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Imidacloprid efficacy against brown planthopper, *Nilaparvata lugens* under elevated carbon dioxide and temperature

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Influence of elevated CO_2 and temperature (elevated condition (EC)) vis-à-vis ambient CO_2 and temperature (ambient condition (AC)) on plant (rice) growth, insect *Nilaparvata lugens* (brown planthopper (BPH)) population and insecticide (Imidacloprid) efficacy was evaluated under open top chamber conditions. EC had a positive effect on rice crop through increase in tillers numbers (18.4%), reproductive tillers (20.5%) but inflicted negative effect on 1000-grain weight (11.7%) and grain yield (11.9%). Likewise, higher canopy cover of the plant was noticed under EC (16.1 cm) when compared to AC (12.9 cm). With respect to BPH population during 2013 and 2014, EC exhibited positive effect by enhancing its mean population to 66.1 and 49.4 hoppers hill^{-1} respectively, compared to corresponding 36.8 and 29.5 hoppers hill^{-1} under AC. With respect to Imidacloprid efficacy against BPH, LC_{50} was significantly lower under EC (0.044%) in comparison to AC (0.065). Similarly, in 2013 under AC, 500, 600, 700 l ha^{-1} spray volume caused >50% BPH mortality than 400 l ha^{-1} at 5 day after spray. However, during the same exposure period under EC, only 700 and 600 l ha^{-1} produced more than 50% mortality compared to 500 and 400 l ha^{-1}. Positive influence of EC on BPH population resulted in significantly higher yield loss (41.1%) compared to ambient (26.5%) in untreated check. Though LC_{50} under EC was less, higher canopy size and more BPH population resulted in increase in spray volume to cause similar mortality as of AC. The present results indicated that spray volumes of 400 and 500 l ha^{-1} was found insufficient to manage BPH population under EC; hence the current management strategies for BPH needs to be redefined under changing climatic conditions.

Keywords: Basmati rice, brown planthopper, climate change, elevated CO_2, insecticide.

ATMOSPHERIC CO_2 level has increased from 280 ppm during pre-industrial period to 400 ppm at present and Intergovernmental Panel on Climate Change (IPCC) projected it to reach 550 ppm by 2050 (ref. 1). Further by 2100, atmospheric CO_2 would reach 730–1020 ppm in the

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absence of a proper monitoring on emissions. Among the various sectors amenable for climate change damages, agriculture is one such important sector as it is severely affected by climate change which has vital impact on future food security and social welfare[2]. In the regions of increased CO_2, about 30% reduction in crop yield is likely due to direct positive physiological effects[3]. Climate change might reduce 15% of irrigated rice yields in developing countries by 2050 and an increase in rice price by 12% (ref. 4). More than half of the world's population depend on rice as staple food[5]. India holds the status of largest rice cultivated area (43.9 m ha), with production of 106.7 million tonnes and an average productivity of 3.01 tonnes ha^{-1} (ref. 6). However, rice productivity in India is still lower compared to Sri Lanka (3.51 tonnes ha^{-1}) and China (6.26 tonnes ha^{-1})[7]. Due to intensive and extensive cultivation systems followed in rice, in the recent past various pests (insect, diseases and weeds) have increased[8]. Three decades of post-green revolution, insects, diseases and weed complex of rice ecosystems have been subjected to major paradigm shift resulting in low productivity[9,10]. In the recent years, outbreak of brown planthopper (BPH), *Nilaparvata lugens* (Stal.) was noticed very often in North India that posed serious threat to rice production[7]. On the other hand, there is a huge global demand for increasing the rice production to 771.1 million tonnes by 2030 (ref. 11). In addition, climate change also poses significant scientific, political and financial challenges on food production. Increasing concentration of greenhouse emissions is one of the primary causes of global warming which pose potential threat to productivity of rice and in turn the food security.

In general, insects are most vulnerable to environmental factors because they act as a crucial function in the survival, development and reproduction of insect pests and their associated natural enemies[12]. Compared to plants and other vertebrates, insects respond more quickly to any changes in the climate due to shorter generation period and higher reproductive rates. Climate change directly affects insect pest by altering their physiology and behaviour[13] and indirectly via natural enemies, host plants and other challengers[14,15]. Apart from direct effect of climate change on insect pests, it also affects efficacy of pesticides through changes in temperature, CO_2 levels, rainfall, relative humidity, pH, soil properties, morphological and physiological changes in crop plants[16]. Many studies have been confined to the impact/effect of climate change (CO_2 levels, temperature, ozone and CO_2 × temperature) on different insect pests so far, however the availability of information on the efficacy of insecticides under elevated temperature and ambient CO_2 condition is meagre[17–24]. Earlier workers[25] have predicted increase in pesticides expenditure due to climate change in US, thereby resulting in reduction of producer benefits and an increase in cost of production. Similarly, McCarl and Reilly[26] also reported eventual reduction in societal benefits due to increased pesticide cost under climate change. Previously, studies in US reported increase in plant protection measures in cereals and root crops with the increase in rainfall whereas pesticide doses on fruits, vegetables and beans increased with high temperatures[27]. Climate change might reduce the accumulation of pesticide load in the environment through increased degradation and accelerated volatilization as well[28]. Unfortunately, no studies were carried out in rice earlier, despite being a dominant ecosystem in India. In majority of the studies conducted through modelling approach and further related to historical climatic data, there is a serious lack of field information of insecticide efficacy under projected climatic situation.

In the near future, rice ecosystem is going to experience the aggravated BPH population under elevated CO_2 condition[20,23,24]. Existing pest management strategies need to be re-examined through meticulous research planning to combat the probable effect of increasing atmospheric CO_2 on plant growth parameters and insect populations. With the intention of finding out effective management strategy in the near future, the present experiment was designed to measure elevated CO_2 impact on insecticidal efficacy against BPH.

Studies on the effect of spray volume and dose on insecticide efficacy against the BPH population on rice (*Oryza sativa* L.; variety Pusa Basmati 1401) were undertaken in open top chambers (OTCs) during rainy season (June–October) of 2013 and 2014 at Indian Agricultural Research Institute (IARI), New Delhi (28°38′N, 77°09′E and 228.61 m). Experimental site is classified as semi-arid type with annual rainfall of 708.7 mm, mostly (80%) received during July to October (Supplementary Table 1). During the cropping period, seasonal mean air temperature was 28.2°C and 28.3°C in 2013 and 2014 respectively. During the experimental period, mean daily evaporation was 4.8 and 5.9 mm d^{-1} respectively, during 2013 and 2014. Throughout the study period, crops (mainly in the vegetative period) received a net precipitation of 1196.8 and 451 mm respectively, during 2013 and 2014. Soil type at the experimental site is Holambi series, belongs to Indo-Gangetic alluvium with pH, 8.30; organic C, 0.35%; electrical conductivity, 0.16 dSm^{-1}; alkaline $KMnO_4$ extractable N, 156 kg ha^{-1}; Olsen P, 24.4 kg ha^{-1} and NH_4OA extractable K, 241.6 kg ha^{-1}.

Two OTCs were used for the present study; each maintained under elevated (CO_2 × temperature) and ambient (CO_2 × temperature) conditions. Under elevated condition (EC), 570 ± 25 ppm CO_2 level was maintained through external CO_2 supply from 9:30 a.m. to 4:30 p.m. from paddy transplanting till harvest, whereas ambient condition (AC) of 397 ± 25 ppm CO_2 level was achieved with free atmosphere air. Only during day time CO_2 was provided inside the ITC, as during day time only plants utilizes CO_2 for photosynthesis. Similarly, elevated temperature (3°C > ambient) was maintained with partially covering the upper portion of the OTCs with polyvinyl chloride (PVC) sheets. Preferably PVC sheets of 120 μm thickness was used which transmits 90% of sunlight resulting in approximately 3°C increase of temperature within the OTC than AC[23,29]. Throughout the study period, maximum and minimum temperature of OTC was recorded daily (Supplementary Figure 1) with the help of data logger (Model TC 800D, Ambetronics, Switzerland). Sensors (Model TRH 511, Ambetronics, Switzerland) that were fitted in the middle of each OTC provided precise data to the logger. Season-long daytime average CO_2 in the ambient and elevated OTCs were 390 and 578 ppm in 2013, and 391 and 583 ppm in 2014 respectively (Supplementary Figure 1). Under each EC and AC, one OTC had uninfested crop and the other was exposed to BPH infestation. In order to acquire BPH infestation, five pairs of laboratory reared adult BPHs were released onto potted plants under elevated and ambient CO_2 conditions, only after 10–15 days exposure of plants to CO_2.

Fifth instar nymphs (7th day after emergence) were selected for toxicological bioassay (rice-stem dipping method) against Imidacloprid 17.8SL (Confidor®, Bayer Crop Science)[30]. The rice stems were washed thoroughly with water and dunked into different concentrations of insecticide for 30 sec. For each concentration of the insecticide as well as control (used only distilled water), three replicates were taken. After treatment with insecticide, individual rice stems were allowed for 30 min to air dry and later planted in 500 ml plastic cups containing mixture of soil, vermicompost, sand (1 : 1 : 1) and water. Twenty numbers of 5th instar nymphs were released into plastic cup and covered with muslin cloth and tied with rubber band. The experimental setup was maintained at laboratory condition (28° ± 1°C and 14:10 h L : D). Observation on insect mortality due to insecticide was recorded after 72 h of treatment. The nymphs that did not show any movement even after prodding with a fine brush were confirmed as dead. Lethal concentration (LC_{50}) values were calculated with mortality data from bioassay using Probit analysis.

Spray efficacy of Imidacloprid 17.8SL (Confidor®, Bayer Crop Science) @ 0.006% at four different volumes (400, 500, 600 and 700 l ha^{-1}) against BPH in potted rice under ambient and EC was done. With the help of a hand atomizer (Vintage Atlas Hand Atomizer) different volumes of insecticides spray were achieved. Potted rice plants sprayed with water alone was taken as untreated check. Each treatment was replicated ten times. Observations were made on BPH mortality at 1, 3 and 5 days after treatment. Mean per cent mortality was calculated for each spray volume tested and corrected percent mortality was worked out using Abbott's formula[31].

The following observations on plant parameters were recorded for all the treatments (uninfested and infested), viz. number of tillers, reproductive tillers, 1000-seed weight, number of seeds/panicles and yield. Likewise, canopy circumference was measured at vegetative period (45–50 days after spraying (DAS)), flowering period (85–90 DAS) and post-flowering period (115–120 DAS). 1000-seed weight and grain yield were measured immediately after threshing. Uninfested and infested plants yield were recorded under EC and AC were further compared to determine the effect of elevated $CO_2 \times$ temperature on extent of yield loss due to BPH.

Statistical analyses were performed using SAS Software (version 9.3). Lethal concentration (LC_{50}) values were calculated through probit analysis by using POLO plus (version 2) software. Effect of different spray volume on insecticide efficacy under elevated and ambient CO_2 concentration was analysed using repeated measure analysis of variance (R-ANOVA). BPH population counts were normalized through square root transformation before statistical analysis. Combined effect elevated $CO_2 \times$ temperature on various plant parameters was analysed through *t*-test; and different treatment difference were evaluated with least significant difference (LSD) at 5% confidence interval, i.e. $P \leq 0.05$ (ref. 32).

For an effective bioassay, right stage of the insect is required to detect even small amounts of insecticides and express the response with increasing concentrations. The results of the present experiment showed that 5th instars of BPH had significantly different levels of susceptibility under EC and AC. At 72 h after treatment, LC_{50} was significantly lower under EC (0.044 ml ai/L) in comparison to AC (0.065 ml ai/L; Table 1).

The present study revealed significantly higher BPH populations in the both years under EC than AC. BPH growth and multiplication were enhanced to 66.1 and 49.4 hoppers $hill^{-1}$ during 2013 and 2014 respectively under EC than 36.8 and 29.4 hoppers $hill^{-1}$ under AC (Table 2).

Under elevated and ACs, spray volumes, viz. 400, 500, 600 and 700 l ha^{-1} exhibited differential effect on the BPH population (Figure 1). Under EC, Imidacloprid (0.006%) at 700 l ha^{-1} was found to be very effective in causing BPH mortality followed by 600, 500 and 400 l ha^{-1} efficacy at 1 DAS in both the years. With the decrease in spray volume from 700 to 400 l ha^{-1}, BPH mortality decreased from 55% to 29% (Figure 1 *a*) at 1 DAS during 2013 and 57–23% during 2014 (Figure 1 *b*). At 3 DAS, BPH mortality was 60% with 700 l ha^{-1} while it was 55–29% during first year (Figure 1 *a*) and <50% during second year with 600–400 l ha^{-1} (Figure 1 *b*). At 5 DAS, 700–600 l ha^{-1} resulted in around 70% and 50% mortality, respectively during two years, while 500 and 400 caused <50% mortality (Figure 1).

Under AC, 700, 600, 500 l ha^{-1} caused significantly higher mortality than 400 l ha^{-1} (Figure 1). As spray volumes decreased from 700 to 400 l ha^{-1}, mortality declined from 59% to 41% during first year (Figure 1 *a*) and 60% to 47% during second year at 1 DAS. During the first year at 3 DAS, insecticide-induced BPH mortality

Table 1. Efficacy of Imidacloprid against brown planthopper (BPH) under elevated and ambient conditions

Condition	X^2 (DF)*	Slope ± SE	LC_{50}**	Fiducial limit (%) Lower	Fiducial limit (%) Upper
Elevated condition	1.290(3)	3.254 ± 0.444	0.044^b	0.037	0.050
Ambient condition	1.039(3)	2.932x ± 0.365	0.065^a	0.057	0.075

Elevated condition – 570 ± 25 ppm + >3°C than ambient temperature; Ambient condition – 397 ± 25 ppm + ambient temperature; *Degree of freedom. †Number of insects used. **LC_{50} of one treatment is significantly different if both the lower and upper fiducial limits do not include LC_{50} value of other treatment; The LC_{50} values are expressed as millilitres of ai/L for Imidacloprid.

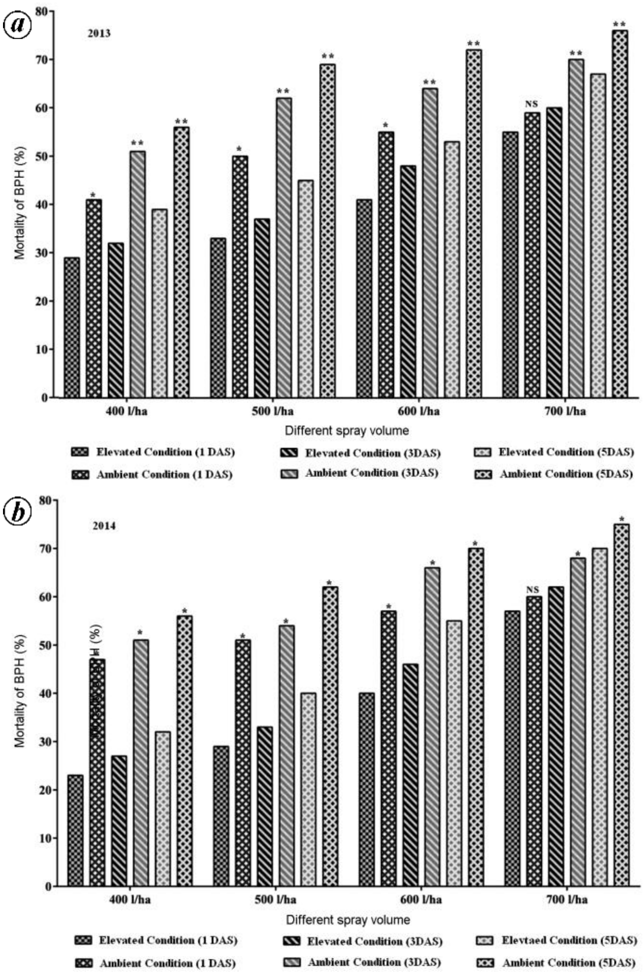

Figure 1. ***a***, Effect of Imidacloprid on brown planthopper (BPH) mortality under elevated and ambient conditions during rainy season 2013. Elevated condition – 570 ± 25 ppm + >3°C than ambient temperature; Ambient condition – 397 ± 25 ppm + ambient temperature; DAS, Days after transplanting, *Significant at 0.05%, **significant at 0.01%. ***b***, Effect of Imidacloprid on BPH mortality under elevated and ambient conditions during rainy season 2014 elevated condition – 570 ± 25 ppm + >3°C than ambient temperature; ambient condition – 397 ± 25 ppm + ambient temperature; DAS, Days after spraying, *Significant at 0.05%, **Significant at 0.01%.

was found to be more than 60% with 500, 600 and 700 l ha^{-1}, meanwhile 51% mortality was recorded with 400 l ha^{-1} (Figure 1 *a*). But during the second year, both 600 and 700 l ha^{-1} produced around 60% mortality whereas 400 and 500 l ha^{-1} produced 50% mortality (Figure 1 *b*). At 5 DAS, 56% of BPH mortality was exhibited with 400 l ha^{-1} as compared to 65–76% BPH mortality with other three spray volumes (500, 600 and 700 l ha^{-1}) during both the years (Figure 1). Thus, the present study revealed that under EC, higher spray volumes were required to produce mortality similar to ACs.

During both the years, significant difference was observed between the uninfested plants canopy circumference at different crop growth stages of two treatments (Table 3). During 2013, plants exposed to EC showed higher canopy circumference of 13.5, 15.8 and 13.6 cm at vegetative (45–50 DAS), flowering (85–90 DAS) and post-flowering (115–120 DAS) phases respectively, compared to 10.2, 12.9 and 10.7 cm under AC at respective stages. Similar trend was observed during 2014 at all three (vegetative, flowering and post-flowering) phases of the crop growth stage. Canopy circumference at vegetative, flowering and post-flowering stages was 13.6, 16.1 and 13.5 cm respectively, under EC in comparison with 10.5, 12.8 and 11.1 cm under AC respectively.

Significantly higher number of tillers ($t = 2.9$, $P = 0.0008$) and reproductive tillers ($t = 3.1$, $P = 0.0006$) was found in uninfested plants (Table 4) grown under EC than AC. While significantly lower 1000-grain weight ($t = 3.4$, $P = 0.005$) and yield ($t = 2.3$, $P = 0.04$) was recorded with plants exposed to EC than AC. Elevated condition thus increased tillering (18.4%), reproductive tillers (20.5%) but 1000-grain weight (11.7%) found to be reduced. Hence, 11.9% of overall decrease in grain yield was experienced under EC compared to AC. Although EC significantly enhanced the plant growth but had negative impact on yield parameters. EC also positively influenced BPH population attributed to more yield loss of 41.1% compared to 26.5% in untreated check under AC (Figure 2). Under AC, spray volumes of 400, 500, 600 and 700 l ha^{-1} resulted a yield loss of 17.3, 12.3, 10.5 and 8.8% respectively in contrast to 32.5, 26.9, 25.3 and 22.4% respectively under EC (Figure 2).

Insecticide efficacy of different spray volume against BPH was studied under EC vis-à-vis AC in OTCs for two years. The study revealed that under EC, Imidacloprid (0.006%) @ 700 l ha^{-1} showed maximum efficacy (50%

Table 2. Number of BPH under elevated and ambient conditions before spray insecticide during rainy season 2013 and 2014

	2013		2014	
Treatment	Ambient condition	Elevated condition	Ambient condition	Elevated condition
400 l/ha	37.1 ± 1.85[b]	68.8 ± 3.46[a]	26.3 ± 2.15[b]	52.4 ± 4.10[a]
500 l/ha	34.7 ± 3.67[b]	65.6 ± 5.13[a]	31.3 ± 4.52[b]	48.6 ± 4.12[a]
600 l/ha	39.5 ± 4.91[b]	68.8 ± 5.19[a]	29.9 ± 3.37[b]	48.4 ± 6.83[a]
700 l/ha	37.7 ± 4.23[b]	62.6 ± 4.85[a]	32.3 ± 5.87[b]	45.8 ± 5.62[a]
Control	35.2 ± 5.21[b]	64.5 ± 3.46[a]	27.5 ± 2.20[b]	51.8 ± 2.42[a]
Mean ± SE	36.8 ± 4.37[b]	66.1 ± 5.27[a]	29.5 ± 3.62[b]	49.4 ± 4.62[a]

Treatment – 2013 (F = (386.33), LSD = (0.03), $P < 0.0001$); 2014 (F = (124.73), LSD = (0.06), $P < 0.0001$). Planthopper counts with same superscripts do not differ significantly. *Mean of 10 replications.

Table 3. Canopy circumferences of Pusa Basmati 1401 under elevated and ambient conditions

	Crop canopy circumference (cm)					
	2013			2014		
Conditions	Vegetative period (45–50 DAS)	Flowering period (85–90 DAS)	Post–flowering period (115–120 DAS)	Vegetative period (45–50 DAS)	Flowering period (85–90 DAS)	Post-flowering period (115–120 DAS)
Elevated condition	13.51 ± 0.41	15.78 ± 0.42	13.64 ± 0.57	13.62 ± 0.47	16.11 ± 0.55	13.46 ± 0.42
Ambient condition	10.24 ± 0.68	12.85 ± 0.52	10.65 ± 0.67	10.53 ± 058	12.76 ± 0.59	11.14 ± 0.51
t-Statistics	$t = 4.0$ ($P = 0.001$)	$t = 3.8$ ($P = 0.001$)	$t = 3.6$ ($P = 0.005$)	$t = 3.2$ ($P = 0.001$)	$t = 4.2$ ($P = 0.001$)	$t = 2.6$ ($P = 0.004$)

Elevated condition – 570 ± 25 ppm + >3°C than ambient temperature; Ambient condition – 397 ± 25 ppm + ambient temperature.

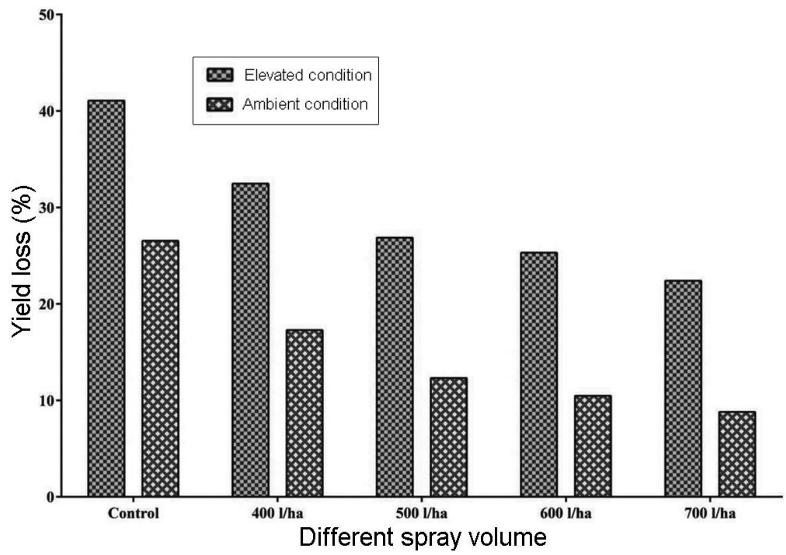

Figure 2. Effect of Imidacloprid on yield loss under elevated versus ambient CO_2 elevated condition – 570 ± 25 ppm + >3°C than ambient temperature; Ambient condition – 397 ± 25 ppm + ambient temperature.

BPH mortality) under EC followed by 600, 500 and 400 l ha^{-1}. While under AC similar level of control (50% mortality) was achieved with dosage of 500 l ha^{-1}. Higher volume of spray required under EC could perhaps be ascribed to higher BPH population owing to increased fecundity due to favourable microenvironment with profuse tillering and enhanced canopy circumference. Hence under changing climatic conditions, there is a need to increase the spray volume in order to effectively manage BPH population. The result of the present study was in accordance with the previous studies on increased spray volumes *Beauveria bassiana* on western flower thrips,

Table 4. Effect of different spray volumes of Imidacloprid 17.8 SL @ 0.006% on rice growth and yield parameters

	Uninfested			700 l/ha			600 l/ha			500 l/ha			400 l/ha			Untreated check		
Parameter	EC	AC	'*t*' value	EC	AC	'*t*' value	EC	AC	'*t*' value	EC	AC	'*t*' value	EC	AC	'*t*' value	EC	AC	'*t*' value
No. of tillers/hill	30.5 ± 1.6	25.7 ± 1.2	$t = 2.9$ (0.0008)	29.5 ± 2.1	24.6 ± 1.9	$t = 1.7^{NS}$	29.9 ± 2.3	24.1 ± 2.0	$t = 1.9^{NS}$	28.7 ± 2.2	24.3 ± 2.5	$t = 1.4^{NS}$	29.3 ± 2.7	23.9 ± 2.1	$t = 1.6^{NS}$	29.2 ± 2.0	24.3 ± 2.1	$t = 1.6^{NS}$
No. of reproductive tillers/hill	27.8 ± 1.5	22.9 ± 1.0	$t = 3.1$ (0.0006)	24.9 ± 2.0	21.1 ± 1.4	$t = 1.5^{NS}$	26.1 ± 1.9	21.3 ± 1.9	$t = 1.7^{NS}$	24.5 ± 2.1	21.6 ± 2.4	$t = 0.9^{NS}$	25.8 ± 2.6	20.9 ± 2.0	$t = 1.5^{NS}$	24.7 ± 2.2	21.2 ± 2.0	$t = 1.1^{NS}$
Seeds per panicles	80.2 ± 6.6	93.4 ± 7.1	$t = 1.4^{NS}$	88.4 ± 9.5	78.7 ± 6.5	$t = 0.8^{NS}$	84.9 ± 10.0	79.1 ± 5.9	$t = 0.5^{NS}$	82.3 ± 9.7	78.1 ± 6.0	$t = 0.4^{NS}$	79.8 ± 8.7	74.7 ± 7.1	$t = 0.5^{NS}$	77.9 ± 10.1	73.2 ± 6.7	$t = 0.4^{NS}$
1000 seed weight (g)	20.4 ± 0.4	23.1 ± 0.8	$t = 3.2$ (0.005)	18.8 ± 1.8	19.1 ± 1.5	$t = 0.2^{NS}$	18.2 ± 1.8	18.7 ± 1.4	$t = 02^{NS}$	18.3 ± 2.0	18.8 ± 1.3	$t = 0.2^{NS}$	17.7 ± 1.9	18.3 ± 1.2	$t = 0.3^{NS}$	16.8 ± 2.4	17.7 ± 18	$t = 0.3^{NS}$
Yield (g)	28.2 ± 1.1	32.0 ± 1.3	$t = 2.3$ (0.04)	24.2 ± 3.0	25.8 ± 1.8	$t = 0.3^{NS}$	23.3 ± 3.1	24.8 ± 1.9	$t = 0.4^{NS}$	22.8 ± 2.8	24.3 ± 2.2	$t = 0.4^{NS}$	21.1 ± 3.1	22.9 ± 2.2	$t = 0.4^{NS}$	18.4 ± 2.7	20.4 ± 2.4	$t = 0.5^{NS}$

EC, Elevated condition (570 ± 25 ppm + >3°C than ambient temperature); AC, Ambient condition (397 ± 25 ppm + ambient temperature); NS, Non-significant.

Frankliniella occidentalis[33], fenpropathrin or methoxyfenozide on grape berry moth, *Paralobesia viteana*[34] and dicrotophos on tarnished plant bug, *Lygus lineolaris*[35].

Apart from affecting the crop yields, climate change also affects the usage of pesticide and their effective dose. Efficacy of pesticides alters with varying temperature and rainfall pattern as well as the morphological and physiological condition of plants[16]. A probable increase in downpour could aggravate pesticide wash-off or leach off resulting in reduced pest control. In contrast at elevated temperatures, metabolic rate gets enhanced in plants that lead to faster uptake of pesticides which tend to be more toxic to pests. Moreover under elevated CO_2, increased thickness of epicuticular wax layer would leads to reduced or slower uptake by host, whereas increased canopy size posed difficulty in proper spray coverage on the host surface which in turn lead to a dilution of the active ingredient. However, the studies related to insecticide efficacy under elevated CO_2 levels and temperatures were sparse and few studies were conducted for biopesticides and organophosphates. Coviella and Trumble[36] reported that climate change had a positive impact on biopesticides where under elevated CO_2 efficacy of *Bacillus thuringiensis* against *Spodoptera exigua* found enhanced. Likewise, expression of *Bt* toxins was also altered under changing climatic conditions[37] due to significant reduction of total N in foliage enhanced through C : N ratio which in turn triggered the larval consumption. Whereas another study indicated that triazophos efficacy against BPH reduced under enriched CO_2 condition[38]. However, most studies were undertaken only either under elevated CO_2 condition or temperature alone; hence a holistic approach is required through exploring the physiological, transcriptional and biochemical mechanism underlying with insecticide, host plant and insect pest. Furthermore, this comprehensive approach would be crucial for devising future pest management strategies under changing environmental conditions.

Under elevated CO_2 condition, higher tiller production was noticed which in turn enhanced the plant density and growth and increase in canopy size provided the congenial micro-environment for BPH multiplication. Some of the earlier studies revealed enhanced photosynthetic rate and lower respiration in plants exposed under elevated CO_2 due to doubling the tillers[39,40]. Likewise during vegetative phase, increase in number of tillers is accredited to increase in temperature[39,41]. In our study, grain yield was decreased by 11.9% under EC than AC. The grain yield increased by 40% at high CO_2 condition due to extra carbohydrate production[42,20], but increasing temperature found to nullify the positive effect of CO_2 (ref 43).

Despite increase in tiller numbers and canopy circumference, under elevated conditions BPH infestation resulted in higher yield loss (%) than ambient which was manifested as hopper burns. Earlier reports also suggest that rice crop with hopper burn under elevated CO_2 suffered more yield loss compared to ambient[20,23]. During the present study, crop experienced 22.4% yield loss under EC even after sprayed with 700 l ha^{-1} Imidacloprid when compared to 8.8% yield loss under AC. Rising concentration of CO_2 could improve the plant growth simultaneously the damage level would also get enhanced by some phytophagus insects[44].

Climate change not only affects the insects but also the plant protection chemicals which are highly sensitive to the environment. Hence, the present study has shown that BPH population would be highly favoured under EC than under AC. Thus under changing climate, crop loss due to BPH may aggravate in future. Therefore, in order to effectively manage the pest, the higher insecticide spray volume will be required under EC. Adaptation strategies need to be developed to combat climate change effects, hence further studies are required in large scale to confirm the results. That might help revise the rice pesticide application rates which will ensure suppression of BPH population effectively and sustained agricultural production in the future.

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