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Nutrient Dynamics and Moisture Distribution under Drip Irrigation System

Thomas, S. L. [a], Bindhu, J. S. [b]*, Pillai, S. P. [a], Beena, R. [a], Biju, J. [c] and Sarada, S. [a]

[a] College of Agriculture, Vellayani, Kerala Agricultural University, India.
[b] IFSRS, Karamana, Kerala Agricultural University, India.
[c] MSSRRS, Moncompu, Kerala Agricultural University, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

A rational nutrient and water use can play a much higher synergic and supplementary effect on plant productivity. Therefore, understanding water and nutrient interaction is of paramount importance for sustainable crop production. Between different methods of irrigation, micro irrigation systems are the most efficient and increasingly adopted worldwide. Drip methods are specifically designed to wet the root zone and to keep root zone at or near an optimum level of soil moisture. Fertigation is the most efficient method of fertilizer application, as it ensures application of the fertilizers directly to the plant roots as per crop demand. Study of the moisture distribution pattern helps in the effective management of drip method. The volume and pattern of soil wetted from a

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*Corresponding author: E-mail: bindu.js@kau.in;

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point source basically depends on soil properties, quantity of water, rate of application and irrigation regime. Dynamics of nutrient explains the way of nutrients uptake, retained, translocated and cycled over time and distance in a system. Drip irrigation distributes water and nutrients uniformly when compared to conventional methods. The amount of fertilizer lost through leaching can be as low as 10 per cent in fertigation whereas it is 50 per cent in the traditional system. Research on the distribution of soil moisture and the dynamics of nutrients can therefore guarantee that the right amount of both water and nutrients are accessible at the root zone, meeting the plant's total and temporal requirement of these two key inputs.

Keywords: Drip irrigation; fertigation; nutrient dynamics; moisture distribution; root zone.

1. INTRODUCTION

The availability of nutrients to plants is significantly influenced by water. It serves as the pathway for nutrients to travel from the soil to the roots of plants so they can be absorbed. Although water and nutrient have their own functions, one can supplement or constrain the other by controlling, restricting or checking functions in plants. If soil water becomes limiting, nutrient availability to the plants gets affected. The nutrient and water interaction may be either positive or negative, depending upon crop growth stages, amounts, combinations and balances [1]. A rational nutrient and water use can play a higher synergic and supplementary effect on plant productivity. Therefore, understanding water and nutrient interaction is of paramount importance for sustainable crop production.

Between different methods of irrigation, micro irrigation systems especially, drip and sprinkler methods seem the most efficient and increasingly adopted worldwide. The most effective method of applying nutrients to plants is by dissolving them in irrigation water (a process known as fertigation), particularly though drip system [2].

2. WATER AND NUTRIENT AVAILABILITY TO THE PLANT

Nutrients, transport via mass flow and diffusion in soil water to the surface of roots. Another method is through root interception. Mass flow is the means by which several transportable nutrients, including calcium (Ca), magnesium (Mg), nitrate-N (NO_3-N), and sulphate (SO_4^{2-}), are transported to the root. The nutrients like potassium (K) and phosphorus (P) move through diffusion. Plant roots often receive micronutrients through soil diffusion[1]. Low soil moisture conditions consequently decrease the uptake of micronutrients. Because plants need fewer micronutrients than macronutrients, the effects of drought stress on micronutrient deficiencies are not as severe as they are for macronutrient deficiencies. But, excessive soil moisture conditions are often linked to shortages in iron (Fe) and zinc (Zn) [3].

3. DRIP IRRIGATION

In drip irrigation, in contrast to surface and sprinkler irrigation, which involves wetting the entire soil profile, water is supplied near to plants so that only a portion of the soil in which the roots grow is moist. Through the development of a deep root system in the area next to the dripper, this irrigation technique allows the plant to use water more directly and effectively. Generally speaking, drip systems are made to exclusively water the soil area that is inhabited by the roots of the plants and to keep this area at or close to the ideal soil moisture level [2].

4. FERTIGATION

Application of fertilisers through micro irrigation system *i.e.* fertigation is the most sophisticated and effective method of fertilization. Water and nutrients are the two main factors for plant growth and development. Fertigation is the most effective way to apply fertilizer because it ensures that the fertilizer is directly applied to the roots of the plants in accordance with crop requirements [4]. It makes it possible to more evenly and effectively apply irrigation water combined with fertilizers that dissolve in water to the crop's root zone. When comparing drip fertigation treatments to soil application of nutrients with drip and basin irrigation, the agronomic efficiency of nutrients was also much greater [5].

5. DISTRIBUTION OF MOISTURE UNDER DRIP IRRIGATION

Moisture distribution pattern is the fundamental prerequisites for the effective planning and operation of an irrigation system. Understanding the pattern of moisture distribution contributes to drip irrigation's efficacy [6].By doing this, the effective root zone will receive precisely the right quantity of fertilizer and water. The amount of soil that a single emitter can wet is a crucial factor in drip irrigation system design. This information is necessary to calculate the emitter numbers needed to wet a sizable amount of soil and guarantee that the plant's water needs will be satisfied.

The volume and pattern of soil wetted from a point source basically depends on soil properties, quantity of water, rate of application and irrigation regime. [7].The ideal emitter spacing is determined by the width and depth of the wetted soil volume, which is influenced by the amount of water provided during irrigation.

5.1 Water Movement in Soil

The entry of water into the surface of soil is very important for effective utilization for optimum crop growth and production as it influence the extent of wetted soil volume and concentration of different nutrients and salts in the root zone. The movement and distribution pattern of soil water resulting from drip sources will be different from those resulting from the conventional methods of irrigation [8]. The water movement depends on the following factors in a drip-irrigated field [9].

- Soil constants such as liquid limit, plastic limit and porosity
- Moisture content of soil prior to irrigation
- Hydraulic conductivity
- Soil and Water temperature
- Infiltration rate into the soil
- Emitter discharge rate
- Spacing of emitters
- Level of water table
- Duration of water application
- Evaporation and root suction

5.2 Effect of Soil Texture on Distribution of Soil Moisture

In sandy soil, SDI or subsurface drip irrigation was studied using a drip line buried at 30 cm below the surface. The results indicated an elliptical wetting pattern, with the wetted depth greater than the wetted radius and a distribution of 94 percent of the water applied below the emitter. For silty soil, the wetting pattern was almost spherical in shape [10].

Sand soil produced the maximum wetted width and depth when varying irrigation water volumes were supplied under drip irrigation, followed by silt clay loam and loam soil [11].Upon comparing the wetting fronts of sandy and clayey soils, it was observed that the horizontal wetting front was higher in clayey soil whereas the vertical wetting front was higher in sandy soil [12].

Results from an analysis of the soil surface wetting pattern under drip irrigation showed that the amount of soil surface wetted area increased approximately in proportion to the amount of soil surface silt content [13].

5.3 Effect of Drip Line Spacing on Distribution of Soil Moisture

In sandy loam soil when drip irrigation was used, three-dimensional water flow for lettuces were observed with drippers spaced 40 cm apart and laterals spaced 65 cm apart. As a result of the compacted soil layer, the wetting front was able to penetrate only to a depth of 25 cm and the radial influence extended uniformly, reaching up to 25 cm after watering and 30 cm after a day [14].

In sandy loam soil, drip lines for SDI were placed at a depth of 0.25 meters, with drippers spaced at 0.30 meters and laterals spaced at 0.91 and 1.82 meters. Water found to have moved vertically integrated to 0.53 m and laterally to the midpoint of both lateral spacings. For 0.91 and 1.82 m lateral spacing, respectively, the cotton yield and irrigation water use efficiency were 3.44 Mg ha-1, 1.764 kg m-3 and 3.22 Mg ha-1, 0.980 kg m-3, respectively, which were statistically at par [15].

5.4 Effect of Drip Line Placement Depth on Distribution of Soil Moisture

Distribution pattern of soil moisture in sandy soil indicated that dripper line at a depth of 15 cm was preferable to one at 10 cm. The average moisture content for a drip line at a depth of 10 cm was found to be 9.4% up to a soil depth of 39 cm, while the average moisture content at a depth of 15 cm was 10.6% up to a soil depth of 43 cm [16].

The deeper the laterals were placed, the greater the wetting depth [17]. When drip laterals were inserted deeper than 15 cm, the wetted depth was found to be greater than the surface wetting, which resulted in a high water content beneath the drippers. These observations of the soil water dynamics under subsurface drip irrigated onions in sandy loam soil revealed an elliptical shape wetting pattern [18].

SDI at 35 cm depth could achieve higher efficiency rates with limited water to maximise yield because the soil moisture content with laterals at 35 cm depth was more uniform than that at 5 cm and 20 cm depth [19].

5.5 Effect of Discharge Rate of Dripper on Distribution of Soil Moisture

When irrigation was withheld for the 7 lph rate of application, the maximum depth of wetted soil 0.84 m was found under the point source, and for the 3.0 lph rate of application, the minimum depth of wetted soil was 0.72 m [20]. As irrigation was stopped for the 7 lph application rate, the maximum wetted depth of 0.84 m was found under the point source, and for the 3.0 lph application rate, the minimum wetted depth was 0.72 m [20].

Discharge rate of two emitters, 1.5 and 4 lph, were used to study pattern of wetting under drip irrigation and it was observed that soil moisture increased with the rate of discharge, measuring 40 cm at 1.5 lph and 52.5 cm at 4 lph. However, following a three-hour application of water, the lowest wetted radius (22 cm) was noted at a higher rate of discharge (4 lph) and the maximum wetted radius (30 cm) at a lower discharge rate (1.5 lph) [21].

With different flow rates of 2, 4, 8, 16, and 24 lph along with different operating times for drip irrigation in squash and grape crops, the form of the soil volume wetted for silt and clay soils was observed. It was found that although wetted soil width did not considerably increase, the depth of wetted soil was nearly twice as deep as it was immediately before irrigation. Wetted soil width increased while wetted soil depth decreased with higher emitter discharge rates [22].

5.6 Effect of Emitter Spacing on Distribution of Soil Moisture

According to a study on drip irrigation under double point sources', the wetted area increased as emitter spacing decreased. The adoption of a shorter emitter spacing to extend the wetted area was found to be beneficial for increasing water content and water use efficiency [23]. When drip irrigation was used to cultivate sugarcane, the effect of emitter spacing was investigated. It was found that the wetted depth was 33.5 cm at emitter spacings of 30 cm and 31.5 cm at emitter spacing of 40 cm [24].

5.7 Effect of Irrigation Regime on Distribution of Soil Moisture

In Rajasthan, an experiment was conducted to examine the impact of irrigation schedule on distribution of moisture under drip irrigation in lime soil. The experiment included two lateral spacings of 20 cm and 40 cm with a dripper discharge of 4 lph, and three irrigation levels: I_1 (ETc – Evapotranspiration coefficient), I_2 (0.7 ETc), and I_3 (0.4 ETc). As irrigation levels rose, so did the soil profile's moisture content. When compared to 40 cm spacing, the moisture content was higher at 20 cm lateral spacing. For all irrigation levels, it was found that the vertical distribution of moisture content increased with depth and decreased near the surface. The findings showed that at each irrigation level, soil moisture increased vertically but dropped horizontally. Furthermore, between 15 and 30 cm of depth, there was a greater increase in soil moisture, and from there, it increased uniformly to a depth of 60 cm [25].

Three irrigation levels (0.3, 0.6, and 0.9 PE) and three fertilizer levels (100, 50, and 150% recommended dose) delivered through drip irrigation were combined in this experiment. In all irrigation levels, the soil's moisture content was higher at 15 cm depth and at 15 and 30 cm radial distances [26].

The optimal method for achieving the highest tomato output in a greenhouse was to combine fertigation with 100% NPK based on 100% of Epan throughout the crop time [27].

5.8 Effect of Duration of Water Application on Distribution of Soil Moisture

Researchers looked into how emitter rate affected the patterns of water distribution under drip irrigation in sandy loam soil [28]. This study demonstrated that low application rates and low antecedent soil water content increased the relative horizontal to vertical water spreading.

The length of the water application determines the width and depth of wetted soil, and both of these increase over time [29]. When compared to wetted width, a higher wetted depth was noted for the loamy sand mixed soil.

6. NUTRIENT DYNAMICS

Dynamics of nutrient explains the way of nutrients uptake, retained, translocated, and cycled over time and distance in a system. [30]. Because of the intricate dynamics of soil nutrient dynamics which ais greatly impacted by interactions between roots and soil, the amount of plant-available soil nutrients varies greatly. Depending on the chemical composition of soil minerals and their interactions with other influencing factors, plants can only absorb a certain percentage of the total amount of nutrients needed for growth and development [31].

When we examine the pattern of nutrient distribution under various irrigation techniques, we find that drip irrigation causes localization of nutrients, surface irrigation causes leaching of nutrients, and drip fertigation results in a uniform distribution of nutrients.

7. NUTRIENT–MOISTUREINTERACTIONS UNDER DRIP IRRIGATION

7.1 Nitrogen

When subsurface drip irrigated cauliflower was given greater N rates and high soil moisture tension, more residual N was seen at soil depths of 0-90 cm. However, nitrogen was lost outside of the root zone when irrigated at low soil moisture tension [32]. At the highest applied nitrogen level (120 kg N ha-^{1}) in tomatoes, drip irrigation resulted in 8.11 percent more total nitrogen uptake than furrow irrigation [33].

In a study, five different nitrogen rates (0,60,120,180, and 240 kg N ha-^{1}) were applied to cotton that was drip-fertigated, whereas only 18 kg of N ha-^{1} was treated to cotton that was surface-irrigated. In cotton that was drip-irrigated, nitrogen recovery varied from 48 to 55 percent, but it was only 43 percent in cotton that was surface-irrigated. Cotton's average total nitrogen uptake under drip fertigation varied from 145 kg N ha^{-1} for the control to 417 kilogram N ha^{-1} for the highest rate. It is evident that raising N rates during drip fertigation caused the corresponding treatments to absorb more N [34]. It is evident that treating with higher N rates under drip fertigation led to higher N uptake by the matching treatments [35].

At shallow depths, the fertigation treatment showed a higher concentration of NO_3-N than in deeper layers [35]. Up to a distance of 30 cm, the available nitrogen gradually increased as the distance from the dripper along and between the laterals rose. At a depth of 15–30 cm and a distance of 30 cm from the dripper, the peak accessible soil nitrogen (207 kg N ha-1) was measured [36].

In the study conducted on tomato, four levels of nutrients (I_1- 75 per cent RD of N and K, I_2- 100 per cent RD of N and K, I_3- 125 per cent RD of N and K, I4- 150 per cent RD of N and K) constituted the main plot treatments and two fertigation intervals (i_1- fertigation once in four days, i_2- fertigation once in eight days) constituted the sub plot treatments. The treatment I_3 recorded the highest N, P and K uptake and it was statistically on par with I_4 [37].

While soil application resulted in a drop in K and an improvement in N status, fertilization treatments increased the soil's N and K status [38]. Research was done to study the effects of irrigation and nitrogen (N) rates on fruit yield, root features, and N uptake. Tomatoes were irrigated at 100%, 80% and 60% of reference crop evapotranspiration (ET_0) and N was supplied at 240 kg N ha^{-1}, 180 kg N ha^{-1}, and 120 kg N ha^{-1} under drip irrigation. Plant N uptake improved from 28.7 to 94% in 2015 and from 14 to 92.3% in 2016 with the application of irrigation and N fertilizer rates. The water use efficiency (WUE) and N rates varied from 25.4 to 37.2 kg m^{-3} and from 20.8 to 36 kg m^{-3} respectively [39].

A fertigation study was conducted to assess the seasonal dynamics of N, P, and K distribution in apple orchard [40].The findings showed that when the orchard was fertigated, the NH_4-N concentrations in the soil volume changed significantly, most likely as a result of its quick oxidation to nitrates. Even though unassimilated nitrogen was leached partially, the N-NO_3 concentration in the soil rose when fertigation was administered. The nitrate-N concentration that was greatest was found 20 cm from the drip emitters.

7.2 Phosphorous

Almost the equal grain yield was obtained by applying DAP at a rate of 33 kg P ha^{-1} by fertigation and by applying a dose of 44 kg P ha^{-1} through the broadcast method in wheat [41].

When water and nutrients were given continuously as opposed to intermittently over two days, corn plants in an experiment produced more biomass output and a higher content of P. When comparing the continuous treatment to the pulsed treatment, the P content of the maize leaves increased by 25% [42].When the necessary dosage of fertilizer was applied with irrigation water at intervals of two days up to 105 days, the phosphorus uptake by chili was higher (12.58 kg ha^{-1}) than it was with conventional irrigation (8.53 kg ha^{-1}) [43].

Under all levels of fertigation, the highest available form of phosphorus in the soil was limited to the surface layer of 0–15 cm. The amount of phosphorus that was accessible reduced as soil depth and distance increased. Phosphorous availability peaked slightly below the dripper [35].

It has been observed that different regimes of P and water supply cause significant alterations in the phenotypic and physiological characteristics of chickpeas [44]. The stomatal conductance, stomatal density, content of chlorophyll, photosynthetic efficiency, accumulation of biomass, and uptake of plant nutrient under fertigation of P under drip system were dramatically improved as compared to the unfertilized condition. The results showed that the stomatal density and conductance were increased by the P fertilizer form and irrigation regime that provided chickpea plants with enough water and P during their early growth stage. This, in turn, significantly improved the P use efficiency (PUE) and photosynthetic performance index (PIABS), which in turn improved biomass accumulation and nutrient uptake.

7.3 Potassium

Higher uptake of potassium (99.1 kg ha^{-1}) in chilli was observed when fertigation was done at every 2 day interval upto 105 days compared to surface irrigation [43]. Higher concentrations of potassium were observed in the upper soil layers, i.e at 0 to 20 cm soil depth, and whereas lower K concentration in the lower 20 to 40 cm of soil depth under fertigation. The emitter's soil depth of 0 to 10 cm was consistently found to be the peak quantity of potassium during fertigation treatment [45].

Due to the entry of K ions on exchange complex of soil, which causes very little transport of the nutrient to the deeper layer, the accessible K content under the drip fertigation system was higher at the surface layer [46]. Plants have an impact on the potassium nitrate (KNO_3) dynamics surrounding a dripper. The mass of KNO_3, soil moisture content, electrical conductivity of soil, and soil water solution were significantly decreased when maize was present compared to when it wasn't. Furthermore, the absorption of KNO_3 is responsible for the variation in KNO_3 dynamics with and without maize [47].

After fertigation, the highest K concentration was observed at 0-15 cm depth under emitter with a distance of 20 cm from dripper [36].

7.4 Micronutrients

The intensive agriculture and imbalance of nutrients use resulted the deficiency of micronutrients in addition to N, P and K. Hence micronutrient support is essential to achieve better productivity and quality of crops [48]. In India, Zn and B, were observed as the most limiting micronutrients in especially under intensive cultivation.

A study was carried out to assess the effect drip fertigation to the quality, yield, and soil nutritional status of cauliflower. Six fertigation levels (100, 90, 80, 70, 60, and 110 percent of the recommended dose) were used as the treatments. The maximum available NPK was obtained through fertigation using the appropriate fertilizer dose. When drip fertigation is used in accordance with required dosage, the amount of accessible micronutrients (Zn, Cu, Fe, and Mn) is raised by 8, 29, 21, and 40%, respectively, in comparison to 60% RD treatment [49].

By using drip irrigation in ground nut, micronutrients improved the yields of pods and haulms, the percentage of shelling, the weight of 100 seeds, and the efficiency of nutrient utilization compared to foliar and soil applications. The pod yield was enhanced by 31–36, 21–33, and 15–21 per cent respectively, by the drip application of Fe, Zn, and B, compared to the control [50].

It was found that micronutrient concentrations were seen to rise in the area surrounding the active root zone upto 30 cm depth as a result of fertigation of young Kinnow orchards with 75% N and 100% P & K applied in three split doses [51].

8. CONCLUSION

In comparison to traditional approaches, drip irrigation can be observed to use less irrigation water, boost irrigation efficiency, and guarantee a consistent distribution of water and nutrients. Fertigation also improves the efficiency with which nutrients are used, resulting in higher production and income. A high yield and high-quality product are mostly dependent on the proper ratio of nutrients and water. The possibility to guarantee that the ideal ratio of water and nutrients is present at the root zone, meeting the plants' complete and timely requirements for these two essential inputs, stems from the study of soil moisture distribution and nutrient dynamics. Future research could optimize the fertigation schedule based on crop growth stages, which could result in less fertilizer being used and more economic viability for the farmers.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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