Journal of Environmental Biology
p-ISSN: 0254-8704 • e-ISSN: 2394-0379 • CODEN: JEBIDP

JEB®

Original Research Paper
Volume 47 Issue 2 March 2026 pp. 304-313
DOI: http://doi.org/10.22438/jeb/47/2/MRN-5736

J. Environ. Biol., 2026

Journal website : www.jeb.co.in ★ E-mail : editor@jeb.co.in

Integrated effects of sewage sludge, farmyard manure, and nitrogen fertilizer on the growth and physiological traits of fodder Sorghum

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Received: 02 April 2025 **Revised:** 07 July 2025 **Accepted:** 12 November 2025

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Abstract

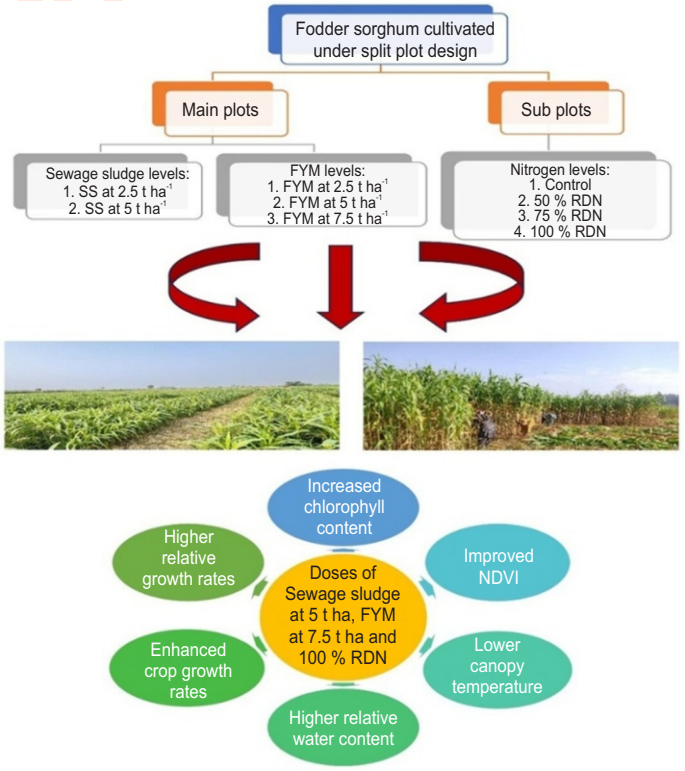
Aim: The present research aims to develop sustainable agriculture strategies that enhance fodder sorghum yield while ensuring soil health and environmental safety.

Methodology: Field experiment was conducted during *kharif* seasons of 2023 and 2024 at Research Farm, Department of Agronomy, Chaudhary Charan Singh Haryana Agricultural University, Hisar, using a split plot design with three replications. Sewage sludge (SS) (2.5 and 5 t ha^{-1}) and FYM (2.5, 5.0 and 7.5 t ha^{-1}) as the main factors. In subplots, four nitrogen levels (control, 50%, 75% and 100% recommended dose of nitrogen) were applied.

Results: Chlorophyll content, relative water content and normalized difference vegetation index (NDVI) was significantly higher with application of 5 t ha^{-1} sewage sludge, 7.5 t ha^{-1} FYM and 100% RDN during both the years. Canopy temperature was significantly lower with 5 t ha^{-1} SS-sewage sludge and 7.5 t ha^{-1} FYM, while 100% RDN treatment further reduced canopy temperature at all stages. Crop growth rate (CGR) and relative growth rate (RGR) were significantly higher with at 5 t ha^{-1} SS-sewage sludge, 7.5 t ha^{-1} FYM and 100% RDN, particularly at early growth stages.

Interpretation: Combined application of sewage sludge, FYM and nitrogen significantly enhanced the crop performance and physiological traits.

Key words: FYM, Growth, Nitrogen, Physiological traits, Sewage sludge, Sorghum



How to cite: Kumar, P., P. Kumar, S. Rani, R. Kumar, A. Kumar, N. Kumar, Jyoti, Ankit, Rachna and R. Munjal: Integrated effects of sewage sludge, farmyard manure, and nitrogen fertilizer on the growth and physiological traits of fodder Sorghum. *J. Environ. Biol.*, **47,** 304-313 (2026).

Introduction

Fodder Sorghum (*Sorghum bicolor* L.) is a critical forage crop across diverse edapho-climatic zones. At 50% flowering stage, single-cut varieties typically yield about 400-500 q ha^{-1} of green fodder and 100-150 q ha^{-1} of dry fodder (Satpal *et al.,* 2020). In Haryana, the total area under sorghum is 40.3 thousand ha under cultivation and total production of sorghum is 21.3 thousand tons with productivity of 528 kg ha^{-1} (Singh *et al.,* 2025). Nitrogen is the most limiting nutrient in Indian soils. It crucially drives plant development, succulence, palatability, leaf-to-stem ratio, shoot elongation, chlorophyll synthesis, and regeneration of tillers. Long-term reliance on chemical fertilizers can disrupt soil structure and nutrient balance (Zaredost *et al.,* 2014).Organic amendments like sewage sludge and FYM help restore soil fertility while supplying essential nutrients. Sewage sludge is rich in organic carbon (~13.9%), N (1.67%), P (1.60%), and K (0.18%), along with micronutrients, but it also contains heavy metals such as Cd, Zn, Pb that require careful risk management (Verma *et al.,* 2017). In sorghum, sewage sludge improves biomass, nutrient uptake, soil pH and micronutrient availability (Zuo *et al.,* 2019; Eid *et al.,* 2021). FYM enhances soil structure and organic carbon, and in synergy with inorganic fertilizers, it improves dry matter and grain yields (Bayu *et al.,* 2006).

Integrating Nitrogen with organic amendments enhances physiological traits: chlorophyll, NDVI, canopy temperature regulation, and water-use efficiency, while highlighting benefits like improved soil health, reduced synthetic fertilizer reliance, and waste recycling (Rehman *et al.,* 2020; Eid *et al.,* 2021).A long-term application of sewage sludge compost in acidic sandy soils showed improved pH, P and K availability, zinc, copper, soil organic matter, and stabilized N, thereby supporting sustainable agricultural practices and long-term productivity gains (Eid et al., 2021). Although numerous studies worldwide have investigated the effects of sewage sludge, farmyard manure (FYM), and nitrogen fertilizers on soil quality and crop yield, but limited information exists on their combined influence on the physiological traits, particularly of sorghum crop that too under semi-arid conditions. Most of the earlier research has focused on general soil fertility improvement and yield enhancement across various crops, but systematic evaluation of physiological responses-such as photosynthetic efficiency, chlorophyll dynamics, water-use efficiency, and biomass partitioning-in sorghum under integrated nutrient management remains scarce. Therefore, this study is novel in its crop-specific (sorghum) and physiology-oriented approach, aiming to understand how integrating sewage sludge, FYM and nitrogen influences key physiological determinants of fodder sorghum productivity.

The limited knowledge about the impact of sewage sludge, FYM and nitrogen has raised research question: to what extent integrated application of sewage sludge, farmyard manure, and nitrogen fertilizer can affect the growth and physiological traits of Fodder Sorghum? The combined application of multiple nutrient sources-both organic and inorganic-has shown promise for long-term crop production by enabling strategic nutrient management through integrated input supply systems, all while preserving the soil's natural resource base. In light of this study was conducted to assess how the combined application of sewage sludge, FYM and nitrogen fertilizer influences the growth performance and key physiological traits of fodder sorghum.

Materials and Methods

A field experiment was performed during *kharif* seasons of 2023 and 2024 at the Research Farm, Department of Agronomy, Chaudhary Charan Singh Haryana Agricultural University, Hisar, located in India's semi-arid, subtropical climatic zone at 29º 10'N latitude and 75º 46'E longitude, 215.2 m above msl (Kumar *et al*., 2022). During summer, the average monthly maximum temperature ranges between 43-45°C. The overall rainfall and distribution in this region vary considerably. Between July and September, the South west monsoon accounts for 80 to 90% of total rainfall.

The experiment was conducted using split plot design, with sewage sludge (2.5 and 5 t ha^{-1}) and FYM (2.5, 5.0 and 7.5 t ha^{-1}) as the main factors. In subplots, four nitrogen levels (control, 50%, 75% and 100% RDN) were applied. In control plots, both sewage sludge and FYM were applied. The optimum application rates of sewage sludge and FYM were 5.0 and 7.5 t ha^{-1}, respectively. All the treatments were replicated three times for statistical accuracy. Plots size was 10 m length×2 m width. Different field operations are shown in Fig.1. Sewage sludge and FYM were primarily applied in solid form and urea in granular form. Nitrogen was applied through Uttam Urea, a commercially available branded urea fertilizer (46% N), supplied by Chambal Fertilisers and Chemicals Ltd., and procured from a certified agro-input supplier in the region. The leaf chlorophyll concentration, was estimated a chlorophyll meter (SPAD-502, Minolta, Japan). A handheld Green Seeker TM (NTech Industries Inc., Ukiah, CA, USA) was used to collect optical sensor data to measure the NDVI. NDVI was calculated from measurement of light reflectance in the red and near infrared regions of the spectrum. A healthy green canopy will absorb most of the red light and reflect most of the NIR light as chlorophyll absorb mainly blue and red light and mesophyll reflects NIR light (Verrels *et al.,* 2008).

For canopy temperature (°C) measurement, a handheld infrared thermometer was used. An operator utilized a hand-held infrared thermometer (Mikron 1600, Mikron Infrared Instrument Co., Inc., Oakland, NJ, USA) to walk across the plots and measure canopy temperatures. For relative water content, five discs of 1 cm diameter were punched from fresh leaf samples. After weighting, the discs were immersed in water overnight to determine their turgid weight. Subsequently, the samples were oven-dried at 70°C to obtain dry weight. Relative water content was calculated as per Barrs and Weatherley (1962). Crop growth rate is the rate of increase in plant dry matter per unit land area per unit time. The above ground sorghum plant and dried plant samples were dried in an oven at 60 °C for 48 hrs. CGR was calculated by the formula given by Watson (1952). RGR measures the increase in plant dry matter relative to its existing

dry weight over a certain time period was calculated using method described by Hunt and Cornelissen (1997). RGR was determined between the 0-20, 20-40, 40-60 and 60-90 days after sowing (DAS). The experimental data for different growth rates and physiological traits were statistically analyzed by ANOVA (Panse and Sukhatme, 1985). The 'F' (variance ratio) test was used to quantify the significance of treatment effects and the critical difference (CD) was calculated according to Cochran and Cox (1992) and Gomez and Gomez (1983).

Results and Discussion

The research on fodder sorghum evaluated the combined effects of sewage sludge, FYM and nitrogen on physiological and growth characteristics. The pH, nitrogen, cadmium, chromium, lead, cobalt and nickel contents in sewage sludge were 8.1, 1.37%, ND, ND, 1.82 mg kg^{-1}, 0.75 mg/kg and 1.24 mg kg^{-1}, while in FYM these were 7.8, 0.72%, ND, ND, 0.49 mg kg^{-1}, 0.14 mg kg^{-1} and 0.58 mg kg^{-1}, respectively. The study assessed their influence

Fig. 1: Different operations and crop stages during crop experiment in 2023 and 2024.

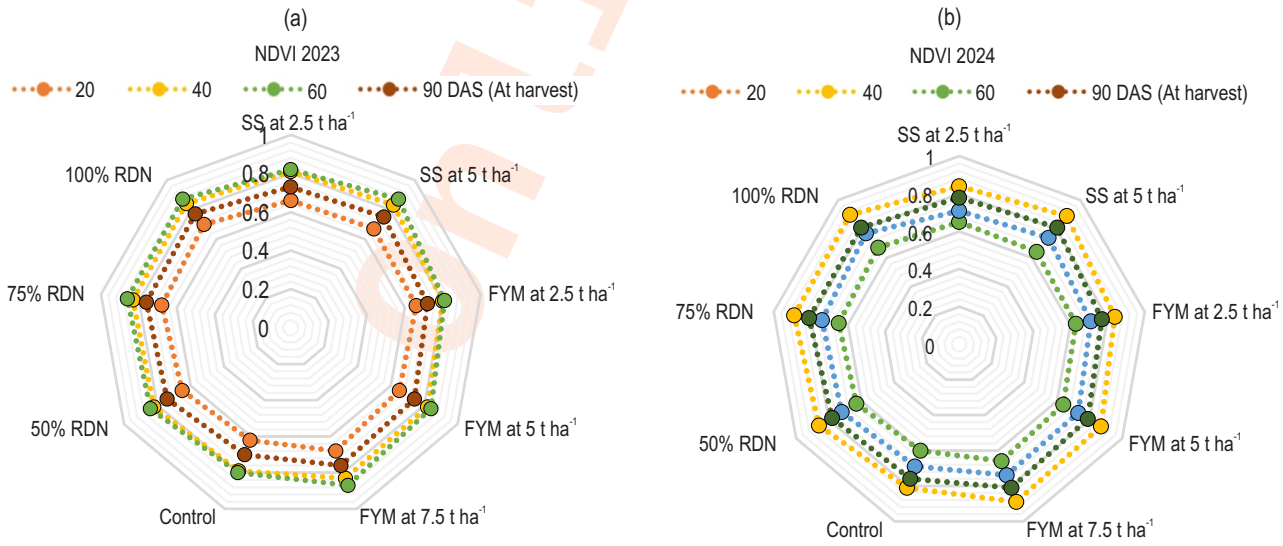


Fig. 2 (a-b): Effect of sewage sludge (SS), FYM and nitrogen levels on normalized difference vegetation index (NDVI) of fodder sorghum during 2023 and 2024.

Table 1: Effect of sewage sludge, FYM and nitrogen levels on leaf chlorophyll content of fodder sorghum during 2023 and 2024

Treatments	Leaf chlorophyll content							
	2023				2024			
	20 DAS	40 DAS	60 DAS	90 DAS (At harvest)	20 DAS	40 DAS	60 DAS	90 DAS (At harvest)
Sewage sludge (SS) levels								
SS at 2.5 t ha^{-1}	35.3	35.9	37.8	36.9	34.3	35.6	38.9	38.0
SS at 5 t ha^{-1}	35.7	38.7	39.3	38.7	34.2	37.6	40.8	39.4
SE(m)±	0.2	0.2	0.2	0.3	0.5	0.3	0.2	0.2
CD at 5%	NS	0.7	0.6	0.9	NS	1.0	0.7	0.5
FYM levels								
FYM at 2.5 t ha^{-1}	35.8	35.8	37.5	36.3	34.4	35.1	38.5	37.9
FYM at 5 t ha^{-1}	35.1	37.1	38.7	37.7	33.7	36.5	39.9	38.7
FYM at 7.5 t ha^{-1}	35.8	39.0	39.6	39.3	34.9	38.2	41.3	39.6
SE(m)±	0.3	0.3	0.2	0.4	0.6	0.4	0.3	0.2
CD at 5%	NS	0.9	0.7	1.3	NS	1.3	0.9	0.6
Nitrogen levels								
Control	32.9	33.2	34.8	33.7	30.2	32.8	35.9	34.8
50% RDN	35.3	37.3	38.5	37.6	32.5	36.2	39.9	38.7
75% RDN	36.4	38.7	40.3	39.3	35.1	37.7	41.6	40.4
100% RDN	37.7	39.9	40.8	40.6	39.5	39.6	42.2	40.9
SE(m)±	0.4	0.4	0.2	0.5	0.6	0.4	0.3	0.2
CD at 5%	1.0	1.1	0.6	1.4	1.6	1.1	0.7	0.6

on parameters such as chlorophyll content, NDVI, canopy temperature, RWC and growth indices like CGR and RGR. The results demonstrated significant improvement in these parameters, underscoring the synergistic effect of organic and inorganic fertilizers in enhancing sorghum growth and physiological efficiency.

Chlorophyll content increased progressively upto 60 DAS and declined thereafter, following the natural trend of leaf senescence (Table 1). At 20 DAS, treatments showed non-significant variation, but at later stages (40, 60, and 90 DAS), significantly higher chlorophyll contents of 38.7, 39.3 and 38.7, was recorded in 2023, and 37.6, 40.8, and 39.4 in 2024 with 5 t ha^{-1} sewage sludge level. This improvement was attributed to the gradual mineralization of organic matter, ensuring steady nitrogen and micronutrient availability essential for chlorophyll synthesis. Similar findings were reported by Lobiuc *et al.* (2023) and Sharma *et al.* (2025), who observed improved photosynthetic activity and leaf greenness under sludge application due to enhanced nutrient availability. FYM applied @ 7.5 t ha^{-1} also resulted in significant higher chlorophyll content (39.0, 39.6 and 39.3 in 2023; 38.2, 41.3, and 39.6 at 40, 60 and 90 DAS, respectively, compared to control. The improvement was associated with increased soil organic carbon, microbial activity and nutrient synchronization with crop demand. Organic fertilizers are known to enhance nitrogen use efficiency and promote balanced nutrient uptake, contributing to chlorophyll formation and leaf longevity (Huang *et al.,* 2022). Further studies have confirmed that organic amendments enhance photosynthetic pigments by improving soil fertility and microbial interactions (Alotaibi *et al.,* 2023; Hassan *et al.,* 2024). Nitrogen fertilization strongly influenced chlorophyll dynamics. Application of 100% RDN increased chlorophyll content by 14.6–20.5% in 2023 and 17.5–30.8% in 2024 over control (Table 1). However, 75% RDN was statistically comparable with 100% RDN at 60 and 90 DAS, indicating diminishing response beyond a threshold level. Nitrogen being a core constituent of chlorophyll directly governs pigment synthesis and photosynthetic efficiency. Ostmeyer *et al.* (2022) reported that optimized nitrogen application enhances chlorophyll formation, light interception, and dry matter production, while Kumar *et al.* (2024) emphasized that partial substitution with organic sources sustains chlorophyll levels and reduces nitrogen losses.

NDVI of fodder sorghum followed a consistent pattern across both years, increasing up to 60 DAS and then declining toward harvest (Fig. 2 a-b). At 20 DAS, treatment differences were statistically non-significant for sewage sludge and FYM, indicating minimal influence of organic amendments at early stage. However, at 40, 60 and 90 DAS, significantly higher NDVI values were recorded with 5 t ha^{-1} sewage sludge than 2.5 t ha^{-1}. In 2023, the NDVI values were 0.83, 0.87 and 0.75 (Fig. 2a), while in 2024, they were 0.74, 0.89 and 0.81, respectively (Fig. 2b).

Table 2: Effect of sewage sludge, FYM and nitrogen levels on canopy temperature of fodder sorghum during 2023 and 2024

Treatments	Canopy temperature (°C)							
	2023				2024			
	20 DAS	40 DAS	60 DAS	90 DAS (At harvest)	20 DAS	40 DAS	60 DAS	90 DAS (At harvest)
Sewage sludge (SS) levels								
SS at 2.5 t ha^{-1}	32.2	31.7	31.5	31.8	32.9	32.1	28.6	29.2
SS at 5 t ha^{-1}	31.8	31.2	30.7	31.3	32.0	31.7	27.7	28.5
SE(m)±	0.12	0.08	0.14	0.08	0.14	0.08	0.11	0.09
CD at 5%	0.38	0.25	0.42	0.24	0.44	0.26	0.34	0.29
FYM levels								
FYM at 2.5 t ha^{-1}	32.5	31.9	31.6	32.0	33.2	32.3	28.8	29.6
FYM at 5 t ha^{-1}	32.1	31.5	31.2	31.6	32.6	31.9	28.1	28.9
FYM at 7.5 t ha^{-1}	31.3	30.9	30.4	31.1	31.6	31.4	27.5	28.2
SE(m)±	0.15	0.10	0.17	0.09	0.17	0.11	0.13	0.11
CD at 5%	0.47	0.31	0.52	0.29	0.54	0.33	0.41	0.36
Nitrogen levels								
Control	33.0	32.2	31.7	32.4	33.5	32.8	29.3	30.1
50% RDN	32.4	31.7	31.4	31.7	32.9	32.1	28.5	29.4
75% RDN	31.5	31.2	30.8	31.3	32.1	31.6	27.8	28.6
100% RDN	31.0	30.7	30.4	30.8	31.3	30.9	27.0	27.5
SE(m)±	0.13	0.17	0.10	0.13	0.18	0.16	0.18	0.17
CD at 5%	0.38	0.47	0.28	0.37	0.52	0.46	0.53	0.48

The improvement may be attributed to higher nutrient availability through sludge mineralization, which sustained canopy greenness and enhanced photosynthetic efficiency. These findings align with Dhanya *et al.* (2022) and Lobiuc *et al.* (2023), who reported that nutrient-rich organic amendments enhance vegetation indices through improved chlorophyll concentration and canopy development. Similarly, FYM application @ 7.5 t ha^{-1} resulted in higher NDVI values (0.83, 0.87, and 0.76 in 2023; 0.74, 0.89 and 0.81 in 2024) at 40, 60, and 90 DAS, compared to 5 and 2.5 t ha^{-1}. The improvement is attributed to enhanced soil organic matter, nutrient cycling, and microbial activity, which promote chlorophyll stability and canopy health. Hassan *et al.* (2024) also noted that organic amendments maintain vegetation indices by improving soil–plant interactions under variable conditions. Among nitrogen levels, 100% RDN produced higher NDVI values (0.70, 0.84, 0.87 and 0.77 in 2023; 0.67, 0.77, 0.90 and 0.81 in 2024) at 20, 40, 60 and 90 DAS, respectively than lower doses. However, NDVI under 75% RDN was statistically comparable to 100% RDN at 60 and 90 DAS, indicating that moderate reductions in nitrogen do not compromise canopy greenness or photosynthetic efficiency. This suggests an efficiency plateau where excessive nitrogen offers limited additional benefit. These results are consistent with Gao *et al.* (2022) and Mitra *et al.* (2023), who emphasized that efficient nitrogen management improves NDVI by enhancing nitrogen uptake and chlorophyll content.

Canopy temperature in fodder sorghum declined progressively up to 60 DAS and then increased toward harvest during both years, reflecting a physiological balance between vegetative growth, peak transpiration, and senescence (Table 2). The application of sewage sludge at 5 t ha^{-1} resulted in significantly lower canopy temperatures of 31.8, 31.2, 30.7 and 31.3°C at 20, 40, 60 and 90 DAS in 2023 and 32.0, 31.7, 27.7 and 28.5°C, respectively, in 2024, as compared application of to 2.5 t ha^{-1} (Table 2). The marked decline at 60 DAS coincided with the peak vegetative stage, where improved nutrient supply enhanced canopy development, water uptake and transpiration, sustaining greater evaporative cooling. Organic amendments have been reported to enhance soil water-holding capacity, nutrient cycling, and canopy cooling efficiency through improved transpiration (Simões-Mota *et al.,* 2022; Marin and Rusănescu, 2023). Similarly, the application of FYM @ 7.5 t ha^{-1} recorded lower canopy temperatures (31.3, 30.9, 30.4 and 31.1°C in 2023; 31.6, 31.4, 27.5, and 28.2°C in 2024) compared to lower levels. The cooling effect of FYM is attributed to improved soil structure, organic carbon and microbial activity that enhance water retention and nutrient supply, leading to greater stomatal conductance and photosynthetic activity. This aligns with earlier findings that FYM improves evapotranspiration efficiency and reduces canopy stress in cereals (Ndiso *et al.,* 2018; Salwan *et al.,* 2024). Nitrogen fertilization had the most pronounced impact, as 100% RDN decreased canopy temperature by 6.1, 4.7, 4.1

Fig. 3(a-b): Effect of sewage sludge(SS), FYM and nitrogen levels on crop growth rate (CGR) of fodder sorghum during 2023 and 2024.

and 4.9% at 20, 40, 60 and 90 DAS, respectively, in 2023, and by 2.8, 5.8, 7.8 and 8.6% in 2024 as compared to the control (Table 2). Temperatures under 75% RDN were statistically similar to 100% RDN at 60 and 90 DAS. Enhanced chlorophyll synthesis, leaf area index and stomatal conductance under adequate nitrogen promote transpiration and canopy cooling, consistent with reports on optimized nitrogen improving canopy cooling and water-use efficiency in cereals (Gao *et al.,* 2022; Almawazreh *et al.,* 2025).

RWC in fodder sorghum increased progressively up to 60 DAS and declined thereafter toward harvest. At 20, 40, 60 and 90 DAS, significantly higher RWC values of 73.7, 77.7, 79.8 and 78.5% in 2023, and 73.4, 77.2, 82.4 and 80.8%, respectively in 2024 were observed with sewage sludge @ 5 t ha^{-1} the application of comparision to 2.5 t ha^{-1} (Table 3). This improvement is attributed to the higher organic matter and gradual nutrient release from sewage sludge, which enhance soil structure, water retention and nutrient availability, maintaining better tissue hydration. Similar results were reported by Kharytonov *et al.* (2023) in sweet sorghum and Sharma *et al.* (2025), who confirmed that sewage sludge enhances physiological traits like RWC through improved root uptake and osmotic regulation. Application of FYM @ 7.5 t ha^{-1} also resulted in higher RWC values of 73.7, 77.9, 80.0 and 78.9% in 2023 and 73.6, 77.6, 82.5 and 81.5%, respectively, in 2024, compared to 5 and 2.5 t ha^{-1} (Table 3). The positive effect of FYM is due to improved soil porosity, aeration, and microbial activity, which support deeper roots and better water extraction. Enhanced nitrogen and potassium uptake further promote turgor and water balance. These findings are in line with Kusvuran *et al.* (2021) and Makarana *et al.* (2023), who observed higher RWC in FYM-treated crops owing to improved soil–plant interactions. Application of 100% RDN increased RWC by 8.5, 9.1, 11.8 and 11.1% at 20, 40, 60 and 90 DAS in 2023, and by 8.9, 9.8, 15.1 and 15.7%, respectively, in 2024 over control (Table 3). Nitrogen deficiency resulted in the lowest RWC, confirming its vital role in maintaining plant water status. Nitrogen promotes protein synthesis, osmotic adjustment, and stomatal regulation, improving water uptake and tissue hydration. Adequate nitrogen also enhances leaf area and transpiration efficiency, sustaining higher RWC under field conditions (Maki *et al.,* 2023; Hassan *et al.,* 2024; Almawazreh *et al.,* 2025).

Crop growth rate observed at different growth stages over two years (2023 and 2024) is presented (p=0.05) in Fig. 3 (a–b). Application of sewage sludge @ 5 t ha^{-1} resulted in significantly

Table 3: Effect of sewage sludge, FYM and nitrogen levels on relative water content in fodder sorghum during 2023 and 2024

Treatments	Relative water content (%)							
	2023				2024			
	20 DAS	40 DAS	60 DAS	90 DAS (At harvest)	20 DAS	40 DAS	60 DAS	90 DAS (At harvest)
Sewage sludge (SS) levels								
SS at 2.5 t/ha	71.4	74.8	76.7	75.9	71.1	74.6	78.4	77.7
SS at 5 t/ha	73.7	77.7	79.8	78.5	73.4	77.2	82.4	80.8
SE(m)±	0.24	0.28	0.22	0.23	0.21	0.37	0.30	0.33
CD at 5%	0.77	0.89	0.69	0.71	0.66	1.18	0.94	1.03
FYM levels								
FYM at 2.5 t/ha	71.4	74.2	76.3	75.5	70.9	74.1	78.4	77.4
FYM at 5 t/ha	72.6	76.7	78.5	77.4	72.3	75.9	80.3	78.9
FYM at 7.5 t/ha	73.7	77.9	80.0	78.9	73.6	77.6	82.5	81.5
SE(m)±	0.30	0.35	0.27	0.28	0.26	0.49	0.37	0.40
CD at 5%	0.94	1.09	0.86	0.87	0.81	1.44	1.15	1.26
Nitrogen levels								
Control	69.4	72.6	73.1	72.4	68.9	71.6	74.0	72.8
50% RDN	72.1	75.8	77.9	76.8	71.7	75.7	79.6	78.7
75% RDN	73.7	77.6	80.3	79.3	73.5	77.4	82.9	81.4
100% RDN	75.3	79.2	81.7	80.4	75.0	78.6	85.2	84.2
SE(m)±	0.26	0.34	0.26	0.29	0.29	0.41	0.45	0.43
CD at 5%	0.74	0.97	0.74	0.85	0.83	1.17	1.29	1.24

Table 4 (a-b): Correlation matrix depicting relationship among different physiological parameters and crop growth indices during

2023	CC	NDVI	CT	RWC	CGR	RGR
CC	1					
NDVI	0.993***	1				
CT	-0.983***	-0.983***	1			
RWC	0.996***	0.991***	-0.976***	1		
CGR	0.91***	0.869**	-0.855**	0.907***	1	
RGR	-0.603	-0.614	0.704*	-0.565	-0.44	1
2024						
CC	1					
NDVI	0.893**	1				
CT	-0.886**	-0.919***	1			
RWC	0.98***	0.919***	-0.954***	1		
CGR	0.942***	0.772*	-0.891**	0.948***	1	
RGR	-0.356	-0.36	0.137	-0.246	-0.203	1

* for p< 0.05, ** for p< 0.01, *** for p< 0.001; CC: Chlorophyll Content; NDVI: Normalized Difference Vegetation Index; CT: Canopy Temperature; RWC: Relative Water Content; CGR: Crop Growth Rate; RGR: Relative Growth Rate

higher CGR than 2.5 t ha^{-1} across both years, with differences significant at all stages, except for 60–90 DAS, where variation was non-significant (NS). The enhanced growth at higher sludge doses may be attributed to improved nutrient availability, particularly nitrogen and phosphorus, promoting leaf expansion, chlorophyll formation, and photosynthetic efficiency, thereby increasing dry matter accumulation and CGR. Similar effects of sewage sludge on crop performance were reported by Shan *et al.* (2021). Increasing FYM levels also improved CGR, with the highest values under 7.5 t ha^{-1} followed by 5 and 2.5 t ha^{-1}. Differences were significant at most stages, except for 60–90 DAS. The gradual nutrient release from FYM ensures sustained

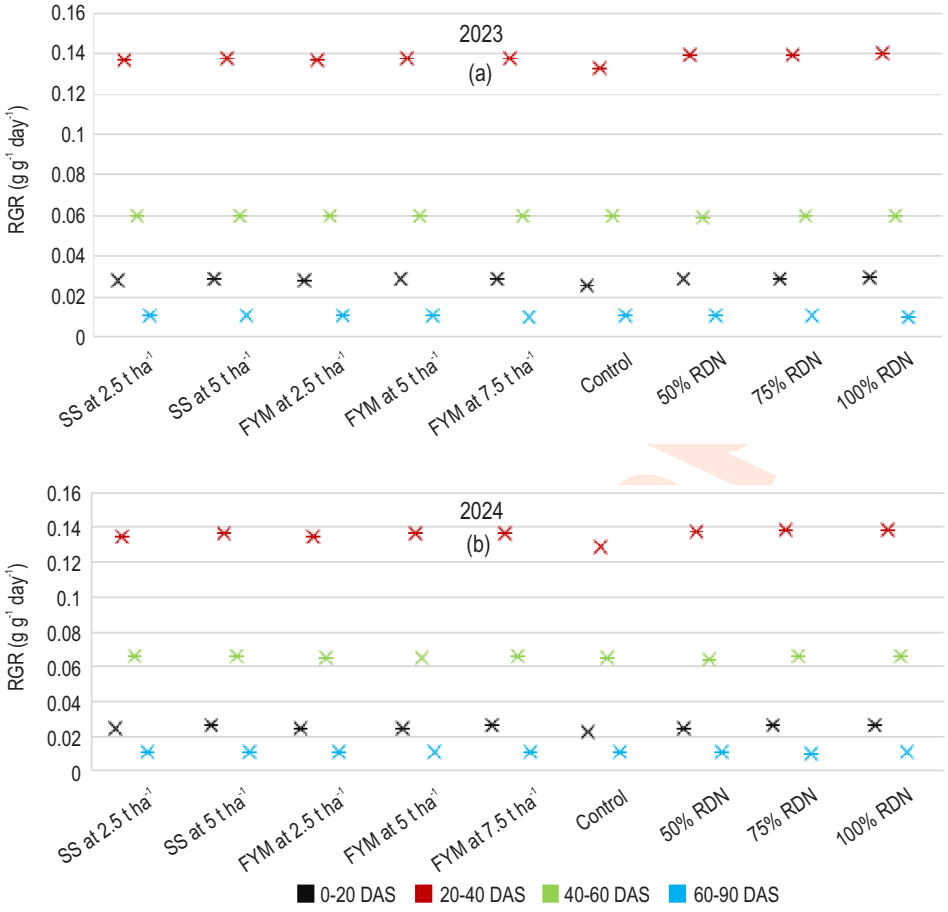


Fig. 4(a-b): Effect of sewage sludge(SS), FYM and nitrogen levels on relative growth rate (RGR) of fodder sorghum during 2023 and 2024.

physiological activity and canopy development, enhancing photosynthesis and growth. These results align with the findings of Bera *et al.* (2024), who reported that organic manures improve soil structure, microbial activity and nutrient availability, leading to prolonged growth benefits. Nitrogen fertilization exerted the strongest influence on CGR. Application of 100% RDN produced 9.8–35.5% higher CGR than control and 2.9–11.2% more than 50% RDN, especially during 20–60 DAS. At 60–90 DAS, 100% and 75% RDN performed similarly, indicating that beyond peak canopy development, extra nitrogen had limited effect. Adequate nitrogen enhanced chlorophyll content, enzymatic activity, and assimilate translocation, promoting biomass accumulation and CGR (Mitra *et al.,* 2023; Gao *et al.,* 2022).

RGR representing the increase in dry weight per unit of existing biomass, was assessed at successive growth intervals during 2023 and 2024 (Fig. 4a–b). Treatments with sewage sludge showed no significant differences in RGR across intervals in either year, likely due to its gradual nutrient release, which ensures uniform nutrient supply and steady biomass accumulation. Similar observations have been reported by Shan *et al.* (2021), who noted that the organic nature of sludge promotes stable growth rather than sharp fluctuations. FYM treatments also exhibited no statistically significant variation in RGR among levels, although values were slightly higher with 7.5 t ha^{-1}. The slow mineralization and nutrient release of FYM, particularly in early stages, likely contributed to this pattern (Hlisnikovský *et al.,* 2021). Moreover, its beneficial effects often become more apparent in later growth or subsequent cropping due to gradual improvements in soil structure and microbial activity (Sarkar *et al.,* 2023). Among nitrogen treatments, the lowest RGR occurred in the control, while the highest was recorded with 100% RDN, which was statistically at par to 75 and 50% RDN at 0–20 and 20–40 DAS. At later intervals (40–60 and 60–90 DAS), differences were non-significant in both years. Adequate nitrogen enhances protein synthesis, chlorophyll content, and photosynthetic efficiency, leading to greater dry matter accumulation and accelerated RGR during vegetative phase (Muhammad *et al.,* 2022). Recent studies also indicate that nitrogen improves nutrient-use efficiency and overall growth compared to unfertilized crops (Sharma *et al.,* 2025a; Chen *et al.,* 2024). While organic sources enhance long-term soil health, the

immediate availability of nitrogen from inorganic fertilizers exerts a more pronounced effect on RGR at early growth. Integrating nitrogen with organic manures such as sludge or FYM can thus optimize short-term growth and sustain soil fertility over time (Makarana *et al.,* 2023).

The correlation matrices for the 2023 and 2024 growing seasons revealed strong interrelationships among physiological parameters and crop growth indices (Tables 4a,b). Significant correlations are denoted by asterisks (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). Chlorophyll content (CC) showed a strong positive correlation with NDVI, RWC and CGR in both years. In 2023, CC was highly correlated with NDVI (r = 0.993***), RWC (r = 0.996***), and CGR (r = 0.910***) (Table 4a), while slightly lower but still significant correlations were observed in 2024 (NDVI: r = 0.893**, RWC: r = 0.980***, CGR: r = 0.942***) (Table 4b). CC was negatively correlated with canopy temperature (CT) in both years (2023: r = –0.983***; 2024: r = –0.886**) and weakly with RGR (2023: r = –0.603; 2024: r = –0.356).NDVI followed a similar trend, showing strong positive correlations with RWC (2023: r = 0.991***; 2024: r = 0.919***) and CGR (2023: r = 0.869**; 2024: r = 0.772*), but negative correlations with CT (2023: r = –0.983***; 2024: r = –0.919***). Its relationship with NDVI and RGR remained weak and negative in both years (2023: r = -0.614; 2024: r = -0.360).CT exhibited strong negative associations with CC, NDVI, RWC and CGR, slightly stronger in 2023 (r = –0.983 to –0.855) than in 2024 (r = –0.954 to –0.886).

The positive correlation between CT and RGR weakened from 2023 (r = 0.704*) to 2024 (r = 0.137) (Table 4a).RWC correlated positively with CC, NDVI, and CGR, with higher values in 2023 (r = 0.907–0.996) than 2024 (r = 0.919–0.980), and negatively with CT (2023: r = –0.976***; 2024: r = –0.954***). Its association with RGR was negative and weaker in 2024.CGR maintained positive relationships with CC, NDVI, and RWC, while correlating negatively with CT (2023: r = –0.855**; 2024: r = –0.891**) and weakly with RGR (2023: r = –0.440; 2024: r = –0.203).Overall, RGR showed weak and generally negative associations with other physiological traits, except for its positive but diminishing correlation with CT across seasons.

The study highlights the practical relevance of integrating sewage sludge, FYM, and nitrogen for improving fodder sorghum productivity through enhanced physiological and growth efficiency. This integrated nutrient approach offers a sustainable and eco-friendly strategy for efficient resource utilization and long-term soil health improvement in fodder-based cropping systems.

Acknowledgments

The authors extend their appreciation to the Department of Agronomy, CCS HAU, Hisar, for their technical help in conducting this experiment.

Authors' contribution: Pawan Kumar: Conceptualization of the study, methodology development, validation, data curation, drafting original manuscript, revision and editing and overall supervision; **Parveen Kumar:** Methodology development, validation and data curation; **Renu Munjal:** Methodology development, data curation and supervision; **Sarita Rani:** Formal analysis and data curation; **Rohtas Kumar, Anil Kumar:** Formal analysis; **Naresh Kumar, Jyoti:** Writing original draft; **Ankit:** Revision and editing of the manuscript and supervision; **Rachna:** Revision and editing of the manuscript.

Funding: No funding.

Research content: The manuscript's research material is original and has not been published elsewhere.

Ethical approval: There is no ethical issues.

Conflict of interest: Authors declare that there are no conflicts of interest.

Data availability: Analysed data of this study are available with the Corresponding author.

Consent to publish: All authors agree to publish the paper in *Journal of Environment Biology.*

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