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Yield, Water Balance and Nitrate Leaching Under Different Irrigation Regimes in Rice Cultivation Under Sub-Tropical Environment: Field Observation and Simulation Modeling using HYDRUS-1D

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Abstract: For irrigated rice, increasing water productivity is essential as water supplies become more limited. Water consumption and risk management can benefit from monitoring the long-term impacts of fertilization and irrigation on the components of the water balance. A field-Lysimeter investigation was carried out and the Hydrus-1D model was calibrated to simulate the nitrate leaching and water balance components. Three distinct irrigation treatments were applied in the lysimetric study: traditional irrigation (continuous ponding) (T1), irrigation three days after the ponded water disappeared from the soil surface (referred to as three days AWD) (T2), and irrigation five days AWD (T3). The results of field experiments indicated that, the conventional irrigation treatment (T1) yielded the highest grain production (6.77–6.94 t ha^{-1}), but demanded the most water (50.6–70.9 cm). Severe irrigation restriction (T3) achieved significant water savings up to 39.3%, yet resulted in substantial yield reductions of up to 26.4%. The relative crop responses remained consistent across both years. A moderate irrigation reduction (T2) provided a balanced trade-off, saving 16.6–22.8% of water while limiting yield penalties to roughly 13%. Consequently, T2 emerged as the optimal management strategy to improve water productivity and sustain rice production in water-limited environments without causing severe yield losses. The Hydrus-1D model was well fitted with the field data (calibration efficiency was about 94%). The HYDRUS-1D simulations demonstrated that AWD irrigation reduced soil water storage and increased root-zone drying compared with continuous ponding. However, reductions in cumulative root water uptake and nitrogen uptake were relatively small, particularly under the three-day AWD treatment. Surface, root-zone, and bottom-boundary nitrogen dynamics showed similar temporal patterns among treatments, indicating that moderate AWD can maintain crop water and nitrogen acquisition while reducing water use. Among the AWD treatments, three-day AWD (T2) appeared to provide the best balance between water conservation and maintaining favorable root-zone conditions. Overall, integrating field observations with model simulations identified three-day AWD (T2) as the most suitable irrigation strategy for improving water productivity while sustaining rice yield and efficient water and nitrogen use.

Keywords: Boro rice, Alternate wetting and drying, Water balance, Nitrate leaching, Hydrus-1D model

INTRODUCTION

In agricultural production systems, appropriate water management techniques are essential for ensuring the availability of nutrients such as nitrogen (N) and creating the right amount of soil moisture. Over 50% of the world's population is fed rice (Fageria, 2007), and the high and consistent yield of this crop is directly linked to the high rate of N fertilizer application. Humid areas, particularly those with Boro rice, are significantly affected by diffuse agricultural pollution, which is distinct from the paucity of water in drought-prone areas (Ma et al., 2021, Shekhar et al. 2020; Das et al. 2026).

Nearly half of the global rice-growing area is cultivated under flooded (ponded) irrigation conditions, accounting for about 75% of total world rice production (Tabuchi and Hasegawa, 1995). High production is attained by high inputs (water, fertilizer, pesticide, etc.) and appropriate management practices (Zhang et al., 2024). Among the various factors influencing the increase in rice production, irrigation plays the most significant role, followed by fertilizer application and varietal improvement. The sustainability of paddy production depends on the efficient and sustainable use of water resources, along with technologies that minimize the use of agricultural chemicals. In Bangladesh, nitrate in ground water is a concern in irrigated rice-based cropping systems. Rice is generally grown under ponded water. The combination of high-N fertilizer input culture with ponded water may lead to an increased risk of nitrate leaching (Boonphue et al., 2026).

One of the extensively advocated water-saving irrigation techniques for rice cultivation is the application of alternate wetting and drying (AWD) regime, which controls the wetness or dryness of the field surface and increases water productivity in rice production (Das et al., 2026; Boonphueet al., 2026; Zhang et al., 2024; Shekhar et al., 2020; Ali, 2018; Bouman et al., 2005). Rainfall is abundant in humid regions, where rain-fed irrigation is essential for most crops. Rainfall uncertainty in terms of timing, frequency, and volume can alter soil water mobility (Li et al., 2021), which in turn can alter N transport and transformation processes (Han et al., 2021). Furthermore, under AWD conditions, rice fields undergo dramatic changes in soil moisture, which has a major effect on surplus output and water storage capacity (Ouyang et al., 2015; Boonphue et al., 2026).

Surface runoff, seepage and percolation make it easy to lose too much nitrogen to the surrounding water environment, which is currently recognized as a major factor responsible for groundwater pollution and lake eutrophication (Diaz et al., 2008; Cameira et al., 2019; Jayaraman et al., 2021). Because crop fertilizer has a low recovery rate, irrigation or precipitation causes a considerable amount of residual nitrogen to leak into groundwater (Tamini et al., 2002). Specifically, because of its fluidity, nitrate contributes more to groundwater pollution than any other form of N (Pandey et al., 2018). According to reports, the N application of more than 50% of the rice in the Asian subcontinent needs to be lowered to reach the environmental N-fertilizer optimum, which is 160–190 kg N ha^{-1} (Zhang et al., 2018). Reduced N application rates have been shown in numerous studies to affect crop development or yield (Ma et al., 2021; Zhu et al., 2017; Stone et al., 2016). This lack of adequate quantitative research is unlikely to persuade farmers and policymakers to prioritize agricultural water management and maximize N fertilizer expenditures. Instead, it will exacerbate the impact of agricultural diffuse pollution in rice fields and increase the need to optimize N application.

Numerous research studies have investigated nitrate leaching under varying soil types, cropping systems, and management practices. Most of these investigations have focused on crops cultivated under unsaturated or non-ponded conditions (Moreno et al., 1999; Yets et al., 1992; Ferguson et al., 1991; Casey et al., 2002; Roth and Fox, 1990). In contrast, irrigated rice fields remain continuously ponded throughout much of the growing season. Consequently, the magnitude and behavior of nitrate leaching in such flooded agricultural soils may differ substantially from those observed in upland or dry-land cropping systems. Accurately quantifying N loss loads requires time-consuming and arduous onsite monitoring over an extended period of years. In particular, model simulation techniques are crucial to agro-hydrology research and should not be overlooked when assessing, predicting, and analyzing the different combinations of water and nitrogen management approaches (Kroes et al., 2019).

Several models have been used in rice production systems, including APSIM (Amarasingha et al., 2015), ORYZA (Yuan et al., 2017), and CERES-Rice (Devkota et al., 2015). While these models are very good at simulating crop growth, they fall short in terms of simulating N transfer and transformation. HYDRUS-1D has been widely used in this context to mimic the movement of heat, water, and solutes in diverse environments (Gupta et al., 2023; Chen et al., 2022; Shekhar et al., 2021; Li et al., 2017). The N transformation between urea, ammonia, and nitrate is described by a sequential first-order decay chain. It can adapt to diverse boundary conditions and model the dynamics of soil water and solutes, including nutrient absorption by roots (Šimunek et al., 2008). It is reported by various researchers that HYDRUS-1D can reproduce water and solute dynamics (Devappa et al., 2026; Zúniga-Gutierrez et al., 2025; Zheng et al., 2024; Cheng et al., 2024; Thao et al., 2024; Mahbub et al., 2023; Shekar et al., 2020; Kanzari et al., 2018;). Hydrus-1D has also been coupled with DSSAT for simulations of the soil water dynamics in the soil-plant-atmosphere system (Shelia et al., 2018).

The objectives of this study were to observe the yield variation, dynamic changes of water balance components and nitrate leaching under three different irrigation regimes using HYDRUS-1D model in irrigated Boro rice cultivation in a sub-tropical environment.

MATERIALS AND METHODS

Experimental Site, Soil and Climate

The experiments were conducted at the Raised-bed Lysimeter, Bangladesh Institute of Nuclear Agriculture (BINA), Mymensingh, Bangladesh (Latitude 24^0 43' N, longitude 90^0 26' E, and 7.2 m above mean sea level), during 2020-2022. The local climate is humid and subtropical with summer-dominant rainfall. The average annual rainfall over 30 years (1991-2022) at the site was approximately 2314 mm, which was mostly concentrated from April to September. The texture of the experimental soil was loam.

Irrigation Treatments, Variety and Design

The water management practices followed were as follows:

- T_1 = Traditional irrigation (continuous ponding)
- T_2 = Irrigation three days after the ponded water disappeared from the soil surface (referred to as three days AWD)
- T_3 = Irrigation five days AWD (during the growing season)

The experimental design was a randomized complete block (RCB) with three replications, and the test rice variety was "Binadhan-24."

Experimental Setup and Cultural Practices

A raised-bed lysimeter, with a properly controlled environment, was used for the experiment. It is a non-weighing gravity-type lysimeter. With an effective soil depth of 0.54 m and a soil surface size of 1.2 m2 (1.2 m × 1.0 m), the lysimeter boxes offer enough root zone depth for the majority of field crops. The boxes had separate arrangements for irrigation, drainage and soil water measurements. Ali and Rahman (2016) provided a detailed description of the construction of the lysimeter along with facilities for experimental use. Crops grown in the control condition in the lysimeter had a barrier to the lysimeter walls for horizontal movement of water and solute. Moreover, in the micro-level experimental environment, the climate and nutrients of the crops compete, resulting in errors in heat reflection due to the visible surface walls of the lysimeters compared with those under field conditions.

The prescribed amounts of urea (240 kg/ha), TSP (115 kg/ha), MOP (70 kg/ha), gypsum (47.5 kg/ha), and ZnSO4 (3.5 kg/ha) were applied to the experimental mixture (Uddin et al., 2020). Seedlings that were 35~40 days old were transplanted in mid-January (15-17 January) every year, and the crop was harvested on the second week of May (10-12 May). All but urea fertilizer was applied at the time of transplanting. Three equal splits of urea were used as a top dressing at 10, 36, and 64 days following transplantation. Weeding was performed as needed. Insecticide was sprayed at the pre-flowering and grain formation stages. The drainage loss was measured at the bottom outlet of the lysimeter.

Measurements and Analysis

Daily weather data were gathered, including humidity, radiation, wind speed, and air temperature, from the nearest BMD weather station (200 m from the experimental field). The gravimetric approach was used to determine the soil moisture of the soil samples taken at various depths. A pressure plate device was used to measure the physical characteristics of the soil, such as field capacity and permanent wilting point. The hydrometer method was used to measure the percentages of sand, silt, and clay, while the core sampler method was used to determine the bulk density of the soil. Chemical properties were determined in the laboratory following standard methods. Table 1 lists the fundamental characteristics of the test soils.

Table 1: Basic soil properties of the different layers.

Soil Layer (cm)	Soil Particle Fraction (%)			Bulk Density (g cm^{-3})	Field capacity (%VWC)	Wilting point (%VWC)	Organic Matter (%)	pH (H_2O)
	Sand	Silt	Clay					
0-18	49.67	37.93	12.40	1.21	37.60	17.93	1.12	7.22
19-36	45.87	40.27	13.87	1.26	38.13	17.37	1.32	7.23
37-54	48.33	36.40	15.27	1.29	37.37	17.47	1.33	7.38

The soil moisture during different growth stages and at harvest time was measured with a TDR-300 (digital moisture meter), and the irrigation amount was collected with respect to date. Plant height and the leaf area index (LAI) were measured and documented at each stage of rice growth. Drainage was collected from the bottom drainage tap at every stage of the rice growing period. The water samples were immediately stored at -20 °C after being collected. A spectrophotometer was used to measure the amount of nitrogen in the water samples. Specifically, hydrochloric acid acidification-UV spectrophotometry was used for assessing ammonia nitrogen (NH_4^+ -N) and Naismith's reagent UV spectrophotometry for nitrate-nitrogen (NO_3^--N).

Description of Model HYDRUS

The HYDRUS-1D model was developed using the numerical solution of Richards' equation (Eq. 10) to simulate water flow in both saturated and unsaturated zones (Šimůnek et al., 2012):

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S_r \tag{1}$$

where θ denotes the water content ($cm^3\ cm^{-3}$), while z and t indicate the soil profile depth coordinate (cm) and time (day), respectively. The root water uptake term ($cm^3\ cm^{-3}\ day^{-1}$) is represented by S_r, and K(h) denotes the unsaturated hydraulic conductivity (cm day^{-1}) as a function of the water pressure head h (cm). In addition, the mathematical relationships describing θ(h) and K(h) are presented as follows (Van Genuchten, 1980):

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s-\theta_r}{(1+|\alpha h|^n)^m} & (h<0) \\ \theta_s & (h\geq 0) \end{cases} \tag{2}$$

$$K(h) = K_s S_e^{\lambda}\left[1-\left(1-S_e^{\frac{1}{m}}\right)^m\right]^2 \tag{3}$$

where Ks represents the saturated hydraulic conductivity (cm day^{-1}), θs and θr denote the saturated and residual water contents ($cm^3\ cm^{-3}$), respectively, and l, m, and α are empirical shape parameters (-). The Se effective saturation is computed as follows:

$$S_e = \frac{\theta(h)-\theta_r}{\theta_s-\theta_r} \tag{4}$$

Evapotranspiration and Root Water Uptake

In the model, reference evapotranspiration (ET_0) is estimated using the Penman–Monteith equation based on daily meteorological data (Allen et al., 1998). The potential crop evapotranspiration (ETc) is then determined by multiplying ET_0 by the crop coefficient (Kc). Next, transpiration and evaporation are divided via the LAI (Belmans et al., 1983):

$$E_p = ET_C \times e^{-Kgr\times LAI} \tag{5}$$

For rice, the Kgr, or the global sun radiation extension coefficient was chosen as 0.3 (Phogat et al., 2010). The difference between ETc and potential evaporation is hence potential transpiration. Furthermore, the water stress response was parameterized via a piecewise linear function (Feddes et al., 1978), which included four pressure heads related to root water uptake, as: water intake remains at the greatest level between h_2 and h_3, whereas it fluctuates (decreases or increases) linearly between h_3 and h_4 (or h_1 and h_2). If $h > h_1$ and $h < h_4$, then the root should stop absorbing water.

Transport and Transformation

The convection–diffusion equation can be used to compute the first-order chain reactions that result from the three N forms found in rice cultivation, urea, NH_4^+ -N, and NO_3^--N (Šim °unek et al., 2008):

$$\frac{\partial \theta C_1}{\partial t} = \frac{\partial}{\partial z}\left(\theta D_1^w \frac{\partial C_1}{\partial z}\right) - \frac{\partial q C_1}{\partial z} - \mu'_{w,1}\theta C_1 \tag{6}$$

$$\frac{\partial \theta C_2}{\partial t} + \frac{\partial \rho S_2}{\partial t} + \frac{\partial a_v G_2}{\partial t} = \frac{\partial}{\partial z}\left(\theta D_2^w \frac{\partial C_2}{\partial z}\right) + \frac{\partial}{\partial z}\left(a_v D_2^g \frac{\partial G_2}{\partial z}\right) - \frac{\partial q C_2}{\partial z} - \mu'_{w,2}\theta C_2 + \mu'_{w,1}\theta C_1 + \gamma_{s,2}\rho - r_{a,2} \tag{7}$$

$$\frac{\partial \theta C_3}{\partial t} = \frac{\partial}{\partial z}\left(\theta D_3^w \frac{\partial C_3}{\partial z}\right) - \frac{\partial q C_3}{\partial z} - \mu'_{w,3}\theta C_3 + \mu'_{w,2}\theta C_2 - r_{a,3} \tag{8}$$

where the subscripts 1, 2, and 3 refer to urea, NH_4^+-N, and NO_3^--N, respectively; C, S, and G denote nitrogen concentrations in the liquid (mg L^{-1}), solid (mg g^{-1}), and gas (mg g^{-1}) phases, respectively; ρ represents the soil dry bulk density (g cm^{-3}); Dw and Dg are the dispersion coefficients for nitrogen transport in the liquid and gas phases (cm^2 day^{-1}), respectively; q is the volumetric water flux (cm day^{-1}); γs is the zero-order rate constant in the solid phase (day^{-1}); ra denotes passive root nitrogen uptake; and μw and $μw^0$ are the first-order rate constants for nitrogen transformation in the liquid phase (day^{-1}) and the sequential reactions among urea, NH_4^+-N, and NO_3^--N (day^{-1}), respectively.

Initial and Time-Variable Boundary Conditions

Simulations of the HYDRUS-1D were performed on a daily time step, starting from the transplanting stage. The lysimeter soil column, divided into four layers, was represented as a 54 cm deep paddy soil profile as illustrated in Figure 1. The upper boundary condition was defined as an atmospheric boundary condition with surface ponding, where the maximum allowable water depth (hmax) was set to 10 cm before the onset of surface runoff, reflecting the capacity of the paddy field to retain standing water. On the basis of percolation flow measured at the lysimeter bottom, the deep drainage boundary was identified as the bottom boundary condition. During transplanting, the shallow pond water depth was designated as the initial condition for water flow for each season.

The first concentrations of urea in the soil profile were calculated by dividing the N application rate of the basic fertilizer by the horsepower at transplanting. The initial concentrations of ammonia and nitrate N were determined via linear interpolation of the observed data at the prescribed depths. Similarly, the urea concentration used as the upper boundary condition was derived from the top-dressed fertilizer application rate and incoming water flux during the tillering and heading stages. The bottom boundary condition was specified as a Dirichlet boundary. The simulation commenced on the day following transplanting and continued through to the end of the milky-ripening stage, as irrigation and drainage were discontinued once the paddy field entered the yellow-ripening stage.

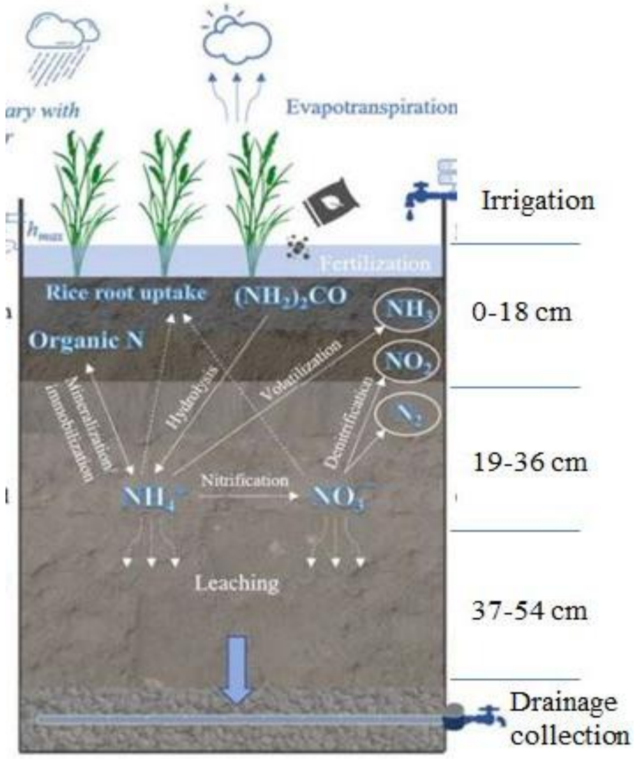


Figure1: HYDRUS-1D model's N first-order chain reaction process and the lysimeter experiment's water flow boundary conditions

Model Input Parameters

The soil hydraulic parameters of van Genuchten model were calibrated on the basis of the observed bulk density dataset and the particle size distribution, as displayed in Table 1. To analyze solute transport, the longitudinal dispersivity was initially estimated as one-tenth of the soil profile depth and subsequently calibrated (Phogat et al., 2013). The molecular diffusion coefficients in free water (Dw) for NH4+-N and NO3−-N were 1.52 and 1.64 cm2 day−1, respectively, while the diffusion coefficient of NH3 in soil air (Dg) was 18,057.6 cm2 day−1. Nitrogen uptake rates were estimated by linear interpolation of the measured total N content in rice between two sampling intervals. Rice roots were assumed to absorb mineral N forms (NH4+-N and NO3−-N) passively without limitation (cmax = 1000 mg L−1), whereas urea uptake was not considered (cmax = 0 mg L−1). In addition, only NH4+-N was included in active uptake, with the Michaelis–Menten constant set at 0.31 mg L−1 (Duan et al., 2007). For the first-order N transformation processes, the temperature and water-content dependencies are commonly neglected (Hanson et al., 2006). Because direct estimation of N transformation parameters is difficult in practice, the parameters were initially obtained from published studies (Mo'allim et al., 2018; Yang et al., 2017; Li et al., 2025) and subsequently calibrated and validated (Table 4). Ammonia volatilization was assumed to occur only at the soil surface, whereas mineralization/immobilization processes were considered to be predominantly active within the root zone (Li et al., 2025). In addition, the nitrification and denitrification parameters were first uniformly assigned throughout the soil profile and later adjusted for each individual layer. Urea and NO_{3-}-N were assumed to exist solely in the liquid phase (i.e., Kd = 0 cm3 g−1), whereas the distribution coefficient (Kd) of NH_{4+} -N between the liquid and solid phases was set to 3.5 cm^3 g^{-1}, consistent with previous studies (Tan et al., 2015; Hanson et al., 2006; Dash et al., 2015).

Table 3: The soil hydraulic characteristics were calibrated for various soil layers.

Depth (cm)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_s (cm day^{-1})
0-18	0.0494	0.4284	0.0107	1.5176	42.25
19-36	0.0527	0.4214	0.0102	1.5284	40.23
37-54	0.0518	0.4185	0.0131	1.493	40.12

Note: The θ_s is the saturated water content, θ_r is the residual water content, the α and n are the van Genuchten shape parameters, and K_s is the saturated hydraulic conductivity.

Table 4: The calibrated parameters of the N first-order chain reaction for different soil layers.

Depth (cm)	DL (cm)	K_d (cm^3 g^{-1})	K_v (day^{-1})	K_n (day^{-1})	K_{dn} (day^{-1})	K_m (day^{-1})	K_h (day^{-1})
0-18	5.4	4.5	0.035	0.04	0.26	0	0
19-36	5.4	4.5	0.035	0.04	0.26	0	0
37-54	5.4	4.5	0.035	0.04	0.26	0	0

Note: K_m represents the net production rate of NH_{4+} -N associated with mineralization/immobilization processes; K_d denotes the distribution coefficient of ammonia N; K_v is the ammonia volatilization coefficient; K_n represents the nitrification rate; Kdn is the denitrification rate; DL denotes the longitudinal dispersivity; and K_h is the hydrolysis rate.

Calibration of HYDRUS Model

HYDRUS-1D model was calibrated against the observed soil water content and drainage data.

RESULTS AND DISCUSSION

Yield and Yield Attributes

The average effects of irrigation treatments on yield and yield-contributing characteristics are presented in Table 5. During 2020–21, significant differences among irrigation treatments were observed for all parameters except plant height and number of tillers per plant. Most yield-related traits of Binadhan-24 declined with increasing water stress, although the number of tillers per plant did not follow this trend. The highest grain yield (6.77 t ha^{-1}) was recorded under treatment T_1 (normal irrigation with continuous ponding), followed by T_2 (5.87 t ha^{-1}), whereas the lowest yield was obtained under T_3 (5.21 t ha^{-1}). Previous studies (Ali, 2018; Islam et al., 2020) also reported a 5–15% reduction in Boro rice yield under AWD irrigation applied for 3 or 5 days compared with conventional irrigation practices.

In 2021–22, irrigation treatments significantly affected panicle length, number of grains per panicle, grain yield, and 1000-grain weight (Table 5). Similar to the previous year, the maximum grain yield was achieved under T_1(6.94 t ha^{-1}), followed by T_2 (6.01 t ha^{-1}) and T_3 (5.11 t ha^{-1}).

Table 5: Average effects of irrigation treatments on the yield and yield-contributing traits of Binadhan-24

Year	Treatment	Plant height (cm)	Tiller per plant (No.)	Panicle length (cm)	Seed per panicle (nos)	1000 grain wt (gm)	Grain yield (t/ha) adjusted at14% MC
2020-2021	T_1	92	11	23.13 a	128 a	25.94 a	6.77 a
	T_2	85	12	22.63 b	117 ab	25.67 b	5.87 ab
	T_3	83	12	22.03 b	98 b	25.33b	5.21 b
	F test at (5%)	NS	NS	S	S	S	S
2021-2022	T_1	90	12	23.93 a	127 a	26.49 a	6.94 a
	T_2	88	13	22.93 b	109 ab	25.93 b	6.01ab
	T_3	82	12	22.23 b	94 b	25.61 b	5.11 b
	F test at (5%)	NS	NS	S	S	S	

Note: Tukey's honest significant difference (THSD) test indicates that means with the same letter are not statistically substantially different at the 5% probability level.

Irrigation Water Required, Comparative Irrigation Savings and Yield Penalty

The total irrigation water required, comparative water savings and yield loss for different treatments are summarized in Table 6. The results indicate that reducing irrigation substantially decreased the total irrigation amount and increased water savings; however, it also caused a corresponding reduction in grain yield.

Table 6: Number of irrigation, total irrigation amount, water savings of Binadhan-24 under field conditions

Year	Irri. Treatment	Total irrigation amount (cm)	Yield, t/ha	Water savings (%, compared to T1)	Yield reduction (%, compared to T1)
2020-2021	T_1	70.9	6.77	-	-
	T_2	54.7	5.87	22.8	13.3
	T_3	43.0	5.21	39.3	23.0
2021-2022	T_1	50. 6	6.94	-	-
	T_2	42.2	6.01	16.6	13.4
	T_3	40. 8	5.11	19.3	26.4

During the 2020–2021 season, the conventional irrigation treatment (T1) required the highest irrigation amount of 70.9 cm and produced the maximum grain yield of 6.77 t ha^{-1}. Reducing irrigation under T2 decreased the irrigation amount to 54.7 cm, representing a 22.8% water saving, while grain yield declined moderately to 5.87 t ha^{-1}, corresponding to a 13.3% yield reduction compared with T1. A further reduction in irrigation under T3 lowered the irrigation amount to 43.0 cm, resulting in a substantial 39.3% water saving. However, this treatment also reduced grain yield to 5.21 t ha^{-1}, representing a 23.0% yield reduction relative to the conventional irrigation treatment. These findings suggest that although greater irrigation reduction significantly conserved water, excessive water deficit adversely affected crop growth and grain production.

A similar trend was observed during the 2021–2022 season. The conventional irrigation treatment (T1) received 50.6 cm of irrigation water and produced the highest grain yield (6.94 t ha^{-1}). The T2 treatment reduced irrigation to 42.2 cm, achieving 16.6% water savings while maintaining a relatively high grain yield of 6.01 t ha^{-1}, equivalent to only a 13.4% reduction compared with T1. Under the more restrictive irrigation treatment (T3), irrigation water was further reduced to 40.8 cm, providing 19.3% water savings but causing the grain yield to decline to 5.11 t ha^{-1}, which was 26.4% lower than the control.

The results also highlight the trade-off between irrigation water savings and grain yield. While T3 achieved the greatest water conservation in both years, it consistently resulted in the largest yield penalties. In contrast, T2 provided a more balanced outcome by reducing irrigation water by 16.6–22.8% while limiting yield losses to approximately 13%. This suggests that moderate irrigation reduction can improve irrigation water productivity without causing severe reductions in grain yield.

Overall, the findings demonstrate that Binadhan-24 can tolerate moderate reductions in irrigation with relatively small yield penalties, whereas severe irrigation deficits significantly reduce productivity. Therefore, the T2 irrigation schedule appears to be the most suitable management option under the tested conditions, offering a practical compromise between water conservation and grain production. Such an irrigation strategy could contribute to improving irrigation efficiency and enhancing the sustainability of rice production in water-limited environments.

Calibration Efficiency of the Model

The observed and predicted soil water balances are shown in Fig.2. The average model efficiency was found as 93%.

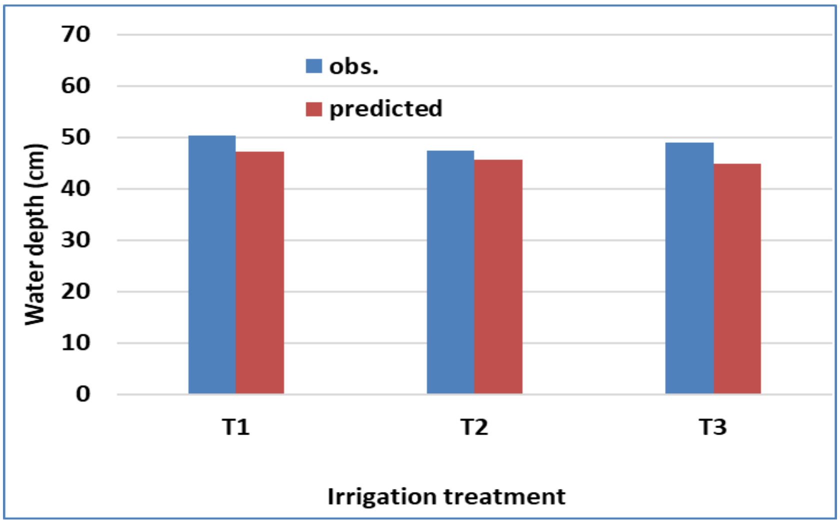


Figure 2: Observed and predicted soil water balance

Simulated Results

Simulated Root Water Uptake and Evaporation

The cumulative actual root water uptake increased continuously throughout the rice growing season under all irrigation treatments (Figure 3). Root water uptake was relatively slow during the early growth stage (0–40 DAS), followed by a more rapid increase during the active vegetative and reproductive stages. At harvest, cumulative root water uptake was highest under T1 (≈40 cm), followed by T2 (≈37 cm) and T3 (≈36 cm), indicating a slight reduction in crop water extraction under AWD conditions. Cumulative evaporation also increased progressively during the season and reached approximately 7.8–8.0 cm under all treatments. Differences in cumulative evaporation among treatments were negligible, suggesting that AWD primarily affected crop water uptake rather than soil evaporation losses.

Root-Zone Water Status and Soil Water Storage

Distinct differences in root-zone water dynamics were observed among irrigation treatments (Figure 4). Under continuous ponding (T1), root-zone pressure head remained relatively stable throughout the growing season, generally fluctuating between 0 and −500 cm. In contrast, AWD treatments exhibited pronounced declines in pressure head during drying cycles, particularly during the late growth stage. The lowest pressure head values were observed under T3, reaching below −6000 cm, indicating severe soil drying before irrigation events. Soil water storage exhibited repeated wetting and drying cycles corresponding to irrigation schedules. Continuous ponding maintained comparatively stable soil water storage throughout the season, whereas AWD treatments showed progressively larger fluctuations. The reduction in soil water storage was greatest under T3, reflecting the longer drying interval between irrigation applications.

Surface NH_4^+-N and NO_3^--N Dynamics

Surface NH_4^+-N concentrations displayed a characteristic cyclic pattern throughout the season, with concentration increases immediately following fertilizer application and subsequent declines due to plant uptake, nitrification, and transport processes (Figure 5). Surface NH_4^+-N gradually decreased from approximately 0.25 ppm cm^{-3} during the early season to below 0.10 ppm cm^{-3} near harvest under all treatments.

In contrast, surface NO_3^--N concentrations declined sharply during the initial growth stage and remained close to zero for the remainder of the season. This trend suggests rapid nitrate transformation, uptake, or downward movement shortly after fertilizer application. Treatment effects on surface NO_3^--N concentrations were minimal.

Bottom-Boundary NH_4^+-N and NO_3^--N Dynamics

Bottom-boundary NH_4^+-N concentrations increased during the early growth stage and reached peak values of approximately 0.27–0.28 ppm cm^{-3} before gradually declining toward the end of the season (Figure 6). The temporal patterns were similar among treatments, although slightly higher residual NH_4^+-N concentrations were observed under AWD treatments. Bottom-boundary NO_3^--N concentrations declined rapidly from initial values of approximately 4.5–5.0 ppm cm^{-3} to nearly zero within the first 20 days after transplanting and remained negligible thereafter. No substantial treatment differences were observed.

Root-Zone NH_4^+-N and NO_3^--N Dynamics

Root-zone NH_4^+-N concentration increased during the early growth stage and reached a maximum of approximately 0.27–0.28 ppm cm^{-3} around 15–20 DAS (Figure 7). Thereafter, concentrations gradually declined until harvest due to continuous plant uptake and nutrient depletion. Root-zone NH_4^+-N concentrations were slightly higher under T3 than T1 during portions of the season, indicating reduced nitrogen removal under the more severe AWD treatment. Root-zone NO_3^--N concentrations decreased sharply within the first 10–20 days and remained close to zero throughout the remainder of the growing period. Similar trends were observed under all irrigation treatments.

Simulated Nitrogen Uptake by Rice Roots

Cumulative NH_4^+-N uptake increased steadily throughout the growing season under all treatments (Figure 8). The highest uptake was observed under T1 (approximately 8.0 ppm cm^{-2}), while T2 and T3 exhibited slightly lower values (approximately 7.7 and 7.6 ppm cm^{-2}, respectively). The differences among treatments became more apparent during the reproductive stage when crop nutrient demand was greatest. Cumulative NO_3^--N uptake increased rapidly during the early growth stage and then continued at a slower rate until harvest. Final cumulative NO_3^--N uptake was approximately 2.9–3.0 ppm cm^{-2} for all treatments, indicating limited treatment effects on nitrate acquisition.

Discussions

These results confirm that AWD successfully reduced soil water availability compared with conventional flooding. The greater reduction in pressure head under T3 indicates increased soil matric suction and greater water stress potential, whereas T2 maintained a more favorable balance between water conservation and root-zone moisture availability. The dominance of NH_4^+-N over NO_3^--N at the soil surface is consistent with flooded rice systems where ammonium is generally the predominant inorganic nitrogen form. The repeated concentration peaks reflect fertilizer application events and subsequent nitrogen transformations within the soil profile. The rapid depletion of NO_3^--N at the lower boundary suggests strong nitrate uptake and/or denitrification processes within the flooded rice environment. The gradual decline in NH_4^+-N concentration indicates progressive nitrogen utilization by the crop throughout the growing season. The slightly greater NH_4^+-N uptake under continuous ponding corresponds with the higher cumulative root water uptake observed in Figure 3. Nevertheless, the relatively small differences among treatments suggest that moderate AWD can conserve water while maintaining nitrogen uptake comparable to conventional flooded rice cultivation.

Overall, the HYDRUS-1D simulations demonstrated that AWD irrigation reduced soil water storage and increased root-zone drying compared with continuous ponding. However, reductions in cumulative root water uptake and nitrogen uptake were relatively small, particularly under the three-day AWD treatment. Surface, root-zone, and bottom-boundary nitrogen dynamics showed similar temporal patterns among treatments, indicating that moderate AWD can maintain crop water and nitrogen acquisition while reducing water use. Among the AWD treatments, three-day AWD (T2) appeared to provide the best balance between water conservation and maintaining favorable root-zone conditions.

SUMMARY AND CONCLUSION

For irrigated rice, increasing water productivity (WP) is essential as water supplies become more limited. Water consumption and risk management can benefit from monitoring the long-term impacts of fertilization and irrigation on the components of the water balance. A field-Lysimeter investigation was carried out and the Hydrus-1D model was calibrated to simulate the nitrate leaching and water balance components. Three distinct irrigation treatments were applied in the lysimetric study: traditional irrigation (continuous ponding) (T1), irrigation three days after the ponded water disappeared from the soil surface (referred to as three days AWD) (T2), and irrigation five days AWD (T3).

The results of field experiments indicated that, the conventional irrigation treatment (T1) yielded the highest grain production (6.77–6.94 t ha^{-1}), but demanded the most water (50.6–70.9 cm). Severe irrigation restriction (T3) achieved significant water savings up to 39.3%, yet resulted in substantial yield reductions of up to 26.4%. The relative crop responses remained consistent across both years. A moderate irrigation reduction (T2) provided a balanced trade-off, saving 16.6–22.8% of water while limiting yield penalties to roughly 13%. Consequently, T2 emerged as the optimal management strategy to improve water productivity and sustain rice production in water-limited environments without causing severe yield losses.

The Hydrus-1D model was well fitted with the field data (calibration efficiency was about 94%). The HYDRUS-1D simulations demonstrated that AWD irrigation reduced soil water storage and increased root-zone drying compared with continuous ponding. However, reductions in cumulative root water uptake and nitrogen uptake were relatively small, particularly under the three-day AWD treatment. Surface, root-zone, and bottom-boundary nitrogen dynamics showed similar temporal patterns among treatments, indicating that moderate AWD can maintain crop water and nitrogen acquisition while reducing water use. Among the AWD treatments, three-day AWD (T2) appeared to provide the best balance between water conservation and maintaining favorable root-zone conditions.

Thus, considering yield, irrigation water savings, and HYDRUS simulations of soil water storage, water uptake and nitrogen dynamics, three-day AWD seems a viable option for practical implementation strategy for the study area, as well as other similar areas.

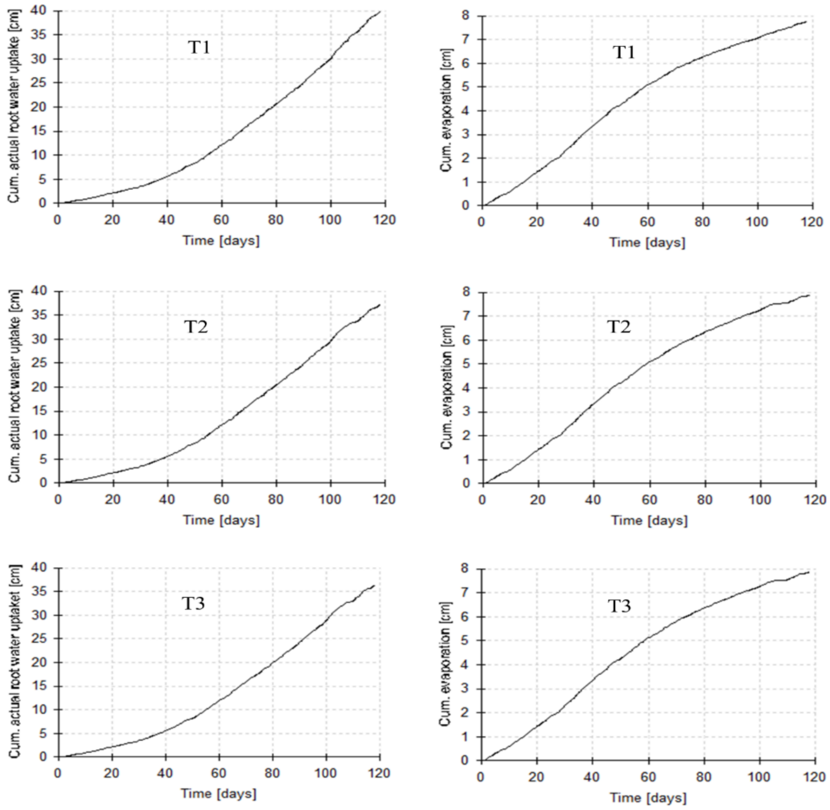


Figure 3: Simulated cumulative actual root water uptake and cumulative soil evaporation under different treatments

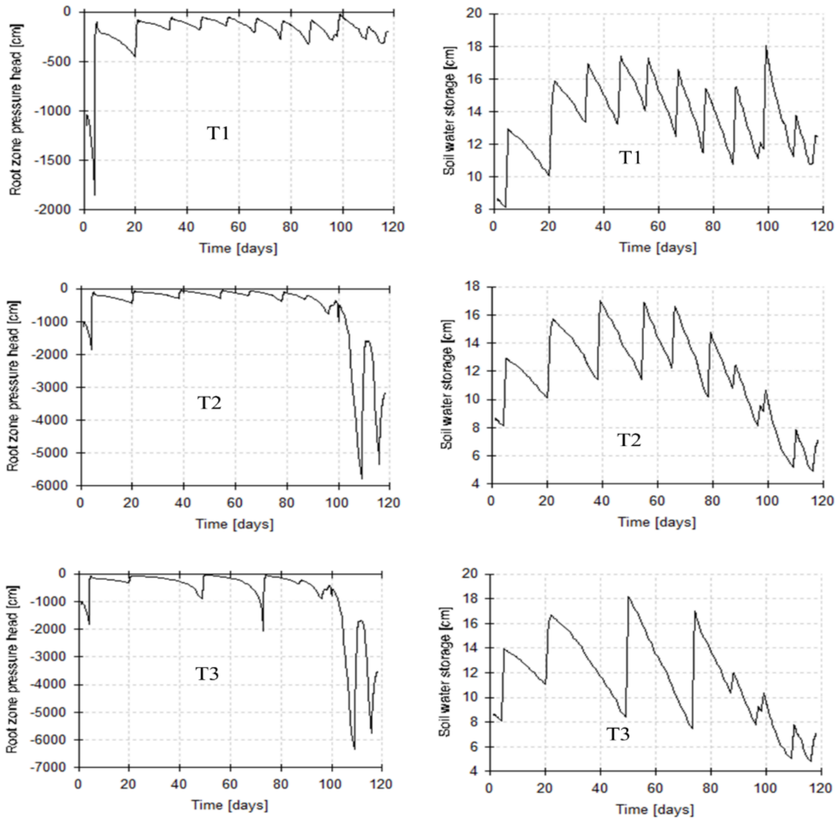


Figure 4: Temporal variation in root-zone pressure head and soil water storage under different treatments

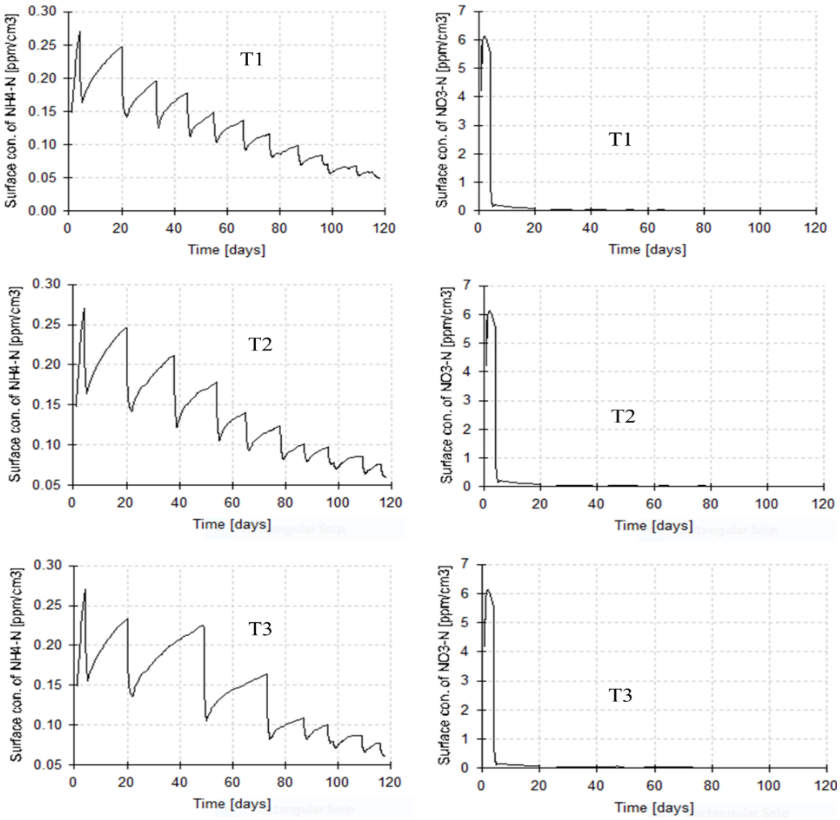


Figure 5: Simulated surface concentrations of NH_4^+-N and NO_3^--N under different treatments

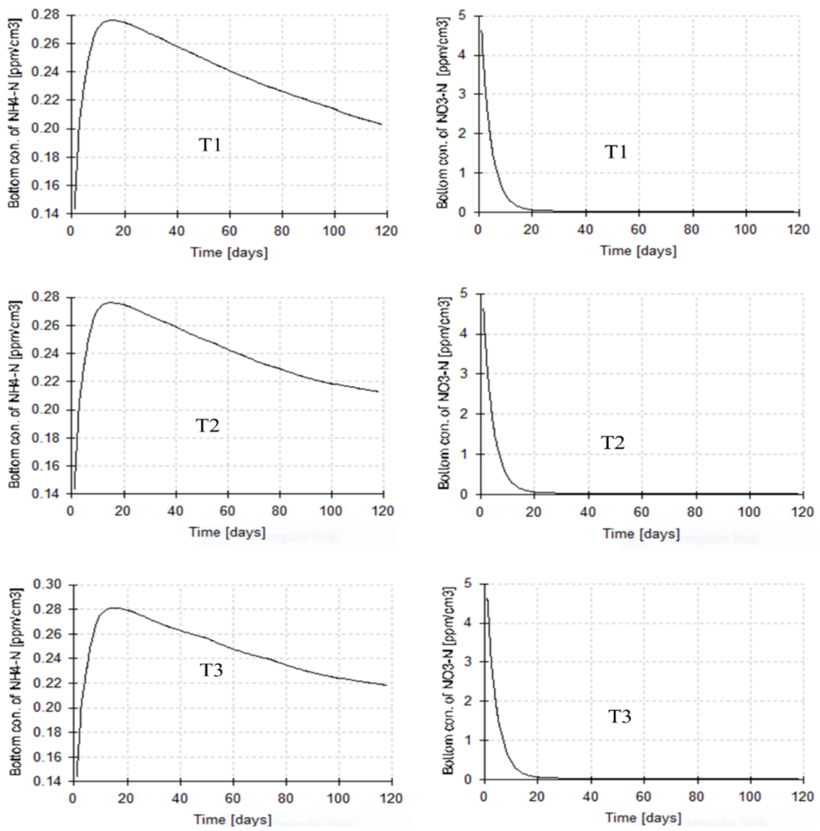
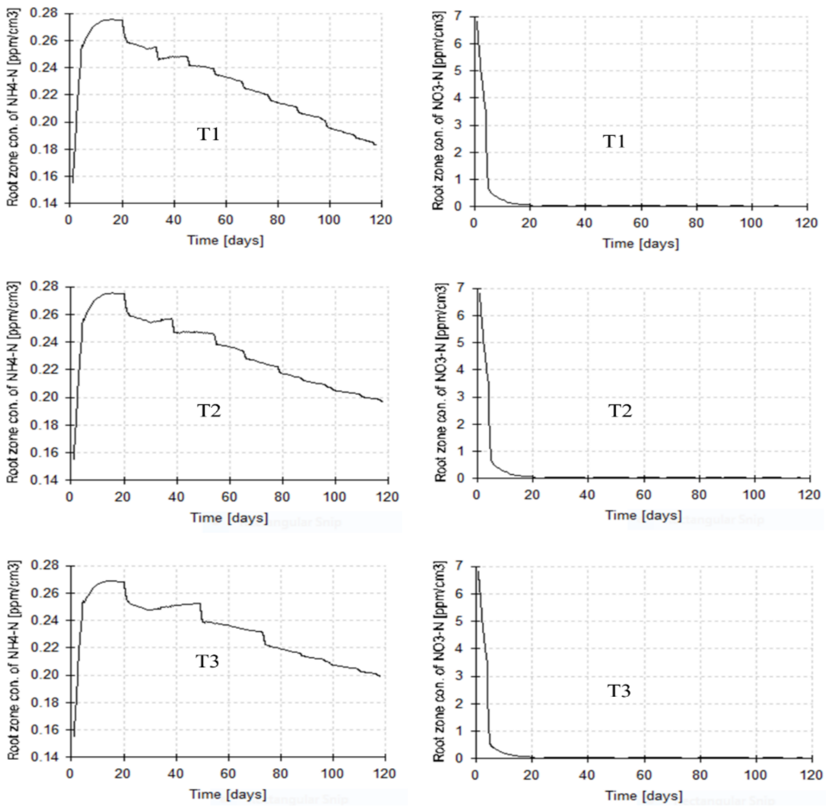
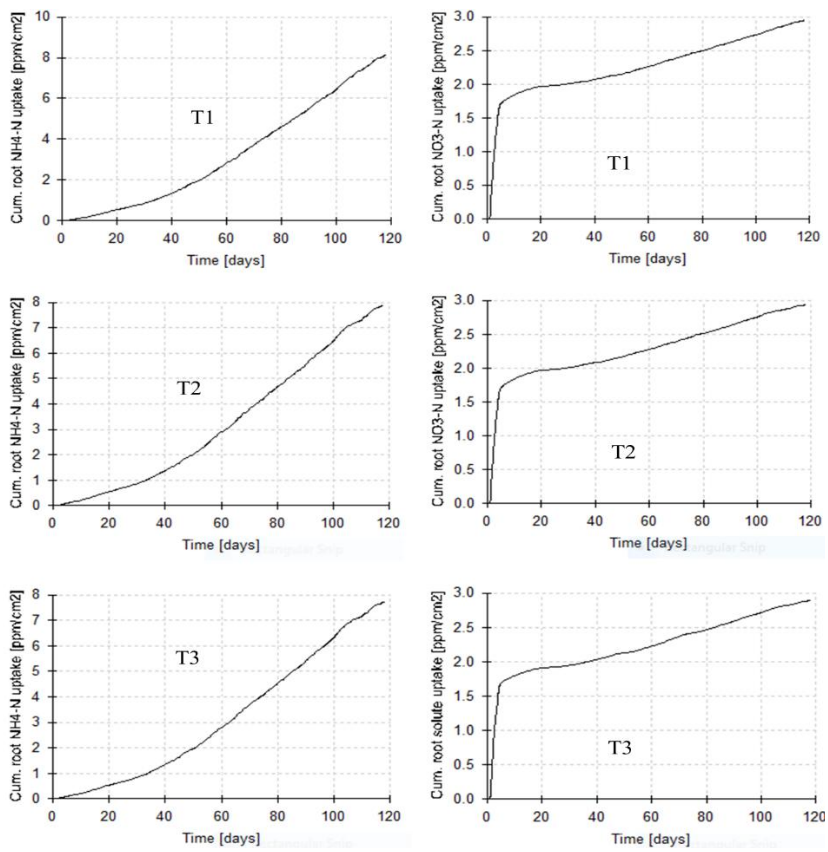


Figure 6: Simulated bottom-boundary concentrations of NH_4^+-N and NO_3^--N under different treatments



<u>Figure 7</u>: Simulated root-zone concentrations of NH_4^+-N and NO_3^--N under different treatments



<u>Figure 8</u>: Simulated cumulative uptake of NH_4^+-N and NO_3^--N by rice roots under different treatments

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