Greenhouse gas emissions from integrated nutrient management practices in pearl millet + *Melia dubia* agri-silvi system

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Climate change induced due to the magnitudinal rise in proportions of carbon dioxide (CO_2) and nitrous oxide (N_2O) in the environment has emerged as an indubitable concern across the globe. Hence, the impact of various organic forms of manure on greenhouse gas (GHG) emissions from the soil and global warming potential (GWP) was studied in pearl millet + *Melia dubia* agri-silvi system. Replacing 25% of nitrogen with farmyard manure (FYM), poultry manure and pongamia green leaf manure (PGLM) elevated CO_2 emissions by 8.81%, 12.39%, 15.88% and N_2O emissions by 47.5%, 49.8% and 55.8% respectively, compared to full recommended dose of fertilizer through neem-coated urea treatment. Also, 100% recommended dose of fertilizer (RDF) using neem-coated urea is effective in reducing GWP by 19% over 100% RDF through normal urea. GWP of all the treatments ranged from 1029 (unfertilized) to 1807 kg CO_2 eq. ha^{-1} (sole crop without trees). The study also reported lower CO_2 and N_2O emissions under the tree compared to sole crop without trees, which suggests that agroforestry would reduce the overall GHG emissions. Also, use of organic manure along with inorganic fertilizers showed better carbon efficiency ratio and soil fertility status in spite of increase in GWP.

Keywords: Agri-silvi system, carbon dioxide, global warming potential, greenhouse gases, nitrous oxide.

CARBON dioxide (CO_2) concentrations have risen from 280 ppm in the pre-industrial era[1] to 419 ppm as measured at Mauna Loa on May 2021. According to National Oceanic and Atmospheric Administration–Earth System Research Laboratories (NOAA–ESRL), a 43% and >50% increase in CO_2 and N_2O emissions[2] respectively, was observed in the present day in comparison with pre-industrial era, elucidating a striking change in the climate. In India, agriculture is mostly responsible for these emissions (~16%). Agroforestry is one of the viable options in solving this issue by bringing trees into the limelight. Planting varieties such as *Melia dubia*, a money-spinning tree, assures buyback and requires low maintenance expenditure. Cylindrical and straight bole of *Melia* brings vast scope for introducing intercrops like pearl millet, which is a C_4 crop in the *M. dubia* plantations[3]. In addition, intercropping between the trees showed higher sequestration of carbon in the soil and a decrease in N_2O emissions[4].

Fertilizers like neem-coated urea reduce the nitrification rate that will aid in improving nitrogen efficiency and uptake by plants, and reduces NO_3^- and N_2O discharge into the environment[5]. Organic manure application, viz. farmyard manure (FYM), pongamia green leaf manure (PGLM), poultry manure and biofertilizer as partial substitution is vital for enhancing the productivity and soil organic carbon (SOC), and to reduce the reliance on chemical fertilizers. Nevertheless, it may increase greenhouse gas (GHG) production from the soil[6]. The negotiating linkage between soil health and higher yield versus GHG emissions must be taken into consideration when advocating organic manure substitution for chemical fertilizer[7]. In view of the above, the present study was conducted to estimate the CO_2 and N_2O emissions from organic manure amended soils and evaluate global warming potential (GWP) under pearl millet + *M. dubia* agri-silvi system.

The experiment was conducted during *kharif* 2017 at All India Coordinated Research Project (AICRP) on Agroforestry, Hyderabad. Soil characteristics of the experimental site were texture: sandy loam, pH: slightly acidic (6.23), EC: 0.135 dS m^{-1} (suitable for all crops), organic carbon: 0.77%, available nitrogen: 287.6 kg ha^{-1} (medium), available phosphorus: 41.31 kg ha^{-1} (low) and available potassium: 214.0 kg ha^{-1} (medium). Total rainfall received during the growing season was 6.6 mm in 0.4 rainy days. The mean weekly maximum temperature during the crop growing period was 30.3°C, whereas mean minimum temperature was 21.9°C.

Pearl millet was intercropped in six-yr-old *M. dubia* plantations on 4 July 2017 and harvested on 6 October 2017. The experiment was laid out in randomized block design with three replications and treatments comprising AF_1: control, AF_2: 100% RDF using normal urea, AF_3: 100% RDF using neem-coated urea, AF_4: 75% RDN + 25% N using poultry manure, AF_5: 75% RDN + 25% N using FYM, AF_6: 75% RDN + PGLM @ 10 t ha^{-1}, AF_7: 75% RDN + *Azotobacter* @ 500 g ha^{-1} and AF_8: sole crop without trees (100% RDF). The entire recommended dose of fertilizers to crop was 80–40–30 NPK kg ha^{-1}. Based on treatment specifications, organic manure application was done two weeks before sowing. Table 1 presents the nutrient content of various types of organic manures. Basal and split doses of chemical fertilizers were applied according to International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) guidelines[8].

Sampling was done in all the plots at an interval of 0, 30 and 60 min during morning hours (09:00–11:00 AM) using closed chamber technique on different days[9]. Chambers of 53 × 33 × 37 cm size with acrylic sheets of

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6 mm thickness and aluminium frames were mounted on an iron stand. Anchors were installed within the crop rows at 10 cm depth into the soil to ensure that there was no gas exchange between chamber and atmosphere during sampling, and the frames were saturated with water to make the system airtight. Chambers were mounted on frames prior to making observations each time. Samples were taken using a syringe of 20 ml equipped with a stopper by hypodermic needle (24 gauge) through rubber septum located on top of the chamber. To record the temperature inside the chamber during sampling period, a thermometer was inserted into the chamber through the septum. One tiny rotary fan was firmed in the chamber to homogenize the sample. Gas samples were taken immediately for analysis to the CRIDA laboratory. A gas chromatograph (GC) fitted with a thermal conductivity detector (TCD) and electron capture detector (ECD) was used for estimating the fluxes of CO_2 and N_2O respectively, and the fluxes were computed using the following equations[10]

$$CO_2 - C \text{ flux (mg m}^{-2}\text{ h}^{-1}) = (\Delta X \times EBV_{(STP)} \times 12 \times 10^3 \times 60)/(10^6 \times 22{,}400 \times T \times A),$$

$$N_2O - N \text{ flux } (\mu\text{g m}^{-2}\text{ h}^{-1}) = (\Delta X \times EBV_{(STP)} \times 28 \times 10^3 \times 60)/(10^6 \times 22{,}400 \times T \times A),$$

where ΔX is the variation in fluxes at 60 and 0 min (in ppm for CO_2 and ppb for N_2O), $EBV_{(STP)}$ the volume of the chamber at standard temperature and pressure, T the time (60 min) and A is the area covered by the chamber (m^2).

Total emissions during the cropping period were estimated by averaging the emissions obtained on different stages of crop growth and multiplying them with crop duration.

GWP is used as an index for measuring the potentiality of each gas to entrap heat in the atmosphere with respect to standard gas, i.e. CO_2. GWP of CO_2 is 1 and N_2O is 310, according to IPCC[1]. GWP was calculated using the following equation[11]

$$\text{GWP (kg } CO_2 \text{ eq. ha}^{-1}) = CO_2 \text{ emission (kg ha}^{-1}) \times 1 + N_2O \text{ emission (kg ha}^{-1}) \times 310.$$

Carbon equivalent emission (CEE) and carbon efficiency ratio (CER) were calculated using the following equations[7]

$$\text{CEE} = \text{GWP} \times 12/44,$$

$$\text{CER} = \text{Grain yield (in terms of C)/CEE}.$$

On an average, 44% of total biomass is the carbon content in grains as given by Lal[12].

The data recorded were analysed using analysis of variance (ANOVA). Significant differences among mean values were evaluated with least significant difference (LSD) at 5% probability level, as suggested by Gomez and Gomez[13].

CO_2 fluxes varied between 6.3 and 20.2 kg ha^{-1} d^{-1} during the pearl millet growing season (Figure 1 *a*). With the first dose of fertilizer application after sowing, flux levels had escalated because of higher nitrogen availability that hastened the mineralization process of organic carbon and soil respiration[14]. The peaks of CO_2 fluxes at 15 days after sowing (DAS) were 20.2 and 19.6 kg ha^{-1} d^{-1} in treatments AF_8 and AF_2 respectively. Later, a decline in CO_2 emissions was observed and this trend continued till the next dose of fertilizer application. CO_2 emissions from the soil were mainly due to SOC decomposition by microorganisms[15]. In all the treatments, lower CO_2 flux was observed before cropping period whereas during the vegetative stage, emissions were significantly higher and reached peak a during 45–60 DAS. At initial stage of seed germination, CO_2 emissions were especially due to soil organic matter decomposition. However, the rise in CO_2 fluxes from 45 to 60 DAS was probably due to greater accessibility of carbon substrates by microbes during that period[16].

Seasonal CO_2 fluxes were lower in treatments which were under tree shade (922–1380 kg ha^{-1}) and higher in sole crop without trees (1495 kg ha^{-1}) (Table 2). Lower CO_2 emissions from tree-based intercropping were by virtue of its carbon storage capacity in the wood and more productive utilization of soil carbon through biological activity compared with sole crop without trees, possibly because the microbial communities are more diverse[17].

Seasonal CO_2 emissions were significantly affected due to the integrated nutrient management treatments and varied from 1495 (fertilized treatments) to 922 kg ha^{-1} (unfertilized or control treatment). This might be due to higher nitrogen accessibility from the applied chemical fertilizer that aided in increased biomass. This in turn caused increase in the canopy cover and created shade when compared to control treatment. Shading develops a microclimate that moderates changes in the soil temperature and moisture by providing homogenous conditions for soil respiration. Increased soil respiration leading to a greater microbial activity was observed when fertilizer application was carried out[18].

Among different fertilized treatments in *M. dubia*, 100% RDF through neem-coated urea showed significantly

Table 1. Nutrient content of various types of organic manure used in the study on dry weight basis

	Nutrient content (%)		
Organic manure	N	P	K
Poultry manure	1.34	0.90	0.60
Farmyard manure	0.40	0.36	0.53
Pongamia green leaf manure	2.75	2.41	2.42

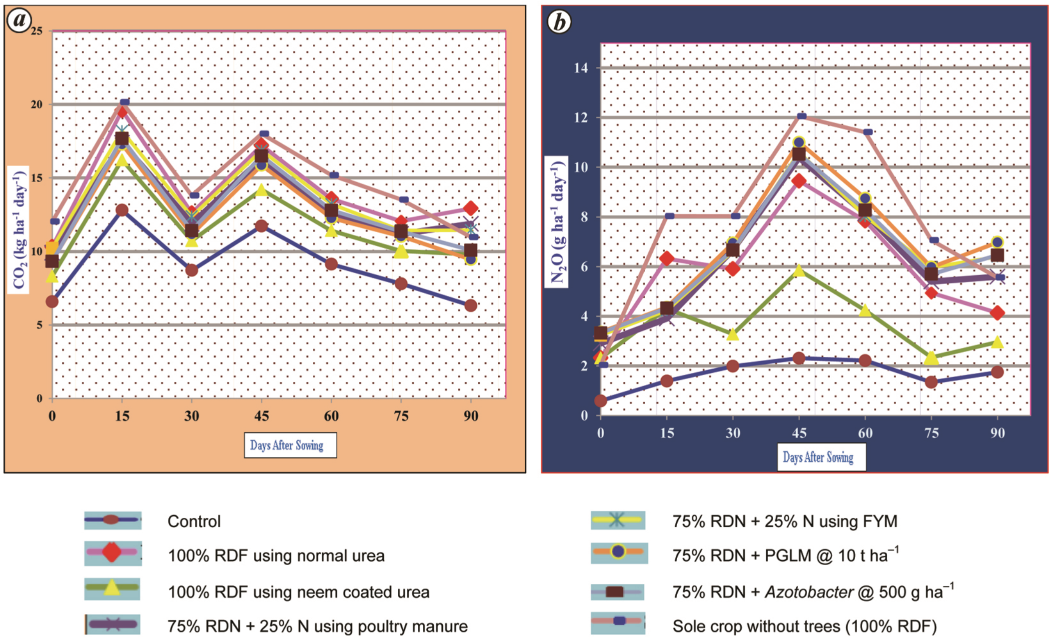

Figure 1. (***a***) CO_2 and (***b***) N_2O emissions from the soil in pearl millet + *Melia dubia* agri-silvi system with various nutrient management practices.

Table 2. Seasonal emissions of carbon dioxide (CO_2), nitrous oxide (N_2O) and carbon equivalent emissions influenced by nutrient management practices in pearl millet + *Melia dubia* agri-silvi system

Treatment	CO_2 emission (kg ha^{-1} season^{-1})	N_2O emission (g ha^{-1} season^{-1})	Global warming potential (kg CO_2 ha^{-1})	Carbon equivalent emissions (kg C ha^{-1})
AF_1	922	345	1029	281
AF_2	1380	744	1610	439
AF_3	1146	510	1304	356
AF_4	1288	763	1525	411
AF_5	1247	752	1480	427
AF_6	1328	795	1575	407
AF_7	1276	764	1512	416
AF_8	1495	1007	1807	493
Mean	1260	710	1480	404
SEm ±	29	61	34	9
CD (P = 0.05)	88	185	104	28

lower seasonal CO_2 emissions (1146 kg ha^{-1} season^{-1}). These results were in conformation with the recommendations of Hala *et al.*[5]. Higher CO_2 fluxes in PGLM treatment were due to higher decomposition of green manure. Lower C : N ratio of PGLM showed higher CO_2 fluxes due to rapid decomposition of carbon[7]. Application of chemical fertilizer alone or in conjunction with FYM helped in conserving the slow and active pools of carbon release at the soil surface, thereby sequestering SOC and improving soil quality[19]. Higher CO_2 losses with poultry manure treatment than inorganic fertilizers early in the cropping period were attributed to the higher levels of available carbon which might have enhanced the microbial activity causing increase in soil CO_2 flux. These results were in confirmation with those of Sistani *et al.*[20]. Application of biofertilizers restores the natural nutrient cycle and helps in the building up of organic matter in the soil[21].

The N_2O fluxes ranged between 0.59 and 12.06 g ha^{-1} d^{-1} during the pearl millet growing season, wherein 0.59 g ha^{-1} d^{-1} was observed in control and 3.36 g ha^{-1} d^{-1} in PGLM-treated plots early in the cropping period (Figure 1 *b*). Slightly higher N_2O emissions were observed after sowing, which could be due to the application of basal dose of fertilizer that causes hydrolysis of urea and rainfall that occurred prior to sowing, and cultural operations during sowing might have enhanced the role of nitrifying microbes. On application of urea and a combination of urea and organic manure, a rise in the fluxes was observed in all the treatments which might be due to availability of substrate for nitrification[22]. Later, decline in the peak followed till it reached to a lower concentration of N_2O emissions. Similar N_2O fluxes were observed in other studies upon application of fertilizer nitrogen[7,23,24]. N_2O fluxes in the control plot were low during the study and never more than 2.31 g ha^{-1} d^{-1}. After a

Table 3. Grain yield, amount of C fixed in grains and carbon efficiency ratio (CER) influenced by nutrient management practices in pearl millet + *M. dubia* agri-silvi system

Treatment	Grain yield (kg ha^{-1})	C fixed in grains (kg ha^{-1})	CER
AF_1	852	375	1.33
AF_2	2340	1030	2.34
AF_3	2920	1285	3.65
AF_4	1983	873	2.13
AF_5	1443	635	1.49
AF_6	2667	1173	2.88
AF_7	1187	522	1.26
AF_8	3182	1400	2.84
Mean	2073	912	2.24
SEm ±	84	37	0.11
CD ($P = 0.05$)	255	112	0.33

rainfall event that occurred on 12 DAS, N_2O fluxes increased significantly in all the treatments, which is in line with the results of Majumdar *et al.*[25].

N_2O fluxes from sole crop without trees (2.03 g ha^{-1} d^{-1}) were lower in the early growing season compared to those treatments in *M. dubia*, except in control. These results were in agreement with Cuellar *et al.*[26]. Later in the season, the emissions were lower in the treatments in *M. dubia*. This is in accordance with Beaudette *et al.*[27], who noticed three times higher N_2O emissions in conventional mono-cropping in comparison with tree-based intercropping system. Application of 100% RDF using neem-coated urea resulted in lower N_2O fluxes during most part of the crop growth period and led to significant reduction in seasonal N_2O emissions. This may be due to the properties of neem-coated urea like slow release of fertilizer and reduction in nitrification rate. Prilled normal urea when coated with neem showed that nitrogen availability was slow and continuous throughout the cropping period which causes increases in the efficiency of fertilizer[28].

Table 2 shows the seasonal N_2O fluxes observed during the study period, in which significantly higher emissions were from 100% RDF using normal urea (744 g ha^{-1} $season^{-1}$) than from 100% RDF using neem-coated urea (510 g ha^{-1} $season^{-1}$), highlighting role of neem-coated urea in reducing N_2O emissions. These results were in conformity with those of Hala *et al.*[5], who noticed higher nitrate levels in 100% RDF using normal urea treatment. The continuous higher supply of NH_4^+–N and NO_3^-–N in slow-release fertilizers like neem-coated urea was favourable for crop growth and nitrogen assimilation by the crops. Hence, significantly higher dry matter production, nitrogen uptake, nitrogen content and grain yield were observed in 100% RDF using neem-coated urea treatment.

Seasonal emissions of N_2O ranged from 752 g ha^{-1} $season^{-1}$ in 75% RDN + 25% N FYM treatment (AF_5) to 795 g ha^{-1} $season^{-1}$ with 75% RDN + PGLM treatment (AF_6). Significant difference was not observed among PGLM (AF_6), *Azotobacter* (AF_7), poultry manure (AF_4) and FYM (AF_5) treatments, but the FYM (AF_5) treatment had comparatively lower emissions. In treatments AF_6, AF_7 and AF_4, nitrogen was present in the available forms, which resulted in higher N_2O emissions when compared with the FYM treatment because of gradual decomposition and greater C : N ratio of FYM with respect to PGLM. Pathak *et al.*[9] observed that a combination of urea and FYM decreased N_2O emissions in comparison with 100% RDF using normal urea. Manna *et al.*[21] reported higher N_2O fluxes from poultry manure in the early crop growth period because litter can be easily mineralized as nitrogen available is in the organic form. Also, carbon in the poultry litter when applied to the soil may trigger microbial activity, promoting greater N_2O release. The control plot tended to have the lowest N_2O flux throughout the study period, which is rational that nitrogen was not applied.

GWP of all the treatments ranged between 1029 (unfertilized) and 1807 kg CO_2 eq. ha^{-1} (sole crop without trees) (Table 2). Highest GWP was observed in the treatment AF_8 (sole crop without trees – 1807 kg CO_2 eq. ha^{-1}). However, the organic treatments, i.e. AF_4, AF_5, AF_6 and AF_7 remained on par with each other, but were significantly higher than AF_3 (100% RDF through neem-coated urea) and AF_1 (control).

Percentage increase in GWP with organic manure application was 13.5%, 16%, 16.9% and 20.8% with FYM (T_5), *Azotobacter* (T_7), poultry manure (T_4) and PGLM (T_6) treatments respectively, compared to 100% RDF through neem-coated urea treatment (T_3). The study revealed that 100% RDF through neem-coated urea is effective in reducing GWP by 19% over 100% RDF through normal urea.

CEE was lower in the control treatment (281 kg C ha^{-1}). Also, 100% RDF using neem-coated urea (AF_3) showed reduced CEE when compared with the treatments including organic manure. Among various organic manure treatments, the lowest CEE was observed in AF_6, i.e. 75% RDN + PGLM @ 10 t ha^{-1} (Table 2).

Carbon efficiency ratio (CER) (carbon stored in the grains by pearl millet per unit of C emitted) was highest in 100% RDF using neem-coated urea (3.65), followed by

75% RDN plus PGLM @10 t ha^{-1} (2.88) and sole crop (2.84). Lowest CER was observed in T_7, as this had smaller amounts of carbon fixed in pearl millet (Table 3). Similar results were reported by Bhatia *et al.*[7]. Thus, use of PGLM along with 75% RDN may increase GWP, but improves soil fertility without compromising on CER.

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