinent (average seed yield in NWPZ: 50.4 q/ha, NEPZ: 44.4 q/ha) (www.iari.res.in). In addition to its abundance in the IGP, wheat crop is also one of the most ozone sensitive crop, thus, making it an interesting case to assess the impacts of increasing levels of ambient ozone concentrations in the urban areas (Schiferl and Heald, 2018; Burney and Ramanathan, 2014). The experimental setup consisting of two treatments and four replicates with a total of six experiments was established in the month of November and was placed for a complete crop cycle i.e. from germination (stage 1) to ripening (stage 9) (Zadoks *et al.*, 1974) ending in month of April after the harvesting of the crop.

The wheat kernels were obtained from IARI and planted in pots (25 cm diameter × 30 cm depth) by equally dividing the pot in four portions. Each pot contained 13 kg of soil collected from the IARI agricultural fields and was pretreated with Di Ammonium Phosphate (DAP) to maintain fertilizer balance before sowing. Fertilizers, Nitrogen (N), Phosphorous (P) and Potassium (K) were applied as recommended (120 : 60 : 60) i.e., 1g per pot

(Mina *et al.*, 2018). Sowing of the wheat crop was done on 7 December 2016 and germination of the plant was observed on 14 December 2016. The harvest cycle of the crop was completed in 117 days after germination (DAG) i.e. 07 April 2017. Zadok scale (Zadoks *et al.*, 1974) representing growth on scale of 00 to 92 (germination to harvest) was used to refer the growth of the plant in order to understand the overall growth cycle of the wheat crop at different stages. Each experiment involved two treatments with four replicates (four pots) in each treatment. Thus, the study design comprised a total of 24 pot samples as shown in Fig. 1 and described in the equation below.

$$4S(TA\ EI)+4S(TB\ EI)+4S(TA\ EII)\\ +4S(TB\ EII)+4S(TA\ EIII)+4S(TB\ EIII)=24S$$

Experiment I (EI) was characterized with limited FPM deposition, the plants were washed every 10 days with distilled water to maintain ambient conditions. The plants were exposed to all other ambient pollutants, including surface ozone and weather conditions, such as rainfall and natural wind turbulence. In Experiment II (EII), labelled as 'open pot experiment', no washing was done and no barrier was provided. The plants were exposed to all ambient pollutants, including surface ozone and FPM and natural weather conditions. Experiment III (EIII) was conducted inside a partially closed chamber (2 m × 2 m × 2 m dimensions) with top and upper half of sidewalls covered with plastic sheet (see Fig. 1) to block vertical deposition of FPM on the plants and prevent washing of the plants through rainfall. A gap of 1 m from the ground surface was maintained at each side of the chamber to allow adequate horizontal wind movement through the chamber. Adequate sunlight was maintained through the sheet by regularly washing it with clean water.

Further, for each experiment, the wheat crops were subjected to two different treatments, i.e., Treatment A (TA), in which the plants were exposed to ambient surface ozone concentrations along with FPM, and Treatment B (TB), in which the plants were treated with 1% ascorbic acid spray to remove the impact of surface ozone on the crops. The overall description of the treatments and experimental setup has been summarized in Table 1.

2.3 Quantification of Atmospheric Pollutants Load at Experimental Site

Background air quality monitoring at the experimental site was commenced one month prior to the sowing and continued throughout the crop cycle at 10-day interval for 8 hours per day i.e., from November 03 to April 05 2017. Continuous ozone monitoring was carried out using portable monitor Aeroqual S 500 (New Zealand made) which is a semiconductor based gaseous sensor providing ozone values either in parts per million (ppm) or in

Table 1. Experimental design and treatment.

S. No.	Experiment	Type of settings	Treatment	Mode of application	Characteristics	Type of pollutants exposed
1	1TA	Open pots	Water washing	Foliar spray	Ambient conditions	Ambient FPM
2	1TB	Open pots	1% ascorbic acid water solution and water washing	Foliar spray	Ambient conditions	No exposure (Controlled)
3	2TA	Open pots	No treatment	NA	Ambient conditions	Ambient FPM and ambient O_3
4	2TB	Open pots	1% ascorbic acid water solution	Foliar spray	Ambient conditions	Ambient O_3
5	3TA	Chamber	No treatment	NA	Low wind speed within the chamber contributing to pollutant accumulation	Elevated FPM and elevated O_3 (Exposed)
6	3TB	Chamber	1% ascorbic acid water solution	Foliar spray	Low wind speed within the chamber contributing to pollutant accumulation	Elevated FPM

microgram per cubic meter (μg/m^3) (Punithavathy *et al.*, 2015). The instrument was calibrated against the ozone UV photometer. The sensor head works on the Gas Sensitive Semiconductor (GSS) principle (Mustafa and Mohammed, 2012) estimating the ozone partial pressure by the observed conductance of ozone. The instrument provides a range of 0.0 to 0.150 ppm ozone measurement and can measure values as low as 0.001 ppm. The detailed working principle and instrument design has been discussed by (Williams *et al.*, 2013).

Fine particulate matter (FPM) concentration was determined by GRIMM aerosol monitor (Model 1.108), which is an optical particle counter (OPC) and monitor aerosols in 15 different size ranges (ranging from 0.3 μm to 20 μm) by light scattering method. The reproducibility of the instrument is ±3% over the whole measuring range (GRIMM, 2010) and its accuracy for fine size particles has also been established in past studies (Pfister *et al.*, 2017; Ragazzi *et al.*, 2017; Sinha *et al.*, 2011). Both the instruments were programmed to record 10-minute average concentration of ambient surface O_3 and FPM. A zero calibration was conducted before each monitoring in both instruments. A manual check was conducted regularly throughout the sampling period each day to ensure that there is no power supply disruption or instrument stoppage.

2.4 Morphological and Biochemical Growth Parameters of the Plant Material

A number of parameters categorized as growth, biochemical and yield attribute were considered to assess the impact of surface ozone and FPM on the productivity of wheat crop. Table 2 summarizes the attributes considered in the current study along with an overview of the methodological formulae employed to estimate these parameters.

2.5 Statistical Analysis

Several statistical techniques were deployed for the analysis of the experimental data. Descriptive analysis estimated the percentage change in these parameters within different treatments and different growth stages of the crop cycle, i.e., vegetative, reproductive and grain formation stages. Comparative analysis was performed to understand the independent and combined effects of FPM and surface ozone on wheat crop. Further, one-way analysis of variance (ANOVA) without transformation was conducted on the dataset using SPSS software.

3. RESULTS

3.1 Background Atmospheric Load of FPM and Surface Ozone during the Experimental Period

The observed air quality during the entire crop cycle indicated that the concentration of both FPM as well as surface ozone exceeded the recommended air quality standards indicating a high built up of pollutants at the experimental site. The FPM load i.e. PM_1, $PM_{2.5}$ and PM_{10} observed for the month of November was 71±43 μg/m^3, 87±48 μg/m^3 and 176±48 μg/m^3 which eventually increased at the onset of winters leading to an inverse relationship with boundary layer height (BLH) (Wang *et al.*, 2019). The highest recorded concentrations of PM_1, $PM_{2.5}$ and PM_{10} were in the months of December and January ranging from 115±57 μg/m^3, 127±58 μg/m^3, 212±61 μg/m^3 and 159±77 μg/m^3, 172±79 μg/m^3, 280±108 μg/m^3 respectively (Fig. 2). The pollutant build-up during these months could be attributed to the meteorological conditions prevalent in the city characterized with low wind speed and high temperature decreasing the horizontal and vertical movement of pollutants. February and March observed the least concentration build-up i.e. 87±55 μg/m^3 of PM_1, 79±27 μg/m^3 of $PM_{2.5}$, 154±12 μg/m^3 of PM_{10} and 24±24 μg/m^3 of PM_1, 32±38 μg/m^3 of $PM_{2.5}$, 99±31 μg/m^3 of PM_{10}, respectively. It is important to highlight that the PM load was found to be above the prescribed National Ambient Air Quality Standards (NAAQS) prescribed by Central Pollution Control Board (CPCB) i.e. 60 μg/m^3 and 40 μg/m^3 for PM_{10} and $PM_{2.5}$ throughout the monitoring period as evident from Fig. 2.

A similar trend of increased surface ozone concentration was observed. The ozone concentration peaked in December and January. Fig. 3 presents the variation in the concentration of surface ozone which was found to be higher than the prescribed NAAQS standard i.e. 100 μg/m^3 throughout the crop cycle. The concentration of surface ozone was observed to be 314±45 μg/m^3, 337±45 μg/m^3, 335±18 μg/m^3, 317±23 μg/m^3 and 320±23 μg/m^3 for the months of November, December, January, February and March, respectively. Higher ozone concentration in winter months can be attributed to the reactive hydrocarbon emitted due to biomass burning resulting in higher ozone concentration buildup (Dumka *et al.*, 2019). Considering the fact that the concentration of both surface ozone and FPM are found to be higher in the experimental site, it presents a suitable case to estimate the

Table 2. Growth, biochemical and yield parameters under consideration for experiment.

Type of parameter	Experiments/ Tasks performed	Parameter unit	Type of setup	Methodological overview/Formula used
Growth parameters	Tiller count	Number	Field (TERI SAS)	Physical counting of every parameter, i.e., tiller and leaf were carried out by hands to estimate the number of each unit of the plants being grown
	Leaf count	Number	Field (TERI SAS)	
	Plant height (Small)	cm	Lab (TERI SAS)	The length of the leaf of wheat plant was estimated using a centimetre scale through visual observations and interpretation
	Plant height (Medium)	cm	Lab (TERI SAS)	
	Plant height (Large)	cm	Lab (TERI SAS)	
	Root length (Small)	cm	Lab (TERI SAS)	The length of the root of wheat plant was estimated using a centimetre scale through visual observations and interpretation
	Root length (Medium)	cm	Lab (TERI SAS)	
	Root length (Large)	cm	Lab (TERI SAS)	
	Dust deposition estimation	mg/cm^2	Wet lab (TERI SAS)	Gravimetric analysis
Biochemical parameters	pH estimation	Number	Wet lab (TERI SAS)	pH Meter was used to estimate the acid content of the leaf extract
	Ascorbic acid content estimation	mg/g	Wet lab (TERI SAS)	Titration/Spectroscopy
	Total chlorophyll content estimation	mg/g	Wet lab (TERI SAS)	Centrifuge/Spectroscopy
	CHNS analysis	%	Lab (IIT Madras) outsourced	Mass spectroscopy (Grinded samples)
	Relative water content estimation	%	Wet lab (TERI SAS)	Mass spectroscopy (Grinded samples) $RWC = (\text{Fresh weight} - \text{Dry weight})/(\text{Saturated weight} - \text{Dry weight}) \times 100$
	Air Pollution Tolerance Index (APTI) estimation	Number	Wet lab (TERI SAS)	Mathematical formulations using Microsoft Excel 2013
Yield parameters	Spikelet count	Number	Field (TERI SAS)	Physical counting of every spikelet was carried out by hands to estimate the number of each unit of the plants being grown
	Spike length	cm	Lab (TERI SAS)	The length of the leaf of wheat plant was estimated using a centimeter scale through visual observations and interpretation
	Weight per spike of plant	g	Lab (TERI SAS)	Weighing balance
	Average number of grains	Number	Lab (TERI SAS)	Physical counting of grains was carried out by hands to estimate the number of each unit of the plants being grown
	Harvest index	g/g	Wet lab (IARI CESCRA)	Quantity of yield v/s total biomass produced

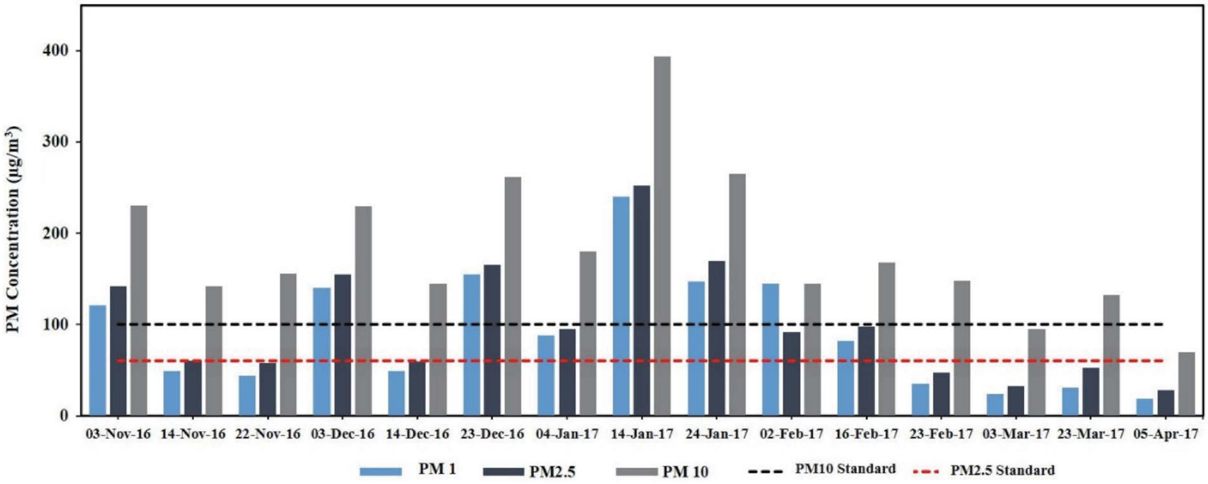

Fig. 2. FPM concentration variation during the crop cycle.

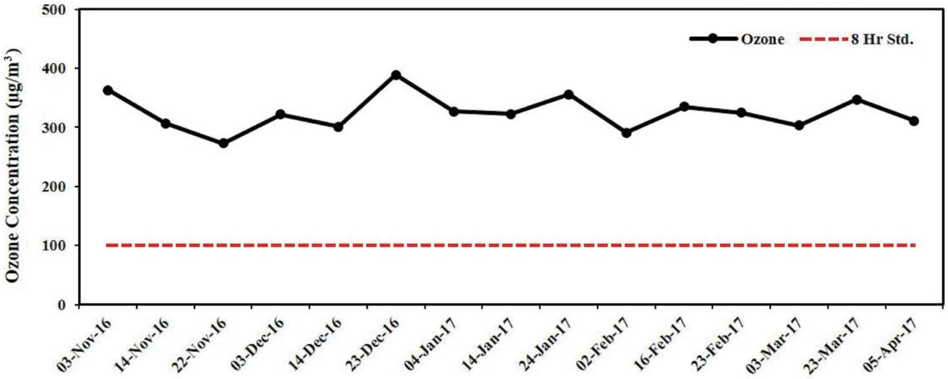

Fig. 3. Surface ozone concentration variation during the crop cycle.

impacts of these pollutants on the productivity of wheat crops in ambient conditions which is prevalent throughout the IGP.

3.2 Effects of Surface Ozone and FPM on Wheat Crop

3.2.1 Growth Parameters

The results indicated a significant difference in the values of the growth parameters estimated for different experiments in both the vegetative as well as reproductive stages. The values of all the growth parameters were observed to be the lowest in EIII TA, i.e. fully exposed set up, while highest in EI TB, i.e., controlled set up as presented in Fig. 4. This could be attributed to the difference in the levels of exposure to air pollutants in the two sets of experiments. The plants grown in the chamber experienced elevated levels of surface ozone and FPM due to decreased wind speed and vertical dispersion of pollutants which could be considered as the reason for the observed trends in the morphological parameters.

Experiments in which wheat crop was exposed to both the pollutants i.e. EII TA witnessed a higher decline in their growth parameters in comparison to the experiments in which crop was exposed to any one of the pollutant i.e. EII TB and EI TA as evident from the parameter estimates presented in Table 3. The present study also highlights an important observation regarding the impact of ambient surface ozone and ambient FPM on the growth parameters of the wheat crop.

The crops grown in EI TA, i.e., exposed to ambient ozone witnessed a higher decline in the growth parameters in comparison to EII TB, i.e., exposed to ambient

Table 3. Variations in growth and biochemical parameters of wheat crops under the three experiments.

Parameters	Vegetative stage						Reproductive stage					
	Experiment I (No SPM)		Experiment II (+Ambient SPM)		Experiment III (−Ambient SPM)		Experiment I (No SPM)		Experiment II (+Ambient SPM)		Experiment III (−Ambient SPM)	
	TA	TB	TA	TB	TA	TB	TA	TB	TA	TB	TA	TB
Growth parameters												
Plant height (Small)	40.5±1.7	42.7±2.9	39.2±2.9	42±2.1	36.7±2.3	38.5±2.3	45.5±3.41	45.65±3.16	43.50±3.69	46.40±2.25	40.10±3.03	41.75±2.75
Plant height (Medium)	49±4.7	51±3.3	48.5±2.9	49.8±3.1	45±2.8	45±1.9	51.20±2.53	53.45±2.84	50.35±2.62	52.85±5.38	40.70±14.15	48.47±1.08
Plant height (Large)	57.8±3.4	61.5±1.7	56.9±3.7	60.5±3.1	54.2±6.07	55.5±5.8	60.25±5.42	67.25±2.98	59.90±3.38	63.52±3.40	57.25±5.85	58.90±6.25
Root length (Small)	17.45±1.76	18.87±2.17	16.67±1.78	18.1±2.7	16.6±2.16	16.6±0.47	18±3.39	19.6±2.19	17.25±1.98	18.52±1.56	17.20±2.09	17.35±0.42
Root length (Medium)	19.8±1.8	22.5±1.58	19.45±0.98	20.8±3.75	18.77±1.47	19.35±3.8	20.6±3.34	23.15±1.58	20.01±0.91	21.65±1.83	19.55±1.16	19.80±4.14
Root length (Large)	22.25±3.66	26.12±2.1	22.1±5.2	25.15±2.6	20.05±1.9	22±1.8	23±2.16	26.89±2.10	22.72±5.34	26±3.63	20.97±1.91	22.87±1.85
Biochemical parameters												
Chlorophyll content	12.6±1.18	13.9±1.98	12.4±1.65	13.5±1.6	10.69±1.35	10.92±1.42	14.04±1.09	14.40±1.60	12.92±1.31	13.20±0.72	11.19±1.41	11.43±1.07
Relative Water Content (RWC) (%)	68.9±1.6	72.6±2.26	66.4±6.37	71.24±4.74	31.7±6.51	39.65±2.95	70.36±4.27	71.71±2.33	65.58±6.4	68.11±1.66	30.86±6.41	38.77±2.9
Air Pollution Tolerance Index (APTI)	6.6±0.16	8.2±0.03	7.14±0.38	7.8±0.32	3.24±0.096	4.86±0.33	10.15±0.54	10.28±0.46	9.40±0.48	9.65±0.44	5.78±0.08	6.89±0.26

Data represented as mean value±standard deviation

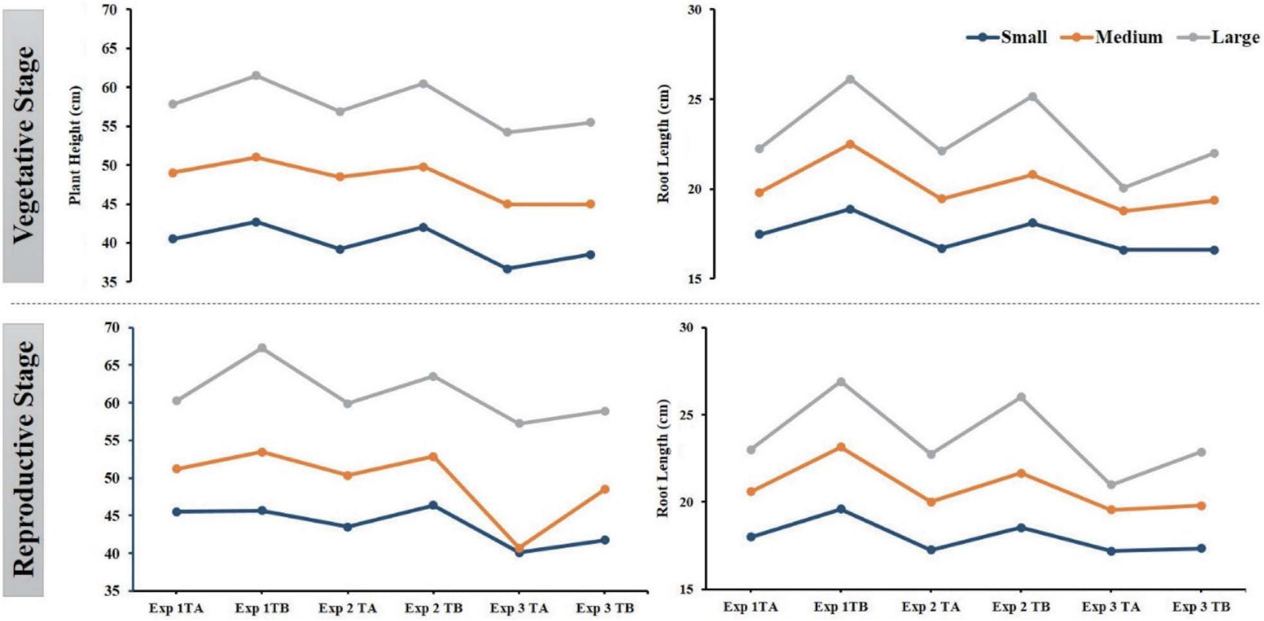

Fig. 4. Growth parameters estimations for different experiments in the vegetative and reproductive stage.

FPM. A ~13%, 5%, 15% and 10% decline in root length, plant height, number of tillers and number of leaves was observed in crops of EI TA in comparison to EII TB in its vegetative stage. Similar declining trend of ~7% and 4% was observed in the root length and plant height, respectively was observed in EI TA in comparison to EII TB in its reproductive stage as well (Fig. 4). This clearly indicates that ambient surface ozone produced more negative impacts on the growth parameters of wheat crop in comparison to FPM. To further statistically signify the experimental observations, one-way ANOVA was conducted on the dataset. The results of the ANOVA testing are presented in Table 4. The possible impacts of surface ozone and FPM on wheat crop in ambient conditions has been found to be statistically significant ($p \leq 0.05$) on plant height, number of tillers and all the yield parameters. The ambiguity in ANOVA results of the growth parameters could be attributed to small sample size, however, the experimental observations clearly indicate a substantial percentage decline in the values of growth parameters with increased exposure to surface ozone and FPM.

3.2.2 Biochemical Parameters

The results of the experiments revealed a similar trend for biochemical parameters as well, with maximum decline in the parameters of the crop plants grown in third experimental setup having elevated concentration of both the pollutants under consideration. Preliminary analysis pointed that ~56%, 23% and 61% decline in relative water content (RWC), chlorophyll content and air pollution tolerance index (APTI) was observed in EIII TA, i.e., fully exposed setup in comparison to EI TB, i.e., control setup in the vegetative stage, while ~57%, 23% and 44% decline was observed in the reproductive stage. In order to assess the impact of both the pollutants on the biochemical parameters of wheat crops, percentage decline among EII TA, EI TA and EII TB was conducted. The descriptive results highlighted a ~8% and ~6% decline in the chlorophyll content between EI TA & EII TA and EI TA & EII TB, respectively indicating the increased decline in biochemical parameters due to surface ozone exposure. The difference in the values of biochemical parameters for EI TA and EII TB reveal that surface ozone produces higher negative impacts on the productivity of wheat crop in comparison to FPM in ambient settings.

In addition to descriptive analysis, the results of one-way ANOVA also revealed statistically significant difference between the biochemical parameters in various experimental setups as presented in Table 4. In contrast to growth parameters, it was observed that exposure to surface ozone and FPM produce significantly higher impacts on the biochemical parameters which further reduces the overall crop productivity.

Table 4. F-values for different variables for applying ANOVA to the response of wheat crops on different treatments under different experiments at vegetative and reproductive stage.

Parameters	Vegetative stage		Reproductive stage	
	F-value	Sig.	F-value	Sig.
Growth parameters				
Plant height (Small)	**3.17**	**0.032**	2.069	0.061
Plant height (Medium)	2.25	0.094	2.076	0.116
Plant height (Large)	1.75	0.173	2.333	0.085
Number of tillers*	**4.33**	**0.009**	**4.33**	**0.009**
Number of leaves*	1.15	0.369	1.15	0.369
Root length (Small)	0.904	0.5	0.783	0.575
Root length (Medium)	1.16	0.36	1.246	0.329
Root length (Large)	2.02	0.123	2.069	0.117
Biochemical parameters				
Chlorophyll content	**2.93**	**0.042**	**4.571**	**0.007**
Relative Water Content (RWC) (%)	**63.05**	**0**	**65.525**	**0**
Air Pollution Tolerance Index (APTI)	**215.74**	**0**	**83.453**	**0**

$P \leq 0.05$ Significance level

* These parameters remain same in both the stages

Table 5. Variations in yield parameters of wheat crops under the three experiments.

Parameters	Experiment I (No SPM)		Experiment II (+Ambient SPM)		Experiment III (−Ambient SPM)	
	TA	TB	TA	TB	TA	TB
Spikelet count	45.25 ± 1.89	42 ± 2.16	42 ± 1.41	43 ± 4.24	37.5 ± 3.31	37.5 ± 3.41
Spike length	8.12 ± 0.10	8.6 ± 0.31	7.99 ± 0.12	8.19 ± 0.23	7.38 ± 0.09	7.72 ± 0.06
Weight per spike of plant	1.61 ± 0.10	1.71 ± 0.21	1.54 ± 0.27	1.67 ± 0.05	1.37 ± 0.06	1.4 ± 0.11
Average number of grains	39.25 ± 1.89	44 ± 3.46	38.5 ± 2.64	38.5 ± 1.73	34 ± 5.65	34.25 ± 2.87
Harvest yield	0.55 ± 0.01	0.58 ± 0.04	0.55 ± 0.01	0.55 ± 0.01	0.50 ± 0.06	0.53 ± 0.011

Data represented as mean value ± standard deviation

3.2.3 Yield Parameters

The yield attributes of wheat crop also experienced negative implications of the exposure to air pollutants. Variables like spikelet count, spike length, average number of grains witnessed a drastic decline as reported in Table 5.

Highest values for yield attributes were obtained in the controlled experimental setup with no exposure to either surface ozone or FPM. The harvest index of EIII TA declined by 14% when compared with EI TB. A similar decline in other yield parameters was also observed for EIII TA in comparison to EI TB. The comparison between the values of yield parameters for EI TA, EII TA and EII TB highlighted that surface ozone had a higher impact on the overall productivity of wheat crops in comparison to FPM. Further, the results of ANOVA analysis verified that there is statistical difference in all the yield parameters among different experimental setups and treatments as represented in Table 6. This indicates that surface ozone and FPM reduces the productivity of the wheat crops even in the ambient environments.

In addition, a constituent analysis was also conducted at the harvesting stage to assess the variation in the composition of carbon, hydrogen and nitrogen (CHN) in the wheat crop under different treatments and experimental setups. Fig. 5 represents the variation in the percentage composition of CHN in the grains, shoot system and root system of wheat crop under different experiments.

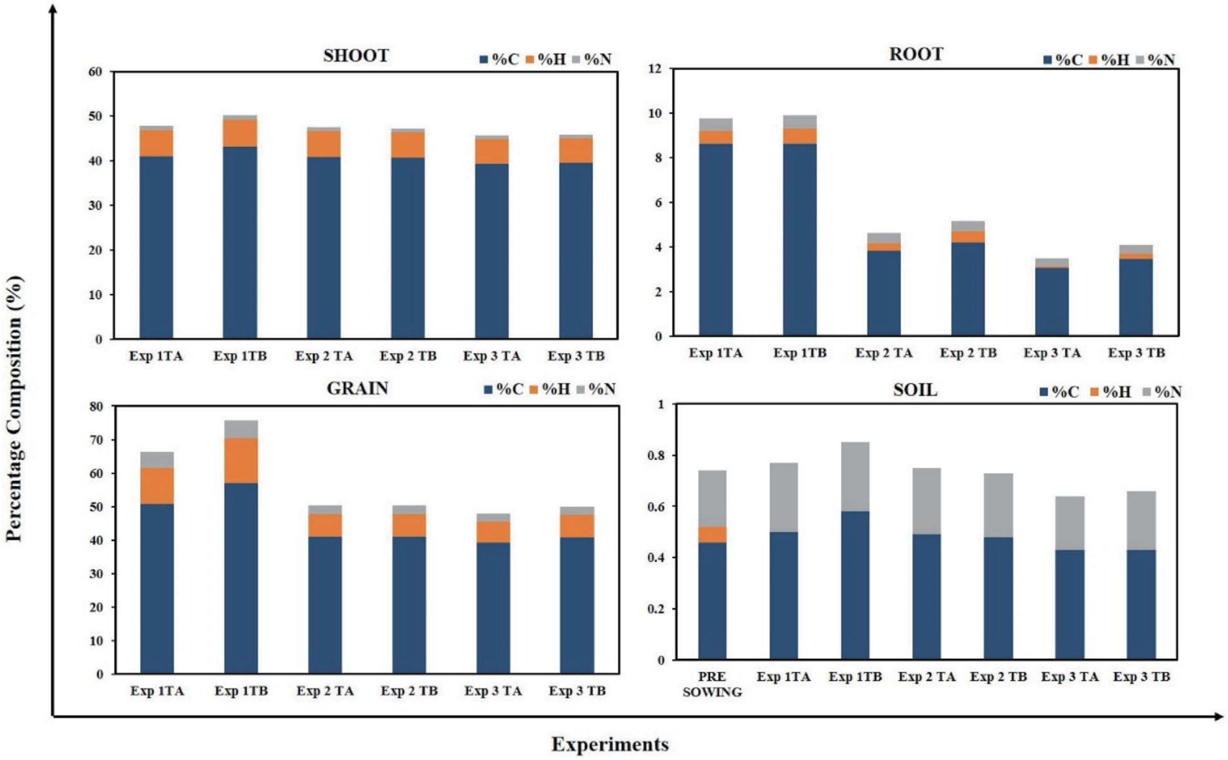

Fig. 5. CHN composition analysis in the wheat crop at the grain formation stage.

Table 6. F-values for different variables for applying ANOVA to the response of wheat crops on different treatments under different experiments at grain formation stage.

Parameters	Grain formation stage	
	F-value	Sig.
Spikelet count	4.554	0.007
Spike length	22.019	0
Weight per spike of plant	3.075	0.035
Average number of grains	4.964	0.005
Harvest yield	2.86	0.045

$P \leq 0.05$ Significance level

The results of the experiment revealed that the CHN composition was found to be maximum in the controlled experiment and lowest in the fully exposed experimental setup, i.e., EIII TA. Moreover, the overall trend also remained similar to that observed in the growth and biochemical parameters.

The vivid difference in the values of all the growth, biochemical and yield attributes highlight that surface ozone and FPM produce negative impacts on the overall crop cycle and productivity of wheat crops even if present in ambient conditions and not an extreme scenario of high pollution intensity.

4. DISCUSSION

Numerous studies have been conducted in past that have assessed the impact of increased levels of surface ozone on varieties of crops at a local, national, regional and global level (Pleijel *et al.*, 2018; Zhao *et al.*, 2018; Ghude *et al.*, 2014; Teixeira *et al.*, 2011). Majority of the existing experimental studies have simulated elevated surface ozone level scenario by providing externally ozone dosage to plants in order to assess its impacts on their productivity (Liu *et al.*, 2018; Daripa *et al.*, 2016). In contrast, limited studies exist that evaluate the impacts of surface ozone on crop productivity in ambient environments. It has been extensively reported that increased levels of surface ozone in the atmosphere produces significant decline in the physiological as well as biochemical growth of plants and crops (Wilkinson *et al.*, 2012; Rai *et al.*, 2007). Wheat crops, especially are among the most ozone sensitive crop species and have experienced massive loss in productivity due to the ever increasing levels of surface ozone (Schiferl and Heald, 2018). Apart from surface ozone, FPM produces both direct as well as indirect impacts on the crop productivity by altering the amount of sunlight reaching the plants or by causing phytotoxic damage to the plants (Sonkar *et al.*, 2019; Mina *et al.*, 2018b; Lombardozzi *et al.*, 2012; Wilkinson *et al.*, 2012). FPM interacts with the plant leaves by depositing on the foliar surface leading to its modification and further affecting the leaf gas exchange, this reduces the overall plant growth (Rai, 2016). For specifically wheat crops FPM is reported to be detrimental and hindering the overall crop growth (Zhou *et al.*, 2018).

The results of the present study indicated that exposure to surface ozone reduced morphological as well as biochemical growth of wheat crop even in ambient settings. As highlighted in the previous sections of the paper that the levels of surface ozone always exceeded the NAAQ standards throughout the crop cycle, thus indicating high levels of exposure to wheat crops. An interesting result was also observed wherein exposure to ambient surface ozone produced relatively more decline in wheat productivity in comparison to exposure to ambient FPM. This is among the first studies that has evaluated the simultaneous impacts of both surface ozone as well as FPM on wheat crop productivity under ambient conditions, thus providing new insights to the existing research gaps.

5. SUMMARY AND CONCLUSION

The present study conducted a preliminary experimental analysis to assess synergistic impacts of surface ozone and FPM on the morphological and biochemical parameters of one of the most important staple crops of India, i.e., wheat (HD2967) in ambient settings of Delhi. The observations of the experiments highlighted that exposure to elevated levels of FPM and surface ozone produces the highest decline in the overall productivity of the crop plant. It was also observed that synergistic exposure to both the pollutants, even in ambient conditions lead to a statistically significant decline in both biochemical and yield parameters. However, exposure to only ambient ozone produced a statistically significant decline in the biochemical parameters of wheat crop in comparison to exposure to only FPM. Considering the fact that the present study is a preliminary evaluation of the combined effects of surface ozone and FPM on wheat crop, it is imperative to undertake detailed studies that quantify the direct and indirect effects of both PM and ozone pollution on crops to identify plausible solutions to mitigate this challenge. Furthermore, such damage could potentially amplify the crop losses that would result from either pollutant alone. As India's growth is accompanied by climate change and air pollution, hence, greater risks of food shortages, air-pollution must be considered as potential food security issue.

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REFERENCES

Agrawal, A., Upadhyay, V.K., Sachdeva, K. (2011) Study of aerosol behavior on the basis of morphological characteristics during festival events in India. Atmospheric Environment, 45, 3640-3644. https://doi.org/10.1016/j.atmosenv.2011.04.006

Burney, J., Ramanathan, V. (2014) Recent climate and air pollution impacts on Indian agriculture. Proceedings of the National Academy of Sciences of the United States of America, 111, 16319-16324. https://doi.org/10.1073/pnas.1317275111

Chauhan, A. (2010) Effect of ambient air pollutants on wheat and mustard crops growing in the vicinity of urban and industrial areas. New York Science Journal, 3, 52-60.

Daripa, A., Bhatia, A., Ojha, S., Tomer, R., Chattaraj, S., Singh, K.P., Singh, S.D. (2016) Chemical and natural plant extract in ameliorating negative impact of tropospheric ozone on wheat crop: A case study in a part of semiarid north West India. Aerosol and Air Quality Research, 16, 1742-1756. https://doi.org/10.4209/aaqr.2014.10.0263

Debaje, S.B. (2014) Estimated crop yield losses due to surface ozone exposure and economic damage in India. Environtal Science and Pollution Research, 21, 7329-7338. https://doi.org/10.1007/s11356-014-2657-6

Dumka, U.C., Gautam, A.S., Tiwari, S., Mahar, D.S., Attri, S.D., Chakrabarty, R.K., Permita, P., Hopke, P.K., Hooda, R. (2019) Evaluation of urban ozone in the Brahmaputra River Valley. Atmospheric Pollution Research, 11(3), 610-618. https://doi.org/10.1016/j.apr.2019.12.013

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, 5685-5691. https://doi.org/10.1002/2014GL060930

GRIMM (2010) Specification for portable laser aerosol spectrometer and dust monitor Model 1.108/1.109, Users Manual.

Gurjar, B.R., Ravindra, K., Nagpure, A.S. (2016) Air pollution trends over Indian megacities and their local-to-global implications. Atmospheric Environment, 142, 475–495. https://doi.org/10.1016/j.atmosenv.2016.06.030

Hansen, E.M.Ø., Hauggaard-Nielsen, H., Launay, M., Rose, P., Mikkelsen, T.N. (2019) The impact of ozone exposure, temperature and CO_2 on the growth and yield of three spring wheat varieties. Environmental and Experimental Botany, 168, 103868. https://doi.org/10.1016/j.envexpbot.2019.103868

Kamal, M.Z.U., Yamaguchi, M., Azuchi, F., Kinose, Y., Wada, Y., Funada, R., Izuta, T. (2015) Effects of ozone and soil salinity, singly and in combination, on growth, yield and leaf gas exchange rates of two Bangladeshi wheat cultivars. Asian Journal of Atmospheric Environment, 9(2), 173–186. https://doi.org/10.5572/ajae.2015.9.2.173

Kumar, M., Parmar, K.S., Kumar, D.B., Mhawish, A., Broday, D.M., Mall, R.K., Banerjee, T. (2018) Long-term aerosol climatology over Indo-Gangetic Plain: Trend, prediction and potential source fields. Atmospheric Environment, 180, 37–50. https://doi.org/10.1016/j.atmosenv.2018.02.027

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, 126972. https://doi.org/10.1016/j.chemosphere.2020.126972

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

Liu, H., Liu, S., Xue, B., Lv, Z., Meng, Z., Yang, X., Xue, T., Yu, Q., He, K. (2018) Ground-level ozone pollution and its health impacts in China. Atmospheric Environment, 173, 223–230. https://doi.org/10.1016/j.atmosenv.2017.11.014

Lombardozzi, D., Sparks, J.P., Bonan, G., Levis, S. (2012) Ozone exposure causes a decoupling of conductance and photosynthesis: Implications for the Ball-Berry stomatal conductance model. Oecologia, 169, 651–659. https://doi.org/10.1007/s00442-011-2242-3

Mina, U., Chandrashekara, T.K., Kumar, S.N., Meena, M.C., Yadav, S., Tiwari, S., Singh, D., Kumar, P., Kumar, R. (2018) Impact of particulate matter on basmati rice varieties grown in Indo-Gangetic Plains of India: Growth, biochemical, physiological and yield attributes. Atmospheric Environment, 188, 174–184. https://doi.org/10.1016/j.atmosenv.2018.06.015

Monks, P.S., Archibald, A.T., Colette, A., Cooper, O., Coyle, M., Derwent, R., Fowler, D., Granier, C., Law, K.S., Mills, G.E., Stevenson, D.S., Tarasova, O., Thouret, V., Von Schneidemesser, E., Sommariva, R., Wild, O., Williams, M.L. (2015) Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer. Atmospheric Chemistry and Physics, 15, 8889–8973. https://doi.org/10.5194/acp-15-8889-2015

Mustafa, Y.A., Mohammed, S.J. (2012) Measurement of ground level ozone at different locations. American Journal of Environmental Sciences, 8, 311–321.

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

Pathak, H., Tewari, A., Sankhyan, S., Dubey, D., Mina, U., Kumar, V., Jain, N., Bhatia, A. (2011) Direct-seeded rice: Potential, performance and problems - A review. Current Advances in Agricultural Sciences (An International Journal), 3, 77–88.

Pleijel, H., Broberg, M.C., Uddling, J., Mills, G. (2018) Current surface ozone concentrations significantly decrease wheat growth, yield and quality. Science of the Total Environment, 613–614, 687–692. https://doi.org/10.1016/j.scitotenv.2017.09.111

Punithavathy, I.K., Vijayalakshmi, S., Jeyakumar, S.J. (2015) Assessment of Ground-Level Ozone and Its Variability with Meteorological Parameters at Karaikal, India. Universal Journal of Environmental Research and Technology, 5, 233–240.

Rai, P.K. (2016) Impacts of particulate matter pollution on plants: Implications for environmental biomonitoring. Ecotoxicology and Environmental Safety, 129, 120–136. https://doi.org/10.1016/j.ecoenv.2016.03.012

Rai, R., Agrawal, M., Agrawal, S.B. (2007) Assessment of yield losses in tropical wheat using open top chambers. Atmospheric Environment, 41, 9543–9554. https://doi.org/10.1016/j.atmosenv.2007.08.038

Roy, S., Beig, G., Jacob, D. (2008) Seasonal distribution of ozone and its precursors over the tropical Indian region using regional chemistry-transport model. Journal of Geophysical Research: Atmospheres, 113, 1–15. https://doi.org/10.1029/2007JD009712

Schiferl, L.D., Heald, C.L. (2018) Particulate matter air pollution may offset ozone damage to global crop production. Atmospheric Chemistry and Physics, 18, 5953–5966. https://doi.org/10.5194/acp-18-5953-2018

Sharma, R., Sachdeva, K., Sharma, A.R. (2017) Worsening Of Urban Air Quality: Role of Meteorology and Episodic Events during Winter Months. Indian Journal of Air Pollution Control XVI & XVII, 54–60.

Sharma, S., Khare, M. (2017) Simulating ozone concentrations using precursor emission inventories in Delhi - National Capital Region of India. Atmospheric Environment, 151, 117–132. https://doi.org/10.1016/j.atmosenv.2016.12.009

Shukla, K., Srivastava, P.K., Banerjee, T., Aneja, V.P. (2016) Trend and variability of atmospheric ozone over middle Indo-Gangetic Plain: impacts of seasonality and precursor gases. Environmental Science and Pollution Research, https://doi.org/10.1007/s11356-016-7738-2

Sinha, B., Singh Sangwan, K., Maurya, Y., Kumar, V., Sarkar, C., Chandra, B.P., 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, 9555–9576. https://doi.org/10.5194/acp-15-9555-2015

Sonkar, G., Mall, R.K., Banerjee, T., Singh, N., Kumar, T.V.L., Chand, R. (2019) Vulnerability of Indian wheat against rising temperature and aerosols. Environmental Pollution, 254, 112946. https://doi.org/10.1016/j.envpol.2019.07.114

Teixeira, E., Fischer, G., van Velthuizen, H., van Dingenen, R., Dentener, F., Mills, G., Walter, C., Ewert, F. (2011) Limited potential of crop management for mitigating surface ozone impacts on global food supply. Atmospheric Environment, 45, 2569-2576. https://doi.org/10.1016/j.atmosenv.2011.02.002

Tiwari, S., Dumka, U.C., Kaskaoutis, D.G., Ram, K., Panicker, A.S., Srivastava, M.K., Tiwari, S., Attri, S.D., Soni, V.K., Pandey, A.K. (2016) Aerosol chemical characterization and role of carbonaceous aerosol on radiative effect over Varanasi in central Indo-Gangetic Plain. Atmospheric Environment, 125, 437-449. https://doi.org/10.1016/j.atmosenv.2015.07.031

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, 329-340. https://doi.org/10.4209/aaqr.2013.12.0354

Vaid, A., Mahajan, V., Sharma, P.K., Gupta, S., Ajrawat, B., Jamwal, A. (2017) Impact of varietal demonstrations of wheat HD-2967 in Kathua. Maharasthra Journal of Agricultural Economics, 20(2), 115-116.

Wang, C., Jia, M., Xia, H., Wu, Y., Wei, T., Shang, X., Yang, C., Xue, X., Dou, X. (2019) Relationship analysis of $PM_{2.5}$ and boundary layer height using an aerosol and turbulence detection lidar. Atmospheric Measurment Techniques, 12, 3303-3315. https://doi.org/10.5194/amt-12-3303-2019

Watanabe, M., Yamaguchi, M., Matsumura, H., Kohno, Y., Koike, T., Izuta, T. (2011) A case study of risk assessment of ozone impact on forest tree species in Japan. Asian Journal of Atmospheric Environment, 5(4), 205-215. https://doi.org/10.5572/ajae.2011.5.4.205

Wilkinson, S., Mills, G., Illidge, R., Davies, W.J. (2012) How is ozone pollution reducing our food supply? Journal of Experimental Botany, 63, 527-536. https://doi.org/10.1093/jxb/err317

Williams, D.E., Henshaw, G.S., Bart, M., Laing, G., Wagner, J., Naisbitt, S., Salmond, J.A. (2013) Validation of low-cost ozone measurement instruments suitable for use in an air-quality monitoring network. Measurment Science and Technology, 24, 065803. https://doi.org/10.1088/0957-0233/24/6/065803

Yamaguchi, M., Watanabe, M., Matsumura, H., Kohno, Y., Izuta, T. (2011) Experimental studies on the effects of ozone on growth and photosynthetic activity of Japanese forest tree species. Asian Journal of Atmospheric Environment, 5(2), 65-78. https://doi.org/10.5572/ajae.2011.5.2.065

Zadoks, J.C., Chang, T., Konzak, C. (1974) A decimal code for the growth stages of cereals. Weed Research, 14, 415-421. https://doi.org/10.1111/j.1365-3180.1974.tb01084.x

Zhao, H., Zheng, Y., Wu, X. (2018) Assessment of yield and economic losses for wheat and rice due to ground-level O_3 exposure in the Yangtze River Delta, China. Atmospheric Environment, 191, 241-248. https://doi.org/10.1016/j.atmosenv.2018.08.019

Zhou, L., Chen, X., Tian, X. (2018) The impact of fine particulate matter ($PM_{2.5}$) on China's agricultural production from 2001 to 2010. Journal of Cleaner Production, 178, 133-141. https://doi.org/10.1016/j.jclepro.2017.12.204