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Temporal variability and drain spacing effect of sub surface drainage system on Nitrate leaching loss in adsali sugarcane grown in sodic vertisol

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Abstract
Soil salinization and sodification severely constrain agricultural productivity, particularly in irrigated vertisols of semi-arid regions. Subsurface drainage systems are widely adopted for reclamation of sodic soils, but drain spacing strongly influences nitrate (NO_3^-) leaching, posing risks to nitrogen (N) use efficiency and water quality. A field experiment was conducted during 2024-25 at Agricultural Research Station, Kasbe Digraj, Sangli, Maharashtra, India to quantify the temporal variability of nitrate leaching under different drain spacings in adsali sugarcane (Saccharum officinarum L.) grown on sodic vertisol. The SSDS was installed at 120 cm depth with lateral spacings of 15, 25, and 40 m, along with a control (no drainage). Drainflow samples were collected after rainfall and irrigation events, and analyzed for NO_3^- concentration. Results showed that adsali sugarcane utilized 314.92 lakh L ha^{-1} water annually, of which 63.38% was discharged through drainage. Mean NO_3^- concentrations in drainflow water varied significantly with drain spacing, ranging from 5.96 mg L^{-1} (15 m) to 3.83 mg L^{-1} (40 m), compared with 7.13 mg L^{-1} in control. Annual NO_3-N losses were highest under 15 m spacing (113.33 kg ha^{-1}) and lowest under 40 m spacing (73.63 kg ha^{-1}). Temporal peaks in nitrate leaching coincided with fertilizer application (January-February), whereas minimum losses occurred during monsoon months. Overall, the 40 m drain spacing significantly reduced nitrate leaching without impairing drainage function. These findings suggest that optimized Sub surface drainage system design can enhance nitrogen use efficiency while mitigating environmental risks in sodic vertisols.

Keywords: Subsurface drainage, sodic vertisol, drain spacing, nitrate leaching, sugarcane, nitrogen loss

Introduction
Soil salinization and sodification is a global and dynamic problem and is projected to increase in future under climate change scenarios. The global figure of soil salinization have been reported as 952.2 million ha. According to an estimate, 20% of total cultivated and 33% of irrigated agricultural lands worldwide are afflicted by high salinity (Shrivasata and Kumar, 2015) [5]. Around 52 million ha lands are salt-affected in South Asia (Mandal *et al.*, 2018) [9]. In India, around 6.73 million ha area is salt affected, which is around 2.1% of geographical area and 5% of net cultivated area of the country, is salt-affected, of which 2.96 million ha is saline and the rest 3.77 million ha is sodic (Arora and Sharma, 2017) [1]. Nearly 75% of salt-affected soils in the country exist in the states of Gujarat (2.23 million ha), Uttar Pradesh (1.37 million ha), Maharashtra (0.61 million ha), West Bengal (0.44 million ha), and Rajasthan (0.38 million ha) (Mandal *et al.,* 2018, Challa *et al.* 1995) [9, 3]. The salinized areas in India continue to increase each year due to introduction of irrigation in new areas (Patel *et al.,* 2011) [12]. The rate of increase is around 10% annually (Jamil *et al.,* 2011) [7]. According to Sharma *et al.* (2014) [14], unless preventive/ameliorative attempts are taken, the salt-affected areas are estimated to treble, i.e., increase from 6.74 to 16.2 million ha by 2050. In Maharashtra, the area of salt affected soils is 6.06 lakh ha area (1.84 lakh ha saline and 4.22 lakh ha sodic soils) (Challa *et al.,* 1995) [3].

Subsurface drainage systems is one of the most effective strategies to reclaim and manage problematic soils. Agriculture Research Station, Kasbe Digraj recommended subsurface drainage system (1.25 m depth and lateral spacing of 25 m) with integrated use of gypsum (50% of gypsum requirement) and green manuring (*Dhaincha*) for improvement of deep black saline-sodic soils.

The technology is widely adopted in salt affected soils of Krishna command area of South Maharashtra, however, most of the farmers installed SSDS with closer drain spacing's (10-20 m). The presence of nitrate-nitrogen (nitrate-N) in subsurface tile drainage water is a topic of intense scrutiny due to several water quality issues. Nitrate concentrations in drainage water exceeded the allowable values in a larger part of the year. Baker (1980) [2] reported average NO_3-N concentrations for subsurface drainage water was 8 to 20 mg N L^{-1}, The NO_3-N concentrations in drain discharge varied from 5.58 -13.02 mg L^{-1} in saline vertisols of Tungabhadra command area (Meti *et al.*, 2024) [10]. Skaggs *et al.* (2005) [16] showed, with experimental data and modeling, that an increase in nitrate load with increased drainage intensity would likely be common due to the greater water flow from the drainage system. Many researcher showed that greater nitrate loads with narrower drain spacings increases nitrate leaching (Nangia *et al.,* 2010; Sands *et al.,* 2008) [11, 13], even with low concentrations, higher rainfall and drainage still give large Nitrate loads (Kladivko, 2021) [8]. If such water is used for human consumption, it may cause hypoxia and methemoglobinemia in infants and animals. Also nitrate leaching from soil profile is responsible for low N use efficiency, eutrophication and health hazard on downstream users (Christen and Ayers 2001) [4].

Considering the N losses through close drain spaced systems and its adverse effect on environment; the experiment was planned with objective to find out the temporal variability and effect of different drain spacing's of sub surface drainage systems on nitrate leaching losses in sodic vertisol.

Methodology

A field experiment on "Nitrate leaching losses as influenced by different drain spacing of sub surface drainage system in sodic vertisol" was conducted during 2024-25 at Agricultural Research Station, Kasbe Digraj, Sangli of Maharashtra State (India). Geographically, the location of the experimental site was N 16^0 53' 404" latitude and E 074^0 30' 691" longitude. This tract is lying in plain zone of upper Krishna basin. The soil of the experimental area is grouped under sodic verisol, comprises member of fine montmorillionite clay having high swell-shrink property, characterized by very high clay content (58.40%), very low hydraulic conductivity (0.15 cm hr^{-1}), highly alkaline (pHs 8.41) with high exchangeable sodium percentage (32.04), medium in soil organic carbon content (6.27 g kg_{-1}), low in soil available Nitrogen (161.35 kg ha^{-1}) and Phosphorus (13.32 kg ha^{-1}) whereas very high in Potassium (431.3 kg ha^{-1}).

A subsurface drainage system was installed in the month of March 2024 with 80 mm diameter perforated pipes at 120 cm drainage depth with 15, 25 and 40 m spacings between laterals. Each drain spacing was hydrologically isolated by 20 m buffer space in between the treatments. *Dhainacha,* green manuring crop was taken and *in situ* incorporation of the *Dhainacha* was done at flowering stage. Broadcasting of gypsum @ 5 t ha^{-1} as a soil amendment was done at the time of green manuring crop incorporation in soil. Ridges and Furrow were opened at 135 cm spacing between two furrows. Two eye bud sets of sugarcane variety Co 86032 were planted in furrow with 135 X 30 cm spacing. The recommended dose of nutrients to adsali sugarcane was 500:200:200 N, P_2O_5 and K_2O kg ha^{-1} given through commercial grade urea (46% N), single superphosphate (16% P_2O_5) and muriate of potash (60% K_2O). Nitrogen fertilizer dose was applied in 4 split (10% recommended dose at planting and 12 week after planting, 40% recommended dose after 8 week and at earthing up stage. Phosphorus and Potassium fertilizer dose were applied in 2 equal split at planting and at earthing up of adsali sugarcane. Total 22 irrigatons of 10 cm depth were given in one year span of adsali sugaracne. The metrological data of daily rainfall, maximum and minimum temperature, maximum and minimum relative humidity were obtained from Automated Weather Station installed at Agriculture Research Station, Kasbe Digraj, total 963 mm rainfall was received during the experimentation in 69 rainy days. The effective rainfall was computed using the method mentioned in FAO Document No. 25 (Dastane, 1974) [5]. Month wise precipitation volume is calculated by multiplying effective rainfall (mm) and treatment area (m^2). Month wise irrigation water volume (m^3) was calculated by multiplying treatment area (m^2) × water depth (m). The crop evapotranspiration water loss is calculated by using formula ETc = Kc X ETo. The ETo values were obtained from Automated Weather Station, K Digraj. Dingre *et al.*, 2021 [6] estimated Kc values irrigated sugarcane were used for evapotranspiration water loss. The water balance is governed by the basic physical principle of conservation of mass (Easton*,* 2016) *i.e.* Inputs = output + change in soil moisture storage. Accordingly Drain water = (Precipitation water + Irrigation Water) - (ETc water + Change in soil moisture).

Water sampling from each treatment of 15, 25 and 40 m drain spacing of sub surface drainage system was done periodically. Periodical drain flow water was done from drain chamber at 24, 48 and 72 hrs after effective rainfall as well as 24, 48 and 72 hrs after each irrigation. In case of control treatment (without drainage system) a sampling chamber was inserted in soil at 120 cm depth, the bottom end of the chamber was kept open so as to collect the soil water at 120 cm depth. The top end of the chamber was kept 1 m above the soil surface and kept close to avoid entry of runoff and rain water. The percolated water in a sampling chamber was collected 24, 48 and 72 hrs after irrigation or rainfall and used for analysis after filtration. The water sample were analysed for NO_3-N concentration. The data obtained was statistically analysed with z test for comparison between treatments.

Results

Water footprint of adsali sugarcane

A month wise temporal variation in water footprint of adsali sugarcane grown in sodic vertisol with sub surface drainage system was presented in table 1. During one year of growth span of adsali sugarcane on sodic vertisol, 314.92 lakh litre ha^{-1} water was used. Out of total water used in one year span, 80.20 lakh litre ha^{-1} water (*i.e* 30.14% of total water used) came from precipitation whereas remaining 69.86% water (*i.e* 220 lakh litre ha^{-1}) was came from 23 irrigation. Also out of total water consumed, 63.38 percent water (*i.e* 199.60 lakh litre water ha^{-1}) was drained out from sub surface drainage system in adsali sugarcane. The water requirement of sugarcane (ETc) was 36.62 percent of total water applied to adsali sugarcane.

Nitrate ion Concentration of Drain Flow Water: The effect of different drain spacing of sub surface drainage system on temporal variation of NO_3 ion concentration in drainflow water was presented in table 2. The drain spacing of sub surface drainage system recorded significant change in NO_3 ion concentration in drainflow water from adsali sugarcane grown on sodic vertisol. The nitrate concentration of drain water from adsali sugarcane grown on sodic vertisol varies from 1.02 to 12.13 mgL^{-1}. The treatment of 40 m drain spacing of sub surface drainage system recorded lower average annual NO_3 concentration in drainflow water (1.98 mg L^{-1}), whereas, higher average annual NO_3 concentration was reported in control treatment (7.13 mg L^{-1}). The z score for NO_3 ion concentration in drain water in control treatments *vs* 15, 25 and 40 m drain spacing was found higher than critical z value (1.93) indicates significant higher NO_3 ion concentration in drain water of control as compare to NO_3 ion concentration in drain water of all the tested drain spacing of subsurface drainage system. The average annual NO_3 ion concentration of drain flow water from 40 m drain spacing of sub surface drainage system (3.88 mg L^{-1}) was found significant lower as compared to average annual average annual NO_3 ion concentration of drain flow water from 15 and 25 m drain spacing of sub surface drainage system (5.96 and 4.37 mg L^{-1}, respectively) (z score = 2.40 and 3.35, respectively). High NO_3 ion concentration in close drain spacing mostly occur because of highly mobility of NO_3 ion due to the repulsion of anions by negatively charged soil particles. The results corroborated the findings of Simunic *et al.* (2011).

The month wise temporal variability was found in NO_3^- concentration of drain flow water in all the treatments. NO_3^- concentration was found high in the month of January and February 2025. Whereas, low NO_3^- concentration was observed in the month of August 2024. This might be due to split application of Urea fertilizer to adsali sugarcane in the month of January 2025 which subsequently came into soil solution and drainflow water in the month of January and February 2025. Low NO_3^- concentration in the month of August 2024 might be because of incorporation of green manure crop in the month August 2024, the native N from soil may be utilized for decomposition of organic biomass.

Nitrate N Loss in Drain Flow Water

Annual Nitrate loss is the product of water flow multiplied by NO_3^- concentration. The effect of different drain spacing of sub surface drainage system on temporal variation of NO_3-N loss in drain flow water was presented in table 3. The drain spacing of sub surface drainage system recorded significant NO_3-N loss in drainflow water from adsali sugarcane grown on sodic vertisol.

The total annual NO_3-N loss in drain water from adsali sugarcane grown on sodic vertisol ranged between 73.63 to 113.33 kg ha^{-1}, which was 14.71 to 22.67 percent of added Nitrogen through urea fertilizer. The total annual NO_3-N loss in drain flow water from 15 m drain spacing of sub surface drainage system (113.33 kg ha^{-1}) was found significant higher as compared to total annual Nitrogen loss in drain flow water from 25 and 40 m drain spacing of sub surface drainage system (82.43 and 73.63 kg ha^{-1}, respectively) (z score = 1.97 and 2.57, respectively). High N loss in close drain spacing mostly occur because of highly mobility of NO_3 ion due to the repulsion of anions by negatively charged soil particles. Nitrogen loss in 25 m and 40 m drain spacing of sub surface drainage system were found at par with each other. In all the treatments, month wise temporal variability was found for N loss from drain flow water. Nitrogen loss was found higher in the month of January 2025, whereas, low Nitrogen was observed in the month of July, 2025. This might be due to split application of Urea fertilizer to adsali sugarcane in the month of January 2025 which subsequently came into soil solution and drainflow water. Low N loss in July 2025 was due no addition of N fertilizer since January 2025.

Table 1: Monthwise temporal variation water footprint of adsali sugarcane grown on sodic vertisol

Month	Rainwater (L/ha)	Irrigation water (L/ha)	Total water (L/ha)	Sugarcane Etc (L/ha)	Drainflow discharge (L/ha)
Aug-24	1786000	2000000	3786000	629300	3156700
Sep-24	1344000	2000000	3344000	579000	2765000
Oct-24	1252000	2000000	3252000	719200	2532800
Nov-24	170000	2000000	2170000	693000	1477000
Dec-24	320000	2000000	2320000	706800	1613200
Jan-25	0	3000000	3000000	976500	2023500
Feb-25	0	2000000	2000000	1066800	933200
Mar-25	56000	3000000	3056000	1618200	1437800
Apr-25	132000	3000000	3132000	1734000	1398000
May-25	2350000	1000000	3350000	1624400	1725600
Jun-25	1280000	0	1280000	717000	563000
Jul-25	802000	0	802000	468100	333900
Total	94,92,000	2,20,00,000	3,14,92,000	1,15,32,300	1,99,59,700

Table 2: Effect of different drain spacings of SSD system on drain water Nitrate concentration of adsali sugarcane grown in sodic vertisol.

Treatments	NO_3^- concentration of drain water (mg L^{-1})			
Months	Control	15 DS	25 DS	40 DS
August-2024	1.12	1.11	1.04	1.02
Sept -2024	0.57	1.71	1.68	1.70
Oct -2024	9.08	7.21	4.49	4.18
Nov-2024	7.03	7.28	5.16	4.67
Dec-2024	7.77	7.17	4.92	4.29
Jan-2025	11.77	12.00	7.93	7.35
Feb-2025	12.00	9.36	7.53	5.79
March-2025	12.13	8.69	7.60	6.85
April-2025	10.32	5.38	3.72	3.20
May-2025	7.67	4.87	3.60	2.70
June-2025	2.86	3.59	2.46	2.66
July-2025	3.26	3.10	2.25	1.58
Mean	7.13	5.96	4.37	3.83
SD	4.06	3.12	2.26	1.98
				z score
Control *vs* 15 DS				1.339
Control *vs* 25 DS				3.475
Control *vs* 40 DS				4.267
15 DS *vs* 25 DS				2.402
15 DS *vs* 40 DS				3.345
25 DS vs 40 DS				1.031

Table 3: Nitrogen loss as influenced by different drain spacing of SSD system with adsali sugarcane grown in sodic vertisol

Treatments	Nitrogen loss in drain water (kg ha^{-1})		
Months	15 DS	25 DS	40 DS
August-2024	3.50	3.28	3.22
Sept -2024	4.74	4.65	4.72
Oct -2024	18.26	11.37	10.59
Nov-2024	10.76	7.61	6.89
Dec-2024	11.57	7.93	6.91
Jan-2025	24.28	16.04	14.89
Feb-2025	8.74	7.02	5.41
March-2025	12.50	10.93	9.85
April-2025	7.52	5.20	4.48
May-2025	8.39	6.22	4.65
June-2025	2.02	1.39	1.50
July-2025	1.04	0.76	0.52
Total	113.33	82.43	73.63
Mean	9.44	6.87	6.13
			z score
15 DS *vs* 25 DS			1.9740
15 DS *vs* 40 DS			2.5683
25 DS *vs* 40 DS			0.7510

Conclusion

- Temporal variability was found in NO_3^- concentration of drain flow water in all the treatments. Fertilizer application has more pronounce effect on drainwater NO_3^- concentration than irrigation and environmental factor.
- The total annual NO_3-N loss in drain water from adsali sugarcane grown on sodic vertisol ranged between 73.63 to 113.33 kg ha^{-1}, which was 14.71 to 22.67 percent of added Nitrogen through urea fertilizer.
- The total annual NO_3-N loss in drain flow water from 40 m drain spacing of SSDS was found significant lower as compared to 15 m drain spacing of SSDS, however, it was found at par with 25 m drain spacing of SSDS.

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