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Soil water and potassium dynamics simulation under drip fertigated Kinnow mandarin in sandy loam soils

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ABSTRACT

The availability of water and nutrients in the root zone of the crop is very important for improving agricultural production. Studies on water and nutrient distribution in the crop root zone are essential for the appropriate design of drip fertigation systems. In the present study, water and potassium (K) dynamics under drip fertigated Kinnow mandarin in the sandy loam soil were studied. To simulate the water and potassium dynamics in the soil, HYDRUS 2D model was calibrated and validated. The results revealed that the HYDRUS-2D model was able to simulate both water and solute dynamics with R^2 values ranging from 0.90-0.95 for soil water and 0.92-0.95 for potassium. The moisture content in the active root zone was near field capacity at 24 and 48 h after irrigation but significantly declined after 72 h. Potassium concentration was found higher in the upper layers of the soil (0-30 cm) and lower in deeper layers (30-60 cm) at 24, 48 and 72 h after fertigation. The results indicated that soil moisture and potassium were efficiently utilized by Kinnow trees with 4 Lh^{-1} dripper without much wastage, as the active root zone of the Kinnow was found between 15-30 cm depth. Thus, 4 Lh^{-1} dripper was the optimum discharge size for drip fertigation in sandy loam soils. This information can be helpful for designing of drip fertigation system for citrus crop under sandy loam soils for improving productivity.

1. INTRODUCTION

Kinnow mandarin (*Citrus reticulata* Blanco), a hybrid of King mandarin (*Citrus nobilis*) and Willow leaf mandarin (*Citrus deliciosa*), is a commercially important fruit variety of citrus. Kinnow has become the most favorable cultivar among citrus growers in northern India because it has adapted very well under arid and semi-arid climatic conditions where other citrus varieties have failed (Sharma *et al*., 2007). In India, the productivity of citrus including Kinnow is less compared to the productivity of citrus elsewhere. One of the main reasons for the decline in yield and quality of citrus is the water stress during critical growth stages of the crop and nutrient deficiency in the soil of citrus orchards (Wang *et al*., 2006). Secondly, due to a lack of awareness among the farmers about the quantity of water and fertilizers to be applied to citrus crops at different growth stages under drip fertigation. To supply water and nutrients to the plants in proper amounts, judicious application of irrigation and fertilizer can be helpful in designing drip irrigation schedules for perennial horticultural crops. However, the appropriate design of a drip fertigation system requires detailed knowledge of water and nutrient distribution in the root zone(Singh *et al.,* 2020a).

Sufficient water and nutrients availability in the root-zone of the crop is essential for higher quality and production of citrus (Mostert and Van, 2000). This information can be obtained either by conducting field experiments or by modelling studies (Dash *et al.,* 2023). However, conducting field experiments to obtain such information is costly and time consuming. Therefore, numerical simulation is an efficient approach for investigating optimal drip management practices (Cote *et al*., 2003). Moreover understanding the soil hydraulic behaviour is essential for modelling the dynamics of moisture in soil (Singh *et al*., 2021a). Numerical models can represent a powerful tool to analyze the wetting pattern during the distribution and redistribution process

(Provenzano, 2007, Singh *et al.,* 2021b). Thus, a properly calibrated and validated water and solute transport model has to be selected which is effective in reducing cost and time. Several models have been developed to simulate water and nutrient distribution in soil under drip fertigation. These models serve as valuable tools in designing drip fertigation system. Simunek *et al*. (1999) developed the HYDRUS-2D software package for simulating two dimensional movement of water, heat and multiple solutes in variably saturated media. Mathematical models to simulate the water and potassium movement under drip fertigation were developed by Rivera *et al.* (2008).The accuracy of numerical, analytical and empirical models were evaluated to estimate wetting patterns under surface and subsurface drip irrigation (Kandelous and Simunek, 2010). Similarly, water and nitrate distribution pattern from point source drip irrigation was studied using HYDRUS-2D (Li *et al.,* 2005, Skaggs *et al*. 2004. Several researchers have simulated the soil water and nutrient dynamics in the different seasonal crops like Onion, Potato and Okra under drip irrigation system using HYDRUS-2D. (Ajdary *et al*., 2007; Patel and Rajput, 2008, 2010; Satpute *et al.,* 2015; Singh *et al.,* 2020b; Surendran and Chandran, 2022). Attempts have been made by the researchers to understand the dynamics of water and nitrate under perinneal crops like citrus. For instance, Phogat *et al*., 2013 used the HYDRUS-2D model to simulate water and nitrate movement in the soil under orange tree planted in lysimeter for Australian soil conditions. Seasonal simulation of water, salinity and nitrate dynamics under drip irrigated mandarin was studied by Phogat *et al*. 2014 using HYDRUS-2D. However, potassium dynamics studies especially in perinneal fruit crops like citrus are very few in the Indian context. Among the essential nutrients, potassium (K) plays a vital role in improving the yield and quality in citrus. Application of K increases the citrus fruit yield and quality and is more effective in increasing the fruit weight, peel thickness and juice volume (Ashraf *et al.,* 2010, Quaggio *et al*., 2011). The review suggests that modeling of soil nutrient dynamics particularly potassium (K) in citrus under drip fertigation are very few, signifying the importance of the present study. Therefore, the objective of this study was to study the water and potassium dynamics under drip fertigated Kinnow mandarin cultivated in the sandy loam soils using the HYDRUS-2D model.

2. MATERIALS AND METHODS

Experimental Site

The experiment was conducted in 2010-11 at the orchard of Centre for Protected Cultivation Technology (CPCT), ICAR-Indian Agricultural Research Institute, New Delhi (latitude of 28°22'48"N and longitude of 77°7'48"E and average elevation of 230 m above mean sea level). Climate of Delhi is categorized as semi-arid, subtropical with hot dry summer and cold winter and it falls in the Agro-eco-region-IV. The average annual temperature in Delhi is 24°C. The months of May and June are the hottest with an average maximum temperature of 39.7°C. The mean temperature in the winters is 14°C with the coldest month in January, and the minimum temperature as low as 1°C. The mean annual rainfall of Delhi is 710 mm of which 75% is received during the monsoon season (June to Sept). The relative humidity ranges from 34.1 to 97.9 % and wind speed ranges from 0.45 to 3.96 ms^{-1}.

Soil Properties of Experimental Plot

The soil samples from the experimental plot were collected from 0 to 60 cm depth at an interval of 15 cm to determine the soil physical and chemical properties. The physical properties of soil namely particle size distribution, bulk density, field capacity, permanent wilting point and hydraulic conductivity (Jackson, 1973) are presented in Table 1. Soil moisture retention characteristics of experimental soil at various matric potentials were determined by Pressure Plate Apparatus (Richards and Weaver, 1944). The moisture characteristics curve of soil of experimental field is provided in Fig. 1. In all the four layers, from 0-15 cm to

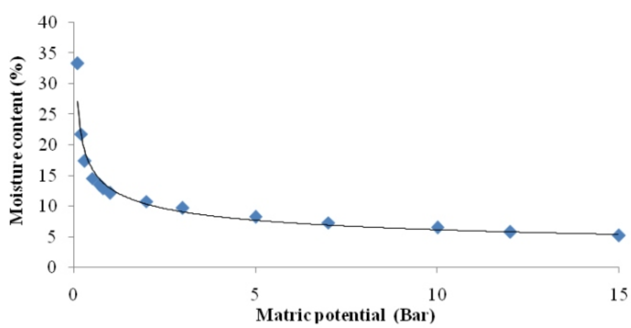

Fig. 1. Moisture characteristics curve of soil of experimental plot

Table: 1
Physical properties of soil of the experimental site

Depth (cm)	Mineral content % mass			Textural class	Hydraulic conductivity (cm h^{-1})	Bulk density (g cm^{-3})	FC (%)	PWP (%)
	Sand	Silt	Clay					
0-15	72	12	16	Sandy loam	1.29	1.53	21.67	6.25
15-30	69	10	21	Sandy loam	1.32	1.59	26.86	6.22
30-45	56	20	24	Sandy loam	1.23	1.57	27.34	9.86
45-60	52	26	22	Sandy loam	1.15	1.56	26.81	9.94

45-60 cm depth was majorly dominated by sandy loam soil. The different chemical properties like pH, EC (Jackson, 1973), available nitrogen (Subbiah *et al.*, 1956), phosphorous (Olsen *et al.*, 1954) and potassium (Hanway and Heidal, 1952) were also estimated by standard laboratory methods. The chemical properties of experimental soil are presented in Table 2.

Experimental Design

The experimental field consisted of 3 rows of 10 year old Kinnow trees with 27 trees in each row, and spacing of trees was 4 m × 5 m. The recommended dose of Nitrogen (N) and Phosphorus (P) was 800 g plant^{-1}yr^{-1} and 400 g plant^{-1}yr^{-1}, respectively. The amount of N and P applied in each treatment were same as that of recommended dose, but the amount of Potassium (K) applied was varied as 600,700 and 800 g plant^{-1}yr^{-1} under different treatments. To apply the N, P and K nutrients; urea, urea phosphate and muriate of potash (MoP) fertilizers were used. The experiment consisted of nine treatments having three levels of irrigation *i.e.* 60, 80 and 100% of crop evapotranspiration (ET_c) and three levels of potassium fertilizer *i.e.* 600, 700 and 800 g plant^{-1}yr^{-1}. The fertilizer levels were in the main plot treatments whereas the irrigation levels were in the sub-plot treatments. All the treatments were replicated three times following a split plot design (Desai *et al*., 2014). The treatments used in the experiment are presented below:-

T_1 = 60% of ET_c with 600 g K plant^{-1}yr^{-1}; T_2 = 60% of ET_c with 700 g K plant^{-1}yr^{-1}; T_3 = 60% of ET_c with 800 g K plant^{-1}yr^{-1}; T_4 = 80% of ET_c with 600 g K plant^{-1}yr^{-1}; T_5 = 80% of ET_c with 700 g K plant^{-1}yr^{-1}; T_6 = 80% of ET_c with 800 g K plant^{-1}yr^{-1}; T_7 = 100% of ET_c with 600 g K plant^{-1}yr^{-1}; T_8 = 100% of ET_c with 700 g K plant^{-1}yr^{-1}; T_9 = 100% of ET_c with 800 g K plant^{-1}yr^{-1}.

Crop Water Requirement

Crop evapotranspiration was calculated using the previous five years average of meteorological data, in CROPWAT software. CROPWAT software developed by FAO, uses Penman-Montieth equation for estimation of ET_c and is used for scheduling of irrigation (Allen *et al*., 1998). The quantity of water applied to Kinnow mandarin trees was calculated by the formulas provided below:-

$$ET_c = ET_o \times K_c \qquad ...(1)$$

Where, ET_c = Crop evapotranspiration (mm); ET_o = Reference evapotranspiration (mm); K_c = Crop coefficient.

Drip Irrigation System

Drip irrigation system consisted of underground sub main line of 50 mm diameter and lateral lines of 16 mm diameter. The laterals had two drip emitters of 4 Lh^{-1} discharge at a spacing of 50 cm placed at each tree. Treatment wise laterals were connected from sub main line for irrigation of the Kinnow trees with different levels of irrigation and potassium. Each lateral line was provided with flow control valve at the start of line to control the duration of irrigation and fertigation treatment. The duration of operation of drip system was determined for different levels of irrigation based on water requirement and emitters discharge. The efficiency of the drip irrigation system was considered as 90% (Sivanappan, 1994).The treatment wise drip irrigation and fertigation schedule followed based on the crop growth stages are available in Desai *et al*., 2013, 2014. The layout of drip irrigation system for 1 replication with 9 treatments, drip laterals and plant spacing is shown in Fig. 2.

Table: 2
Chemical properties of soil

Depth (cm)	pH	EC (dsm^{-1})	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
0-15	8.1	0.16	87.52	9.51	175.42
15-30	8.3	0.14	81.69	6.13	136.73
30-45	8.5	0.13	74.35	3.11	98.73
45-60	8.5	0.13	65.20	2.87	87.14

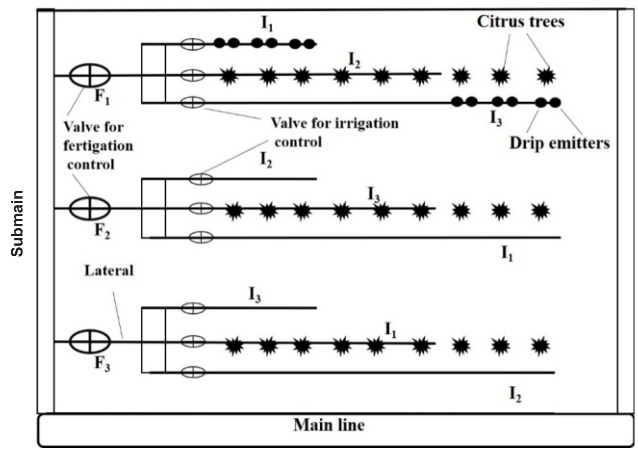

Fig. 2. Layout of drip irrigation system for Kinnow trees

Sample Collection and Analysis

The amount of water and available potassium in different layers of soil, their spatial and temporal distribution was determined by gravimetric method and flame photometer method (Hanway and Heidal, 1952), respectively. The soil samples were collected from different depths (0-15, 15-30, 30-45, 45-60 cm) before fertigation, and after 24, 48, and 72 h after fertigation for water and potassium dynamics studies. The moisture content was represented as volumetric water content (%) whereas the potassium content was expressed in concentration (mg mL^{-1}).

HYDRUS-2D Model

HYDRUS-2D is a finite element model, which solves the Richard's equations for variably saturated water flow and convection-dispersion type equation for heat transport. The flow equation includes a sink term to account for water uptake by plant roots. The program is used to simulate water and solute movement in unsaturated, partially saturated or fully saturated porous media. Simulation can be done in non-uniform soils as well. It can simulate the flow and transport in the vertical plane, horizontal plane and in three dimensional region exhibiting radial symmetry about vertical axis. A detail description of model and related theory is presented in the report documents version 2.0 of HYDRUS (Simunek *et al*., 1999 and 2011).

Governing Water Flow Equation

The governing flow equation considers two-dimensional isothermal Darcian flow of water in a variably saturated rigid porous medium and assumes that the phase plays an insignificant role in the liquid flow process. The flow equation used in the HYDRUS-2D is given by the following modified form of the Richard's equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[k\left(K_{ij}^A \frac{\partial h}{\partial x_j} + KA_{iz}\right)\right] - S \quad ...(2)$$

Where, θ = Volumetric water content, [L^3L^{-3}]; h = Pressure head [L]; S = Sink term [T^{-1}]; x_i (i = 1, 2) are the spatial co-ordinates [L]; t = Time [T]; K_{ij}^A = Components of a dimensionless; anisotropy tensor KA and K = Saturated hydraulic conductivity function [LT^{-1}] given by:

$$K(h, x, z) = Ks(x, z)\, Kr(h, x, z) \quad ...(3)$$

Where, *Kr* = Relative hydraulic conductivity and *Ks* = Saturated hydraulic conductivity (LT^{-1}).

The anisotropy tensor K_{ij}^A in (1) is used to account for an anistropic medium.

Two-dimensional soil water flow in variably saturated, rigid, isotropic porous medium under surface drip irrigation is described by the modified form of Richards' equation. The equation is given by:-

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial r}\left(K_r \frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - \frac{\partial K}{\partial z} - WU(h,r,z) \quad ...(4)$$

Governing Solute Transport Equation

To simulate solute transport, HYDRUS-2D model uses the following equation:-

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial r}\left(\theta D_{rr}\frac{\partial C}{\partial r} + \theta D_{rz}\frac{\partial C}{\partial z}\right) + \frac{1}{r}\left(\theta D_{rr}\frac{\partial C}{\partial r} + \theta D_{rz}\frac{\partial C}{\partial z}\right) + \frac{\partial}{\partial z}\left(\theta D_{zz}\frac{\partial C}{\partial z} + \theta D_{rz}\frac{\partial C}{\partial r}\right) - \left(\frac{\partial q_r C}{\partial r} + \frac{q_r C}{r} + \frac{\partial q_z C}{\partial z}\right) \quad ...(5)$$

Where, C [ML^{-3}] is solute concentration in the soil water, q_r and q_z [LT^{-1}] are the components of the volumetric flux density, D_{rr}, D_{zz} and D_{rz} [L^2T^{-1}] are the components of the dispersion tensor. These components were given by (Bear, 1972).

$$\theta D_{rr} = \varepsilon_L \frac{q_r^2}{|q|} + \varepsilon_T \frac{q_z^2}{|q|} + \theta \tau D_0 \quad ...(6)$$

$$\theta D_{zz} = \varepsilon_L \frac{q_z^2}{|q|} + \varepsilon_T \frac{q_r^2}{|q|} + \theta \tau D_0 \quad ...(7)$$

$$\theta D_{rz} = (\varepsilon_L - \varepsilon_T)\frac{q_r q_z}{|q|} \quad ...(8)$$

Where, |q| [LT^{-1}] is the absolute value of the volumetric flux density; ε_L and ε_T[L] are the longitudinal and transversal dispersivities. D_0 [L^2T^{-1}] is the molecular diffusion coefficient of the solute in free water, and τ is the tortuosity factor. In this study, eq's, 2, 3 and 4 are solved numerically using HYDRUS-2D (Simunek *et al*., 1999) with initial and boundary conditions that closely reproduce drip irrigation systems.

Initial and Boundary Conditions

Initial distribution of water content in different soil layers within the domain was kept as observed in the experimental field. For investigating the influence of drip emitter discharge, soil hydraulic properties and frequency of water input on wetting patterns, a time dependent flux boundary condition at the surface in a radius of 25 cm from emitter position was used as the wetted radius of the emitter was 25 cm.

Input Parameters

Soil hydraulic properties used to parameterize the soil in HYDRUS-2D are listed in the Table 3, where ϴs and ϴr are saturated and residual water contents, respectively; α, soil water retention function is a constant related to soil sorptive properties; η is dimensionless parameter related to

Table: 3
Soil hydraulic parameters

Soil layer	Qr (ϴr)	Qs (ϴs)	Alpha (α) (cm^{-1})	η	Ks ($cm\ h^{-1}$)	L
1	0.0404	0.3741	0.0079	1.4202	1.29	0.5
2	0.0395	0.3749	0.0059	1.4736	1.32	0.5
3	0.0337	0.3606	0.0048	1.5252	1.23	0.5
4	0.0262	0.3681	0.0142	1.3874	1.15	0.5

the shape of water retention curve, Ks represents the saturated hydraulic conductivity and L represents pore connectivity (dimensionless). Simulation was carried out applying irrigation from point source as in real case for each individual dripper. The data collected from the field were used to calibrate the model. The other data required for the model were obtained from field experiment and literatures.

System Geometry

The simulation were done for a soil profile of depth Z = 60 cm and radius r = 30 cm with drip emitter placed at surface. The flux radius was taken equal to the wetted radius considering emitter in centre. Two 4 L h^{-1} drippers per tree at 50 cm distance were placed. Fig. 3 shows the conceptual diagram of simulated area and boundary conditions.

3. RESULTS AND DISCUSSION

Calibration of Model

The initial values of water and potassium at different depths with respect to emitter were considered in the model for calibration. Field soil samples from T_5 treatment (80% ET_c and 800 g K $plant^{-1}yr^{-1}$) were collected to determine spatial and temporal distribution of water and potassium after 24, 48 and 72 h of fertigation. The T_5 treatment (80% ET_c and 800 g K/plant/year) was selected for the dynamics studies, as it was the best performing among all the nine treatments in terms of yield and quality of Kinnow fruits (Desai *et al*., 2014).The model simulated values were plotted using the output file of HYDRUS-2D. Graphical displays available in post processing file of models gives spatial and temporal distribution of water and potassium in simulated layers at pre-decided time. X axis shows the water content (Vol, %) and potassium concentration (mg mL^{-1}) and Y axis shows the depth of soil. The performance of the model was evaluated by plotting the simulated and observed values of water and potassium in soil.

Soil Moisture Distribution

Fig. 4 shows observed and simulated water content at different depths followed a similar trend and not much difference was observed. However, the values of simulated soil moisture were less than observed values at various depths after 24, 48 and 72 h of irrigation. Simulated and observed moisture values matched well between 15-45 cm depth. The simulated values of soil moisture matched the measured values more closely at soil depths of 25 and 50 cm, which is the most active root zone for water and nutrient uptake for citrus (Phogat *et al*., 2013). The root distribution of citrus at different levels of drip irrigation were concentrated between 0-60 cm (Bhatnagar and Kaul, 2012). The values of observed and simulated water content after 24, 48 and 72 h of fertigation varied from 19 to 26% and 18 to 24%, respectively. The moisture in the soil after 24 h and 48 h of fertigation was almost near to field capacity in topsoil layers. The decline in the moisture level in the topsoil layers was noted at 72 h after irrigation. Drip irrigation showed higher soil moisture content of 26% just after the irrigation and decreased to 18.5% after the 48 h of irrigation (Rahul and Manikandan, 2021). Soil moisture content was lower in the deeper layers (30-45 cm and 45-60 cm) as compared to the upper layers (0-15 cm and 15-30 cm). Lower soil

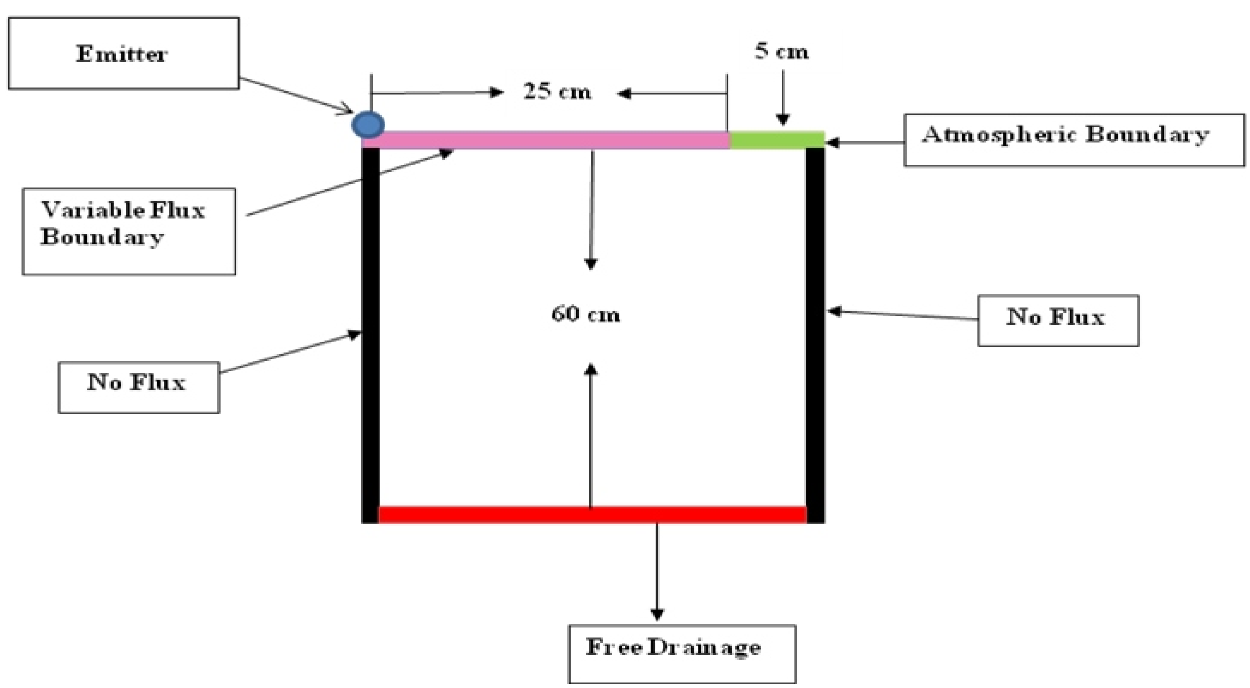

Fig. 3. Conceptual diagram of HYDRUS-2D simulation

moisture content in the deeper layers in the citrus field is attributed to more root water uptake from the deeper soil (Tahir *et al*., 2016). To find the closeness between observed and simulated water content values, coefficient of determination (R^2) between the values were estimated. The R^2 values for simulated and observed water content at different depths varied from 0.90-0.95. Coefficient of determination between the measured and simulated soil water content in the citrus orchards using HYDRUS ranged from 0.8-0.94 which indicated a good model performance (Tu *et al*., 2021). The graphs indicating the correlation between observed and simulated water content are shown in Fig. 5.

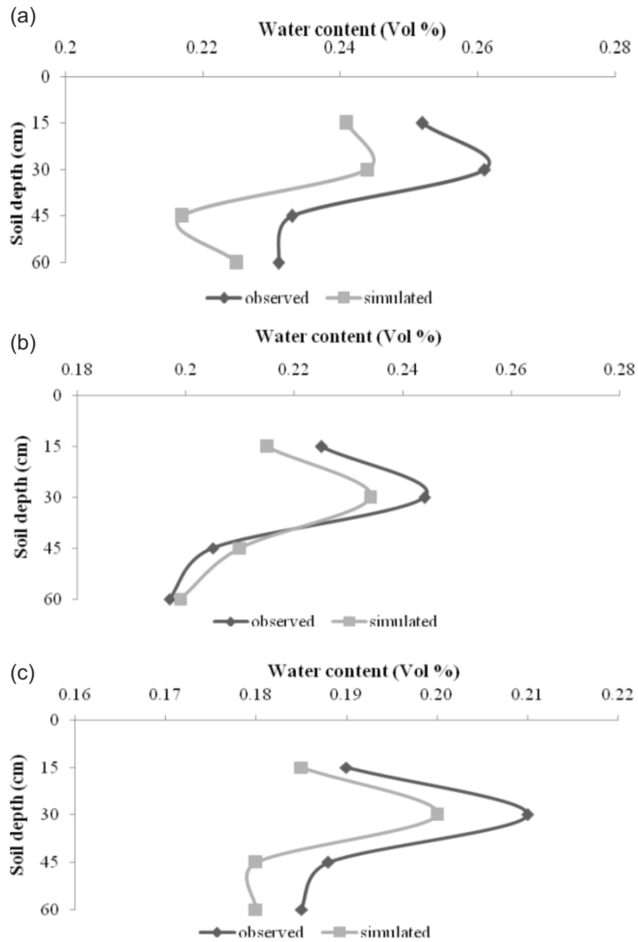

Fig. 4. Simulated and observed water content (%) at a) 24 b) 48 and c) 72 h after fertigation

Simulation of water distribution by HYDRUS-2D after 24, 48 and 72 h of fertigation with 4 Lh^{-1} emitter in sandy loam soil are shown in Fig. 6 through colour spectrum. The range of the volumetric water content (%) as per the colour spectrum varied from 12% to 32% expressed as decimal values (Fig. 6). The X axis shows radial distance of 30 cm from emitter whereas Y axis shows the soil depth of 60 cm. The figure shows that soil moisture was found maximum in top layers (0-15 cm and 15-30 cm) after 24 h and 48 h of irrigation. However, decline in the moisture level in the top soil layers was noted at 72 h after irrigation. Irrigation interval based on soil metric potential ranges from 1 to 3 days and decreasing soil moisture content in the soil is observed after 48 h under drip irrigation system (Rahul and Manikandan, 2021). In the study 3 days irrigation interval was maintained as the Kinnow trees were matured. This indicated that soil moisture was available for citrus trees in the root zone upto 48 h after irrigation and 3 days irrigation interval was appropriate for optimum utilization of this moisture for crop growth.

Potassium Distribution

Fig.7 shows simulated and observed potassium at different depths followed similar trend. The observed and simulated values of potassium varied between 0.017 to 0.011 and 0.014 to 0.009 (mg mL^{-1}) respectively after 24, 48 and 72 h of fertigation. The potassium concentration in the soil was found maximum between 0-30 cm depth and further reduced between 30-60 cm depth. Higher potassium concentration was found in the upper layer of the soils at 0-25 cm and lower at 25-40 cm soil depth in the sandy loam soils irrespective of before or after fertigation (Mishra, 2001). The closeness between observed and simulated potassium values were determined by coefficient of determination. The R^2 values for simulated and observed potassium varied from 0.92-0.95. The R^2 between observed and simulated potassium varied between 0.91-0.96 under drip irrigation system in different soils indicating a good agreement and model performance (Mirzaei and Biegi,

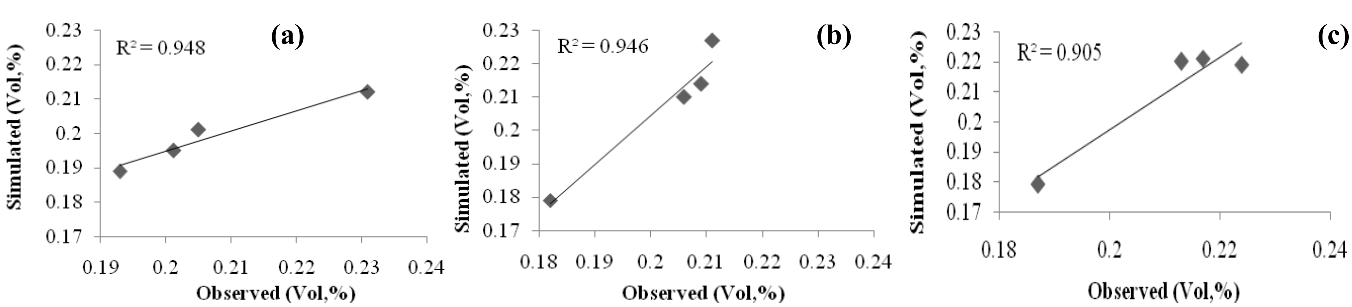

Fig. 5. Correlation between observed and simulated water content a) 24 b) 48 and c) 72 h after fertigation

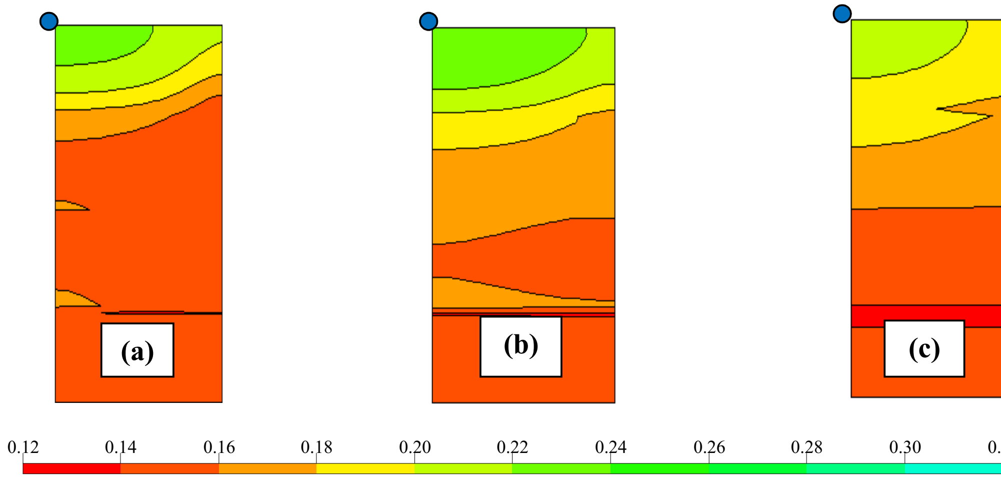

Fig. 6. Simulated water distribution (%) after a) 24 b) 48 and c) 72 h of fertigation

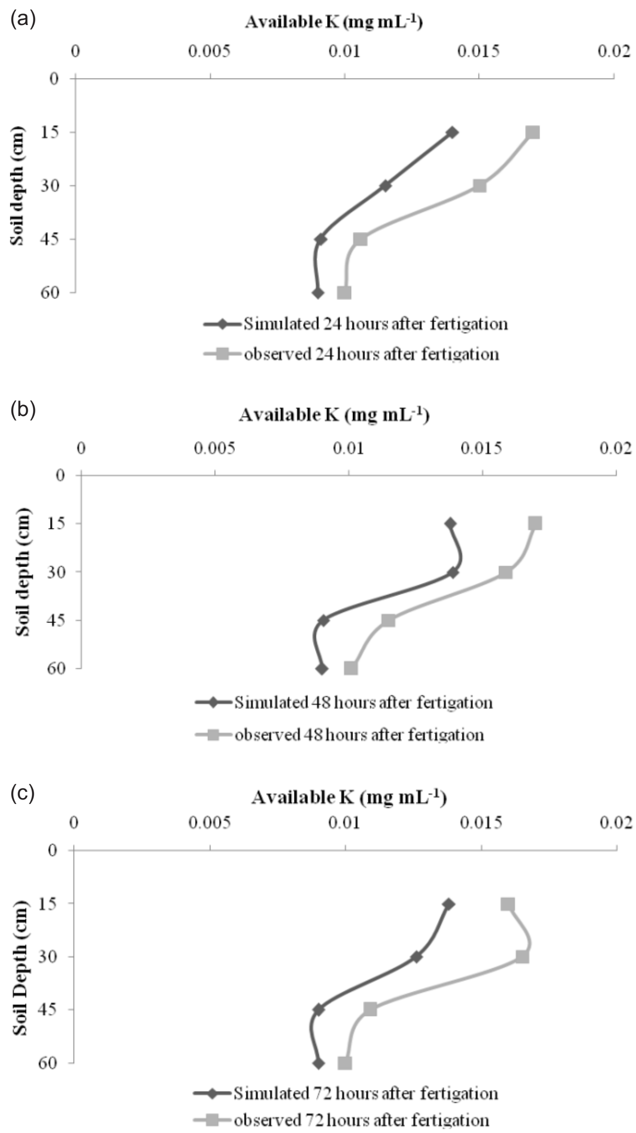

Fig. 7. Simulated and Observed K (mg mL^{-1}) in soil at a) 24 b) 48 and c) 72 h after fertigation

2020). The graphs depicting the correlation between observed and simulated potassium are shown in Fig. 8.

The HYDRUS-2D simulation of potassium distribution after 24, 48 and 72 h of fertigation with 4 Lh^{-1} discharge emitter in sandy loam soil are shown through colour spectrum in Fig. 9. The X axis shows radial distance of 30 cm from emitter whereas Y axis shows the soil depth of 60 cm. The figure shows that potassium in soil was found maximum in top layer at 24 h after fertigation. The movement of the potassium in soil was very slow and was restricted to only top layers even after 48 and 72 h. The mobility of K in soil is low and mainly occurs by the process of diffusion (Silva *et al*., 2016). Availability of potassium depends on the soil texture at different depths and with maximum accumulation in clay soils followed by loam and maximum movement in sandy soils (Oldham and Jones, 2020; Singh and Tomar, 2023). The soil of the study area was sandy loam due to which the movement was not significant in the deeper layers. The movement of potassium also depends on the availability of soil moisture. The deeper layer of the soils from 45-60 cm had less moisture as compared to upper layers (0-30 cm) due to which the potassium concentration was higher in the upper layers. The high potassium levels in the top 30 cm soil layer indicated that more potassium was available for Kinnow roots as the active root zone (highest root density) was between 15-30 cm depth. The fibrous roots of citrus trees develops the dense roots above 45 cm depth and then expands radially and vertically with depth (Morgan *et al*., 2007).The presence of potassium in top layers even 3 days after fertigation revealed that the possibilities of potassium leaching in soil are very low as compared to other nutrients like nitrogen under drip fertigation and its effective utilization by the citrus roots sufficient water and nutrient concentration in the crop root zone of citrus is necessary for optimal nutrient uptake (Scholberg *et al*., 2002).

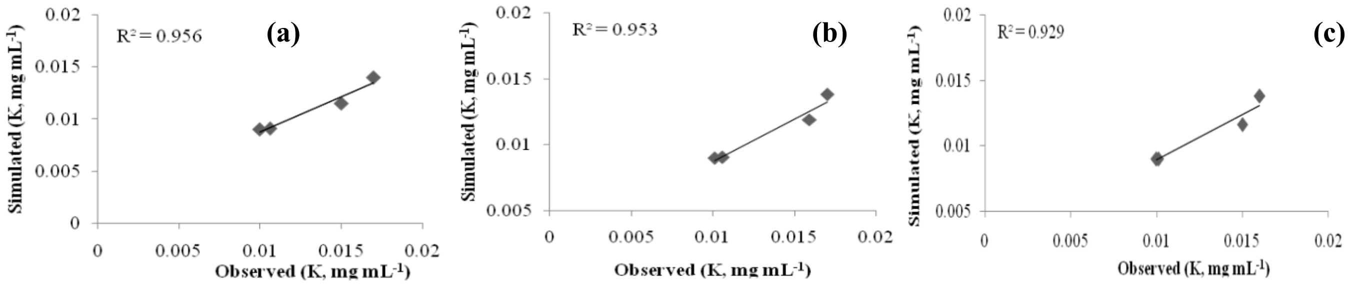

Fig. 8. Correlation between observed and simulated potassium after a) 24 b) 48 and c) 72 h of fertigation

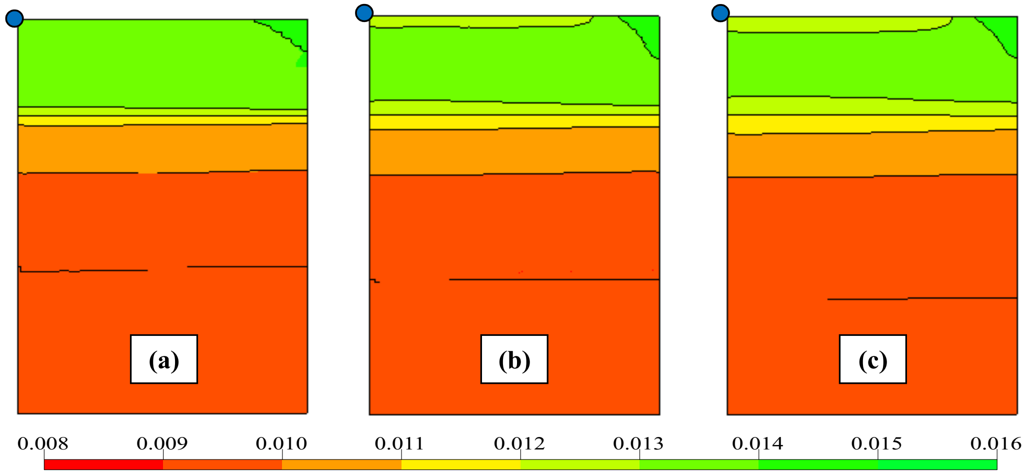

Fig. 9. Simulated potassium (mg mL^{-1}) after a) 24 b) 48 and c) 72 h of fertigation

4. CONCLUSIONS

In this study water and potassium dynamics were simulated under drip fertigated Kinnow mandarin using the water and solute transport model HYDRUS-2D in the sandy loam soil. HYDRUS-2D model was able to simulate both water and potassium dynamics in the sandy loam soil with good accuracy. The values of observed and simulated water content varied from 19 to 26% and 18 to 24% whereas potassium concentration varied between 0.017 to 0.011 mg mL^{-1} and 0.014 to 0.009 mg mL^{-1} respectively after 24, 48 and 72 h of fertigation. The R^2 values between observed and simulated soil moisture and potassium ranged from 0.90-0.95 and 0.92-0.95 respectively. The simulation studies indicated that potassium was present in the region of top 30 cm, which could be easily utilized by roots of Kinnow trees as the highest root density was between 15-30 cm depth. The soil water content was maintained in the active root zone at 24 and 48 h after irrigation but significantly declined after 72 h which indicated that irrigation interval of three days with 4 Lh^{-1}emitter in Kinnow trees was appropriate. The information can be helpful for designing of drip fertigation system for citrus crop under sandy loam soils for improving productivity. HYDRUS-2D model could be applied for different soil conditions and crops for planning appropriate design strategies for drip irrigation system.

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REFERENCES

Ajdary, K., Singh, D.K., Singh, A.K. and Khanna, M. 2007. Modeling of nitrogen leaching from experimental onion field under drip fertigation. *Agric. Water Manage.,* 89: 15-28.

Allen, R.G., Pereira, L., Raes, D. and Smith, M. 1998. Crop evapotranspiration guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. UN-FAO, Rome, Italy.

Ashraf, M.Y., Attiya, G., Ashraf, M., Hussain, F. and Ebert, G. 2010. Improvement in yield and quality of Kinnow (*Citrus deliciosa* × *Citrus nobilis*) by potassium fertilization, *J. Plant Nutr.*, 33(11): 1625-1637.

Bear, J. 1972. Dynamics of fluids in porous media. Dover Publications, Inc. New York.

Bhatnagar, P. and Kaul, M.K. 2012. Root distribution studies in 'Kinnow' mandarin by root excavation method under drip system with differential irrigation treatments. In: International CIPA Conference 2012 on Plasticulture for a Green Planet. 1015: 333-337.

Cote, C.M., Bristow, K.L., Charlesworth, P.B. and Cook, F.J. 2003. Analysis of soil wetting and solute transport in sub-surface trickle irrigation. *Irrig. Sci*., 22 (3-4): 143-156.

Dash, D., Senapati, S.C., Sahu, A.P. and Paramaguru, P.K. 2023. A comparative study between continuous and pulse drip systems on the yield of tomato (*Lycopersicon esculentum*) in sandy loam soil under the moist sub-humid condition. *Indian J. Soil Cons.,* 51(2): 122-131.

Desai, S., Rajurkar, G., Singh, D., Sonawane, A. and Ranganath, H.K. 2013. Standardization of fertilizer dosage and irrigation scheduling for Kinnow plants. *Environ. and Ecol.*, 31(2A): 697-700.

Desai, S., Hasan, M., Sonawane, A., Rajurkar, G.B. and Singh, D. 2014. Effect of different levels of drip irrigation and potassium fertilizer on fruit yield and quality of Kinnow (*Citrus reticulata* Blanco). *Int. Agric. Eng. J.*, 23(2): 50-56.

Hanway, J.J. and Heidal, H. 1952. Soil analysis methods as used in Iowa state college soil testing laboratory. Iowa Agriculture, 57: 1-31.

Jackson, M.L. 1973. Soil chemical analysis. Practice hall, New Delhi.

Kandelous, M.M. and Simunek, J. 2010. Comparison of numerical, analytical and empirical models to estimate wetting patterns for surface and subsurface drip irrigation. *Irrig. Sci*., 28(5): 435-444.

Li, J., Zhang, J. and Rao, M. 2005. Modeling of water flow and nitrate transport under surface drip fertigation. *Trans. ASAE.,* 48(2): 627-637.

Mishra, P. 2001. Studies on water and potassium dynamics in soil under fertigation and furrow irrigation in Radish, M.Sc. thesis, Division of Agricultural Engineering, IARI, New Delhi.

Mirzaei, F. and Biegi, A.M. 2020. Modeling distribution of potassium in the soil in under drip irrigation. *J. Soil Water Sci.*, 4(1): 122-131.

Morgan, K.T., Obreza, T.A. and Scholberg, J.M.S. 2007. Orange tree fibrous root length distribution in space and time. *J. Am. Soc. Hortic. Sci*., 132(2): 262-269.

Mostert, P.G. and J.L. Van. 2000. Gains in citrus fruit quality through regulated irrigation. Proc. XXV IHC-Part 6. *Acta Hort*., 516. ISHS.

Patel, N. and Rajput, T.B.S. 2008. Dynamics and modeling of soil water under sub-surface drip irrigated onion. *Agric. Water Manag.*, 95(12): 1335-1349.

Patel, N. and Rajput, T.B.S. 2010. Use of simulation modeling for enhancing potato production using subsurface drip. *Potato J*., 37(1-2): 21-27.

Oldham, L. and Jones, K. 2020. Potassium in mississippi soils. information sheet 894 (POD-06-20). Mississippi State University Extension.

Olsen, S. R., Cole, C.V., Watanbe, F.S. and Dean, L.A. 1954. Estimation of available phosphorus in soils by extracting with sodium bicarbonate. USDA Circular No. 939.

Phogat, V., Skewes, M.A., Cox, J.W., Alam, J., Grigson, G. and Šimůnek, J. 2013. Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree. *Agric. Water Manag.*, 127: 74-84.

Phogat, V., Skewes, M.A., Cox, J.W., Sanderson, G., Alam, J. and Šimůnek, J. 2014. Seasonal simulation of water, salinity and nitrate dynamics under drip irrigated mandarin (*Citrus reticulata*) and assessing management options for drainage and nitrate leaching. *J. Hydrol.*, 513: 504-516.

Provenzano, G. 2007. Using HYDRUS-2D simulation model to evaluate wetted soil volume in subsurface drip irrigation systems. *J. Irrig. Drain. Eng*., 133(4): 342-349.

Quaggio, J. A., Junior, D.M. and Boaretto, R.M. 2011. Sources and rates of potassium for sweet orange production. *Sci. Agric.*, 68(3): 369-375.

Rahul, R. and Manikandan, M. 2021. Estimation of irrigation interval and soil water content distribution for drip irrigated eggplant using tensiometer under mulching condition. *Indian J. Soil Cons*., 49: 23-31.

Richards, L.A. and Weaver, L.R. 1944. Moisture retention by some irrigated soils as related to soil moisture tension. *J. Agr. Res*., 69:215-235.

Rivera., R.N.C., Miranda, J.H., Duarte, S.N., Botrel, T.A. 2008. Model applied to water and potassium dynamics under drip irrigation - Sensitivity analysis. *Eng. Agric., Jaboticabal*, 28(3): 448-459.

Satpute, S.T., Singh, M., Khanna, M. and Singh, D.K. 2015. Modelling nutrient leaching below crop root zone of onion under drip fertigation. *J. Agric. Eng*., 52(4): 50-58.

Scholberg, J.M.S., Parsons, L.R., Wheaton, T.A., McNeal, B.L. and Morgan, K.T. 2002. Soil temperature, nitrogen concentration, and residence time affect nitrogen uptake efficiency of citrus. *J. Environ. Qual.* 31:759-768.

Silva, A.O., Silva, D.J., and Bassoi, L.H. 2016. Nitrate and potassium concentration in fertigated soil cultivated with wine vines. *Ciênc. Agrotec*., 40: 305-316.

Sharma, S., Singh, B., Rani, G., Zaidi, A.A., Hallan, V., Nagpal, A. and Virk, G.S. 2007. Production of Indian citrus ringspot virus-free plants of Kinnow mandarin (*Citrus nobilis Lour × C. deliciosa Tenora*) employing chemotherapy coupled with shoot tip grafting. *Plant Biotechnol.,* 8: 1-8.

Šimůnek, J., Šejna, M. and van Genuchten, M.Th. 1999. *The HYDRUS-2D software package for simulating the two-dimensional movement of water, heat and multiple solute in variably-saturated media.* International Groundwater Modeling Centre, Colorado School of Mines Golden, Co 80401.

Šimůnek, J., Van Genuchten, M.T. andŠejna, M. 2011. The HYDRUS software package for simulating two-and three-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Technical manual, version, 1: 241.

Singh, D., Patel, N., Patra, S. and Singh, N. 2020a. Growth and yield of cauliflower under surface and subsurface drip irrigation with primarily treated municipal wastewater in a semi-arid peri-urban area. *Curr. Sci.*, 119(8): 1357.

Singh, D., Patel, N., Gadedjisso-Tossou, A., Patra, S., Singh, N. and Singh, P.K. 2020b. Incidence of Escherichia coli in vegetable crops and soil profile drip irrigated with primarily treated municipal wastewater in a semi-arid peri urban area. *Agric.*, 10(7): 291.

Singh, D., Mishra, A.K., Searing, A., Thomas, A., Kumar, M., Patra, S. and Mariappan, S. 2021a. Soil pore and hydraulic conductivity relationship under different tillage practices in a maize-wheat cropping system. *Indian J. Soil Cons*., 49(2): 139-144.

Singh, D., Patel, N., Patra, S., Singh, N., Roy, T., Caucci, S. and Hettiarachchi, H. 2021b. Efficacy of drip irrigation in controlling heavy-metal accumulation in soil and crop. *J. Environ. Eng. Sci.,* 16(3): 109-121.

Singh, Y.P. and Tomar, S.S. 2023. Effect of tillage and water management practices on pearl millet - wheat cropping system productivity, water - balance and soil properties of alluvial soil. *Indian J. Soil Cons.,* 51: 2: 144-154.

Sivanappan, R.K. 1994. Prospects of micro irrigation in India. *Irrig. Drain. Syst*., 8: 49-58.

Skaggs, T.H., Trout, T.J., Simunek, J. and Shouse, J. 2004. Comparison of HYDRUS-2D simulation of drip irrigation with experimental observations. *J. Irrig. Drain. Eng.*,130(4): 304-310.

Subbiah, B.V. and Asija, G.L. 1956. A rapid procedure for the estimation of available nitrogen in the soil. *Curr. Sci.,* 25: 259-260.

Surendran, U. and Chandran, K.M. 2022. Development and evaluation of drip irrigation and fertigation scheduling to improve water productivity and sustainable crop production using HYDRUS. *Agric. Water Manag.*, 269: 107668.

Tahir, M., Lv, Y., Gao, L., Hallett, P.D. and Peng, X. 2016. Soil water dynamics and availability for citrus and peanut along a hillslope at the Sunjia red soil critical zone observatory (CZO). *Soil Tillage Res*., 163: 110-118.

Tu, A., Xie, S., Mo, M., Song, Y. and Li, Y. 2021. Water budget components estimation for a mature citrus orchard of southern China based on HYDRUS-1D model. *Agric Water Manag.*, 243: 106426.

Wang, R., Xue-gen, S., Zhang, W. Y., Xiao-e, Y. and Juhani, U. 2006. Yield and quality responses of citrus (*Citrus reticulate*) and tea (*Podocarpus fleuryi Hickel.*) to compound fertilizers. *J. Zhejiang Univ. Sci.,*7: 696-701.