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Assessment of greenhouse gas emission pattern of climate resilient pearl millet withvaried plant population and fertility level under rainfed condition

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ABSTRACT

In the present scenarios of changed climatic condition, the crop should thrive in challenging environments and should have lower carbon footprints to establish climate resilient agricultural system. Keeping in mind, a field experiment was conducted during kharif season of 2022 and 2023 to find out the effect of plant population and fertility level on GHGs from rainfed pearl millet (Pennisetum glaucum) in the research farm of Bihar Agricultural College, Sabour, Bihar. There were nine treatment combinations comprised of three levels of plant population (M1- 45 X 20 cm, M_2- 50 X 20 cm and M_3- 50 X 25 cm) in the main plot and three fertility levels with N:P:K (S_1- 90:45:45, S_2- 120:60:60 and S_3- 150:75:75 kg N: P_2O_5: K_2O/ha) as sub-plot treatments. The experiment was laid out under a split-plot design with three replications. Significant changes were recorded in the greenhouse gas emission pattern of pearl millet with the variance of treatments. The optimum spacing ensured adequate sunlight and nutrient access for individual plants and balancing fertilizer application helped to mitigate greenhouse gas emission by promoting healthier growth of the plant. It was experienced that CO_2 emission was enhanced as the plant population and fertility levels increased. Meanwhile, N_2O gas emission was decreased with higher planting density but increased with increase in fertility levels irrespective of all the observed stages. The most threatening factor global warming potential was also higher with wider plant spacing and high fertilizer application.Therefore, the optimum plant population of 45 X 20 cm along with the nutrient level of $N_{120}P_{60}K_{60}$ kg ha^{-1} would be recommended for climate-enduring pearl millet cultivation under rainfed condition. By agronomic intervention of optimizing spacing and fertility level would make the pearl millet to be the part of sustainable crop diversification opportunity.

Keywords: *Carbon dioxide emission, Fertility, Global warming potential, Nitrous oxide emission, Pearl millet, Plant population, Yield*

Introduction

Currently, India holds the top position in global millet production. During the 2022-23 period, three major millet varieties—Bajra (Pearl millet), Sorghum, and Bulk wheat—together accounted for more than 18% of the world's total millet production. In India, Pearl millet (Bajra) makes up 38.4% of production, followed by Sorghum at 7.21%, with Bulk wheat contributing a minimal share. The top ten millet-producing states in India include Rajasthan, Karnataka, Maharashtra, Uttar Pradesh, Haryana, Gujarat, Madhya Pradesh, Tamil Nadu, Andhra Pradesh, and Uttarakhand. These states collectively contributed about 98% of India's total millet production during the 2023-24 period [1]. Bihar is emerging as a new potential producer of millets.

India has 15.48 million hectares of land under millet cultivation, yielding 10.901 million tons. The country is the leading producer of pearl millet, accounting for 62% of India's total millet production, followed by Sorghum (26%), Finger millet (9%), and small millets (3%) [1], [2]. Millet farming is often practiced with minimal management, especially in less fertile and drought-prone regions, limiting yield potential.

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Rainfed pearl millet relies on monsoon rainfall without irrigation. Haryana leads in pearl millet productivity, followed by Madhya Pradesh and Uttar Pradesh. Together, five states—Rajasthan, Maharashtra, Uttar Pradesh, Gujarat, and Haryana—account for more than 90% of the country's total pearl millet production. Due to the increasing production and consumption of millets, 2023 was declared the International Year of Millets by the United Nations. This declaration is expected to foster millet cultivation expansion at both state and national levels, enhancing the existing agroecosystem's efficiency, inclusivity, resilience, and sustainability.

Coarse cereals, often referred to as nutria-cereals, are rich in dietary fiber, antioxidants, proteins, and minerals. Pearl millet, a key gluten-free grain, is highly nutritious, containing protein, dietary fiber, essential fatty acids, and minerals like potassium, zinc, magnesium, calcium, and iron, contributing to nutritional security for many rural communities. Recognizing its nutritional value, several state governments have incorporated pearl millet, either whole or processed, into school meals. Malnutrition remains a significant concern in India, and pearl millet can play a vital role in alleviating undernutrition, particularly among the impoverished. As a result, it has been described as a "true pearl" for Indian farmers [3]. Additionally, pearl millet is a rich source of protein and contains approximately 60-78% carbohydrates, 11-12% protein, and 3.0-4.6% fat [24]. Its high nutritional content provides an opportunity for developing processed, value-added products, particularly for health-conscious urban consumers, including

those with diabetes and heart conditions [26].
Human activities, particularly urbanization, industrialization, excessive fossil fuel use, and the indiscriminate application of chemical fertilizers and pesticides, have negatively impacted the environment. These practices intensified after the Green Revolution, have led to soil degradation, reduced fertility, pesticide resistance, pollution of air and water, and increased greenhouse gas emissions, disrupting biological balance and promoting the emergence of new pests, thus endangering both human health and the environment. Agricultural practices also influence the global carbon cycle, contributing to a global temperature increase of 0.6 ± 0.2°C in the 20th century, with a standard rate of temperature rise of 0.17°C per decade since 1950 [15]. In the 1990s, agricultural land use accounted for 15% of global greenhouse gas (GHG) emissions [13], with most N2O (nitrous oxide) and about two-thirds of CH4 (methane) emissions originating from agriculture. Adaptation strategies are crucial to addressing the vulnerabilities posed by climate change [28], though the implementation of such strategies remains costly and unclear [20], [21].
Climate-resilient crops, such as millet, can reduce GHG emissions and maintain high yields with proper fertilizer management. Millets have a lower carbon footprint, potentially reducing emissions by 23.30% when replacing rice in the kharif season. As a C_4 crop, pearl millet demonstrates excellent water and nutrient use efficiency and thrives in high temperatures. Consequently, pearl millet is drought- and heat-tolerant, making it more adaptable to climate change [14]. Therefore, appropriate agronomic practices, such as precise nitrogen fertilizer application, proper plant geometry, and efficient water management, can reduce GHG emissions [12]. Additionally, the use of neem-coated urea fertilizers can inhibit nitrification, improving nitrogen uptake by plants while reducing NO_3^- and N_2O emissions [18]. To ensure the sustainability of millet production in the face of climate change, studies have been conducted to assess the effects of plant population density and nutrient management practices on GHG emissions under different planting and fertilizer conditions.

Materials and Methods

Site description

The present study was carried out at a research farm of at Bihar Agricultural University Farm, Sabour, Bhagalpur during kharif season for two consecutive years of 2022 and 2023. The climate of Sabour, Bhagalpur is sub-tropical having moderate annual rainfall, hot and dry summers and cold winter. Maximum and minimum temperature recorded for the same period varied in between 30.7 to 34.9 C and 20.0 to 26.8 C, respectively. The average annual rainfall of this place is about 1150 mm. Monthly average values of weather Parameters of 2018 and 2019 were presented in fig. 1(a) and (b).
The soil was clay-loam in texture having with pH- 7.4, Electrical Conductivity- 0.29 dSm^{-1}, organic carbon- 4.6 g kg^{-1}, Available N – 228.5 Kg N ha^{-1}, Available P- 19.22 Kg P_2O_5 ha^{-1}, Available K- 210.4 Kg K_2O ha^{-1} at the beginning of the experiment.
Treatment details: The experiment was set up with nine treatment combinations comprised of three levels of plant population (M_1- 45 X 20 cm, M_2- 50 X 20 cm and M_3- 50 X 25 cm) as main plot treatments and three fertility levels with N:P:K (S_1- 90:45:45, S_2- 120:60:60 and S_3- 150:75:75 kg N: P_2O_5: K_2O/ha) as sub-plot treatments. The experiment was laid out under split-plot design with three replications.

Crop management details

Pearl millet variety *ProAgro 9048* was transplanted at 20 days seedling on mid-August at varing population and fertility levels as per experimental design. One-third of the nitrogen and full dose of phosphorus and potassium were applied through di ammonium phosphate and muriate of potash at basal whereas, rest of the nitrogen was applied through urea in two equal splits at knee high and panicle initiation stage. Herbicidal application of atrazine @500g/haas pre-emergence followed by 2,4- D as post-emergence applied at 12 DAT for weeds control. The crop was grown under a complete rainfed situation with no irrigation application.

Estimation of the yield attributes and yield

In each experimental plot one-meter square area was randomly selected at different places at the harvesting stage and different yield attributes were measured. From each net plot, earhead was separately harvested, dried and threshed. Further, 1000 grains were counted randomly from five selected plants of each net plot and their weight was taken in grams. Grains of each plot were cleaned and weighed in kg $plot^{-1}$ and further converted in q ha^{-1}. The difference of sun-dried harvest of each net plot and grain yield gave the stover yield (kg $plot^{-1}$). Further these values were calculated in terms of q ha^{-1}. The Harvest index was calculated as ratio of economic yield (grain yield) to biological yield and expressed in percentage.

$$\text{Harvest Index (\%)} = \frac{(Economic\ yield) Grain\ Yield}{Biological\ yield (Grain + Straw)} \times 100$$

Collection and estimation of greenhouse gases

The greenhouse gases i.e. N_2O and CO_2 were collected from each plot of pearl millet through gas collection chambers 590mm × 590mm × 920mm made up of imported plaxy glassat at an interval of 7 days throughout the growing period and consecutive 5 days after fertilization and irrigation. Gas chambers were placed in between the rows of pearl millet plants and GHGs gas samples were collected using 50 mL syringe with 3-way stop clock at an intervals of 0, 15 and 30 mins. Collected gas samples were stored in pre-evacuated vials and labelled with date of collection, plot number and time of collection, and temperature of the greenhouse gas chamber. The Gas samples were analyzed by a gas chromatograph (Trace GC 1100, Thermo Fischer) equipped with electron capture detector (ECD) for analysing N_2O. CO_2 was reduced to CH4 with hydrogen in a nickel catalytic methanizer at 350°C and then detected by the flame ionization detector (FID). The carrier gas was nitrogen at a flow rate of 35 mL min^{-1}. The temperatures for the column and ECD detector were maintained at 60°C and 300°C, respectively. The oven and FID were operated at 60°C and 300°C, respectively. The gas emission flux was calculated from the difference in gas concentration according to the equation of Zheng(1998).

$$F = \rho h \left(\frac{dC}{dt}\right) 273 (273 + T)^{-1}$$

where F is the gas emission flux (mg m-2 hr-1), ρ is the gas density at the standard state, h is the height of the chamber above the soil (m), C is the gas mixing ratio concentration (mg m-3), t is the time intervals of each time (h), and T is the mean air temperature inside the chamber during sampling.

Results and Discussion

Two years of experimental data indicate that a plant population of 45 cm x 20 cm produced the best results in various yield attributes of pearl millet, such as 17.32 ears m^{-2}, ear length of

25.72 cm, and ear weight of 54.38 g. It also led to higher yields, with 35.86 q ha^{-1} for grain and 83.09 q ha^{-1} for stover, compared to other plant populations (Table 1, Table 2). This improvement is likely due to the fact that an optimal plant population helps maintain intra-species competition, enabling better use of resources like space, light, nutrients, and moisture. This efficient resource utilization enhances nutrient uptake, promotes translocation to the sink, and results in higher photosynthate accumulation. Wider plant spacing, on the other hand, leads to the underutilization of nutrients in the soil, making it less beneficial for pearl millet cultivation. Generally, optimal spacing allows for healthy root zone development, which increases the area for root growth [22], [25]. This enhances the availability and absorption of nutrients, improving metabolic activity, translocation, and nutrient synthesis, ultimately boosting growth parameters, yield attributes, and crop yield. In contrast, wider spacing leaves soil uncovered, leading to nutrient loss and reduced nutrient utilization.

Among different fertility levels, the application of $N_{150}P_{75}K_{75}$ kg ha^{-1} resulted in the highest yield-contributing attributes, such as 17.55 ears m^{-2}, 26.31 cm ear length, and 54.27 g ear weight, alongside yields of 35.71 q ha^{-1} for grain and 82.42 q ha^{-1} for stover (Table 1, Table 2). This is because nitrogen fertilizer enhances nitrogen availability, promoting meristematic cell division and cell elongation, which contributes to increased plant height, dry matter accumulation, and tiller number [25]. The healthy growth driven by adequate fertilization is crucial for improving yield attributes and overall crop yield. Balanced fertilization improves nitrogen use efficiency and ensures a rapid, sufficient nutrient supply, leading to optimal crop growth. Over-fertilization, however, can lead to nutrient losses through leaching, denitrification, and volatilization, which are minimized by applying the optimal fertilizer dose [7]. Therefore, applying the appropriate fertilizer amounts ensures efficient nutrient utilization by the crop's extensive root system, leading to higher photosynthate production and improved grain and stover yields. Additionally, the $N_{120}P_{60}K_{60}$ kg ha^{-1} fertility level yielded comparable results to higher doses, with 34.70 q ha^{-1} for grain and 80.53 q ha^{-1} for stover.

As a climate-resilient crop, millet's greenhouse gas emission rate is lower as compared to other cereal crops, particularly when optimal soil and water management practices are followed [5], [11]. Data analysis revealed that wider plant spacing (50 x 25 cm) resulted in higher nitrous oxide emissions (32.99 kg N_2O ha^{-1} day^{-1}) compared to narrower spacing (29.84 kg N_2O ha^{-1} day^{-1}) at 20 days after transplanting (DAT) (Table 3). This trend continued at 35, 50, and 65 DAT, as well as at harvest. However, wider spacing emitted significantly lower levels of carbon dioxide at all stages of growth, with emissions of 59.02, 47.76, 37.76, 29.18, and 20.02 kg CO_2 ha^{-1} day^{-1} at 20, 35, 50, 65 DAT, and harvest, respectively, compared to the 45 cm x 20 cm spacing. The lower number of plants in wider spacing results in less root respiration, thereby reducing carbon dioxide emissions. Conversely, narrow spacing leads to a higher plant population, which uses more soil nutrients, thereby reducing nitrous oxide emissions. Nitrogen losses through denitrification, leaching, and volatilization further contribute to reduced nitrous oxide emissions in these conditions [4].

Under the M_3S_1 treatment (50 x 25 cm and $N_{90}P_{45}K_{45}$ kg ha^{-1}), the least amount of CO_2 was emitted at 46.23 kg CO_2 ha^{-1} day^{-1} and 28.50 kg CO_2 ha^{-1} day^{-1} at 35 and 65 DAT, respectively, compared to other treatments (Table 5). This treatment also resulted in the lowest Global Warming Potential (GWP), at 650 kg CO_2eq ha^{-1}, when compared to other fertility levels (Fig 2). It is clear that higher fertilization, particularly at the $N_{150}P_{75}K_{75}$ kg ha^{-1} level, increased greenhouse gas emissions, especially nitrogenous gases like N_2O (32.03, 36.02, 27.02, 22.10, and 15.99 kg N_2O ha^{-1} day^{-1} at 20, 35, 50, 65 DAT, and harvest). Many researchers have shown that nitrous oxide emissions increase linearly with the amount of mineral fertilizer applied [10], [17], [29]. Nitrogenous fertilizers, in particular, provide substrates for denitrifying bacteria, accelerating microbial decomposition, nitrogen loss, and N_2O emissions. Increased fertilizer application also promotes stronger root growth, which in turn increases root respiration and greenhouse gas emissions. This relationship between higher fertilization rates and increased emissions has been well-documented by several researchers [8], [16], [19], [23], [30].

It was quite obvious that there was a positive correlation among yield contributing characters, yield with CO_2 emission. The correlations between yields both grain ($r = 0.934$, $p<0.01$) as well as straw yield (($r = 0.946$, $p<0.01$)) with CO_2 emission were highly significant. However, N_2O emission did not show any significant relation with yield and yield attributes (Table 6).

In addition, nitrous oxide (N_2O) emissions trend was also observed during days after N-fertilizer application.The experimental data evidenced that nitrogenous fertilizer application significantly enhanced N_2O emissions (Fig 3). The N_2O emission rate was maximum just after 2^{nd} day of application irrespective of dose of application (90, 120, 150 kg N ha^{-1}) and rate of emission was slower down with days nearly 8 days after application. The rate of emission tends to be higher shortly after the application of nitrogenous fertilizers, primarily due to increased microbial activity in the soil that converts nitrogen into N_2O [11] by enhancing nitrogen availability in the soil with immediate nitrogen fertilizer application. After initial burst of N_2O production, the readily available nitrogen is gradually taken up by plants and microbes, or converted to other forms, leading to a decrease in the substrate for microbial activity.

Conclusion

Agro-ecosystem restoration under changed climatic conditions besides food and nutritional security is the urgent need of the day. Shifting towards the crop diversity could be an efficient way to mitigate the ill impact of climate change. Whereas, Pearl millet is one of the promising crops for ensuring nutritional attributes even under high temperatures, prolonged droughts, and nutrient-deprived soils. Therefore, cultivation techniques of adequate planting density and balanced nutrient management can be suggested from these experimental findings for better establishment of Pearl millet. Therefore, to attain the promising returns the optimum plant population of 45 cm x 20 cm and fertility level of $N_{120}P_{60}K_{60}$ kg ha^{-1} would be recommended for rainfed areas. Further, for lowering greenhouse gas emissions as well as global warming potential the fertilizer dose of $N_{120}P_{60}K_{60}$kg ha^{-1} would be suggested for climate-ready pearl millet cultivation. However, optimum fertilizer requirement for the pearl millet needs to be validated in different agro-climatic zones under rainfed condition to come up with specific conclusion. More experimentation should to be conducted under improved fertilization practices like slow releasing nitrogen fertilizers, customized and controlled fertilizers in near future to reduce greenhouse gas emission level from pearl millet.

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Conflicts of Interest: The authors declare no conflict of interest.

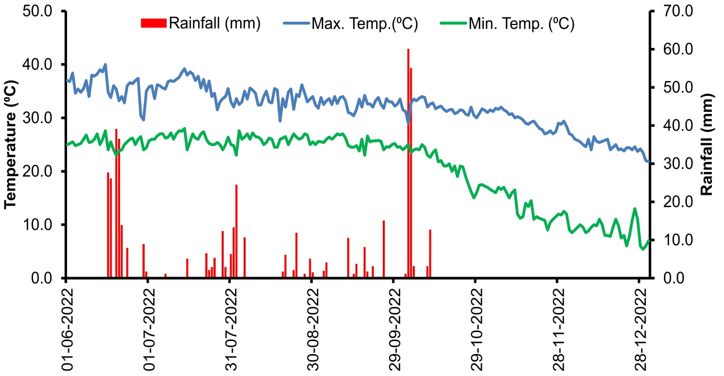

Fig.1 (a): Weather parameters during experimentation under 2022

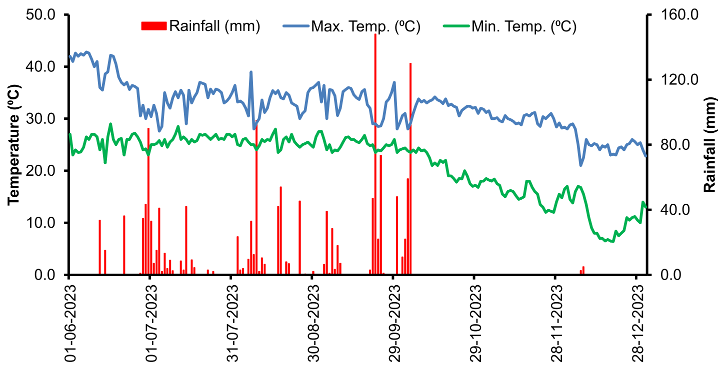

Fig.1 (b): Weather parameters during experimentation under 2023

Table 1: Effect of plant population and fertility levels on number of ears, ear length and ear weight of pearl millet

Treatments	No. of ears (ears m^{-2})	Ear length (cm)	Ear weight (g)
Plant population			
M_1 (45 cm x 20 cm)	17.32	25.72	54.38
M_2 (50 cm x 20 cm)	16.84	25.68	54.02
M_3 (50 cm x 25 cm)	16.06	25.46	50.12
SEm±	0.20	0.06	1.08
CD (P<0.05)	0.79	NS	4.32
Fertility level (kg N: P_2O_5: K_2O ha^{-1})			
S_1 ($N_{90}P_{45}K_{45}$)	15.81	24.26	50.67
S_2 ($N_{120}P_{60}K_{60}$)	16.87	25.29	52.32
S_3 ($N_{150}P_{75}K_{75}$)	17.55	26.31	54.27
SEm ±	0.14	0.07	1.08
CD (P<0.05)	0.43	0.22	3.34
Interaction M x S	NS	NS	NS

Table 2: Effect of plant population and fertility level on test weight, grain yield, stover yield and harvest index of pearl millet

Treatments	**Test weight (g)**	**Grain yield (q ha^{-1})**	**Stover yield (q ha^{-1})**	**Harvest index (%)**
Plant population				
M_1 (45 cm x 20 cm)	11.36	35.86	83.09	30.14
M_2 (50 cm x 20 cm)	10.91	35.06	80.64	30.30
M_3 (50 cm x 25 cm)	10.17	33.22	77.36	30.04
SEm±	0.33	0.49	1.06	0.18
CD (P<0.05)	NS	1.91	4.15	NS
Fertility level (kg N: P_2O_5: K_2O ha^{-1})				
S_1 ($N_{90}P_{45}K_{45}$)	10.31	33.74	78.15	30.15
S_2 ($N_{120}P_{60}K_{60}$)	10.82	34.70	80.53	30.11
S_3 ($N_{150}P_{75}K_{75}$)	11.43	35.71	82.42	30.23
SEm ±	0.38	0.40	1.06	0.17
CD (P<0.05)	NS	1.24	3.26	NS
Interaction M x S	NS	NS	NS	NS

Table 3: Effect of plant population and fertility levelson nitrous oxide (kg N_2O ha^{-1} day^{-1})

Treatment	**20 DAT**	**35 DAT**	**50 DAT**	**65 DAT**	**At harvest**
	kg N_2O ha^{-1} day^{-1}				
Plant population					
M_1 (45 cm x 20 cm)	29.84	33.87	25.02	19.83	13.03
M_2 (50 cm x 20 cm)	31.49	35.40	26.34	21.52	15.48
M_3 (50 cm x 25 cm)	32.99	37.00	28.03	23.20	17.14
SEm±	0.08	0.10	0.07	0.13	0.06
CD (P<0.05)	0.31	0.38	0.29	0.52	0.25
Fertility level (kg N: P_2O_5: K_2O ha^{-1})					
S_1 ($N_{90}P_{45}K_{45}$)	30.89	34.90	25.90	20.88	14.44
S_2 ($N_{120}P_{60}K_{60}$)	31.40	35.34	26.48	21.58	15.22
S_3 ($N_{150}P_{75}K_{75}$)	32.03	36.02	27.02	22.10	15.99

SEm ±	0.07	0.07	0.07	0.08	0.13
CD (P<0.05)	0.23	0.22	0.21	0.26	0.40
Interaction M x S	NS	NS	NS	NS	NS

Table 4: Effect of plant population and fertility levels on carbon dioxide (kg $CO_2 ha^{-1} day^{-1}$)

Treatments	**20 DAT**	**35 DAT**	**50 DAT**	**65 DAT**	**At harvest**
	kg CO_2 ha^{-1} day^{-1}				
Plant population					
M_1 (45 cm x 20 cm)	67.56	54.86	43.96	34.87	26.53
M_2 (50 cm x 20 cm)	63.70	51.82	40.88	31.90	22.86
M_3 (50 cm x 25 cm)	59.02	47.76	37.76	29.18	20.02
SEm±	0.22	0.25	0.12	0.17	0.12
CD (P<0.05)	0.86	0.98	0..46	0.67	0.46
Fertility level (kg N: P_2O_5: K_2O ha^{-1})					
S_1 ($N_{90}P_{45}K_{45}$)	61.92	50.09	40.02	31.13	21.96
S_2 ($N_{120}P_{60}K_{60}$)	63.51	51.54	40.80	32.08	23.38
S_3 ($N_{150}P_{75}K_{75}$)	64.84	52.80	41.77	32.73	24.08
SEm ±	0.14	0.11	0.13	0.12	0.13
CD (P<0.05)	0.44	0.33	0.41	0.35	0.40
Interaction M x S	NS	S	NS	S	NS

Table 5: Interaction effect of plant population and fertility levels on carbon dioxide (kg $CO_2 ha^{-1} day^{-1}$) at 35 DAT and 65 DAT

Treatments	**At 35 DAT (kg $CO_2 ha^{-1}$ day^{-1})**				**At 65 DAT (kg $CO_2 ha^{-1}$ day^{-1})**			
M_1(45 cm x 20cm)	53.27	55.03	56.27	54.86	34.13	35.33	35.13	34.87
M_2(50 cm x 20cm)	50.77	52.00	52.70	51.82	30.77	31.97	32.97	31.90
M_3(50 cm x 25cm)	46.23	47.60	49.43	47.76	28.50	28.93	30.10	29.18
Mean	50.09	51.54	52.80		31.13	32.08	32.73	
	M x S				**M x S**			
SEm (±)	0.29				0.24			
C.D at 5%	0.90				0.73			

Table 6: Pearson's correlation matrix

	TW	GY	SY	HI	N_2O	CO_2	EN	EL	EW
TW	1	**0.989****	**0.989****	0.535	-0.443	**0.899***	**0.972****	0.731	**0.955****
GY		1	**0.992****	0.588	-0.535	**0.934****	**0.945****	0.665	**0.976****
SY			1	0.484	-0.544	**0.946****	**0.953****	0.668	**0.949****
HI				1	-0.214	0.418	0.458	0.340	0.705
N_2O					1	-0.785	-0.269	0.216	-0.455
CO_2						1	0.805	0.412	**0.867***
EN							1	**0.840***	**0.921****
EL								1	0.709
EW									1

***Correlation is significant at the p<0.01; *Correlation is significant at the p<0.05*
TW-Test weight; GY-Grain yield; SY-Straw yield; HI-Harvest index; N_2O-Nitrous oxide emission; CO_2- carbon dioxide emission; EN-No. of Ear m^{-2}; EL- Ear Length, EW- Ear weight

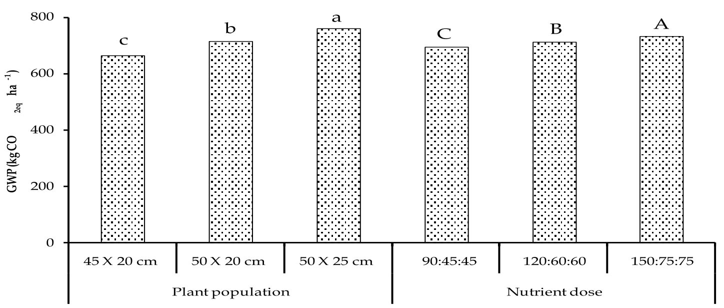

Fig.2: Effect of plant population and fertility level on Global Warming Potentiality (Same letters in each bar are not significantly different in DMRT at p<0.05)

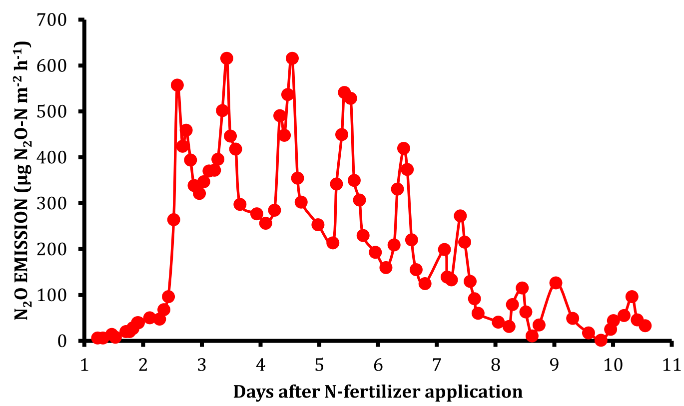

Fig.3: Nitrous oxide emission pattern after N- fertilizer application

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