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Nitrogen management and supplemental irrigation affected greenhouse gas emissions, yield and nutritional quality of fodder maize in an arid region

Irshad Ahmad [a,*], Zhengang Yan [a], Muhammad Kamran [a], Khushnuma Ikram [b], Muhammad Usman Ghani [a], Fujiang Hou [a,*]

[a] State Key Laboratory of Grassland Agro-ecosystems, Key Laboratory of Grassland Livestock Industry Innovation, Ministry of Agriculture and Rural Affairs, Engineering Research Center of Grassland Industry, Ministry of Education, College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou 730020, PR China

[b] Department of Biotechnology, Abdul Wali Khan University Mardan, Mardan 23200, Pakistan

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ABSTRACT

Deficit and erratic precipitation in arid regions and imbalance nitrogen (N) fertilization can result in lower yield and nutritional quality of fodder maize. The objectives of the experiment were to investigate the effect of N (urea 46% N) rates i.e., 225 (N_1), 300 (N_2) and 375 kg N ha^{-1} (N_3) under 600 (W_1) and 900 mm ha^{-1} (W_2) supplemental irrigation levels on the greenhouse gas (GHG) emissions, yield and nutritional quality of fodder maize. The treatments combination comprised of N_1W_1, N_2W_1, N_3W_1, N_1W_2, N_2W_2 and N_3W_2. N fertilization and supplemental irrigation levels significantly affected soil moisture content (SMC) and soil temperature (ST), whereas maximum SMC and minimum ST were recorded in N_3W_2. Increasing N rate decreased soil ammonium nitrogen content (NH_4^+-N) and increased nitrate nitrogen content (NO_3^--N) and maximum NH_4^+-N was recorded in N_1W_1 and maximum NO_3^--N in N_3W_1. Methane (CH_4) uptake was higher in W_1 compared with the W_2, and maximum CH_4 uptake was recorded in N_3W_1 followed by N_3W_2. Nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions were higher in W_1 compared with the W_2, and maximum N_2O and CO_2 emissions were recorded in N_3W_1. Cumulative emission of N_2O and CO_2, CH_4 uptake, global warming potential (GWP), and greenhouse gas intensity (GHGI) were higher in W_1 compared with W_2 and their maximum values were recorded in N_3W_1. Treatment N_3W_2 significantly improved the forage yield and nutritional quality of fodder maize by improving the crude protein content and ether extract content, while reducing neutral detergent and acid detergent fibers contents. In conclusion, treatment N_3W_2 improved SMC, forage yield, grain yield, and nutritional quality of fodder maize as well as reduced GHG emissions, GWP and GHGI in an arid region.

1. Introduction

Deficit and unpredictable precipitation and improper nutrients management in arid and semi-arid regions can inhibit crops growth and development and results in lower yield and quality (Ren et al., 2008, 2017; Ali et al., 2018; Su et al., 2020). In China, dry land accounts for 60% of the cultivated area and the deficit and erratic precipitation and frequent droughts in these regions limit crops yield and quality (Jia et al., 2020, 2021a). Optimum nitrogen (N) fertilization and irrigation are the main factors affecting crops growth, but the excessive application of water and N will not only waste water resources but also cause great harm to the ecological environment (Ali et al., 2019a; Xu et al., 2020; Ahmad et al., 2021a, 2021b; Meng et al., 2021). Water deficiency is significantly increasing due to climatic change and higher water use, and thus negatively affects the yield of crops (Spedding et al., 2004). Irrigation is an important agricultural technique to increase the productivity of crops (Ali et al., 2019a). Under excessive irrigation condition, most of the N fertilizer applied to the crops is leached in the form of nitrate nitrogen (NO_3^--N), and an optimum irrigation could reduce the risk of NO_3^--N leaching into deeper soil profile (Meng et al., 2021; Xia et al., 2021). Irrigation can maintain sufficient water and meet the roots demand for water (Ali et al., 2019a; Xu et al., 2020). N is important for crops production, however excessive use of N fertilizers could reduce N use efficiency and degrading water and soil quality by increasing the concentration of NO_3^--N in groundwater and in topsoil (Godfray et al., 2010; Zhu et al., 2012; Hu et al., 2013a). Godinot et al. (2016) depicted that higher yield can be obtained through the application of inorganic fertilizers. However, 50% of N is lost in the forms of leaching,

* Corresponding authors.
E-mail addresses: irshad@lzu.edu.cn (I. Ahmad), cyhoufj@lzu.edu.cn (F. Hou).

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volatilization, soil erosion and denitrification and thus negatively affects the biodiversity, human health and environment (He and Zhou, 2016; Ma et al., 2014). Application of chemical fertilizers affects soil quality and greenhouse gas (GHG) emissions (Ma et al., 2014). Increasing efficiency of N fertilizers and water harvesting strategies could minimize the ecological damages (Zhang et al., 2009). Optimized N application and irrigation could enhance the soil water content and N uptake (Bialczyk and Lechowski, 1995). Zhang et al. (2021) suggested that application of N (240 kg N ha^{-1}, half as a basal dose and half top dressing) in winter wheat reduced methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions, greenhouse gas intensity (GHGI) and global warming potential (GWP) and improved the N use efficiency and grain yield. Therefore, optimum N fertilization and irrigation are the most important factors for increasing the yield of fodder maize and reduce GHG emissions, GWP and GHGI.

In China, the total GHG emissions from 1990 to 2013 have been increased from 3487.7 to 12550.2 Mt CO_2-eq (Ding et al., 2017). Human activities have a major role in GHG emissions and global warming (Han et al., 2019). Agriculture is a main source of GHG emissions, which is estimated as 10–12% of total anthropogenic (2007–2016), having 70% CH_4, 90% N_2O and 20% CO_2 emissions (Luo et al., 2017; Wang et al., 2019). CH_4 is produce by methanogenic bacteria and the soil emits CH_4 when its production is higher compared with its consumption by methanotrophic bacteria (Lourenco et al., 2019; Lan et al., 2020). CH_4 is an important GHG having 33 times higher relative GWP than CO_2 over a hundred year time scale (Ma et al., 2020). N_2O is also an important trace gas in atmosphere because of its importance for greenhouse effect and stratospheric ozone depletion (Intergovernmental Panel on Climate Change (IPCC), 2001). N_2O emission is increasing approximately at a level of 0.26% $year^{-1}$ (IPCC, 2007). Agricultural soil contributes to 67% of global anthropogenic N_2O emission (Mosier et al., 1998; Kroeze et al., 1999). Nutrients management could reduce N_2O and CH_4 emissions and GHGI (Mosier et al., 2006; Sintim and Flury, 2017). Excessive usage of chemical fertilizers could lead to higher CO_2 and N_2O emissions (Sun et al., 2020). N fertilization directly or indirectly influences nitrification and denitrification and thus affects N_2O emission (Raza et al., 2021). N fertilization also inhibits atmospheric CH_4 uptake and is dependent on N rates (Mosier et al., 1991; Castro et al., 1995). Irrigation could enhance or reduced GHG emissions (Liu and Greaver, 2009; Trost et al., 2016). N fertilization and irrigation affects N_2O emission (Trost et al., 2014). Therefore, optimum N fertilization and irrigation are important to reduce GHG emissions, GWP and GHGI in arid regions.

The nutritional quality of forage determines the utilization efficiency, regulates the digestion and absorption of forage, energy intake and nutrient acquisition by livestock, and affects the yield and quality of livestock products (Richman et al., 2015). Neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein content (CP), and ether extract (EE) are the commonly used indexes to measure the nutritional quality of forages. CP is the most important indicator to evaluate forages quality, and higher the CP the higher will be the nutritional quality (Yang et al., 2021). NDF is used to estimate the potential feed intake, and higher the NDF the worse the nutritional quality of the forages and the lower the feed intake of livestock, whereas the ADF is used for the estimation of digestibility, and higher the ADF the lower will be the nutritional quality of the forages and the lower will be the digestibility in livestock (Rotger et al., 2006). EE includes fats, fatty acid esters and fat soluble vitamins and therefore also referred as crude fat. EE is also an important indicator of forages quality and animal prefers forages with higher crude fat, CP and total phenolics and lower lignin and tannin (Agetsuma et al., 2019). Crude fats have more energy per unit dry weight compared with the carbohydrates (National Research Council, 1989). Thus, improving the nutritional quality of fodder maize is important for livestock husbandry.

Previous research suggested that N fertilization and irrigation could improve the yield of various crops (Ali et al., 2019a; Su et al., 2020; Xu et al., 2020; Ahmad et al., 2021a, 2021b). However, the effect of N fertilization and supplemental irrigation levels on the soil physio-chemical properties, GHG emissions, GWP, GHGI, yield and nutritional quality of fodder maize is limited, especially in arid regions. Due to deficit precipitation (110.7 mm) in the study area a large amount of flood irrigation is applied to fodder maize. Furthermore, N is applied at a higher rate (> 450 kg N ha^{-1}) for fodder maize production in the region. The objectives of the experiment were to: (1) examine the effect of N fertilization and supplemental irrigation levels on soil water content, soil temperature, soil ammonium nitrogen content (NH_4^+-N) and NO_3^--N; (2) to investigate the effect of N fertilization and supplemental irrigation levels on GHG emissions, cumulative GHG emissions, GWP and GHGI; (3) to study the effect of N fertilization and supplemental irrigation levels on forage yield, yield components, grain yield and nutritional quality of fodder maize in an arid region. The results of the current experiment provide important insights regarding improvement of productivity of fodder maize in arid regions and reduce GHG emissions, GWP and GHGI.

2. Methods and materials

2.1. Experimental site, experimental design and field management

The experiment was carried out in 2015 and 2016 at the experimental station of Lanzhou University, Minqin Oasis (103°05′N, 38°38′E), Gansu province, China. The climate of the research area is an arid desert type. The rainfall is deficit having higher evaporation, and the daily temperature changes greatly. The mean annual temperature of the experimental site was 7.6 °C having frost free days of 175. The multi-year average precipitation was 110.7 mm and the average annual evaporation was 2643.9 mm, which is 24 times the amount of precipitation. The average wind speed was 2.2 m s^{-1}, whereas the highest in spring was 2.7 m s^{-1} and in autumn 1.9 m s^{-1}. The nutrient status of the top 0–10, 10–20, and 20–30 cm soil layer has been shown in Table 1. Meteorological data of the study site including precipitation and temperature were obtained from the Gansu meteorological bureau and was shown in Fig. 1.

Maize variety Jin Pingguo No. 618, which is commonly grown for fodder production in arid regions was sown in the current experiment. Each plot was 100 m^2 (10 m × 10 m) and the inter row and intra plant spacing was maintained at 30 cm. To prevent side seepage, each plot was isolated with an impermeable plastic membrane and a ridge is raised. The plot to plot distance was maintained at 2 m. The experimental design used was factorial design having four repeats. There were two factors in the experiment and factor A was N rates i.e., 225 (N_1), 300 (N_2) and 375 kg N ha^{-1} (N_3) and factor B was two supplemental irrigation (drip irrigation) levels i.e., 600 (W_1) and 900 mm ha^{-1} (W_2). As a whole there were six treatments in the experiment and the treatment combination comprised of N_1W_1, N_2W_1, N_3W_1, N_1W_2, N_2W_2, and N_3W_2. Three different levels of N (urea, 46% N) were applied in two split doses, whereas half of the N was applied at seedbed preparation and the other half before tasseling stage. The two supplemental irrigation levels were uniformly applied after sowing, at jointing stage, at tenth leaf stage, at silking stage, and at milk stage to all the experimental plots. In W_1 in

Table 1
The soil chemical properties of the experimental site of the soil layers (0–30 cm).

Soil layer (cm)	SOC (g kg^{-1})	TN (g kg^{-1})	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	TP (g kg^{-1})	AP (mg g^{-1})
0–10	5.51	1.07	5.41	4.5	0.86	10.87
10–20	4.73	0.86	5.33	4.4	0.74	9.25
20–30	4.35	0.83	4.17	4.7	0.68	8.19

SOC: soil organic carbon content; TN: total nitrogen content; NO3−-N: nitrate nitrogen content; NH4 + -N: ammonium nitrogen content; TP: total phosphorus; AP: available phosphorus. Data is the mean of two years (in 2015 the NO3−-N was lower whereas higher during 2016)

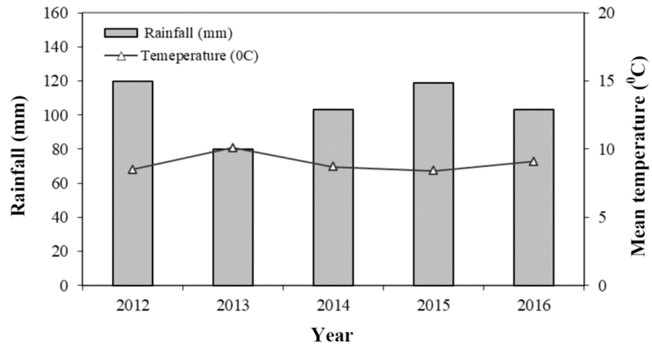

Fig. 1. Annual precipitation and mean temperature from 2012 to 2016 at the experimental site.

each stage 120 mm irrigation and in W_2 in each stage 180 mm irrigation was applied. Recommended dose of phosphorus (single super phosphate, 16% P_2O_5) and potassium (potassium sulfate, 45% K_2O) at rates of 150 kg ha^{-1} were applied at the time of seedbed preparation to all treatments.

2.2. Samplings and measurements

2.2.1. Soil moisture content (SMC, %) and soil temperature (ST, °C)

SMC from 0 to 30 cm soil depth was determined at the time of sowing, sixth leaf stage, tasseling stage, dough stage, and at physiological maturity stage. SMC was measured uses the gravimetric method and the samples were dried in an oven at 105 °C for 24 h, and then at 75 °C till constant weight (Zhang et al., 2019).

SMC (%) $=$ (Fresh soil ***weight*** − Dry soil weight)/Dry soil ***weight*** × 100

Mercury-in-glass geo-thermometers with bent stem were installed in the center of each replication at a soil depth of 5 cm to determine the ST. ST was measured at the time of sowing, sixth leaf stage, tasseling stage, dough stage, and at physiological maturity stage. The ST was recorded at 08, 10, 14, and 18 h daily.

2.2.2. NH_4^+-N and NO_3^--N

NH_4^+-N and NO_3^--N from 0 to 30 cm soil depth were determined at sixth leaf stage, tasseling stage, dough stage, and at physiological maturity stage. Soil samples were sieved through 2.0 mm sieve and then were extracted with 0.01 M $CaCl_2$ solution (Hu et al., 2013b). The extracts were then analyzed with an automated continuous flow analyzer (TRAACS 2000 system, Bran and Luebbe, Norderstedt Germany).

2.2.3. GHG collection and measurements

GHG emissions were measured at the time of sowing, sixth leaf stage, tasseling stage, dough stage, and at physiological maturity stage during both growth seasons. A static box (black box) was used to collect and measure GHG emissions from 9:00–11:30 AM. The static box was made of stainless steel. It consists of a square base, the outer side was 35 cm long, the inner side was 27.5 cm long, and the box bottom side was 30 cm long to ensure the determination of the whole plant. The height of the box was designed at 30 cm, 100 cm and 200 cm. In each equidistant we installs fans for mixed gases inside the box. The base was inserted in soil at 50 mm at the time of sowing. When measuring, the box was put into the groove of the base vertically. The fans were turned on and at 0, 10, 20 and 30 min after the box is covered, and 50 ml gas was collected from the box. Temperature inside the box and ST of 5 cm soil depth before and after the cover were measured. The sampled gas was connected to the Los Gatos Research (LGR) CO_2 and CH_4 analyzer (DLT-100, Model No. 908–0011–0001, Los Gatos Research, 3055 Orchard Drive San Jose, United States) to measure CH_4 and CO_2 concentrations, and the LGR CO and N_2O gas analyzer (Model No. 908–0015–0000, Los Gatos Research, 3055 Orchard Drive San Jose, United States) to measure N_2O concentration. The gas emissions flux was calculated as follows (Hu et al., 2013b).

$$F = \rho \times \frac{V}{A} \times \frac{Ps}{Po} \times \frac{To}{T} \times \frac{dc}{dt}$$

Where, F is gas emission flux, ρ is density of CH_4, N_2O, and CO_2 under standard state, and A is base area of static box (m^2), V is volume of the static box (m^3), P_S is the atmospheric pressure (kPa) where sample is collected, P_0 is the atmospheric pressure under standard conditions (101.325 kPa), and T is absolute temperature inside the static box during sampling (Kelvin, K), T_0 is the absolute temperature in the standard condition (273.2 Kelvin, K), dc/d_t is rate of change of gas concentrations over time.

2.2.4. Cumulative emissions CO_2, N_2O and CH_4, GWP and GHGI

Cumulative emission of CO_2, N_2O and CH_4 were calculated according to Afreh et al. (2018).

$$Y = \frac{\sum_{i=1}^{n}(F_i + F_{i+1})}{2} \times (t_{i+1} - t_i) \times 24$$

Where, Y is cumulative emissions of growth period (kg ha^{-1}). F_i is gas emissions fluxes of CO_2, N_2O and CH_4, F_{i+1} is next measured fluxes, (t_{i+1}-t_i) is numbers of days between two adjacent measurement, n is the total determination number.

GWP was calculated according to Afreh et al. (2018).

$$\mathrm{GWP(kg\ CO2eq.ha{-}1yr{-}1)} \quad = 298Y_{N_2O} + 25Y_{CH_4}$$

Where Y_{N_2O} is the N_2O cumulative flux in kg ha^{-1} and Y_{CH_4} is the CH_4 cumulative flux in kg ha^{-1}, 298 and 25 are the conversion coefficients of N_2O and CH_4 to CO_2-eq. (Forster et al., 2007).

GHGI was calculated according to Lyu et al. (2019) as follows;.

GHGI (kg CO_2-eq t^{-1} crop yield yr^{-1}) = GWP / Grain Yield

2.2.5. Forage yield (kg ha^{-1})

Two square meter area was randomly selected in each replication at sixth leaf stage, tasseling stage, dough stage, and at physiological maturity stage for the determination of forage yield. The plants were cut at ground level and immediately weighted with electronic balance.

2.2.6. CP (%), NDF (%), ADF (%) and EE (%)

The CP was determined at sixth leaf stage, tasseling stage, dough stage, and at physiological maturity stage. The plants initially used for measuring the forage yield were dried in an oven at 65 °C till constant weight (Lloveras and Iglesias, 2001; Cheng et al., 2015). The whole plants were crushed and ground into powder by using a Thomas–Wiley laboratory Mill (Model 4, Thomas Scientific, Swedesboro, NJ, USA) of 1 mm sieve. We weighed (0.3–0.4 g) samples and were mineralized by using H_2SO_4-H_2O_2, and the N content was determined by using Kjeldhal analyzer (FOSS, Västra Götaland, Sweden, Nelson and Sommers, 1973). CP was determined as N content multiplied by 6.25 (Nelson and Sommers, 1980; Lloveras and Iglesias, 2001).

The NDF, ADF and EE were determined at physiological maturity stage. Five plants were randomly selected in each replication in central rows by avoiding side rows and cut at ground level. The whole plants were cut in small pieces and dried in an oven at 65 °C until constant weight (Cheng et al., 2015). The whole plants were crushed and ground into powder by using a Thomas–Wiley laboratory Mill (Model 4, Thomas Scientific, Swedesboro, NJ, USA). Standard procedures were used for NDF, ADF and EE analysis. Standard procedure (Van Soest et al., 1991; Robinson et al., 1999; Elgersma et al., 2013) was used for the determination of NDF and ADF by using the ANKOM fiber technique and the instrument used was ANKOM A220 semi-automatic cellulose analyzer (ANKOM Technology, Macedon NY, USA). Procedure of the Association of Official Analytical Chemists (AOAC, 2000) was used for the determination of crude fat or EE by using the Soxlet extraction method. The instrument used was ANKOM AXT15i automatic fat analyzer (ANKOM Technology, Macedon NY, USA).

2.2.7. Ear length, ear diameter, grains per ear, and grain yield

Ten ears were randomly selected from each replication for measuring the ear length, ear diameter and grains per ear. Ear length was measured with measuring tape, whereas ear diameter with a digital vernier caliper. Six central rows were harvested at the time of harvest maturity. The cobs were detached from the husks and air-dried for 10 days. After threshing the grain yield was measured and expressed in t ha^{-1}.

2.3. Statistical analysis

Treatments effect on the SMC, ST, NH_4^+-N, NO_3^--N, GHG emissions, cumulative emission of CO_2, N_2O and CH_4, GWP, GHGI, forage yield, CP, NDF, ADF, EE, ear length, ear diameter, grains per ear, and grain yield of fodder maize were examined with analysis of variance by using SPSS 17.0. Mean comparisons were determined with least significant difference test (LSD test) at $P \leq 0.05$.

3. Results

3.1. SMC (%) and ST (°C)

N fertilization and supplemental irrigation levels significantly affected SMC and ST at sixth leaf stage, tasseling stage, dough stage, and at physiological maturity stage during both growth seasons (Fig. 2). SMC increased after sowing and reached to its maximum at dough stage during both growth seasons. ST was higher at sowing and then decreased at sixth leaf stage, again increased at tasseling stage and then showed a decreasing trend until physiological maturity stage. SMC was high and ST was low during 2015 growth season, whereas SMC was low and ST was high during 2016 growth season. SMC was high and ST was low in W_2 compared with the W_1 during both growth seasons. During 2015 growth season, under W_1 increasing N rate increased SMC and then decreased it at N_3, whereas under W_2 increasing N rate gradually increased SMC. During 2016 growth season, increasing N rate gradually increased SMC under both supplemental irrigation levels. During 2015 growth season, under W_1 increasing N rate decreased ST and then increased it at N_3, whereas under W_2 increasing N rate decreased ST. During 2016 growth season increasing N rate decreased ST under both supplemental irrigation levels. Maximum SMC and minimum ST during both growth seasons were recorded in N_3W_2.

3.2. NH_4^+-N and NO_3^--N

Application of N and supplemental irrigation levels significantly affected NH_4^+-N and NO_3^--N during 2015 and 2016 growth season (Fig. 3). NH_4^+-N and NO_3^--N were high at sixth leaf stage, decrease at tasseling stage, again increase at dough stage and then decrease at physiological maturity stage, whereas minimum NH_4^+-N and NO_3^--N were recorded at physiological maturity stage. NH_4^+-N and NO_3^--N were low during 2015 growth season while high in 2016 growth season. NH_4^+-N and NO_3^--N were higher in W_1 and lower in W_2 during both growth seasons. During 2015 growth season, minimum NH_4^+-N at sixth

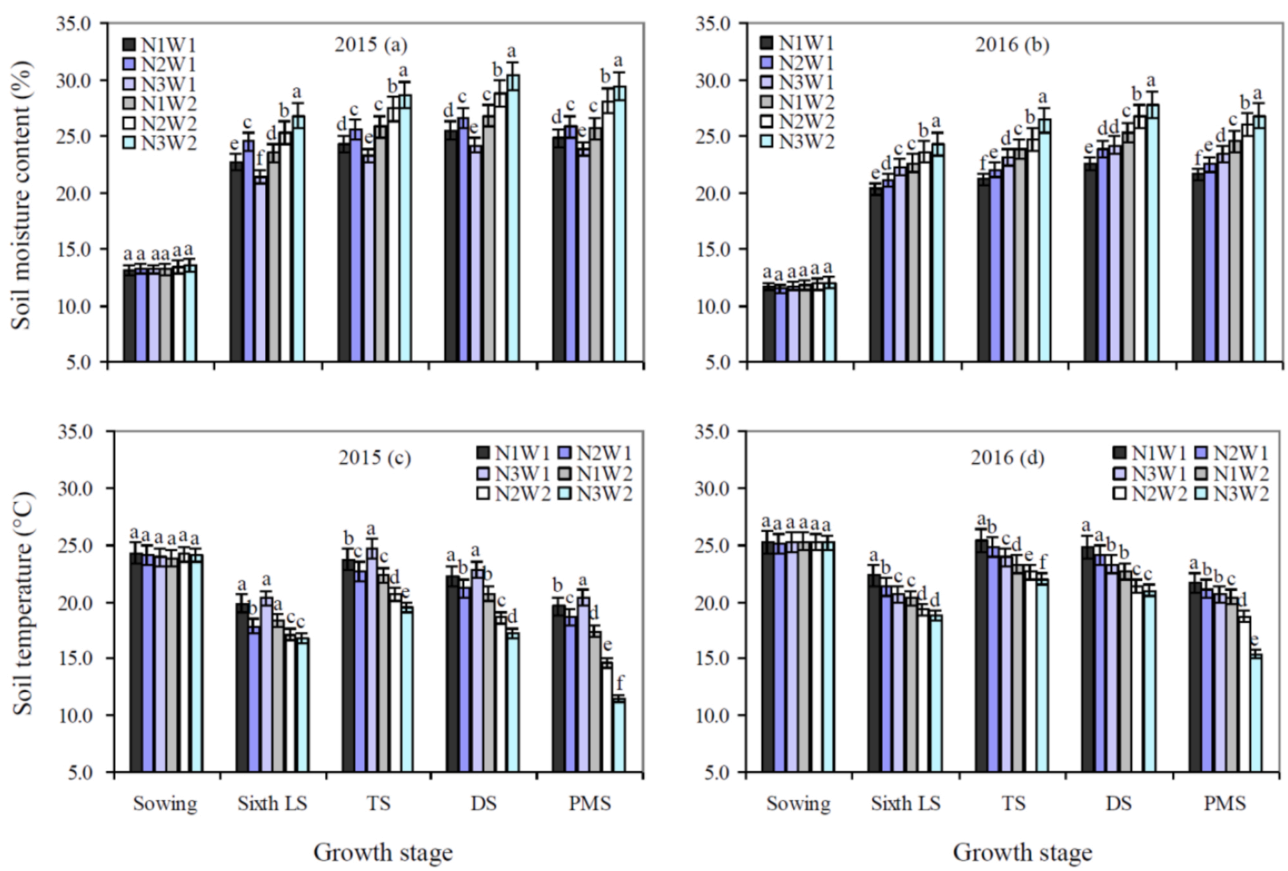

Fig. 2. Effects of nitrogen rates and supplemental irrigation levels on soil moisture content (a, b) in the top 30 cm of the soil depth and soil temperature (c, d) at 5 cm soil depth at the time of sowing, sixth leaf stage (Sixth LS), tasseling stage (TS), dough stage (DS), and at physiological maturity stage (PMS) of fodder maize in an arid area during 2015 and 2016 growth season. N_1W_1 (225 kg ha^{-1} nitrogen + 600 mm ha^{-1} irrigation level); N_2W_1 (300 kg ha^{-1} nitrogen + 600 mm ha^{-1} irrigation level); N_3W_1 (375 kg ha^{-1} nitrogen + 600 mm ha^{-1} irrigation level); N_1W_2 (225 kg ha^{-1} nitrogen + 900 mm ha^{-1} irrigation level); N_2W_2 (300 kg ha^{-1} nitrogen + 900 mm ha^{-1} irrigation level) and N_3W_2 (375 kg ha^{-1} nitrogen + 900 mm ha^{-1} irrigation level). Vertical bars represent the means ± SD ($n = 4$).

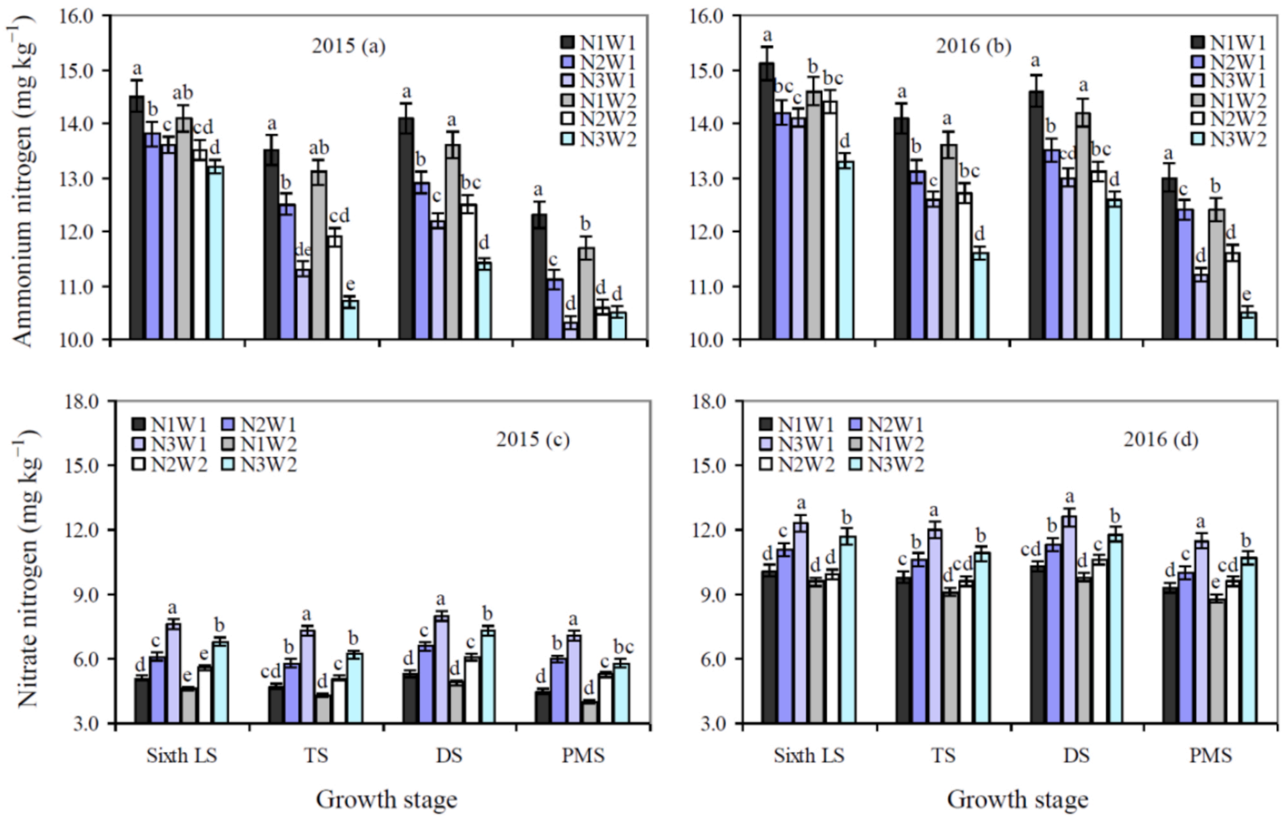

Fig. 3. Effects of nitrogen rates and supplemental irrigation levels on soil ammonium nitrogen content (a, b) and nitrate nitrogen content (c, d) in the top 30 cm of the soil depth at sixth leaf stage (Sixth LS), tasseling stage (TS), dough stage (DS), and at physiological maturity stage (PMS) of fodder maize in an arid area during 2015 and 2016 growth season. Vertical bars represent the means ± SD ($n = 4$). The abbreviation of the treatments names are the same as those described in Fig. 2.

leaf stage, tasseling stage and dough stage were recorded in N_3W_2, and at physiological maturity stage in N_3W_1. During 2016 growth season, minimum NH_4^+-N was recorded in N_3W_2. Increasing N rate gradually increased NO_3^--N and its minimum values were obtained in N_1W_2 during 2015 and 2016 growth season.

3.3. GHG emissions

N fertilization and supplemental irrigation levels significantly affected CH_4, CO_2 and N_2O emissions during 2015 and 2016 growth season (Fig. 4). The soil of the maize field behaved as CH_4 sink. The CH_4 uptake gradually increased after sowing and reached to its maximum at dough stage, and again decreased at physiological maturity stage. Minimum CH_4 uptake was recorded at physiological maturity stage. The CH_4 uptake was higher during 2015 growth season compared with the 2016 growth season. The CH_4 uptake was higher in W_1 compared with the W_2. Under W_1 at the time of sowing, sixth leaf stage and tasseling stage, increasing N rate increased CH_4 uptake and then decreased it under N_3, however at dough stage and at physiological maturity stage, increasing N rate gradually increased CH_4 uptake. Under W_2, increasing N rate increased CH_4 uptake during both growth seasons. Maximum CH_4 uptake at the time of sowing, sixth leaf stage and tasseling stage were recorded in N_2W_1 and at dough stage and physiological maturity stage in N_3W_1 followed by N_3W_2 during both growth seasons.

The CO_2 emission gradually increased after sowing and reached to its maximum at dough stage, and then declined at physiological maturity stage during both growth seasons. The CO_2 emission was higher in W_1 compared with the W_2. Under W_1, increasing N rate increased CO_2 emission during both growth seasons. In 2015 growth season in W_2, increasing N rate gradually increased CO_2 emission; however in 2016 growth season increasing N rate increased CO_2 emission and then decreased it under N_3. The CO_2 emission was lower during 2015 growth season and was higher in 2016 growth season. Maximum CO_2 emission was recorded in N_3W_1 during both growth seasons.

The N_2O emission gradually increased from sowing to sixth leaf stage, decreased at tasseling stage and reached to its maximum at dough stage and then decline at physiological maturity stage during both growth seasons. The N_2O emission was lower during 2015 growth season and was higher in 2016 growth season. The N_2O emission was higher in W_1 compared with the W_2 during both growth seasons. In W_1 and W_2, increasing N rate increased the N_2O emission during both growth seasons. Maximum N_2O emission was recorded in N_3W_1 during both growth seasons. Our results suggested that different N rates under supplemental irrigation levels significantly affected CH_4, CO_2 and N_2O emissions during 2015 and 2016 growth season.

3.4. Cumulative emissions of CO_2, N_2O and CH_4, GWP and GHGI

N rates and supplemental irrigation levels significantly affected cumulative emissions of CO_2, N_2O and CH_4, GWP and GHGI during 2015 and 2016 (Table 2). The interaction between N rates and supplemental irrigation levels on cumulative emission of CO_2, N_2O and CH_4, GWP and GHGI were highly significant during both growth seasons. The cumulative emission of CO_2 and N_2O, GWP and GHGI were lower during 2015 growth season and were higher in 2016 growth season. The cumulative CH_4 uptake was higher in 2015 growth season and was lower in 2016 growth season. The cumulative emission of CO_2, N_2O and CH_4 uptake, GWP and GHGI were higher in W_1 compared with W_2. During both growth seasons, increasing N rate increased cumulative emissions of N_2O, CH_4 uptake, GWP and GHGI. During both growth seasons, in W_1 increasing N rate increased cumulative emission of CO_2. During 2015 growth season, in W_2 increasing N rate increased cumulative emission of CO_2, however in 2016 growth season increasing N rate increased cumulative emission of CO_2 and then decreased it in N_3. Maximum

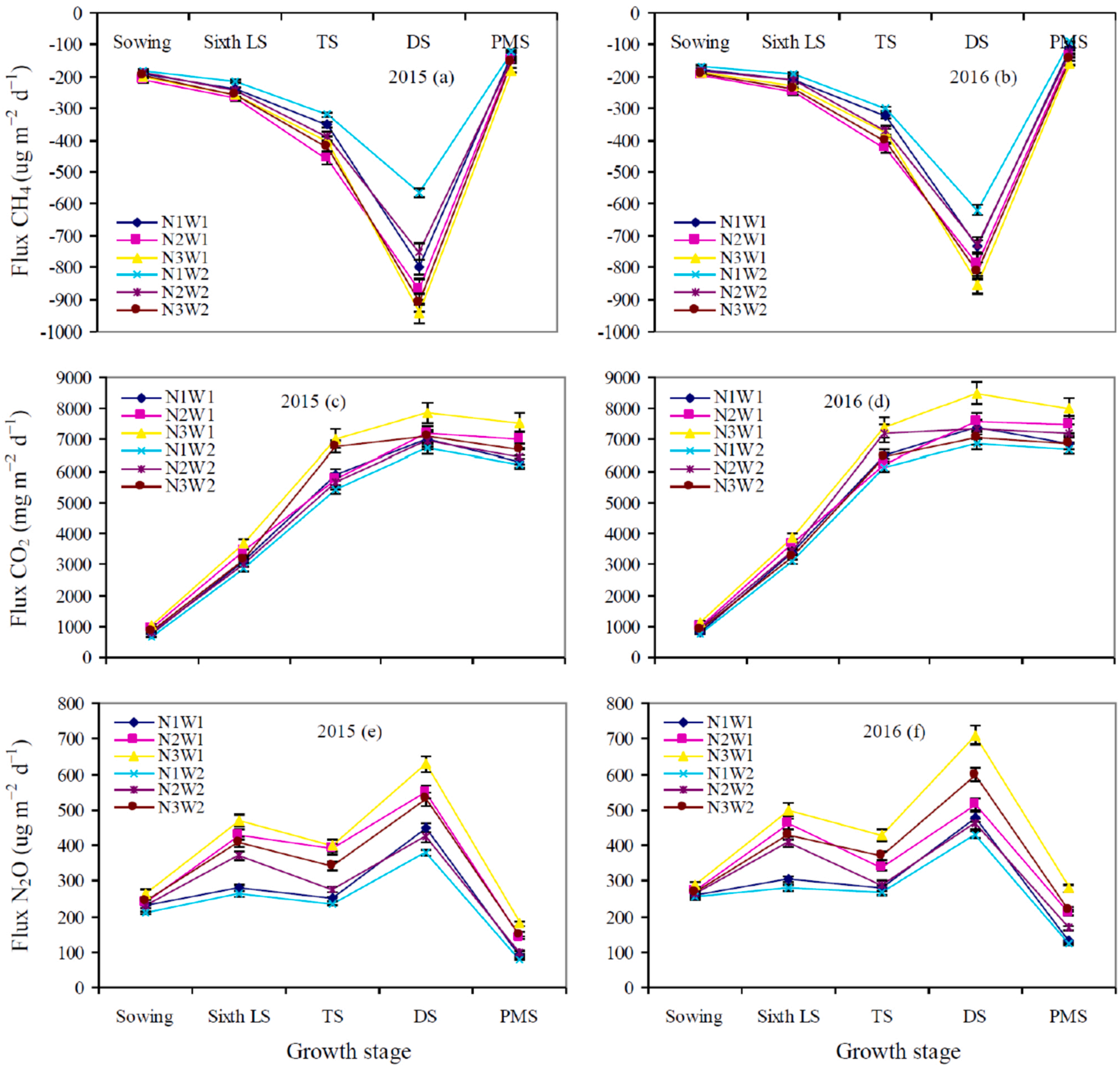

Fig. 4. Effects of nitrogen rates and supplemental irrigation levels on the dynamic of methane emission (a, b), carbon dioxide emission (c, d) and nitrous oxide emission (e, f) at the time of sowing, sixth leaf stage (Sixth LS), tasseling stage (TS), dough stage (DS), and at physiological maturity stage (PMS) of fodder maize in an arid area during 2015 and 2016 growth season. Vertical bars represent the means ± SD ($n = 4$). The abbreviation of the treatments names are the same as those described in Fig. 2.

cumulative emission of CO_2 and N_2O, GWP and GHGI were obtained in N_3W_1 compared with the other treatments.

3.5. Forage yield

Forage yield was significantly affected by N fertilization and supplemental irrigation levels at different growth stages during 2015 and 2016 growth season (Table 3). The interaction between N rates and supplemental irrigation levels on the forage yield was highly significant during both growth seasons. The forage yield reached to its maximum at dough stage and then decrease at physiological maturity stage. The forage yield was lower at physiological maturity stage compared with the dough stage due to yellowing of above-ground plant parts. The forage yield was higher during 2015 growth season compared with the 2016. The forage yield was significantly higher in W_2 compared with the W_1. During 2015 in W_1, increasing N rate increased the forage yield and then decreased it under N_3; however in 2016 growth season increasing N rate increased the forage yield. In W_2 during both growth seasons, increasing N rate increased the forage yield. Maximum forage yield during both growth seasons were recorded in N_3W_2.

3.6. CP (%), NDF (%), ADF (%) and EE (%)

CP is an important indicator of forages quality and higher the CP the higher will be the nutritional quality of forages. CP at different growth stages was significantly affected by N fertilization and supplemental irrigation levels during 2015 and 2016 growth season (Table 4). The interaction between N rates and supplemental irrigation levels on the CP at dough stage in 2015 growth season, and at tasseling stage and physiological maturity stage during 2016 growth season was significant. CP was higher at sixth leaf stage and then showed a decreasing trend and minimum CP was recorded at physiological maturity stage. CP was

Table 2

Effects of nitrogen rates and supplemental irrigation levels on carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) cumulative emissions, global warming potential (GWP) and greenhouse gas intensity (GHGI) in the 2015 and 2016 fodder maize growing season.

Year	Nitrogen rates[a]	Irrigation levels[b]	CO_2 cumulative emission (kg ha^{-1})	N_2O cumulative emission (kg ha^{-1})	CH_4 cumulative emission (kg ha^{-1})	GWP (kg CO_2-eq ha^{-1} yr^{-1})	GHGI (kg CO_2-eq t^{-1} crop yield yr^{-1})
2015	N_1	W_1	5860d	3.42e	-4.65b	903e	0.100c
	N_2	W_1	6097c	4.68b	-5.33c	1262b	0.134b
	N_3	W_1	6849a	5.17a	-5.37c	1406a	0.153a
	N_1	W_2	5542e	3.08 f	-3.75a	823 f	0.084d
	N_2	W_2	5774d	3.70d	-4.64b	987d	0.091 cd
	N_3	W_2	6250b	4.44c	-5.29c	1191c	0.098 cd
	Average	N_1	5700c	3.25c	-4.20a	863c	0.092c
		N_2	5935b	4.19b	-4.98b	1124b	0.112b
		N_3	6550a	4.81a	-5.33c	1299a	0.125a
		W_1	6268a	4.42a	-5.11b	1190a	0.129a
		W_2	5854b	3.74b	-4.56a	1000b	0.091b
	ANOVA[c]	N	**	**	**	**	**
		W	**	**	**	**	**
		N × W	**	**	**	**	**
2016	N_1	W_1	6347d	3.78e	-4.24b	1021e	0.126c
	N_2	W_1	6516c	4.67c	-4.88c	1270c	0.151b
	N_3	W_1	7301a	5.77a	-4.90c	1598a	0.180a
	N_1	W_2	5947f	3.50f	-3.72a	949f	0.101d
	N_2	W_2	6617b	4.13d	-4.38b	1121d	0.112cd
	N_3	W_2	6181e	4.94b	-4.86c	1349b	0.119c
	Average	N_1	6147c	6.64c	-3.98a	985c	0.113c
		N_2	6567b	4.40b	-4.62b	1195b	0.131b
		N_3	6741a	5.36a	-4.88c	1473a	0.149a
		W_1	6721a	4.74a	-4.67b	1296a	0.152a
		W_2	6248b	4.19b	-4.31a	1139b	0.110b
	ANOVA[c]	N	**	**	**	**	**
		W	**	**	**	**	**
		N × W	**	**	**	**	**

Values are means of four replicates and different lowercase letters within a column indicate significant differences at $P \leq 0.05$ (LSD test).

[a] N_1 means nitrogen application at a rate of 225 kg ha^{-1}; N_2 means nitrogen application at a rate of 300 kg ha^{-1}; N_3 means nitrogen application at a rate of 375 kg ha^{-1}.

[b] W_1 means 600 mm ha^{-1} irrigation level; W_2 means 900 mm ha^{-1} irrigation level.

[c] ANOVA indicates analysis of variance; * indicates significance at 5% probability level; ** indicates significance at 1% probability level; ns indicates non significance; N means nitrogen rates; W means irrigation levels.

higher during 2015 growth season, whereas lower in 2016 growth season. CP was significantly high in W_2 compared with the W_1. In W_1 and W_2 during both growth seasons, increasing N rate gradually increased CP. Maximum CP during both growth seasons were recorded in N_3W_2 followed by N_2W_2, whereas minimum CP was recorded in N_1W_1.

NDF, ADF and EE are also important indicators of forages quality. If the NDF and ADF are lower, the nutritional quality of forages will be higher. Our results suggested that NDF, ADF and EE at physiological maturity stage were significantly affected by N rates and supplemental irrigation levels during both growth seasons (Table 5). The interaction between N rates and supplemental irrigation levels on NDF, ADF and EE during 2015, and the interaction between N rates and supplemental irrigation levels on ADF during 2016 growth season was significant. NDF and ADF were lower during 2015 growth season, whereas higher in 2016 growth season. EE was higher in 2015 growth season and was lower in 2016 growth season. NDF and ADF were higher in W_1 and lower in W_2, whereas EE was lower in W_1 and higher in W_2. In W_1 in 2015 growth season, increasing N rate decreased NDF and ADF and again increased NDF and ADF in N_3. In W_1 in 2016 growth season, increasing N rate decreased NDF and ADF. In W_1 in 2015 growth season, increasing N rate increased EE and then decreased it in N_3, however in 2016 growth season increasing N rate increased EE. In W_2 during both growth seasons, increasing N rate decreased NDF and ADF and increased EE. Maximum NDF and ADF during both growth seasons were recorded in N_1W_1 and minimum in N_3W_2. Maximum EE during both growth seasons was recorded in N_3W_2 and minimum in N_1W_1. Our results suggested that N fertilization and supplemental irrigation levels significantly affected the nutritional quality of fodder maize. Treatment N_3W_2 has higher nutritional quality compared with the other treatments during both growth seasons.

3.7. Ear length, ear diameter, grains per ear, and grain yield

N fertilization and supplemental irrigation levels significantly affected ear length, ear diameter, grains per ear, and grain yield of fodder maize (Table 6). The interaction between N rates and supplemental irrigation levels on ear diameter, grains per ear, and grain yield during both growth seasons were significant. The interaction between N rates and supplemental irrigation levels on ear length was significant during 2015 growth season, whereas non-significant during 2016 growth season. Ear length, ear diameter, grains per ear, and grain yield were higher during 2015 growth season, while lower in 2016 growth season. Ear length, ear diameter, grains per ear, and grain yield were higher in W_2 while lower in W_1. In W_1 during 2015 growth season, increasing N rate increased ear length, ear diameter, grains per ear, and grain yield and then decreased it under N_3, however during 2016 growth season increasing N rate gradually increased ear length, ear diameter, grains per ear, and grain yield. In W_2 during both growth seasons, increasing N rate increased ear length, ear diameter, grains per ear, and grain yield. Maximum ear length, ear diameter, grains per ear, and grain yield during both growth seasons were recorded in N_3W_2 compared with the other treatments.

4. Discussion

4.1. Effects of N fertilization and supplemental irrigation on SMC, ST, NH_4^+-N and NO_3^--N

In arid and semi-arid areas deficit and erratic precipitation can

Table 3
Effects of nitrogen rates and supplemental irrigation levels on forage yield (FY, kg ha^{-1}) at sixth leaf stage (Sixth LS), tasseling stage (TS), dough stage (DS), and at physiological maturity stage (PMS) of fodder maize in an arid area during 2015 and 2016.

Year	Nitrogen rates[a]	Irrigation levels[b]	FY (kg ha^{-1}) (Sixth LS)	FY (kg ha^{-1}) (TS)	FY (kg ha^{-1}) (DS)	FY (kg ha^{-1}) (PMS)
2015	N_1	W_1	510f	12400e	25000f	16000f
	N_2	W_1	570d	13600c	29000d	20000d
	N_3	W_1	540e	13000d	27500e	17300e
	N_1	W_2	590c	13800c	31050c	21000c
	N_2	W_2	630b	14400b	34000b	23000b
	N_3	W_2	652a	15000a	35100a	26500a
	Average	N_1	550b	13100b	28025c	18500c
		N_2	600a	14000a	31500a	21500b
		N_3	596a	14000a	31300b	21900a
		W_1	540b	13000b	27167b	17766b
		W_2	624a	14400a	33383a	23500a
	ANOVA[c]	N	**	**	**	**
		W	**	**	**	**
		N × W	**	**	**	**
2016	N_1	W_1	465e	10500f	23000f	14000f
	N_2	W_1	494d	11700e	25700e	16000e
	N_3	W_1	500d	12400d	26400d	18300d
	N_1	W_2	530c	13100c	28300c	20300c
	N_2	W_2	578b	13500b	30210b	21900b
	N_3	W_2	608a	14344a	32413a	23400a
	Average	N_1	497c	11800c	25650c	17150c
		N_2	536b	12600b	27955b	18950b
		N_3	554a	13367a	29415a	20850a
		W_1	486b	11533b	25033b	16100b
		W_2	572a	13644a	30313a	21866a
	ANOVA[c]	N	**	**	**	**
		W	**	**	**	**
		N × W	**	**	**	**

Values are means of four replicates and different lowercase letters within a column indicate significant differences at P ≤ 0.05 (LSD test).
[a] N_1 means nitrogen application at a rate of 225 kg ha^{-1}; N_2 means nitrogen application at a rate of 300 kg ha^{-1}; N_3 means nitrogen application at a rate of 375 kg ha^{-1}.
[b] W_1 means 600 mm ha^{-1} irrigation level; W_2 means 900 mm ha^{-1} irrigation level.
[c] ANOVA indicates analysis of variance; * indicates significance at 5% probability level; ** indicates significance at 1% probability level; ns indicates non significance; N means nitrogen rates; W means irrigation levels.

Table 4
Effects of nitrogen rates and supplemental irrigation levels on crude protein content (CP, %) at sixth leaf stage (Sixth LS), tasseling stage (TS), dough stage (DS), and at physiological maturity stage (PMS) of fodder maize in an arid area during 2015 and 2016.

Year	Nitrogen rates[a]	Irrigation levels[b]	CP (%) (Sixth LS)	CP (%) (TS)	CP (%) (DS)	CP (%) (PMS)
2015	N_1	W_1	9.5e	8.1e	6.4f	5.6e
	N_2	W_1	11.3d	9.2d	7.3e	6.5d
	N_3	W_1	13.1c	11.5c	9.5c	7.6 bc
	N_1	W_2	12.6c	11.0c	8.8d	7.3c
	N_2	W_2	14.2b	12.3b	10.2b	8.1b
	N_3	W_2	16.8a	14.5a	11.1a	8.9a
	Average	N_1	11.0c	9.5c	7.6c	6.4c
		N_2	12.8b	10.7b	8.7b	7.3b
		N_3	15.0a	13.0a	10.3a	8.3a
		W_1	11.3b	9.6b	7.7b	6.6b
		W_2	14.5a	12.6a	10.0a	8.1a
	ANOVA[c]	N	**	**	**	**
		W	**	**	**	**
		N × W	ns	ns	**	ns
2016	N_1	W_1	8.9e	7.5e	5.7e	4.6e
	N_2	W_1	10.2d	8.7d	6.4d	5.3d
	N_3	W_1	11.9 bc	10.7c	8.1 bc	6.8c
	N_1	W_2	11.4c	10.2c	7.6c	6.5c
	N_2	W_2	12.5b	11.5b	8.5b	7.3b
	N_3	W_2	14.3a	12.6a	9.7a	7.8a
	Average	N_1	10.1c	8.9c	6.6c	5.6c
		N_2	11.3b	10.1b	7.4b	6.3b
		N_3	13.1a	11.6a	8.9a	7.3a
		W_1	10.3b	9.0b	6.7b	5.6b
		W_2	12.7a	11.4a	8.6a	7.2a
	ANOVA[c]	N	**	**	**	**
		W	**	**	**	**
		N × W	ns	*	ns	**

Values are means of four replicates and different lowercase letters within a column indicate significant differences at P ≤ 0.05 (LSD test).
[a] N_1 means nitrogen application at a rate of 225 kg ha^{-1}; N_2 means nitrogen application at a rate of 300 kg ha^{-1}; N_3 means nitrogen application at a rate of 375 kg ha^{-1}.
[b] W_1 means 600 mm ha^{-1} irrigation level; W_2 means 900 mm ha^{-1} irrigation level.
[c] ANOVA indicates analysis of variance; * indicates significance at 5% probability level; ** indicates significance at 1% probability level; ns indicates non significance; N means nitrogen rates; W means irrigation levels.

results in lower crops productivity and sometimes complete failure of the crops (Ali et al., 2019a; Jia et al., 2020). In addition, imbalance N fertilization can also leads to lower crops productivity and cause environmental pollution (Su et al., 2020; Ahmad et al., 2021b; Meng et al., 2021). Water and N fertilization are an effective way to improve soil fertility, water and N use efficiency (Galloway et al., 2008). Furthermore, optimum irrigation and N fertilization could increase the soil organic matter, soil total N and total phosphorus contents, thereby improving the soil environment and soil fertility, however under excessive irrigation and N fertilization conditions most of N fertilizer applied to the crops is leached in the form of NO_3^--N and making the ground water unfit for human consumptions (Durani, 2016; Ali et al., 2019a; Meng et al., 2021; Xia et al., 2021). Therefore, optimum irrigation and N fertilization are important to improve the productivity of fodder maize. SMC and ST are important for the crops growth and development (Zhou et al., 2012; Ali et al., 2018). Soil water content significantly affects the soil physio-chemical properties, and plays a key role in nitrification, denitrification and soil respiration (Xu et al., 2019). Our results suggested that SMC was higher and ST was lower during 2015 growth season compared with the 2016. The higher SMC and lower ST during 2015 were attributed to higher precipitation in 2015 compared with the 2016 (Fig. 1). SMC was higher and ST was lower in W_2 compared with the W_1. The higher SMC in W_2 resulted in lower ST compared with the W_1. Our previous research on winter wheat suggested that increasing simulated precipitation and limited irrigation levels improved SMC and reduced ST (Ali et al., 2018). Furthermore, increasing irrigation level increases the crop leaf area index and thus reduces the solar radiation at the soil levels, which results in lower ST (Ali et al., 2019b). Moreover, a more wet soil increases the soil evapotranspiration, thus decreasing ST (Ali et al., 2019a). Our results suggested that N rates also significantly affected SMC and ST. During 2015, under W_1 increasing N rate increased SMC and then decreased it in N_3, whereas under W_2 increasing N rate gradually increased SMC. During 2016, increasing N rate gradually increased SMC under both supplemental irrigation levels. During 2015, under W_1 increasing N rate decreased ST and then increased it in N_3, whereas under W_2 increasing N rate decreased ST. During 2016, increasing N rate decreased ST under both supplemental irrigation levels. Jia et al. (2020) reported that under traditional planting pattern and ridge furrow planting pattern, increasing N rate decreased the soil water storage. However our results suggested that maximum SMC and minimum ST during both growth seasons were recorded in N_3W_2. These results needs further study. N rates and supplemental irrigation levels also significantly affected NH_4^+-N and NO_3^--N. NH_4^+-N and NO_3^--N were higher in W_1 compared with the W_2. Minimum NH_4^+-N was recorded in N_3W_2. Increasing N rate

Table 5
Effects of nitrogen rates and supplemental irrigation levels on neutral detergent fiber (NDF, %), acid detergent fiber (ADF, %) and ether extract (EE, %) at physiological maturity stage of fodder maize in an arid area during 2015 and 2016.

Year	Nitrogen rates[a]	Irrigation levels[b]	NDF (%)	ADF (%)	EE (%)
2015	N_1	W_1	44.6a	26.3a	3.1d
	N_2	W_1	41.8b	23.1b	3.7 bc
	N_3	W_1	43.3a	24.2b	3.4cd
	N_1	W_2	43.8a	25.5a	3.5cd
	N_2	W_2	40.5 bc	21.8c	4.0b
	N_3	W_2	39.2c	20.5d	4.7a
	Average	N_1	44.2a	25.9a	3.3b
		N_2	41.1b	22.5b	3.9a
		N_3	41.3b	22.3b	4.0a
		W_1	43.2a	24.5a	3.4b
		W_2	41.2b	22.6b	4.0a
	ANOVA[c]	N	**	**	**
		W	**	**	**
		N × W	**	**	**
2016	N_1	W_1	46.6a	27.8a	2.6d
	N_2	W_1	43.5 bc	25.8b	3.2bcd
	N_3	W_1	42.3cd	23.9c	3.5 bc
	N_1	W_2	44.8b	26.7ab	3.0cd
	N_2	W_2	41.5de	22.6d	3.7ab
	N_3	W_2	40.7e	21.2e	4.2a
	Average	N_1	45.7a	27.2a	2.8b
		N_2	42.5b	24.2b	3.4a
		N_3	41.5c	22.5c	3.8a
		W_1	44.1a	25.8a	3.1b
		W_2	42.3b	23.5b	3.6a
	ANOVA[c]	N	**	**	**
		W	**	**	**
		N × W	ns	*	ns

Values are means of four replicates and different lowercase letters within a column indicate significant differences at P ≤ 0.05 (LSD test).
[a] N_1 means nitrogen application at a rate of 225 kg ha^{-1}; N_2 means nitrogen application at a rate of 300 kg ha^{-1}; N_3 means nitrogen application at a rate of 375 kg ha^{-1}.
[b] W_1 means 600 mm ha^{-1} irrigation level; W_2 means 900 mm ha^{-1} irrigation level.
[c] ANOVA indicates analysis of variance; * indicates significance at 5% probability level; ** indicates significance at 1% probability level; ns indicates non significance; N means nitrogen rates; W means irrigation levels.

Table 6
Effects of nitrogen rates and supplemental irrigation levels on ear length, ear diameter, grains per ear and grain yield of fodder maize in an arid area during 2015 and 2016.

Year	Nitrogen rates[a]	Irrigation levels[b]	Ear length (cm)	Ear diameter (mm)	Grains per ear	Grain yield (t ha^{-1})
2015	N_1	W_1	13.0f	44.1f	337f	9.0e
	N_2	W_1	13.9d	45.5d	368d	9.4d
	N_3	W_1	13.5e	44.8e	353e	9.2de
	N_1	W_2	14.4c	46.5c	383c	9.8c
	N_2	W_2	15.1b	47.8b	410b	10.9b
	N_3	W_2	15.9a	49.6a	446a	12.2a
	Average	N_1	13.7b	45.3c	360c	9.4c
		N_2	14.5a	46.7b	389b	10.1b
		N_3	14.7a	47.2a	399a	10.7a
		W_1	13.5b	44.8b	352b	9.2b
		W_2	15.1a	48.0a	413a	11.0a
	ANOVA[c]	N	**	**	**	**
		W	**	**	**	**
		N × W	**	**	**	**
2016	N_1	W_1	12.4d	42.3e	302f	8.1e
	N_2	W_1	12.7d	43.1d	321e	8.4e
	N_3	W_1	13.2c	44.0c	334d	8.9d
	N_1	W_2	13.7b	45.0b	361c	9.4c
	N_2	W_2	14.1b	45.7b	384b	10.0b
	N_3	W_2	14.7a	48.1a	423a	11.3a
	Average	N_1	13.0c	43.6c	331c	8.8c
		N_2	13.4b	44.4b	352b	9.2b
		N_3	13.9a	46.0a	378a	10.1a
		W_1	12.7b	43.1b	319b	8.5b
		W_2	14.2a	46.2a	389a	10.2a
	ANOVA[c]	N	**	**	**	**
		W	**	**	**	**
		N × W	ns	*	**	**

Values are means of four replicates and different lowercase letters within a column indicate significant differences at P ≤ 0.05 (LSD test).
[a] N_1 means nitrogen application at a rate of 225 kg ha^{-1}; N_2 means nitrogen application at a rate of 300 kg ha^{-1}; N_3 means nitrogen application at a rate of 375 kg ha^{-1}.
[b] W_1 means 600 mm ha^{-1} irrigation level; W_2 means 900 mm ha^{-1} irrigation level.
[c] ANOVA indicates analysis of variance; * indicates significance at 5% probability level; ** indicates significance at 1% probability level; ns indicates non significance; N means nitrogen rates; W means irrigation levels.

gradually increased NO_3^--N and its minimum values were obtained in N_1W_2. Maximum NO_3^--N during both growth seasons were recorded in N_3W_1. Previous study suggested that increasing N rate could increase NO_3^--N (Wang et al., 2010; Jia et al., 2021b). Excessive irrigation could also increase NO_3^--N leaching (Xing and Zhu, 2000). NO_3^--N was lower in supplemental irrigation compared with the rain-fed irrigation and application of N at a higher rate resulted in maximum NO_3^--N content in peanut crop (Xia et al., 2021). Lu et al. (2021a) suggested that conventional irrigation and N fertilization has higher NO_3^--N leaching compared with the drip fertigation in wheat-maize rotation system. Drip irrigation is an effective strategy to reduce N leaching and mitigate N_2O emission whereas furrow irrigation could results in higher N leaching (Yu et al., 2022). Li et al. (2022) suggested that optimum N fertilization and irrigation could reduce N leaching and improve the grain yield in spring wheat. Higher precipitation and irrigation could increase N leaching (Wu et al., 2020; Zotarelli et al., 2008), and the possibility of NO_3^--N leaching is higher when heavy precipitation occurs after irrigation in winter wheat-summer maize rotation regions (Lu et al., 2021b). However, our results suggested that NO_3^--N was lower in W_2 compared with the W_1. The reason might be that the study area is an arid area and the annual precipitation is just 110.7 mm, and in W_2 the plants absorbed more NO_3^--N compared with the W_1. Furthermore, our results are consistent with Xia et al. (2021) and Rath et al. (2021) that higher N application increased NO_3^--N leaching compared with the lower N application. Hu et al. (2013b) suggested that application of urea dropped NH_4^+-N, whereas NO_3^--N was higher for a longer period of time. Therefore, optimum irrigation and N fertilization are important to improve the productivity of fodder maize.

4.2. Effects of N fertilization and supplemental irrigation on GHG emissions, cumulative GHG emissions, GWP and GHGI

CH_4, N_2O and CO_2 in atmosphere are the important GHG that result in global warming worldwide and reduction in GHG emissions is a major challenging task to mitigate global warming (Mosier et al., 2006; Smith et al., 2008). Agricultural lands are a main source of N_2O and CH_4 emissions and accounts for 50% and 43%, respectively of global anthropogenic emission (Ding et al., 2017). Applications of chemical fertilizers significantly affect the soil quality and production of maize and thus affect the GHG emissions (Ma et al., 2014). Excessive application of fertilizers could lead to microbial denitrification, N leaching and N_2O emission (Wang et al., 2016; Kim et al., 2008). Optimum N fertilization could reduce GHG emissions compared with the no N fertilization (Trost et al., 2016). Applying N in split doses (half as a basal dose and half top dressing) have a significant effect on GHG emissions, N use efficiency and grain yield in winter wheat (Zhang et al., 2021). Our results suggested that N fertilization and supplemental irrigation levels significantly affected CH_4, N_2O and CO_2 emissions, cumulative emission of CH_4, N_2O and CO_2, GWP, and GHGI. The soil of the maize field behaved as CH_4 sink. CH_4 uptake at different growth stages and cumulative CH_4 uptake was higher during 2015 compared with the 2016. CH_4 uptake at different growth stages and cumulative CH_4 uptake was higher in W_1 compared with the W_2. The lower SMC and higher ST in W_1 resulted in higher CH_4 uptake and cumulative CH_4 uptake. Previous study suggested that CH_4 emission has a positive correlation with soil water content (Zhang et al., 2021); suggesting that higher the soil water content the lower will be CH_4 uptake. Hu et al. (2013b) also reported that CH_4 uptake was negatively correlated with water filled pore spaces and positively with ST. Our results showed that in W_1 at sowing, sixth leaf stage and tasseling stage, increasing N rate increased CH_4 uptake and then decreased it under N_3, however at dough stage and physiological maturity stage, increasing N rate gradually increased CH_4 uptake. Under W_2, increasing N rate increased CH_4 uptake during both growth seasons. Maximum CH_4 uptake at sowing, sixth leaf stage and tasseling stage were recorded in N_2W_1 and at dough stage and physiological maturity stage in N_3W_1 followed by N_3W_2 during both growth seasons. Linquist et al. (2012) suggested that N fertilization affects CH_4 emissions in rice field. N fertilization in split doses resulted in CH_4 uptake in winter wheat (Zhang et al., 2021). Zhu et al. (2019) also depicted that optimum N application enhanced CH_4 uptake. However, some studies suggested that N fertilization inhibit CH_4 uptake and thus indirectly contributes to GHG emissions (Mosier et al., 1991; Castro et al., 1995). This may be due to climatic conditions in the study areas. N_2O is formed through nitrification and denitrification of the soil microorganism (Jiang et al., 2016). N fertilization can provide available N to soil microorganisms and thus accelerates nitrification, denitrification and mineralization of microorganisms to affect the soil N_2O emission (Wang et al., 2018; Sun et al., 2020). Irrigation also influences N_2O emission (Trost et al., 2014). Our results suggested that N_2O emission at different growth stages and cumulative emission of N_2O was lower in 2015 compared with the 2016. The higher SMC and lower ST in W_2 resulted in lower N_2O emission and cumulative emission of N_2O compared with the W_1. Previous research suggested that soil water content affects N_2O emission (Silvia and Bohannan, 2016). Zhang et al. (2021) depicted that with the increase in soil water content the N_2O emission decreased in wheat field. Our results also showed that in W_1 and W_2 increasing N rate increased the N_2O emission and cumulative emission of N_2O. Maximum N_2O emission and cumulative emission of N_2O were recorded in N_3W_1. Nitrogen fertilization can increase NO_3^--N and provides substrate for field soil N_2O production (Linquist et al., 2012). The higher N_2O emission and cumulative emission of N_2O in N_3W_1 may be attributed to higher NO_3^--N. Zhang et al. (2021) also depicted that applying optimized N half as a basal dose and half top dressing reduced NH_4^+-N and NO_3^--N and thus decreased N_2O emission in wheat field. Our results suggested that CO_2 emission and cumulative emission of CO_2 was higher in W_1 compared with the W_2. Under W_1, increasing N rate increased CO_2 emission and cumulative emission of CO_2. In 2015 in W_2, increasing N rate gradually increased CO_2 emission and cumulative emission of CO_2; however in 2016 increasing N rate increased CO_2 emission and cumulative emission of CO_2 and then decreased it under N_3. Maximum CO_2 emissions and cumulative emission of CO_2 were recorded in N_3W_1. N fertilization can increase CO_2 emission (Gagnon et al., 2016; Yang et al., 2018). The carbon in N fertilizers is supposed to be emit as CO_2 (Zhang et al., 2021). CO_2 emission after N fertilization is associated with soil respiration and stimulation of microbial activity (Li et al., 2020). Furthermore, excessive N fertilization in wheat field decomposes into water and CO_2 (Zhang et al., 2017). Our result are in line with Jia et al. (2020), who also depicted that N fertilization under conventional flat planting without plastic mulch and ridge covered with plastic mulch condition enhanced CO_2 and N_2O emissions from maize field. Strategies for reducing GWP should be focus on nitrogen management to reduce GHG emissions and improve grain yield to reduce GHGI (Zhang et al., 2021). GHGI is the ratio of GHG emissions to grain yield and an indicator of the sustainability of production system (Shang et al., 2011; Lyu et al., 2019). GHGI could be reduced through N management practices by improving grain yield while reducing GHG emissions (Mosier et al., 2006). Zhang et al. (2021) reported that applying N into two split doses significantly reduced GWP and GHGI in winter wheat. Wang et al. (2020) suggested that water saving irrigation reduced GWP and GHGI. Our results suggested that N rates and supplemental irrigation levels significantly affected GWP and GHGI (Table 2). GWP and GHGI were lower during 2015 and were higher in 2016. The lower N_2O emission and higher CH_4 uptake in 2015 resulted in lower GWP compared with the 2016. Furthermore, the lower GWP and higher grain yield in 2015 resulted in lower GHGI compared with the 2016. During both years the GWP and GHGI were higher in W_1 compared with W_2. The higher GWP in W_1 was attributed mainly with higher N_2O emission compared with the W_2, whereas the higher GHGI in W_1 was attributed to higher GWP and lower grain yield compared with the W_2. Maximum GWP and GHGI during both years were recorded in N_3W_1 compared with the other treatments. Although the CH_4 emission was lower in N_3W_1 but the N_2O emission was significantly higher which resulted in higher GWP as well as GHGI.

4.3. Effects of N fertilization and supplemental irrigation on nutritional quality and yield of fodder maize

N fertilization and supplemental irrigation levels affected the forage yield, CP, NDF, ADF, EE, ear length, ear diameter, grains per ear, and grain yield of fodder maize. The quality of forage is the most critical factor affecting animal health and production performance. Studies have shown that if the CP of forages ingested by livestock is less than 7%, the microorganisms in the rumen will not be able to effectively decompose the ingested food, resulting in livestock weight loss (Charmley, 2001). Our results suggested that N rates and supplemental irrigation levels affected the nutritional quality of fodder maize. Previous research suggested that N fertilization and irrigation significantly affects the growth and development of crops and improves the grain yield (Jia et al., 2020, 2021a, 2021b; Su et al., 2020; Ahmad et al., 2021a, 2021b). In conclusion, treatment N_3W_2 improved the SMC, forage yield, grain yield, and nutritional quality of fodder maize as well as reduced GHG emissions, GWP and GHGI in an arid region.

5. Conclusion

In conclusion, under supplemental irrigation conditions, three N application rates had a significant impact on the GHG emissions, yield and nutritional quality of fodder maize. N fertilization coupled with supplemental irrigation regime greatly mitigated GHG emissions, GWP and GHGI. N application coupled with supplemental irrigation regimes greatly improved the nutritional quality and yield of fodder maize. Over two maize growing seasons, more soil water content, forage yield and grain yield of fodder maize were provided by 375 kg N ha^{-1} coupled with 900 mm ha^{-1} supplemental irrigation regime. 375 kg N ha^{-1} coupled with 900 mm ha^{-1} supplemental irrigation regime also greatly improved the nutritional quality of fodder maize by improving CP and EE and reducing NDF and ADF. In summary, our findings suggested that compared with other treatments, 375 kg N ha^{-1} coupled with 900 mm ha^{-1} supplemental irrigation regime has a potentiality to ensure nutritional quality and yield while decreasing GHG emissions and warming potential. The findings of the experiment are beneficial for improving the yield and nutritional quality of fodder maize and reducing GHG emissions, GWP and GHGI in arid regions. For a large scale assessment of N fertilization and irrigation impact on GHG emissions and productivity of fodder maize more investigation for different soils, climates and agronomic management would be necessary.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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