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# EFFECTS OF IRRIGATION REGIMES AND NITROGEN MANAGEMENT PRACTICES ON WHEAT PRODUCTIVITY, SOIL HEALTH, AND $CO_2$ EQUIVALENT GHG EMISSIONS IN RAINFED ENVIRONMENTS

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## Abstract

This study evaluates various properties of soil under different nitrogen management practices and irrigation regimes in wheat. The highest yield (3.71 t/ha) was observed with 100% recommended dose of nitrogen surpassing other nitrogen treatments by 7%. Higher nitrogen doses applied into soil recorded highest microbial biomass carbon (242.97 µg C/g soil) which was 31.64% more than control, also had the maximum fluorescein diacetate activity (0.38 µg fluorescein/g/soil/h) and highest dehydrogenase activity (5.96 INTF/g/hr soil) leading to a more biologically compatible ecosystem. 50% RDN + two nano-urea sprays resulted in the lowest $CO_2$ equivalent emissions per ton of grain, offering a more sustainable approach. $CO_2$ equivalent emission per ton of grain under lower number of irrigation was 16.42% higher compared to highest number of irrigation. The strong correlation between microbial activity and yield highlights the importance of nitrogen management for enhancing productivity and soil health.

## Introduction

Wheat (*Triticum aestivum* L.) is the second most important cereal crop in the world and is cultivated on around 30 million hectares, which is nearly 14% of the world's total agricultural area. In India, the production reaches 99.7 million tonnes that representing 13.6% of the world's total wheat production with an average yield of 3371 kg/ha (Gupta *et al*. 2019). However, this average yield remains significantly below the potential yield, highlighting a considerable yield gap. Effective nutrient and water management is crucial for achieving self-sufficiency in food grain production. Urea, commonly used nitrogen fertilizer exhibits low nitrogen use efficiency, ranging from 20 to 50% in most soils. Nano-fertilizers exhibit advantageous features such as high solubility, stability, effectiveness, time-controlled release, targeted activity, low eco-toxicity, and convenient delivery and disposal methods (Suppan 2016). Similarly, water management practices based on critical growth stages significantly enhance water use efficiency, reduce wastage, and improve crop productivity.

Soil microbial biomass carbon (SMBC), serves as a key indicator of the soil's nutritional status and biological activity which plays a vital role in the nitrogen cycling process (Propa *et al*. 2021, Alam *et al*. 2024). Soil enzymes and catalytic proteins are also recognized as the most sensitive indicators of soil quality. In wheat cultivation, water and fertilizer management significantly influence soil microbial communities, plant physiological processes and overall yield quality. Research has shown that different combinations of water and nutrient management can substantially enhance enzyme activities as well as soil respiration intensity and fertilizer use efficiency. The application of nano-urea at 1250 ml/ha (50 g N/ha), which is claimed to substitute 50% of the RDN (~60 kg N), may also contribute to affect the soil nitrogen pool over the long term.

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The adoption of nano urea represents a technological advancement in agriculture, showcasing the potential for innovation to address challenges in farming. This can empower farmers with modern tools and practices. It's important to note that while nano urea holds promise, its real-world impact may vary based on factors such as crop type, soil conditions, and management practices. Keeping these points in view, a field study was conducted with the aim to evaluate the chemical and microbial properties of soil and productivity of wheat to various nitrogen management practices under assured and as well as limited irrigation regimes.

## Materials and Methods

The field trials were conducted at ICAR-Indian Agricultural Research Institute in Jharkhand during the rabi season of 2021-2022. The farm located at 24°16' N latitude, 85°21' E longitude and an elevation of 628 meters above mean sea level, experiences a semi-arid and sub-tropical climate.

The sandy clay loam soil had good drainage but low water-holding capacity, with an acidic pH (5.85), low electrical conductivity (0.712 dS/m), cation exchange capacity (7.8 cmol ($P^+$)/kg), low organic carbon (0.25%) and low nutrient availability-N (150.6 kg/ha), $P_2O_5$ (8.27 kg/ha) and medium $K_2O$ (132.16 kg/ha). Rainfall during crop growth was 100.5 mm, unevenly distributed. The average maximum temperature during sowing was 24.2°C. However, after March, it increased beyond 31°C, which caused heat stress.

The experiment was conducted in a split-plot design with three replications. The main plots were allotted to three irrigation regimes: $I_1$ (5-irrigations on a priority basis), $I_2$ (3-irrigations at CRI, flowering, and milking stage), and $I_3$ (2-irrigations at CRI and flowering stage). Sub-plots were planned for five nano urea-based nitrogen management practices (NMPs) : $N_0$ (control without nitrogen application), $N_1$ (100% RDN, (120 kg N/ha), split as 1/3$^{rd}$ basal, 1/3$^{rd}$ at CRI, and 1/3$^{rd}$ at the 2nd irrigation), $N_2$ (50% RDN, half basal, and half at CRI, with nano-urea spray at 60 DAS), $N_3$ (50% RDN, half basal, and half at CRI, with nano-urea spray at 45 & 70 DAS), and $N_4$ (75% RDN, half basal, and half at CRI, with nano-urea spray at 60 DAS). Plot sizes were 22m×5 m (main) and 5m×4 m (sub). Wheat variety DBW-187 (Karan Vandana) was sown with 22.5×10 cm spacing at 100 kg/ha seed rate. N was applied through prilled urea as per treatment plans, while phosphorus and potassium were applied basally @ N: $P_2O_5$: $K_2O$-120:60:40 kg/ha. Nano-urea (4% N) created by the Indian Farmers Fertilizer Cooperative Limited (IFFCO) was sprayed @ 4 ml of water in the evening as per treatment (Kumar *et al.* 2021). Irrigation commenced at the crown root initiation stage and following critical growth stages, considering local weather conditions, avoiding rainy days and stopped 15 days before harvest. Grain yield from a 2 × 2 m net plot area was recorded post-threshing and expressed in t/ha.

Soil microbial biomass carbon (MBC), dehydrogenase activity (DHA), and fluorescein diacetate activity (FDA) were measured using standard methods (Casida *et al.* 1964, Jenkinson and Powlson 1976, Adam and Duncan 2001). Soil nutrients were determined by standard chemical extraction methods. Greenhouse gas (GHG) emissions were estimated using the Cool Farm Tool (Kayatz *et al.* 2019), which integrates empirical models based on management practices, input-output dynamics, soil, and climate data. Data were analysed using analysis of variance (ANOVA) via the Strengthening Statistical Computing for NARS portal, with treatment comparisons based on the F-test ($p < 0.05$). Stepwise regression was performed using 2023.03.0-daily+82.pro2.c

## Results and Discussion

Irrigation regimes did not result in significant differences in productivity, although nitrogen management had a marked impact (Fig. 1). Among the irrigation treatments, $I_1$ achieved the highest yield at 3.71 t/ha comparable to $I_2$ but significantly higher than $I_3$, which showed a 29%

reduction in yield. Among NMPs, $N_1$ produced the highest grain yield by exceeding 7% compared to $N_3$ and significantly outperforming others. All NMPs - $N_1$, $N_2$, $N_3$ and $N_4$ yielded significantly higher results, increasing by 275.6, 139, 251 and 210.5 %, respectively. The interaction between irrigation and nitrogen revealed that the $I_2N_1$ combination delivered the best productivity.

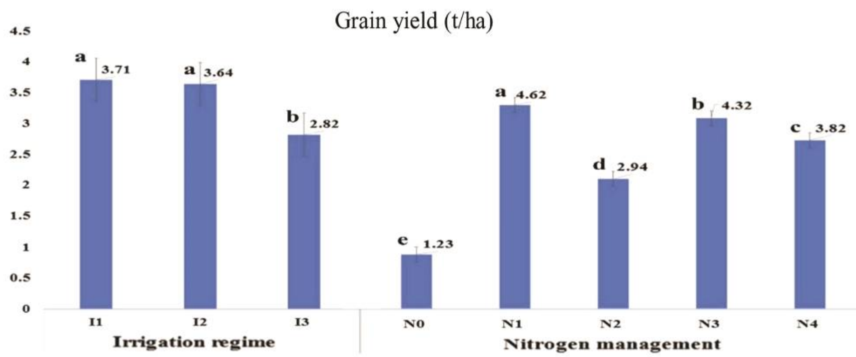


Fig. 1. Effects of irrigation regimes and nitrogen management on yield of wheat $I_1$: 5 irrigations, $I_2$: 3 irrigations, $I_3$: 2 irrigations, $N_0$: control, $N_1$: 100% RDN, $N_2$: 50% RDN+1 NUS, $N_3$: 50% RDN+2 NUS, $N_4$: 75% RDN+1 NUS. Treatments with same letter are not significantly different (p=0.05).

Optimal moisture availability throughout growth stages, favouring more fertile grains and promoted higher yield under $I_1$. Conversely, $I_3$ experienced moisture stress during grain filling that significantly reduced grains/spike by escalating sterile spikelet numbers. Heat stress also possessed negative impact on kernel weight by hampering photosynthate translocation from source to sink. Elevated temperature induced respiratory rate, reduced photosynthesis and decreased grain filling duration, resulting in a substantial yield reduction (Dubey *et al*. 2020, Si *et al*. 2020). Grain yield of wheat was closely related to the LAI, aboveground biomass accumulation (Liu *et al.* 2018) and its remobilization into reproductive parts (Xu *et al.* 2018). $N_1$ had a substantial impact on 1000-grain weight, outperforming other treatments and the control. According to Wang *et al*. 1979, nitrogen sufficiency during ear differentiation extends the activity of the apical dome that helps in increased number of grains/head. The application of nano-urea at 45 and 70 DAS in $N_3$ significantly enhanced vegetative growth, floret development and grain formation compared to other nano-urea treated plots where the application was done at 60 DAS, leading to a substantial increase in yield. Nitrogen fertilization significantly enhanced photosynthetic capacity that leads to improved vegetative growth and more efficient partitioning of photo-assimilates toward reproductive sinks. This resulted in a higher number of grains with increased individual grain weight, thereby contributing to a substantial improvement in grain yield (Shi *et al*. 2016, Guo *et al*. 2019).

Irrigation regimes did not yield significant differences in microbial biomass carbon (MBC), likely due to frequent rainfall up to flowering stage (Fig. 2). However, nitrogen management significantly affected MBC at the flowering stage. The highest MBC was in $N_1$ (242.97 µg C/g soil) which was 31.64% higher than control. $N_2$, $N_3$, and $N_4$ had MBC of 222.11, 222.55, and 233.79 µg C/g soil, respectively. Higher nitrogen doses are correlated with increased MBC (Fig. 2). While irrigation regimes had no significant effect on soil dehydrogenase activity, nitrogen management significantly influenced it. $N_1$ exhibited the highest dehydrogenase activity (5.96 INTF/g/hr soil), similar to $N_4$ (5.65 INTF/g/hr soil), followed by $N_3$ (5.3 INTF/g/hr soil) and $N_2$ (4.96 INTF/g/hr soil), with control being the lowest (4.07 INTF/g/hr soil). $N_1$ also had the maximum FDA activity (0.38 µg fluorescein/g/soil/h) which was statistically at par with $N_4$ (Fig. 3) whereas $N_0$ had the lowest FDA activity (0.28 µg fluorescein/g/soil/hr).

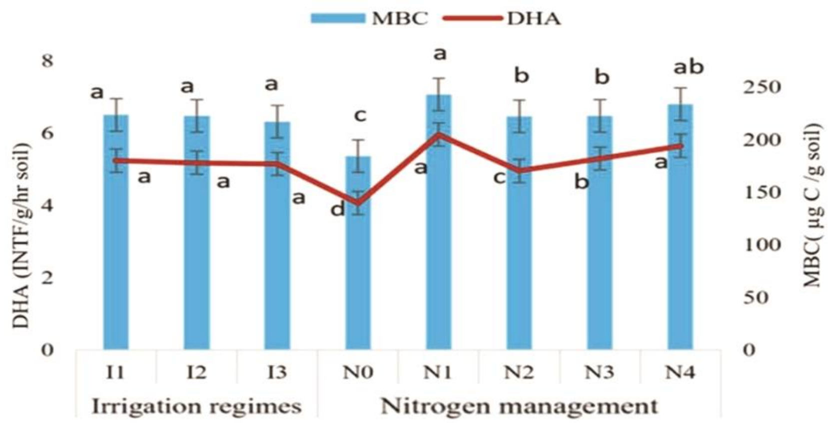


Fig. 2. Effect of irrigation regimes and nitrogen management on MBC and DHA after harvest of wheat. Treatments with same letter are not significantly different (p=0.05).

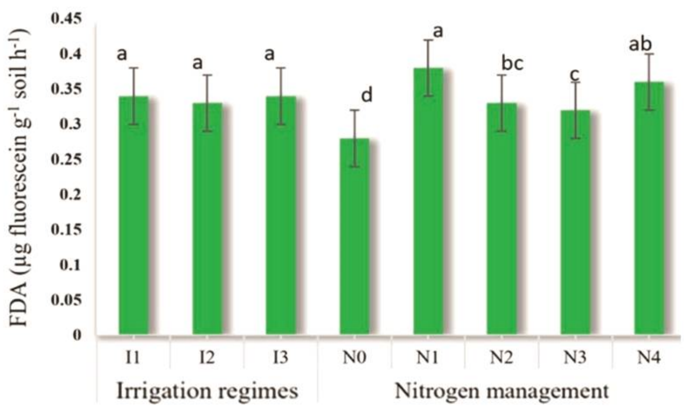


Fig. 3. Effects of irrigation regimes and nitrogen management on FDA after harvest of wheat. Treatments with same letter are not significantly different (p=0.05).

The effect of N fertilization on soil-crop ecosystems resulted in a large rise in MBC, DHA which is a potential reason for a more biologically compatible ecosystem for controlling SOM breakdown and other bio-chemical properties which with time regulates microbial C: N and favours biological efficiency for SOM decomposition, increasing the concentration of MBC (Zang *et al.* 2015, Begum *et al*. 2021). This higher N applied to soil favours higher dehydrogenase activity (Sial *et al.* 2019, Sawicka *et al*. 2020). Higher doses of nitrogen reduce C:N ratio and promote carbon mineralization and glomalin related soil proteins (GRSPs) like Easily Extractable Glomalin-Related Soil Protein (EEGRSP) and Total Glomalin-Related Soil Protein (TGRSP)] contributing to increase in FDA activity in soil (Chaudhary *et al.* 2021, Cordeiro *et al.* 2021). GRSPs plays a role in soil aggregation and carbon sequestration. So, increased GRSP levels may contribute to improve soil structural stability, soil carbon storage that helps in more biological activity (Chaudhary *et al*. 2021).

Both irrigation regimes and nitrogen management practices did not provide any significant effect on available nitrogen within the 0-15 cm soil layer after crop harvest (Table 1). Although data indicated no notable differences in available N, P, K, there was a decreasing trend with higher irrigation levels. The highest levels of available N, P and K were recorded under $I_3$ at 109.13, 7.95 and 86.85 kg/ha, respectively.

**Table 1. Irrigation regimes and nitrogen management on soil nutrient availability after harvest of wheat.**

| Treatment | Available N (kg/ha) | Available P (kg/ha) | Available K (kg/ha) |
|---|---|---|---|
| Irrigation regime | | | |
| $I_1$ | 104.12 | 7.82 | 80.57 |
| $I_2$ | 107.08 | 7.89 | 82.52 |
| $I_3$ | 109.13 | 7.95 | 86.85 |
| SEm ± | 3.53 | 0.18 | 1.43 |
| LSD ($P \leq 0.05$) | NS | NS | NS |
| Nitrogen management | | | |
| $N_0$ | 111.92 | 8.05 | 84.67 |
| $N_1$ | 108.02 | 7.74 | 84.84 |
| $N_2$ | 105.40 | 8.10 | 81.69 |
| $N_3$ | 100.87 | 7.66 | 80.86 |
| $N_4$ | 107.67 | 7.88 | 84.50 |
| SEm ± | 2.90 | 0.18 | 2.61 |
| LSD ($P \leq 0.05$) | NS | NS | NS |

Abbreviations are similar as in Fig. 1.

Irrigation regimes and nitrogen management practices exhibited no significant effect on the available N, P, K content in the 0-15 cm soil depth after harvest. This lack of significant variation may be attributed to the fact that the experimental plot was in its first year of treatment application, during which the inherent buffering capacity of the soil likely stabilized nutrient availability despite varying inputs.

Greenhouse gas (GHG) emissions that expressed as $CO_2$-equivalent per ton of grain were estimated using the Cool Farm Tool. Results indicated that the highest $CO_2$-equivalent emissions per ton of grain were recorded under the $I_3$ treatment. This was primarily due to the significantly reduced grain yield under $I_3$ (29% lower than $I_2$), despite similar total $CO_2$-equivalent emissions across irrigation treatments, thereby increasing the emission intensity per unit of yield (Fig. 4). Similarly, elevated emissions per ton of grain were observed in the control ($N_0$) plots, which also had lower yields. In contrast, the lowest $CO_2$-equivalent emissions per ton of grain were recorded under the $N_3$ treatment, where nano urea was applied twice. Compared to $I_1$, the $I_3$ treatment resulted in a 16.42% higher emission intensity. The control plot ($N_0$) exhibited nearly double the emission intensity per ton of grain compared to $I_3$. Among NMPs the $N_1$, $N_2$, and $N_4$ recorded respectively 34.4, 47.9 and 26.5% higher emissions per ton of grain compared to $N_3$. Regarding treatment interactions, the highest emission intensity (263.9 kg $CO_2$-equivalent/ton of grain) was observed under the $I_3N_0$ combination, while the lowest (115.3 kg $CO_2$-equivalent/ton of grain) was recorded under $I_2N_3$.

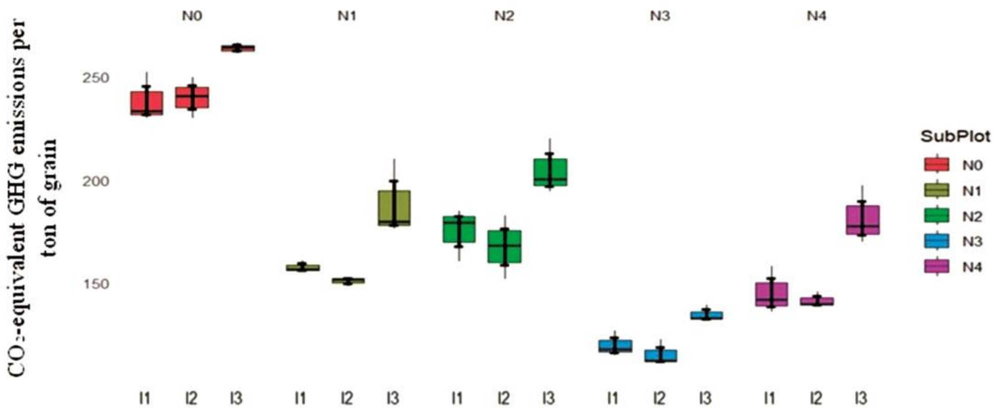


Fig. 4. Effects of irrigation regimes and nitrogen management combinations on $CO_2$ equivalent GHG emission per ton of grain. Abbreviations are similar as in Fig. 1.

Application of a reduced nitrogen dose (~60.05 kg N/ha) under the $N_3$ treatment led to lower energy input requirements and consequently lower $CO_2$-equivalent greenhouse gas (GHG) emissions per ton of grain but able to maintain a relatively high yield that was only 7% less than that achieved with the full recommended dose of 120 kg N/ha (Gao and Cabrera 2023). This improved efficiency shows the potential of optimized nitrogen management *i.e.,* the application of nano urea, in reducing environmental impacts without substantial yield penalties. Under low nitrogen conditions, the elevated substrate C:N ratios can restrict microbial access to nitrogen, thereby reduce the microbial growth and decreasing the rate of carbon mineralization. This microbial limitation tends to suppress the decomposition of organic carbon, particularly that derived from labile sources potentially influencing soil organic matter dynamics in the long term (Gao *et al.* 2020).

In this experiment, a linear regression model was developed to evaluate the relationship between grain yield (GY) and soil microbial properties *i.e.,* MBC and DHA. The model is expressed as: $GY = -5.580186 + 0.015669 \times MBC + 1.060445 \times DHA$. This indicates that each unit increase in MBC and DHA is associated with an expected increase in grain yield of 0.015669 and 1.060445 units, respectively. Both MBC and DHA were found to be statistically significant predictors of GY at the 0.05% significance level. The multiple $R^2$ value of 0.7041 suggests that approximately 70.41% of the variability in grain yield can be explained by the combined influence of MBC and DHA, while the adjusted $R^2$ value of 0.69 confirms a strong model fit by accounting for potential model complexity**.** Stepwise regression analysis further reinforced that grain yield is highly dependent on soil microbial attributes, particularly MBC and DHA. Soil microbes play a pivotal role in nutrient cycling due to their rapid turnover rates and contribute to plant resilience under stress conditions by supporting higher yields (Jenkinson and Ladd 1981, Cook 2014). Adequate nutrient availability, facilitated by microbial activity is more crucial for optimal plant growth and grain formation. Enzymatic and microbial functions collectively contribute to soil fertility by improving the soil's capacity to support vigorous crop growth.

In conclusion applying irrigation at the milk stage of wheat in $I_1$ and $I_2$ irrigation regimes helped to protect the crop from terminal heat stress and prevent significant yield reduction. 100% RDN resulted in significantly higher grain yield of wheat and influenced MBC, DHA, FDA contributing to a more biologically active environment. $N_3$ (50% RDN + 2 nano-urea spray) demonstrated a more sustainable alternative by achieving comparable yield with substantially lower $CO_2$-equivalent greenhouse gas emissions per ton of grain by showing it's potential as an environment friendly nutrient management strategy.

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