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Nutrient uptake and yield of tomato under various methods of fertilizer application and levels of fertigation in arid lands

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Abstract With rising concern about current irrigation and fertilizer NPK management, the present study was conducted to evaluate the effect of sources and methods of fertilizer application on nutrient distribution, uptake, recovery and fruit yield of tomato grown in a sandy soil. Equal amounts of NPK were applied in solid form or through fertigation at levels of 0%, 50%, 75% and 100% with the remainder 100%, 50% and 25% applied as solid fertilizers to the soil. Available NO_3^--N and K were confined to the root zone of tomato in 75% and 100% NPK fertigation levels, while they moved beyond the root zone when they applied in two equal splits as solid fertilizers with drip (0% fertigation) and furrow irrigation. The mobility of P was greater in the root zone following its application through fertigation compared to a solid application as super phosphate. Drip irrigation showed significantly higher absolute growth rate (AGR), total dry weight (TDW) and leaf area index (LAI) of tomato over furrow irrigation. Moreover, tomato plants were able to utilize applied nutrients more efficiently in fertigation system than with conventional solid fertilizer application. Highest AGR, TDW and LAI were recorded when nutrients were applied to 100% by drip fertigation. The fruit yield of tomato was higher with drip irrigation (58.62 t ha^{-1}) than with furrow irrigation, (47.37 t ha^{-1}). Maximum fruit yield was recorded with 100% NPK fertigation (74.87 t ha^{-1}) and was associated with a higher number of fruits per plant and a bigger fruit size than the solid applied fertilizers under both drip and furrow irrigation. On average, tomato accumulated more NPK across the fertigation levels than with drip and furrow irrigation. Similarly, the more controlled application of nutrients in fertigation treatments improved NPK recovery and fertilizer use efficiency (FUE) and resulted in lesser leaching of NO_3^--N and K to deeper soil layers.

Keywords Drip irrigation · Growth rate · NPK distribution · Nutrient uptake · Sandy soil

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Nährstoffaufnahme und Ertrag von Tomaten bei unterschiedlichen Düngungsanwendungsmethoden und Bewässerungsdüngungsstufen in Trockengebieten

Zusammenfassung Die Bedeutung des Bewässerungsmanagements und der NPK-Düngüng steigt stetig an. In einer Studie wurde die Wirkung der Düngerformen und der Anwendungsmethoden auf Nährstoff- Verteilung, -Aufnahme, und -Verwertung untersucht. Weiterhin wurde der Ertrag von Tomaten, die auf sandigem Boden angebaut wurden, untersucht.

Es wurden gleiche Mengen an NPK-Düngemittel ausgebracht (Fertigation* in Stufen von 0%, 50%, 75% und 100% und der Rest von 100%, 50%, 25% und 0% als feste Form). Verfügbares NO_3^--N und K wurde in der Wurzelzone von Tomaten bei einer Fertigationsstufe von 75% und 100% NPK gefunden, während bei einer Anwendung mit festem Düngemittel (0% Fertigation) und Furchenbewässerung sich NO_3^--N und K über die Wurzelzone hinaus bewegten.

Die Mobilität von P war größer bei einer Ausbringung durch Bewässerungsdüngung als bei einer Anwendung als Super-Phosphat. Tomaten der Tropfenbewässerung zeigten eine signifikant höhere absolute Wachstumsrate (AWR), Trockenmasse (TM) und einen signifikant höheren Blattflächenindex (LAI) gegenüber der Furchenbewässerung. Darüber hinaus waren die Tomatenpflanzen in der Lage bei der Bewässerungsdüngung die angewandten Nährstoffe effizienter zu nutzen, als bei der Düngung in herkömmlicher fester Form. Die höchsten AWR, TM und LAI wurden erfasst, wenn die Nährstoffe zu 100% in Form der Bewässerungsdüngung angewendet wurden. Der Ertrag der Tomaten war höher bei der Tropfenbewässerung (58,62 t ha^{-1}), als bei der Furchenbewässerung (47,37 t ha^{-1}). Die maximalen Erträge wurden mit 74,87 t ha^{-1} bei 100% NPK Fertigation erfasst und wurden mit einer höheren Anzahl der Früchte pro Pflanze begleitet. Zudem waren die Früchte der Tomaten größer, als bei der Anwendung fester Düngemittel (sowohl bei der Tropfenbewässerung, als auch bei der Furchenbewässerung). Im Durchschnitt, akkumulierten die Tomaten mehr NPK über die Fertigationstufen als bei den Bewässerungssystemen (Tropfen und Furche). Ähnlich verliefen auch die NPK-Verwertung und die Düngernutzungseffizienz: mit einer geringen Auswaschung von NO_3^--N und K in tiefen Bodenschichten.

*Unter dem Begriff „Fertigation" bzw. „Bewässerungsdüngung" ist die Einspeisung der Dünger via Tropfenbewässerungssystem zu verstehen.

Schlüsselwörter Tröpfchenbewässerung · Wachstumsrate · NPK Verteilung · Nährstoffaufnahme · Sandboden

Introduction

Drip irrigation is an effective way to supply water to the roots of plants and save water amounts, while maintaining high yield and excellent product quality. Similarly, a drip irrigation system can easily be used for fertigation, through which the applied fertilizer is placed to the active root zone and crop nutrient requirements can be met accurately (Or and Coelho 1996; Boyhan and Kelley 2001). A theory behind why fertigation has become the state of the art in plant nutrition in arid environments is that nutrients can be applied in the correct dosage and at the required time appropriate for each specific growth stage. Fertilizers applied under conventional methods of irrigation are generally not efficiently used by the crop (Cassel et al. 2001; Hebbar et al. 2004). In furrow and border irrigation systems, water is used inefficiently and large nutrient losses occur through seepage or percolation. Moreover, when plants receive conventional pre-plant fertilizer followed by two or more side dressings, they initially get a higher dosage of fertilizer than they require while between applications nutrient deficiency may occur (Dangler and Locascio 1990; Locascio et al. 1997). Therefore, alternative soil management practices as well as alternative irrigation systems are needed to allocate water and fertilizers and maximize their application efficiency.

A properly designed drip fertigation system delivers water and nutrients at a rate, duration and frequency optimizing crop water and nutrient uptake, while minimizing leaching of nutrients from the root zone (Gardenas et al. 2005). Besides, it is considered eco-friendly (Phene et al. 1994; Waddell et al. 1999) and also ensures substantial saving in fertilizer usage (Mmolawa and Or 2000; Patel and Rajput 2004). Proper fertigation management requires the knowledge of soil fertility status and nutrient uptake by the crop. Monitoring soil and plant nutrient status is an essential safeguard to ensure maximum crop productivity. According to Mmolawa and Or (2000) soil properties, crop characteristics and growing conditions affect the nutrient uptake. Considering the soil and crop constraints, fertilizers should be applied in synchrony to crop demand and in adequate quantities.

Deficiency of N, P and K is a major production constraint in sandy soils, which have low CEC and high infiltration rates, causing nutrient leaching. Particularly, nitrate and potassium are mobile and can move quickly if there is sufficient water in the soil. Thus, crops cultivated in sandy soil require either large quantities of applied nutrients or adequate strategies to match the nutrient supply with the crop nutrient demands. Careful irrigation applications should be able to avoid moving of such nutrients below the root zone (Drost and Koenig 2001; Hanson et al. 2006).

Tomato is one of the most widely grown vegetable crops in the world and it is reported to be a heavy feeder of fertilizers. Since irrigation and fertilization are intrinsically linked, appropriate irrigation management is required for tomato grown on sandy soils in order to avoid nutrient leaching and groundwater pollution. This is more important especially in tomato production systems, which require substantial inputs of nitrogen fertilizer (Zotarelli et al. 2009). In addition, Locascio et al. (1997) found that yields of large and total tomato fruits on fine sands increased with drip applied N and K compared to pre-plant application. Similar to frequent application of water, split applications of fertilizer through fertigation improves quality and quantity of tomatoes over conventional practice. Hebbar et al. (2004) reported that tomato yield was 33% higher with water soluble NPK fertilizers applied through fertigation than banded and furrow irrigation or banded and drip irrigation, respectively.

Not much information is available on different aspects of fertigation and nutrient uptake patterns by tomatoes under arid conditions. With this background, the present study was conducted in Egypt to examine the effects of the method of fertilizer application on nutrient uptake, recovery and yield of field grown tomato. Moreover, soil fertility status and the distribution of N, P and K in the root zone was examined in response to different irrigation and fertigation treatments in a sandy soil.

Materials and Methods

Location and Soil of Experimental Site

The field experiments were conducted twice at the Main Research Station, National Research Center located in Nubaria region West of Nile Delta of Egypt during the late summer (August-December) of 2007 and 2008. Rainfall amounts of 20 and 24 mm were received during cropping seasons of 2007 and 2008, respectively. The soil of the experimental site was deep and well-drained with 85.5% sand, 11.7% silt and 2.8% clay, an alkaline pH of 8.2, an EC of 0.85 dS m^{-1}, and with 1.5% $CaCO_3$. The average available N, P and K in the top soil was 0, 2 and 17 mg kg^{-1} soil, respectively before the onset of the experiment. The experiment was laid out in a randomized complete block design with six treatments replicated three times in 4.5 m×15 m plots.

Experimental Treatments

The treatments included four levels viz., 0%, 50%, 75% and 100% fertigation of a total amount of (240:80:180 kg ha^{-1}) (N:P:K) with the remainder 100%, 50% and 25% applied in solid form to the soil. In addition two control treatments comprised: (a) a furrow irrigation with 100% solid fertilizer application and (b) a control treatment without mineral NPK application. The fertilizers used in the experiment for solid application were urea, single super phosphate and potassium sulphate, while ammonium nitrates, phosphoric acid and potassium sulphate were the nutrient applied by drip irrigation. The fertilizers were applied weekly in 12 equal splits starting one week after tomato transplanting between September and November. Phosphorus with solid fertilizer was added before planting in full dose and incorporated into the soil at a depth of 10 cm, while N and K fertilizers were added in two equal splits: (a), at transplanting and (b), 28 days after transplanting (DAT). Water soluble fertilizers were injected with water in-line drippers at weekly intervals through venture-type injector. Before cultivation, drip tubing (GR, 40 cm dripper spacing, 4 L h^{-1} discharge rate and 1.5 m apart) was placed directly on the soil surface. Twenty-five day old seedlings of tomato cultivar F1 'TY 70/70' hybrid were transplanted to the field in double rows 40 cm apart provided with one lateral line for each treatment in a density of (32 000 plants ha^{-1}) on August 14, 2007 and August 17, 2008. The crop took 136 and 138 days from transplanting to final picking for 2007 and 2008 respectively.

Measurements of ETc and Soil Analysis

The actual crop water requirement (ETc) was calculated by multiplying the reference evapotranspiration rate with crop coefficient (ETc=ETo×Kc) for different months based on crop growth stages using the model suggested by Penman-Monteith's formula (Allen et al. 1998). The crop coefficient during the both growth seasons was adopted according to Allen et al. (1998) as 0.45, 0.75, 1.15 and 0.80 at initial, developmental, mid and late season stages, respectively. Water amounts used during the 2007 and 2008 growing seasons were 375 and 382 mm for drip irrigation, while 516 and 527 mm were applied for furrow irrigation, respectively. In drip, irrigation frequency was running daily, while in furrow, irrigation was applied at 4 days interval based on the previous 4 days cumulative pan evaporation. To determine spatial distribution of available NPK for each treatment, soil samples were taken from below the drippers at depths of 10 cm down to 60 cm along with a radial line originating at the point-source at distances of 5 cm up to 30 cm using tube auger from the experimental area. The soil samples in the furrow irrigation were taken from the center of the row along columnar direction on furrow for the same previous vertical and lateral distances. The samples were collected from each plot at two selected times namely, 28 and 90 DAT of each growing season, air-dried and ground to pass through 2 mm sieve screen. Analysis of 1 *M* KCl extractable NO_3^--N was performed by the micro-Kjeldahl method modified to recover NO_3^--N (Bremner and Mulvaney 1982). Available P was extracted by 0.5 *M* sodium bicarbonate (Olsen's reagent) and determined by ascorbic acid method for color development (Eaton et al. 1995). Available K was extracted with 1 *M* ammonium acetate and K was measured by flam photometer using the method described by Jackson (1973).

Plant Measurements and Analysis

Plant samples of shoot and fruit tissues were collected at harvest, dried at 70°C, weighed and ground to 0.5 mm size. The samples were analyzed for total N using the micro-Kjeldahl digestion method. The powdered leaf samples were digested in a 1:3 perchloric-nitric acid mixture for total P and K analysis. Phosphorus (vanadomolybdate) and potassium (flame photometry) were determined following the method described by Jackson (1973). Uptake of N, P and K was calculated as the product of the crop biomass (dry weight) and the N, P and K concentrations in plant materials from which the uptake per hectare was derived based on plant population.

Post harvest N, P and K recovery was calculated as: (Nt – No/F) × 100, where Nt equals the total aboveground crop nutrient uptake under treatment, No equals nutrient total uptake under control (unfertilized) and F equals applied fertilizer. Tomato growth failed completely under unfertilized soil hence, no uptake has been occurred under this treatment. Fertilizer use efficiency (FUE) was determined as a factor of total economic yield from all harvests by quantity of fertilizer applied, and expressed as kg yield kg^{-1} NPK. Absolute growth rate (AGR) was determined periodically throughout the growth season using procedures described by Scholberg et al. (2000).

Statistical Analysis

All data were subjected to analysis of variance (ANOVA) using the general linear model (GLM) procedure of SAS software package (SAS Institute 1996). Means were compared by least significant difference (LSD), F test at a probability level 5%.

Results and Discussion

Nitrate Content in Soil

At the time of sampling, wetting patterns under drip lines showed the expected onion shaped within the soil profile (Fig. 1). Under both irrigation methods the downward movement of water was more pronounced than the lateral movement during the growth period of crop due to predominant of gravity force compared with the capillary force within the soil profile. Generally, it was observed that the NO_3^--N was depleted largely from a small wetted volume close to the water source and its movement towards the vertical direction was relatively greater than in the lateral direction. Available NO_3^--N within the wetted soil volume varied significantly due to the application method and fertigation levels. At early growth stage (28 DAT), the concentrations of NO_3^--N around the roots of tomato were significantly higher with 50%, 75% and 100% fertigation than solid fertilizer applied with drip (0% fertigation) and furrow irrigation. A higher NO_3^--N concentration was found mostly in the upper 0–40 cm soil layer with fertigation treatments and maximum values were recorded with 100% fertigation. At this critical stage of growth, however, majority of the roots were between 0–15 cm as tomato plants were still young. Lower concentration of nitrate that was found in this depth is the main cause of variation in yield among the treatments. These results suggested that the amount of nutrient present in top 0–40 cm soil layer may influence the yield of tomato in different treatments particularly when crop roots were not fully developed.

At end of last fertigation cycle (90 DAT), only solid fertilizer applied with drip and furrow irrigation showed significant variations in available NO_3^--N concentration. Both the treatments resulted in little NO_3^--N in the root zone, where most of the applied nitrate distributed near the periphery of the wetted volume due to leaching following the irrigation. Root system at this late stage of growth was fairly occupied the upper 0–40 cm soil and below this depth, only a few roots were observed, consistent with observation reported by Machado et al. (2003). At this time, however, fertigation treatments maintained higher concentration of NO_3^--N in

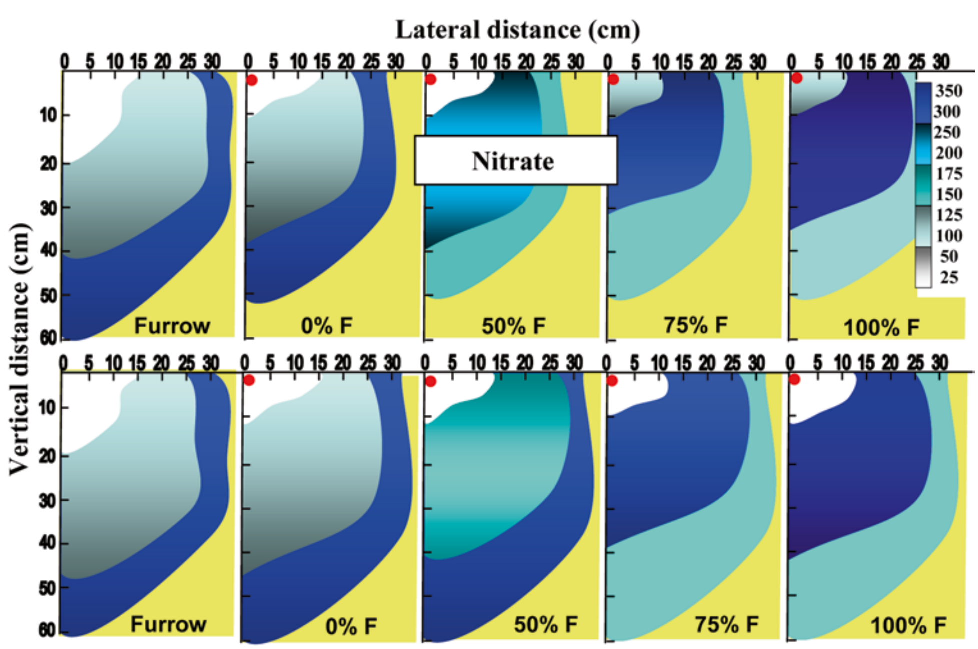

Fig. 1 Distribution of NO_3^--N ($mg\ kg^{-1}$ soil) in root zone at 28 DAT, (upper) and 90 DAT, (lower) as affected by methods of fertilizer application and levels of fertigation (F)

the active root zone particularly with 75% and 100% fertigation levels.

The accumulation of NO_3^--N toward the boundary of the wetted soil volume with solid fertilizer might be the result of mobility due to water mass flow, particularly in furrow irrigation that makes leaching more efficient. This is due not only to the applied fertilizer, but also to NO_3^--N movement from the surface layers, a fact, which has important implication regarding the frequency of nitrate application to soils under different irrigation methods. The process of leaching was enhanced by the higher quantity of water that applied in furrow than in drip irrigation. The contribution of irrigation water towards leaching of the very mobile NO_3^--N ion in the root zone with solid applied fertilizer confirms the results obtained by Singh et al. (2002). The authors reported that NO_3^--N ion is subjected to leaching from the root zone with solid fertilizer under furrow irrigation while drip fertigation treatment maintained high concentration of NO_3^--N at shallow depth. These results suggest that the fertigation process might improve distribution of NO_3^--N in the root zone and maintain higher concentrations for plant uptake as also reported by Li et al. (2004).

Available P Content in Soil

Phosphorus was distributed to a greater soil volume when applied as phosphoric acid through fertigation treatments than applied as 100% solid fertilizer (super phosphate) with drip and furrow irrigation (Fig. 2). Furthermore, increased fertigation levels of P resulted in a greater soil volume to which P was delivered; the P content increased gradually with every increase in fertigation level and reaching a peak value at 100% NPK fertigation level. This suggests that the P could be utilized efficiently by the plants and could be one of the factors for more uptake and yield in fertigation treatment. However, superficial application of P with solid fertilizer resulted in poor utilization efficiency where most of the applied P remained close to soil surface with low available content due to adsorption and precipitation reactions. This point highlights the high P fixation capacity of the soil as well as the importance of split application of fertilizers for improving the use efficiency. The concentration of available P were relatively higher at end of the last fertigation cycle with fertigation of phosphoric acid compared with solid application of super phosphate. Greater mobility of P beyond 25 cm depth observed with 75% and 100% fertigation levels is an added advantage noticed with drip fertigation.

Previous reports (Silber et al. 2003), as well as (Bhat et al. 2007) revealed that drip fertigation places nutrients in active root zone besides maintaining a favorable soil water content resulting in much greater mobility of phosphorus in the tomato root zone. The present results confirm the findings of these studies attributing greater availability of P to high frequency of drip fertigation. Kargbo et al. (1991) reported that the increasing P application frequency resulted in greater P uptake, greater mass flow and mixing reaction, leading to the breakdown of regions of immobile phosphorus. Rubiez et al. (1991) support the hypothesis that continuous P applications in drip irrigation systems will further increase P availability compared with other application methods. Phosphate ion, however, is highly immobile in soils and stress from P deficiency early in growth has considerable negative influence on crop production (Grant et al. 2001). The present findings suggest that continuous appli-

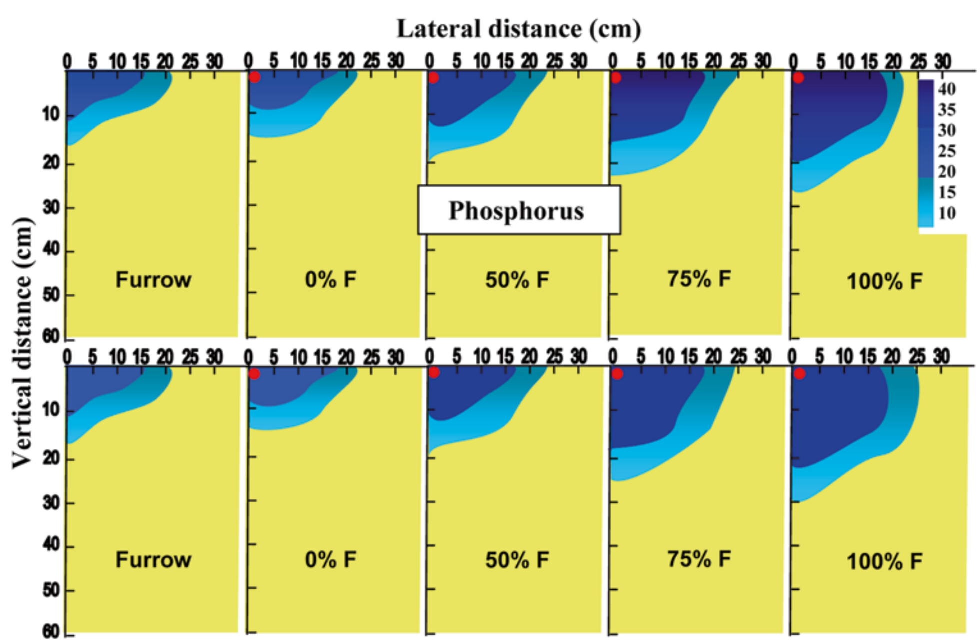

Fig. 2 Distribution of P (mg kg^{-1} soil) in root zone at 28 DAT, (upper) and 90 DAT, (lower) as affected by methods of fertilizer application and levels of fertigation (F)

cation of P fertilizers is needed to satisfy the P fixing needs of the soil and plant requirement.

Available K Content in Soil

Solid application of K-fertilizer in soil resulted in low K content in furrow or even with the slow frequent application of water in drip irrigation with solid fertilizer (Fig. 3). However, fertigation treatments registered a significantly higher K concentration than solid applied fertilizer and the peak values were recorded with 100% fertigation level. This suggests that the split application of K fertilizers through drip fertigation would be a better option for tomato than the solid fertilizer applied to the soil. Moreover, the variation in available K concentration was considerable with fertigation treatments where available K remained in a higher range in root zone at end of the last fertigation cycle. However, a great amount of K was accumulated towards the boundary of the wetted area in drip irrigation or in furrow with solid fertilizer application, indicating a potential leaching risk. In addition, the available K content was appreciably higher with 100% fertigation than with solid fertilizer or any other fertigation level, which indicates that the drip fertigation has the potential to minimize leaching loss and improve the available K status in the root zone for efficient use by the plants. In this soil with low CEC and K adsorption, potassium ion moved along with the water when plants received two side dressings (entire K fertilizer was applied twice during the growth season). Thus, it will be decisive to apply K fertilizers through drip irrigation system in more splits to achieve maximum nutrient use efficiency. These results confirm the findings of several authors (Rivera et al. 2006; Badr 2007), who reported that the split application of K was preferable in comparison with a large single application to initially K deficient soil.

Vegetative Growth

The growth rates of tomato were clearly high in the period between 60 to 75 DAT at the period of fruit filling (Table 1). AGR (indicated in parentheses) increased from 0.3 g plant^{-1} per day^{-1} for transplants to a maximum rate of 6.2 g plant^{-1} per day^{-1} at 75 DAT. Published data include 6–8 g plant^{-1} per day^{-1} for tomato (Scholberg et al. 2000). AGR was only 55% to 68% of maximum rate with solid fertilizer applied under drip and furrow irrigation, respectively. Reductions in growth rate due to application of solid fertilizer typically became obvious only towards the end of the growing season, when NPK depletion in the soil started to affect plant growth. AGR was significantly superior with all fertigation levels over solid fertilizer that applied with drip or furrow irrigation. The differences in AGR due to different methods of applied fertilizer can be referred to complete solubility and availability of water soluble fertilizers direct to the plants as compared to solid fertilizers. The growth response to added NPK was most pronounced with 75% and 100% fertigation levels. Similar findings have been reported on tomato by Locascio et al. (1997) and Hebbar et al. (2004).

The importance of canopy structure for crop growth and yield has been pointed out by Scholberg et al. (2000). The solid fertilizer however, generally tends to cause uneven distribution of fertilizers in the root zone. Alternatively, all of the soluble N, P and K fertilizer can be applied through drip fertigation system, to obtain proper distribution in the

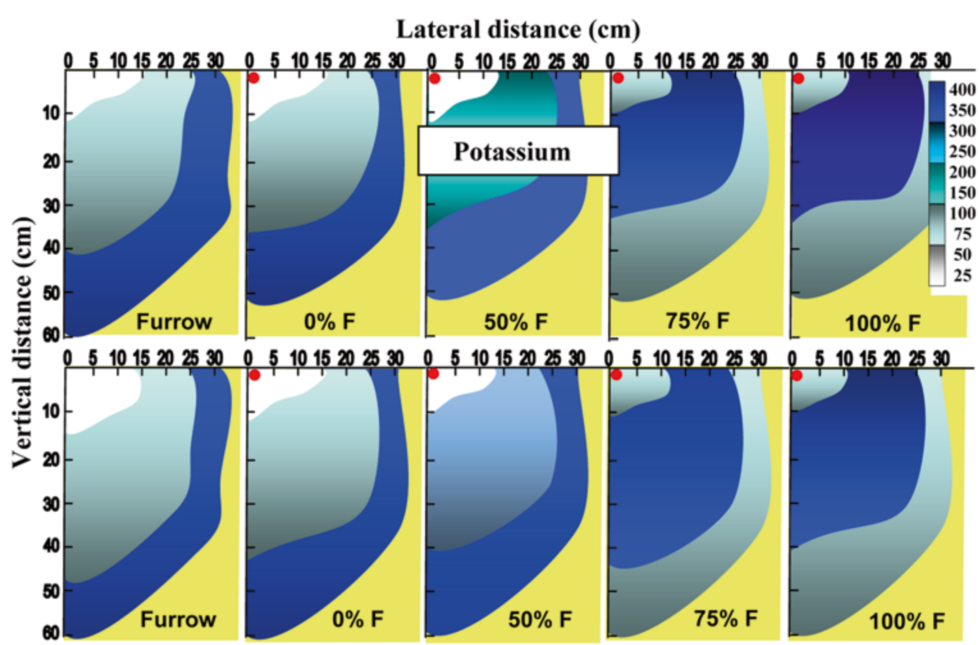

Fig. 3 Distribution of K (mg kg^{-1} soil) in root zone at 28 DAT, (upper) and 90 DAT, (lower) as affected by methods of fertilizer application and levels of fertigation (F)

Table 1 Total dry weight (TDW) and leaf area index (LAI) of tomato as affected by fertilizer application methods and levels of fertigation (Means of two seasons)

Treatments	Total dry weight (g $plant^{-1}$)					LAI at 90 DAT
	25	45	60	75	90 DAT*	
Furrow	7.2 (0.3)	38 (1.5)	89 (3.4)	140 (3.4)	156 (1.1)	2.24
0% Fertigation	7.5 (0.3)	47 (1.8)	103 (3.7)	166 (4.2)	187 (1.4)	3.15
50% Fertigation	8.3 (0.3)	56 (2.4)	118 (4.1)	198 (5.3)	235 (2.5)	3.27
75% Fertigation	8.5 (0.3)	62 (2.7)	127 (4.3)	214 (5.8)	256 (2.8)	3.38
100% Fertigation	8.8 (0.4)	74 (3.3)	145 (4.8)	238 (6.2)	286 (3.2)	3.64
LSD at 5%	–	7	13	18	24	0.28

*DAT = days after transplanting. LSD = least significant difference

Figures in parentheses indicate absolute growth rate

soil. This is the evidence for the longer activity in fertigation, where nutrients were applied frequently to match the uptake by crop and also enhanced the current photosynthesis for developing vegetative growth.

Leaf area index (LAI) at 90 DAT was greater with fertigation, with rising from 3.27 to 3.64 as fertigation level increased from 50% to 100% NPK (Table 1). The increase in LAI with increase in fertigation level was associated with enhances in leaf size and leaves number (data not shown). In contrary, tomato plants received solid fertilizer with drip and furrow irrigation, had typically fewer leaves which were both smaller and thicker. The most drastic changes in leaf parameters typically occurred in tomato plants received solid fertilizer with furrow (2.24) and drip irrigation (3.15). Higher LAI with drip irrigation than furrow irrigation has been reported by Chawla and Narda (2000).

Yield of Tomato

Drip irrigation with solid NPK fertilizers showed significantly higher total yield of tomato (58.62 t ha^{-1}) over furrow irrigation (47.37 t ha^{-1}), which amounted to 24% yield increase (Table 2). This can be attributed to significantly higher number of fruits per plant as well as the fruit weight of tomato in drip irrigation over furrow irrigation.

Table 2 Yield and yield components of tomato as affected by fertilizer application methods and levels of fertigation (Means of two seasons)

Treatments	Fruits No. per plant	Mean fruit weight (g)	Fruit yield kg $plant^{-1}$	Fruit yield t ha^{-1}	Total DW t ha^{-1}
Furrow	17.4	87	1.52	47.37	4.15 (2.37)
0% Fertigation	20.8	93	1.95	58.62	4.83 (2.93)
50% Fertigation	22.2	96	2.13	64.45	5.37 (3.18)
75% Fertigation	22.3	104	2.32	68.76	5.68 (3.42)
100% Fertigation	23.7	112	2.65	74.87	6.17 (3.74)
LSD at 5%	1.6	11	0.15	3.75	0.36 (0.18)

Total dry weight of above ground parts. Figures in parentheses indicate total fruit dry weight

LSD = least significant difference

The distinctive yield performance reflected in drip irrigation over furrow irrigation is further magnified by the application of fertilizers through drip irrigation water, indicating the beneficial use from accessible nutrients if timed to the plant needs. Total fruit yields from the plants that received water soluble NPK at 100% fertigation level (74.87 t ha^{-1}) were significantly greater than 50% fertigation (64.45 t ha^{-1}) and 75% fertigation (68.76 t ha^{-1}), respectively. The soil of the experimental site was very low in available NPK and the high yield potential hybrid variety in the present study was expected to respond better at a higher fertigation level. However, with solid fertilizer applied at two equal splits (50% at transplanting and 50% at flowering on set) with drip and furrow irrigation, yields were reduced, likely due to soluble salts early and later during the season as a result of frequent leaching losses.

Total yield increase with 100% fertigation levels was associated with a significant number of fruit per plant and fruit size (23.7 and 112 g) as compared to solid fertilizers applied with furrow (17.4 and 87 g) and drip irrigation (20.8 and 93 g), respectively. Lara et al. (1996) and Hebbar et al. (2004) reported similar results of improved yield and quality of tomato under drip fertigation. This can be attributed to higher dry matter production and better distribution of nutrients in the root zone of tomato due to drip fertigation and also supports the concept of the positive effect of the right timing of application as a precondition of good management practice. In addition, the application of nutrients including N is essential to obtain high yield. As indicated by El-Tohamy et al. (2009) the yield of Cape gooseberry (husk tomato) plants was significantly increased by increasing N-levels under sandy soil conditions.

Nutrient Uptake and Recovery

Fertigation treatments showed significantly higher total NPK uptake and recovery by tomato and the highest value was obtained under 100% fertigation (Table 3). However, the lowest values were obtained under furrow and drip irrigation with direct application of solid fertilizer indicating a potential leaching risk for this treatment. As was shown before, the applied water soluble NPK in fertigation treat-

Table 3 NPK uptake, recovery and fertilizer use efficiency (FUE) of tomato as affected by fertilizer application methods and levels of fertigation (Means of two seasons)

Treatments	Uptake—kg ha^{-1}			Recovery (%)			FUE kg yield kg^{-1} NPK
	N	P	K	N	P	K	
Furrow	102	12	64	42	15	36	95
0% Fertigation	128	15	80	53	19	44	117
50% Fertigation	146	18	94	58	23	52	129
75% Fertigation	154	22	104	64	28	58	138
100% Fertigation	172	27	117	72	34	65	150
LSD at 5%	14	4	12	6	3	5	9

LSD = least significant difference

ments have been distributed better through the root zone of tomato and having a better availability than solid fertilizers. Fertigation provided nutrients evenly with frequent applications and was responsible for the improvement of nutrient uptake and recovery in the root zone coupled with reduced loss of nutrients primarily because of less leaching under higher fertigation levels. In previous studies, Vasane et al. (1996) and Singandhupe et al. (2003) have reported similar results of increased uptake with fertigation. Similarly, FUE was significantly superior in all the drip irrigation treatments either with solid or with water soluble fertilizers over furrow irrigation (95 kg yield kg^{-1} NPK). Furthermore, FUE was significantly higher in 100% fertigation (150) compared to drip irrigation (117), 50% fertigation (129) and 75% NPK fertigation (138 kg yield kg^{-1} NPK), (Table 3).

In conclusion, the results of the present study indicate that the use of drip fertigation is a good management technique that satisfies the nutrient demand of tomato grown on sandy soils. The nutrient uptake pattern of tomato and the marginal availability of soil N, P and K highlight the importance of split application of nutrients during the growth season to improve and sustain higher yields. The study also explored the plant responses to different fertigation levels under arid land conditions as well as the distribution pattern of nutrients under such conditions which will be helpful for further investigation regarding fertigation studies in arid lands.

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