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Fertigation in Vegetable Crops for Higher Productivity and Resource Use Efficiency

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Precise management of irrigation quantity along with the rate and timing of nutrient application are of critical importance to obtain desired results in terms of productivity and nutrient use efficiency (NUE). The fertigation allows application of right amounts of plant nutrients uniformly to the wetted root volume zone where most of the active roots are concentrated and this helps enhance nutrient use efficiency. It has been found to improve the productivity and quality of crop produce along with improved resource use efficiency. Fertigation is considered eco-friendly as it controls leaching of nutrients especially nitrogen (N)-NO_3. However, to get the desired results knowledge of the system and efficient management are essential. A review is made of the current literature on the use of fertigation covering various aspects of vegetable production including its advantages and constraints to its adoption and nutrient behaviour especially at the practical agriculture level in India.

In agriculture water and nutrients are the two most critical inputs and their efficient management is important not only for higher productivity but also for maintaining environmental quality. Among the various irrigation methods used for water application, micro irrigation systems (MIS) particularly, drip and sprinkler methods seem most efficient and increasingly adopted worldwide. The decade 1990-2000, witnessed a quantum leap in expansion of micro irrigation technology **(Table 1)**, both in developed and developing countries. The area under micro irrigation increased almost six fold during last 20 years – from 1.1 million ha (mha) in1986 to 6.1 million ha (mha) at present. In case of micro irrigation, the highest coverage is in Americas (1.9 mha) followed by Europe and Asia (1.8 mha each), Africa (0.4 mha), and Oceania (0.2 mha) (1). Applying plant nutrients by dissolving them in irrigation water (termed as fertigation) particularly with the drip system is a most efficient way of nutrient application. Fertigation has the potential to supply a right mixture of water and nutrients to the root zone, and thus meeting plants' water and nutrient

Table 1 - Utilisation of micro-irrigation in world					
Year	1981	1986	1991	2000	2006
Area (ha)	436 590	1 030 578	1 826 287	3 201 300	6 089 534
% increase		136.1	77.2	75.3	90.2

Source: (1)

requirements in most efficient possible manner (2). Fertigation allows an accurate and uniform application of nutrients to the wetted area where most active roots are concentrated. Therefore, it is possible to dispense adequate nutrient quantity at an appropriate concentration to meet the crop demand during a growing season. Since fertigation was first used in Israel in 1969 for tomato grown on sand dunes in a field experiment (3), the area under fertigation has since increased rapidly worldwide. The rapid development of trickle irrigation and fertigation systems in many parts of the world followed demands to minimize water loss in agriculture, which arose from the shortage of water caused by increasing household and industrial demands, and the urge to expand area under irrigation. Development was also driven by increasing labour costs, demands to prevent pollution and to minimize soil erosion, increasing compulsion to use saline water sources, and unfavourable soil quality. However, as against approximately 80% of the irrigated land in Israel under fertigation, there is negligible share of fertigation in India. Therefore, this review has been undertaken to bring all information on fertigation of vegetables to popularize the use of fertigation for an efficient use of water and nutrients in eco- friendly manner.

Benefits of Fertigation

Higher nutrient use efficiency: Nutrient use efficiency by crops is greater under fertigation compared to that under conventional application of fertilisers to the soil.

Less water pollution: Intensification of agriculture led by use of irrigation water and indiscriminate use of fertilisers has led to the pollution of surface and ground waters by nutrients. Fertigation helps lessen pollution of water bodies through the leaching of nutrients such as N and potassium (K) out of agricultural fields.

Higher resource conservation: Fertigation helps in saving of water, nutrients, energy, labour and time.

More flexibility in farm operations: Fertigation provides flexibility in field operations e.g. nutrients can be applied to the soil when crop or soil conditions would otherwise prohibit entry into the field with conventional equipment.

Efficient delivery of micronutrients: Fertigation provides opportunity for efficient use of compound and ready-mix nutrient solutions containing small concentrations of micronutrients, which are otherwise very difficult to apply accurately to the soil when are applied alone.

Healthy crop growth: When fertigation is applied through the drip irrigation system, crop foliage can be kept dry thus avoiding leaf burn and delaying the development of plant pathogens.

Helps in effective weed management: Fertigation helps to reduce weed menace particularly between the crop rows. Use of plastic mulch along with fertigation through drip system allows effective weed control in widely spaced crops.

Effective use of undulating soils: The ability of MIS to irrigate undulating soils makes it possible to bring such land under cultivation, which otherwise remain as wastelands or used as pasturelands.

Reduced soil compaction: In MIS reduced need for surface traffic movement during irrigation and nutrient application helps to reduce soil compaction.

However, when fertigation is combined with the use of plastic cover over crop rows; it can bring extra benefits like:

1. Reduction in the evaporational losses of water from the soil surface.
2. Development of salinity on soil surface is delayed.
3. Prevents weed preponderance and consequent reduction in herbicide use.
4. Soil temperature is also regulated when clear or reflecting type of plastic sheets are used.

However, to get maximum benefit of fertigation, care must be taken while selecting the fertiliser and injection equipment and the management and maintenance of the system.

Fertigated nutrients: Eventhough all soluble plant nutrients can be applied through fertigation with drip irrigation, but N and K remain the main nutrients, which can be applied more efficiently, because they move readily with the irrigation water. Fertigation with phosphorus (P) and most micronutrients is not very satisfactory as the carriers of these nutrients move rather poorly with water in the soil and thus do not reach the root zone. Besides, the use of fertigation to apply P and micronutrients together with Ca and Mg may cause precipitation and blockage of the emitters (4). However, Kafkafi (5) argued that application of P via drip irrigation is more efficient than by the

Table 2- Daily consumption rate of nitrogen (N), phosphorus (P) and potassium (K) (kg ha^{-1} day^{-1}) of selected vegetables grown under drip irrigation after emergence or planting

Days planting/ emergence	Tomato greenhouse			Tomato industry			Eggplant			Broccoli			Melon		
	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
1-10	1.00	0.10	2.00	0.10	0.02	0.10	0.05	0.01	0.00	0.02	0.00	0.01	0.15	0.03	0.10
11-20	1.00	0.10	4.00	0.50	0.05	0.30	0.10	0.01	0.00	0.07	0.01	0.02	0.20	0.03	0.25
21-30	1.00	0.10	3.50	1.00	0.16	2.00	0.20	0.01	0.30	1.08	0.12	0.74	0.35	0.07	0.60
31-40	2.50	0.20	3.50	2.80	0.19	2.30	0.25	0.01	0.80	1.22	0.13	0.91	0.90	0.18	1.45
41-50	2.50	0.40	5.50	4.50	0.75	8.00	3.20	0.02	4.90	1.75	0.20	1.35	1.30	0.25	3.00
51-60	2.50	0.60	6.00	6.50	0.80	8.50	2.90	0.08	7.20	1.04	0.13	3.04	2.50	0.25	6.00
61-70	2.50	0.30	4.00	7.50	1.80	9.00	0.25	0.09	1.30	3.02	0.36	4.34	4.30	0.35	7.00
71-80	2.50	0.30	6.00	3.50	0.50	4.50	0.25	0.05	0.50	3.41	0.46	3.95	2.40	0.45	8.00
81-90	1.50	0.30	0.10	5.00	0.50	9.20	0.25	0.05	0.50	2.79	0.38	4.09	1.20	0.43	7.50
91-100	1.50	0.10	0.10	8.00	0.89	9.00	0.25	0.05	0.50	2.09	0.32	3.13	1.00	0.27	3.50
101-110	1.00	0.10	0.10	-	-	-	0.25	0.09	2.00	0.93	0.18	2.74	0.50	0.13	1.00
111-120	1.00	0.10	1.00	-	-	-	1.20	0.15	3.00	0.20	0.09	0.96	0.30	0.07	0.05
121-130	1.50	0.20	1.00	-	-	-	2.40	0.27	3.00	0.18	0.09	0.48	-	-	-
131-150	1.50	0.35	1.30	-	-	-	2.60	0.31	3.00	0.15	0.04	-	-	-	-
151-180	4.00	0.50	3.80	-	-	-	2.30	0.38	1.60	-	-	-	-	-	-
181-200	2.00	0.30	3.00	-	-	-	1.90	0.35	1.60	-	-	-	-	-	-
TOTAL	450	65	710	393	59	520	290	33	380	202	26	165	151	25	385
Variety	F-144			VFM82-1-2			Black Oval			Woltam			Galia		
Date em./pl.	25 Sep**			27 Mar*			10 Sep**			30 Aug**			14 Jan		
Harvest	selective			18 Jul			selective			17 Jan			selective		
Plants/ha	23,000			50,000			12,500			33,000			25,000		
Soil	Sandy			clay			sandy			loam			sandy		
Yield (t/ha)	195			160			51			13			56		

* emergence ** planting

Source: (16)

conventional application to soil, because fertigation supplies P directly to the active roots zone, which enables its immediate uptake, before it undergoes transformations especially fixation in the soil. When the conditions require that P be applied by fertigation, it should be applied alone and the irrigation water should be acidified to prevent clogging of the emitters (6). The soluble forms of the three lesser macronutrients (secondary) – calcium, magnesium and sulphur – do exist but these are much more expensive, not always compatible with mixes and can cause precipitation and clogging. The conventional forms of these nutrients- lime, gypsum and dolomite should be spread in the normal way. When micronutrients need to be applied through fertigation, fully soluble sources or chelates should be used.

Fertilisers for MIS - Solubility, Compatibility and Rate and Frequency of Application

Selection and Compatibility of Fertilisers

Liquid fertilisers are best suited for fertigation as they readily dissolve in irrigation water. In developing countries like India however, inadequate availability and the high cost of liquid fertilisers restrict their use. Fertigation using granular fertilisers poses several problems including differences in solubility in water, compatibility among different fertilisers and problems in filtration of undissolved fertilisers and impurities. Different granular fertilisers have different solubility in water, which is further affected by irrigation water temperature. When the solutions of two or more fertilisers are mixed together, one or more of them may tend to precipitate if the fertilisers are not compatible with each other. Therefore, such fertilisers may be unsuitable for simultaneous application through fertigation and would have to be applied separately (7). For example, when $(NH_4)_2SO_4$ and KCl are mixed together in the tank, the solubility of the mixture is considerably reduced due to the formation of K_2SO_4. Other unusable mixtures include calcium nitrate with any phosphates or sulfates, magnesium sulfate with di- or mono-ammonium phosphate,

Table 3 - Nutrient requirement of open field tomato according to its physiological stages.							
Physiological Stage	Days	Ratio			Kg/ha/day		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
Planting - Flowering	25	1	1	1	1.6	1.6	1.6
Flowering - Fruit Set	20	1	0.5	1.5	2.1	1.0	3.1
Fruit Set- Fruit Ripening	25	1	0.3	2	2.8	0.6	5.6
Fruit Ripening-Harvest	35	1	03	2	3.6	0.6	7.2
Total	**105**				**280**	**90**	**500**
Fertilisation programme							
Physiological Stage	**Fertilisers**	**kg/ha/day ****					
Planting-Flowering	20-20-20	8					
Flowering - Fruit Set	14-7-21	15					
Fruit Set- Fruit Ripening	14-3-28	20					
Fruit Ripening-Harvest	14-3-28	26					

** Plants are irrigated every 3-5 days in heavy soils, and every 2-3 days in light soils. To calculate the fertiliser dose at each irrigation, multiply the daily amount of fertiliser by the days interval between irrigation cycles.

phosphoric acid with iron, zinc, copper and manganese sulfates, etc.

The problem of precipitation and incompatibility among solid fertilisers can be minimised by using two fertilization tanks to separate the fertilisers that interact and cause precipitation, e.g. placing in one tank the calcium, magnesium and microelements, and in the other tank the phosphorus and the sulfate sources.

Nitric or phosphoric acids are used to lower the pH level in fertigation. Their advantage, besides the dissolution of basic precipitates in the line is that they also supply the plants with the essential nutrients, and thereby replace N and P fertilisers. With the use of saline water and in calcareous clay soils, nitric acid increases Ca dissolution and thereby minimizes salinity injury due to Ca/Na competition and also reduces chloride salinity in the root zone, as the nitrate counterbalances excess chloride (8).

Papadopoulos and Ristimäki (9) found that urea phosphate as a source of P gave higher yield of both tomato and eggplant as compared to mono-ammonium phosphate and di-ammonium phosphate even when P_2O_5 supplied was 25% less. Most probable explanation is the "double acidification effect" of the urea phosphate fertiliser. Potassium nitrate is the recommended source of potassium for use in fertigation because of its solubility and added bonus of providing N. It is, however, the most expensive of the K fertilisers.

Fertigation Nutrient Amount

The scheduling of nutrient application through drip irrigation system is vital to get the higher crop productivity and NUE and reduce losses of nutrients through leaching. To get desired results, it is pertinent to know how much amount of nutrients should be applied through fertigation. Dangler and Locascio[10] reported that tomato yields were lower with application of 100% recommended dose of N and K as preplant, compared to when 50% of recommended dose of N and K was applied by fertigation. On a coarse - textured soil, the preplant application of all the P and 40% of the N and K, with 60% of the N and K fertigated with drip irrigation gave higher yield of tomato than the application of whole amount of N and K as preplant (11,12). In a coarse-textured soil, it is essential to supply only part of the N-K requirement via fertigation and to avoid over irrigation and to apply remaining amount of nutrients as preplant. With part of the nutrients applied at planting nutrient leaching losses are reduced and NUE is increased which results into higher yields as compared to when all the nutrients are applied either preplant or through the drip system. However, it was (12) found that in fine-textured soils yields were higher when 100% of the nutrients were applied before planting than when all or parts of the nutrients were applied by fertigation. Preplant incorporation of N and K in the root zone provides nutrients for early growth during a period when irrigation may not be required and before fertigation begins to supply nutrients throughout the bed as crop growth continues. Hartz (13) reported that for celery, the better approach would be to either eliminate the practice of top-dressing, or top-dress only a token amount (22.4- 56.0 kg N/ha), concentrating instead on applying more N through fertigation later in the season when the crop is better able to utilize it. Application of 100 % of recommended dose of fertilisers (RDF) through fertigation improved tomato yield by 21.95 % and 8.49% over fertigation of 50% and 75% RDF, respectively (14). When percentages of fertigated N and K were increased above 75% RDF, yields were increased in sandy loam soil (15).

Rate and Frequency of Nutrient Application during Fertigation

The amount of nutrient to be applied during any given fertigation and the total amount to be applied during the crop season depends on the frequency of fertigation, soil type, nutrient requirements of the crops depending on their physiological stage **(Tables 2 and 3)** and nutrient availability in the soil (17, 18). As the nutrients applied to soil by the fertilisers are not fully available to the plant due to leaching, run-off, volatilization and adsorption losses, corrections need to be made according to the use efficiency of nutrients. According to Hartz (13) the two major factors determining the appropriate N fertigation rate are: level of residual soil NO_3-N present

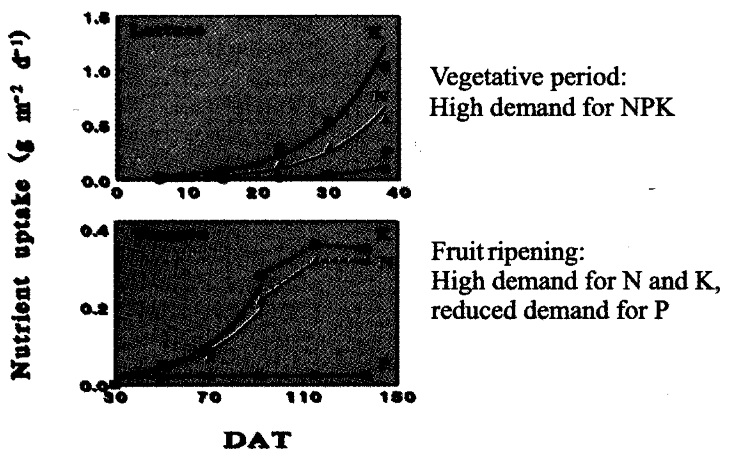

Figure 1 - Rates of uptake of N, P and K during different physiological growth stages of tomato and lettuce. DAT is days after transplanting of the vegetable crops. Source: (19).

and the degree of nutrient leaching expected. In-season soil testing, through conventional laboratory analysis or by the 'quick test' procedure (see 13), the amount of soil residual NO_3-N can be determined. As long as the residual NO_3-N in the wetted root zone is >15-20 mg/kg, little or no additional fertigated N is necessary in celery (13). Further, he also observed that in a typical field situation, each inch of leaching would remove between 11.20-28.0 kg N/ha from the crop root zone. In fields in which leaching is difficult to control (for example very sandy soils) or where excessive irrigation is deliberately applied to overcome poor water distribution uniformity, or to control salinity, one may need to compensate for NO_3-N leaching losses. In such situations, the fertigation frequency as well as the amount applied may need to be increased to prevent transient N deficiency. Obviously, NO_3-N leaching from heavy rain may also require additional fertigation.

Monitoring crop N status through petiole NO_3-N analysis can be very efficient to determine the rate of nutrient application. Petiole sampling can help identify fields in which N availability is low, and thereby to take corrective action necessary. Petiole NO_3-N in excess of 6,000 ppm indicates adequate N availability. As values decrease below 6,000 ppm, the likelihood of restricted N availability affecting plant growth increases (13). For example, the daily application rate of fertigation for lettuce and tomato crops changed during the growing season **(Figure 1)** and thus it is important to apply nutrients by following plant daily demand according to nutrient uptake.

Fertilisers can be injected into the irrigation system at various frequencies such as once a day, on alternate days or even once a week. The frequency depends on irrigation scheduling, soil type, daily nutrient requirement of crop, system design and the farmers' preference (11). In any case, it is extremely important that the nutrients applied in any fertigation cycle are not subject to leaching either during that fertigation or during subsequent fertigations. Smaller the root volume, higher is the frequency of fertigation. The effectiveness of fertigated N will be maximized if it is injected at the end of the irrigation run, with only a 30-40 minute period of clear water to flush the fertiliser from the system. With good irrigation control, fertigation once a week can be as effective as fertigation with each irrigation in celery (13). Sousa *et al* (20) found advantage of fertigation at 0.5 and 1-day intervals compared with at 5-days interval for the surface drip-irrigated melon grown on a sandy soil. Marketable yield and fruit size of subsurface drip-irrigated tomato were significantly higher with daily compared with biweekly or monthly fertigation on a loamy sand soil (21). Similarly, tomato yield was significantly different when N was fertigated at 5-day interval compared with at 9-day via a surface drip system (22). Badr and El-Yazied (23) found that N rate and fertigation frequency resulted in significant differences in N uptake, N recovery and N use efficiency (NUE). Total N uptake was appreciably higher with increasing N rate and with more frequent than with less frequent fertigation. The average N recovery across fertigation frequency was 60 and 54 % and NUE was 221 and 194 kg yield/kg N with 200 and 300 kg N/ha applied, respectively **(Table 4)**. They also observed that total tomato yield and yield components were responsive to N rate and to decreased fertigation frequency. The total fruit yields averaged (67.75, 65.13 and 63.29 t/ha) under the frequencies of 1, 3 and 7 day, respectively were significantly higher than that of the frequency of 14 days (54.32 t/ha) **(Table 4)**. Wide differences in leaf N concentration were observed in the early vegetative stage, which was mainly dependent on the rate of N supply. Although these differences gradually disappeared as the season progressed, the differences in plant size remained until the end of the season. However, daily, alternate day and weekly fertigation did not significantly affect yield in onion (24). The highest yield was recorded in daily fertigation, followed by alternate day fertigation, while the lowest yield was obtained in monthly fertigation frequency. Application of 3.4 kg/ha urea in daily fertigation resulted in highest yield of onion with least amount of NO_3 -N leaching. Thompson *et al* (25) also

Table 4 - Nitrogen (N) uptake, N recovery and NUE by tomato plants as influenced by N application rate and fertigation frequency (the results are the mean of two seasons).										
N rate kg/ha	Fertigation frequency	Tomato yield (t/ha)		Mean fruit weight (g)	Fruit yield (kg/plant)	N uptake (kg/ha)			N recovery %	NUE
		Fruits	shoots			Leaves	Fruits	Total		
200	Daily	52.54	3.45	85.8	1.75	56	103	159	68	240
	3 days	50.76	3.38	83.6	1.63	51	99	150	64	231
	Weakly	49.18	3.29	82.3	1.63	45	93	138	58	223
	Biweekly	42.37	2.80	79.0	1.39	34	85	119	48	189
300	Daily	67.75	4.11	97.9	2.27	68	147	215	64	211
	3 days	65.13	3.95	94.7	2.13	62	135	197	58	202
	Weakly	63.29	3.87	93.5	2.02	56	127	183	53	196
	Biweekly	54.35	3.30	104.8	1.76	43	103	146	41	166
CD (P=0.05)		4.76	0.38	16.4	0.15	7	16	24	-	14

Source: (23)

reported that for subsurface drip-irrigated broccoli grown in a sandy loam or similar textured soils, fertigation frequency is not a critical management variable affecting crop yield and quality. Similarly, the yields of surface drip-irrigated pepper (*Capsicum annum* L.) were not affected by the fertigation interval (11 or 22 days) on a loamy sand soil (26). Locascio and Smajstrla (27) also reported no significant effect of fertigation frequency on tomato yield.

Watering schedule

As the water soluble nutrients move with the wetting front, precise management of irrigation quantity alongwith rate and timing of nutrient application are critical to get desired results in terms of productivity and NUE. To minimize leaching losses of the soluble nutrients applied through drip irrigation and to maximize crop production, precise management of water application is essential since over-irrigation results in nutrient leaching and reduced yields (28). Even with fertigation, over-irrigation can result in severe nutrient deficiencies and reduced crop yields, e.g. excessive drip irrigation reduced tomato yield (29). Drip irrigation can be scheduled by matching a predetermined proportion of the water evaporated from a US weather service class A evaporation pan (E pan) (30, 31), which provides a measure of evapotranspiration (ET). Locascio et al; (81) found that yield of polythene-mulched tomato was high when irrigated at 1.0 E pan than at 2.0 E pan. On a coarse–textured soil, yield of a spring tomato crop was higher when irrigated at 0.5 than at 1.0 E pan, whereas on a fine textured soil, tomato yield was similar under irrigation at 0.5 and 1.0 E pan (29, 32) with water application rates of 20 to 30 cm/ha. Pitts and Clark (33) found that tomato water requirements varied from 1.2 E pan early in the season to 0.8 E pan during fruit development. However, water scheduling according to pan evaporation often over-estimates early crop water needs. When tensiometer scheduling of water at 10 to 15 k Pa was used, less water was applied than with 0.75 E pan application. In tomato, water used per crop was 30 cm with water scheduled to replace 0.75 E pan and 17 cm when irrigation was scheduled by means of magnetic switching tensiometers to apply sufficient water to maintain soils at 10 k Pa (34, 35). In addition to tensiometers, soil water sensors and other techniques like granular matrix sensors (GMSs) (36) and time-domain reflectometry (TDR) (37) can also be used to determine the time of irrigation. Soluble dyes can be applied with the irrigation water to track the depth of water and soluble-nutrient movement (38, 39).

Direct soil moisture monitoring is the essential safeguard to avoid over- or under-watering. Among the common soil moisture monitoring techniques available, the use of tensiometers is among the best options for monitoring drip-irrigated celery (13). Tensiometers should be installed in the plant row, approximately 10-12 inches deep. To ensure that the readings are representative of the whole field installing instruments in different parts of the field is ideal.

Response of Vegetable Crops to Fertigation

The available literature provides sufficient evidence in favour of increased productivity of vegetable crops due to fertigation. The yield of okra under conventional method of fertilisation with 100% of recommended dose of fertilisers and under fertigation with 60% of recommended dose of fertilisers was not significantly different (23.0 t/ha and 23.1 t/ha in the year 2000 and 23.56 t/ha and 23.35 t/ha in the year 2001) (7). This indicates that a saving of 40% in fertiliser use may be achieved if applied through fertigation without affecting the okra yields. More than 16% increase in yield under fertigation (25.21% in the year 2000 and 16.59% in the year 2001) was observed as compared broadcasting method of fertiliser application when 100% recommended dose of fertilisers was applied. Similar results of increase in productivity of chilli crop due to fertigation were reported (40).

Table 5- Effects of drip fertigation on dry pod yield, water saving, water use efficiency, water productivity and B:C ratio in chillies (the results are the pooled means).					
Treatments	**Dry pod yield (kg/ha)**	**% water savings over farmers' method**	**WUE (kg/ha /mm)**	**Water productivity (Rs/m³)**	**B:C ratio**
Surface irrigation at 0.90 IW/CPE ratio+ entire NPK as soil application	1327	-	2.3	2.0	1.77
Drip irrigation at 100% PE + 75% N and K through fertigation	1989	-	3.1	2.5	1.67
Drip irrigation at 100% PE + 100% N and K through fertigation	2217	-	3.4	3.2	1.86
Drip irrigation at 100% PE + 125% N and K through fertigation	2117	-	3.3	2.9	1.78
Drip irrigation at 75% PE + 75% N and K through fertigation	1993	15.9	4.1	3.3	1.67
Drip irrigation at 75% PE +100% N and K through fertigation	2222	15.9	4.6	4.2	1.87
Drip irrigation at 75% PE + 125% N and K through fertigation	2123	15.9	4.4	3.8	1.78
Drip irrigation at 50% PE + 75% N and K through fertigation	2015	36.9	6.0	4.9	1.69
Drip irrigation at 50% PE + 100% N and K through fertigation	2200	36.9	6.5	6.0	1.85
Drip irrigation at 50% PE + 125% N and K through fertigation	2075	36.9	6.1	5.2	1.74
SEd	86				
CD(p=0.05)	186				

Source: (43)

Table 6- Dry chilli pod yield increase (%) due to fertigation and drip irrigation systems			
Treatments	**% increase in dry pod yield due to fertigation over soil application of 100% N and K**	**Treatments**	**% increase in dry pod yield due to drip irrigation over soil application of 100% N and K**
Fertigation of 75% N and K	50.6	Drip irrigation at 50% PE	58.8
Fertigation of 100% N and K	66.8	Drip irrigation at 75% PE	59.2
Fertigation of 125% N and K	58.6	Drip irrigation at 100% PE	58.0

Source: (43)

Fertigation irrespective of the combination of fertilisers has been found superior to the soil application of fertilisers. With only 50% of recommended N through fertigation, higher yield of tomato and egg plant was obtained compared to application of full amount of N through conventional method, suggesting that N is more efficiently utilized when applied with the irrigation water (9). Tu et al (41) in a 4-year (1998-2001) investigation carried out in south-western Ontario, USA found that **(a)** drip-irrigation and fertigation significantly increased tomato yield over the non-treated control, **(b)** percentage of tomato fruit with blossom-end rot was reduced significantly to the negligible level in the drip-irrigated and fertigated treatments, and **(c)** drip-fertigation provided significant yield advantage over drip-irrigation only in the year when rainfall was below normal during the periods of flowering, fruit set and fruit growth, as experienced in the 2001 season. Darwish et al (42) studied the impact of N fertigation in potato and reported that fertigation with continuous N feeding through drip system based on actual N demand and available N in the soil resulted in 55% N recovery; and for spring potato crop in this treatment, 44.8% N need was met from the soil N and 21.8% from the irrigation water. Higher N input increased not only the N derived from fertilisers, but also the residual soil N. Irrigation at 100% PE + fertigation with 100% N and K and, 50% PE + fertigation with 100% N and K being at par recorded 67.06% and 65.78%, respectively higher pod yield of chilli as compared to surface irrigation at 0.90 IW/CPE ratio + entire NPK as soil application **(Table 5)**. However, fertigation of 125% of N and K led to marginal decrease in chilli pod yield over fertigation of 100% of N and K. Fertigation of 75%, 100% and 125% N and K registered 50.6, 66.8 and 58.6% increase in pod yield, respectively over soil application of 100% N and K + surface irrigation **(Table 6)**. Hence, irrespective of the fertiliser dose, there was marked increase in pod yield under fertigation. In green house grown tomato when the same quantity of water and N was applied through drip irrigation a significantly higher tomato yield (68.5 t/ha) was obtained as compared to the yield of 58.4 t/ha and 43.1 t/ha in check basin method of irrigation when the crop was sown both inside and outside the greenhouse, respectively **(Table 7)**. Drip irrigation at 0.5 x E pan along with fertigation of 100% N resulted in increased fruit yield by 59.5% and 116.2% over the control with recommended practices inside and outside the greenhouse, respectively. Under control treatments, both inside and outside the greenhouse, surface irrigation not only resulted in wastage of water through deep percolation below root zone, but also resulted in the leaching of available plant nutrients, poor aeration and reduced

Table 7- Effect of fertigation and irrigation scheduling on the quality parameters of greenhouse-grown tomato.							
Treatments	**Pooled fruit yield (t/ha)**	**Tomato fruit size (cm^3)**	**Root length (m)**	**Pooled WUE (t/ha-mm)**	**TSS (° brix)**	**Ascorbic acid (mg/100 ml of juice)**	**pH**
T1 G.H.C. + Drip irrigation 0.5 x Epan + 100% N	93.2	36.6	49.3	0.224	5.70	42.2	4.29
T2 G.H.C. + Drip irrigation 0.5 x Epan + 125% N	95.9	36.0	49.2	0.231	5.69	42.2	4.29
T3 G.H.C. + Drip irrigation 0.5 x Epan + 150% N	76.8	35.8	42.7	0.185	5.68	42.1	4.28
T4 G.H.C. + Drip irrigation 1.0 x Epan + 100% N	68.5	34.8	23.0	0.088	5.54	41.6	4.27
T5 G.H.C. + Drip irrigation 1.0 x Epan + 125% N	75.6	35.2	21.7	0.097	5.54	41.6	4.28
T6 G.H.C. + Drip irrigation 1.0 x Epan + 150% N	72.6	35.3	20.7	0.093	5.58	41.5	4.27
T7 G.H. C. + Control (100% N + surface irrigated)	58.4	24.3	20.4	0.073	5.18	37.6	4.17
T8 N.G.H.C + Control (100% N + surface irrigated)	43.1	16.2	16.6	0.053	4.64	22.7	3.90
LSD (0.05)	7.5	2.5	3.0	-	0.14	1.5	0.08
G.H.C, Greenhouse crop; N.G.H.C., non-Greenhouse crop.							

Source: (44)

yield. They also found that drip irrigation at 0.5 x E pan in the greenhouse caused an increase in the TSS up to 5.70° brix. In drip irrigation when water was applied in lesser amount, sugar imported by fruits via phloem was concentrated, which helped in increasing the TSS content and pH of tomato. These results are in conformity with those reported by Elkner and Kaniszewski (45). Further drip irrigation at 0.5 x E pan in the greenhouse caused an increase in ascorbic acid content of tomato by 85.9% over the outdoor surface irrigated crop due to less amount of water available to the fruits at shorter interval, which caused osmotic adjustment in the pericarp of tomato and resulted in higher ascorbic acid content and pH (46). Size of the greenhouse drip irrigated tomato at 0.5 x E pan irrespective of fertigation increased by 48.5% over the surface irrigated greenhouse crop and by 122.8% over the surface irrigated outdoor crop, respectively **(Table 7)**. The root length of plants under drip irrigation at 1.0 x E pan was less compared to that under drip irrigation at 0.5 x E pan. Osmotic adjustment and prolonging root cell expansion (47) were ascribed as the causes for increased root length in mildly stressed plants as compared to well-watered plants (48). Bafna et al. (49) reported 41% increase in tomato yield under N application along with drip irrigation at Navsari, Gujarat.

Garlic crop grown under furrow irrigation took up 64 kg P_2O_5/ha, while under fertigation the crop took up 89 kg P_2O_5/ha (50). The respective crop yields were 19.1 and 29 t/ha. Thus, higher yield potential of the crop under fertigation increased P demand of plants by almost 50%. Highest yield of 36.29 t/ ha of fresh tubers was obtained under trickle irrigation as compared to 21.5 t /ha for the furrow irrigated crop (51). Application of 125% recommended dose of water soluble fertiliser with fertigation gave the highest yield of onion seed and improved the yield contributing parameters such as plant height, number of umbels per plot, number of umbels per plant, diameter of umbel and reduced the time to 50% flowering, but the yield was at par with 100% recommended dose of water soluble fertilisers with fertigation **(Table 8)**. Singh et al (53) reported 115.37 and 17.32% increase in broccoli yield with fertigation over drip irrigation and check basin method, respectively. The corresponding values for radish were 47.57 and 8.83% **(Table 9)**. Significant increase in growth parameters (plant height, LAI, fruit dry weight, total dry weight), yield components (number of fruits /plant, mean fruit weight, fruit yield/plant) and total fruit yield was observed with the application of 100% RDF through fertigation over furrow and drip irrigation and soil application of fertilisers (14). The increased yield under fertigation might have resulted due to better water utilization (54), higher uptake of nutrients (49) and excellent soil–water–air relationship with higher oxygen concentration in the root zone (55).

Bhakare and Fatkal (52) recorded the benefit cost (B:C) ratio of Rs. 3.30 under 100% RDF applied through water soluble fertilisers in fertigation as against Rs. 2.78 in 100% RDF with conventional fertiliser application and surface irrigation. Similarly, Muralikrishnasamy *et al* (43) found B:C ratio of Rs. 1.87 with drip irrigation at 75% PE +100% N and K through fertigation over Rs. 1.77 with surface irrigation at 0.90 IW/CPE ratio+ entire NPK as soil application.

Fertigation and Resource Use Efficiency

The fertigation allows application of right quantity of nutrients uniformly to the wetted root volume, where the active roots are concentrated and this helps enhance fertiliser use efficiency. This in turn allows reducing the amount of fertiliser to be applied and ultimately the production costs. Stark *et al* (56) used continuous fertigation of surface drip irrigated

Table 8- Effects of surface and drip irrigation with fertigation on onion seed yield parameters, B:C ratio, water saved, water use efficiency and fertiliser use efficiency					
Treatments	**Onion seed yield (t/ha)**	**B:C ratio (Rs/ Re investe d)**	**Water saved (%)**	**WUE (kg/ha-mm)**	**Fertiliser use efficiency (kg seed/kg nutrient applied)**
100% RDF CFA + SI	0.66	2.78	-	0.90	2.62
100% RDF CFA + DI	0.76	2.84	39.88	1.75	3.05
100% RDF + N through DI	0.81	3.01	39.88	1.86	3.24
125% RDF* + DI	1.03	3.27	39.88	2.37	3.31
100% RDF* + DI	1.00	3.30	39.88	2.30	4.01
75% RDF* + DI	0.91	3.14	39.88	2.09	4.87
50% RDF* + DI	0.80	2.85	39.88	1.83	6.38
S.E. +	0.01		-	-	-
CD at 5%	0.03		-	-	-

RDF – Recommended dose of fertiliser; CFA- Conventional fertiliser application; SI- Surface irrigation; DI- Drip irrigation *RDF applied through water soluble fertilisers

Source: (52)

Table 9 - Yield and water use efficiency (WUE) of broccoli and radish under various treatments.						
Treatments	**Broccoli**			**Radish**		
	Yield (Kg/ha)	**Water applied (mm)**	**WUE (kg/ha/mm)**	**Yield (Kg/ha)**	**Water applied (mm)**	**WUE (kg/ha/mm)**
Fertigation	4301	217	18.70	15200	205	74.15
Drip irrigation	2343	217	10.87	11200	205	54.63
Check basin	1997	306	6.50	10300	310	33.23

Source: (53)

tomato on sandy soils and they reported NUE of 60 % even at 600 kg N/ha application. Bhakare and Bhatkal (52) observed highest FUE when 50% RDF was applied through drip irrigation **(Table 8).** They found lowest FUE when 100% RDF was applied through conventional fertiliser application method and irrigation water was applied by surface application. FUE was significantly higher in 100% NPK fertigation (138 kg yield/kg NPK) compared to furrow irrigation (81), drip irrigation (103), 50% NPK fertigation (114) and 75% NPK fertigation (127) in tomato (14). This was due to better availability of moisture and nutrients throughout the growth stages in drip and fertigation system leading to better uptake of nutrients and production of tomato fruits. Fertigation saves fertiliser nutrients as it permits applying fertiliser in small quantity at a time matching with the plants nutrient need thus, leading to higher NUE (40, 52). Frequent supply of nutrients with irrigation water in fertigation treatments significantly increased NPK uptake and recovery over drip and furrow irrigation (14). The applied NPK in soluble form in fertigation treatments may have been distributed better through root zone of tomato than soil applied treatments, thus producing more available amounts for plant uptake.

Bhakare and Fatkal (52) reported 40% saving of water due to fertigation over conventional fertiliser application and surface irrigation **(Table 8)**. They also recorded WUE of 2.37 kg/ha-mm with 125% RDF applied through water soluble fertilisers with drip irrigation compared to 0.90 kg/ha-mm with 100% RDF through conventional fertilisers + surface irrigation. Singh et al (53) reported 41 and 51% saving in water and 187.69 and 123.14% increase in WUE due to fertigation in broccoli and radish, respectively over check basin method of irrigation **(Table 9)**. Similarly, drip irrigation at 50% PE + 100% N and K through fertigation recorded highest water use efficiency, water productivity and water saving in chilli over farmers' practice of surface irrigation (0.9 IW/CPE ratio) + entire NPK as soil application **(Table 5)**. Water and fertiliser savings to the extent of 30 and 70%, respectively with comparable yield levels was possible under the trickle fertigated crop as compared to the furrow irrigated crop of potato (51). Higher WUE and water saving has been reported by other workers also (14, 58, 59).

Nutrient Dynamics Under Fertigation

Review of available literature gives sufficient indications that fertigated nutrients remain concentrated near

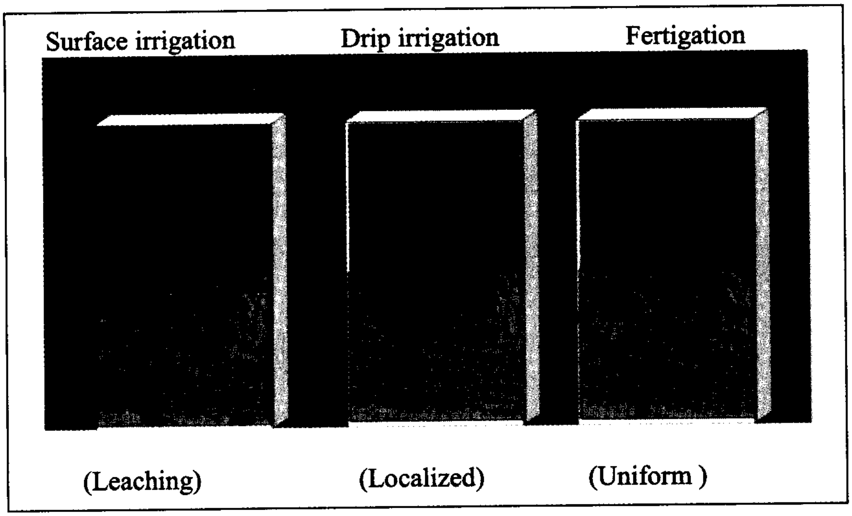

Figure 2 - Nutrient dynamics under surface irrigation, drip irrigation and fertigation, respectively. (Source: WTC, TNAU)

the point of application and thus help in greater nutrient recovery due to improved nutrient availability in the root zone compared to conventional method of fertilisation. Fertigation has been found to help in uniform distribution of fertigated nutrients in the crop root zone **(Figure 2)**. Fertigation maintained higher concentration of NO_3^-N around roots of tomato at a depth of 0-25 cm soil layer particularly with 75% (240 mg/kg soil) and 100% fertigation rates (280 mg/kg soil), compared to entirely soil applied treatments in furrow (54 mg/kg soil) and drip irrigation (75 mg/kg soil), where most of NO_3^-N moved to deeper soil layer (25-50 cm) (14). Higher NO_3^-N was recorded at the end of irrigation at 25-50 cm soil layer, in drip and furrow irrigation, which indicates a potential leaching risk. Singh *et al* (53) observed that when N was applied through fertigation in sprouting broccoli, ammonium form of N dominated in the upper soil layer and almost all the N applied remained confined to the root zone. At harvest (8 days after last fertigation), the maximum NO_3^-N concentration was found within the 30-50 cm layer. In the conventional method of irrigation (check basin method), the nitrate-N dominated and a significant amount was lost through leaching. Under the check basin method, NO_3^-N moved to deeper layer with the advance of the crop stage and at the harvest, the NO_3^- N peak was found in the 70-90 cm layer, indicating leaching loss of N from the root zone. Leaching losses of N were also observed in the treatment in which the fertiliser was applied on soil and water given through drip system. Similarly, under fertigation the peak values of NO_3^-N for the points below the emitter (27.16 g/g of dry soil) and 15 cm away from emitter (29.15 g/g of dry soil) was much higher than those of other points farther away from emitters (ranging from 12.74 to 14.26 g/g of dry soil).

In the case of NH_4^+ N, maximum concentration in fertigation was in the surface layers i.e., between 0-40 cm layers with peak values in the surface layer and decreasing with depth. At the start of experiment NH_4^+ N concentration in the deeper layer was low. But the differences further increased towards the end of the experiment for all fertigation treatments both horizontally and vertically, indicating high concentration in the root zone. Whereas in drip system, except for the point near the emitter, the NH_4^+N concentration did not show any marked difference and was similar throughout the profile. In check basin method, the peak values were always found between 20-50 cm depth with minimum NH_4^+ N concentration in the surface (1-10 cm), which was in sharp contrast to fertigation and drip system, where maximum NH_4^+ N concentration was always found in the surface layers. These results indicate that unlike the conventional methods of irrigation in fertigation maximum amount of applied N remains concentrated near the point of application.

Badr and El-Yazied (23) reported considerable influence of combinations of four fertigation frequencies (1, 3, 7, and 14 day intervals) and two N rates (200 and 300 kg N/ha) on NO_3^-N distribution in the soil profile. In lower soil profiles (50-70 cm soil depth) residual soil NO_3^-N concentration under high N rate (300 kg/ha) was only marginally affected in daily, 3 day and weekly fertigation frequencies (15, 17 and 21 mg N/kg soil, respectively). However, NO_3^-N concentration at the corresponding depth was found high in biweekly fertigation frequency (80 mg N kg/soil). In the upper part of the soil profile NO_3^-N was dispersed more uniformly under daily application, while NO_3^-N distribution showed a zone of leached N soil in the immediate vicinity of the drip line for the less frequent application with a zone of nitrate beyond the leached soil. This may be due to the relatively long irrigation time after fertigation in less frequent fertigated treatments which caused leaching of N from the upper soil layers. Reducing the time interval between successive fertigation application to maintain continuous, optimal water regime in the root zone, may also reduce the variations in nutrient concentration, thereby increasing their availability to plants and reducing their leaching beneath the root zone.

Fate and transport of NO_3^-N is strongly dependent on the soil water content and its movement (61). Water mass flow is the major factor responsible for NO_3^-N movement in the soil and it can move fast enough

Table 10 - Fertiliser salt solubility in water (g/100 g water) at various temperatures					
Temperature	**KCl**	**K_2SO_4**	**KNO_3**	**NH_4NO_3**	**Urea**
10°C	31	9	21	158	84
20°C	34	11	31	195	105
30°C	37	-	-	-	-

Source: (67)

with moving water to deeper soil layers. Li *et al* (62, 63) found that NO_3^-N ion is very mobile in the soil and fertigation treatments maintained high concentration of NO_3^-N at shallow depth.

The mobility of phosphate ion in soils is of primary importance in plant nutrition. Shedeed *et al* (14) reported that phosphate transport in soil applied treatments was too slow for the average rate of root growth into the soil, since P fertilisers are prone to fixation at the point of application. Most of the applied P may be turned to non-soluble form in a short time after its application, and the observed concentrations build up in the upper soil layer could affect root growth and create unfavorable conditions for P uptake. The accumulation of available P at 25-50 cm was tended to be higher in fertigation treatments (8-15 mg kg/soil) because of frequency of fertigation and complete solubility of phosphoric acid compared to soil application in furrow and drip irrigation (3 mg/kg soil) (14).Research done by others (64, 23) has also shown that the mobility of P can be increased when they are applied via fertigation.

Singh *et al* (53) observed that in fertigation treatment, K was confined to the root zone of the radish crop, while it moved in significant quantities beyond the root zone in the conventional method (furrow irrigation). Movement beyond the root zone was also observed in the soil-based fertiliser application with water through drip system but to a lesser a degree. Shedeed *et al* (14) have also reported K leaching losses when soil applied in furrow and drip irrigated tomato compared to K fertigation. They found that fertigation with water soluble fertilisers registered higher available K concentration (194-272 kg/soil) than furrow or drip irrigation. In sandy soil with low CEC and K fixation, potassium ions move along with water and thus, it will be prudent to apply K fertilisers through drip irrigation in more splits to achieve maximum nutrient use efficiency (65, 66).

Frequent supplementation of nutrients with irrigation water increased the availability of N, P and K in the root zone and which in turn influenced the yield and quality of tomato (14).

Chemical and Biological Aspects in Fertigation

Effective fertigation requires an understanding of rate of plant growth including nutrient requirements and rooting patterns, soil chemistry such as solubility and mobility of the nutrients, fertilisers chemistry (mixing compatibility, precipitation, clogging and corrosion) and the quality of water used especially pH, electrical conductivity, salt and sodium hazards and toxic ions (4).

Temperature and fertiliser solubility: Atmospheric temperature plays critical role in the solubility of fertilisers **(Table 10)**. The fertiliser solutions stored during the summer may form precipitates in the autumn due to the diminution of the solubility when the temperatures decrease. Therefore dilution of the solutions stored, is necessary at the end of the summer.

Water quality and fertiliser solubility: Irrigation waters containing high amount of calcium, magnesium and bicarbonates (hard water) and with high pH cause problems like formation of precipitates in the fertilisation tank and clogging of the drippers and filters. Waters with high calcium content and bicarbonates used for the fertigation of sulphate containing fertilisers leads to the formation of precipitate of $CaSO_4$,clogging the drippers and filters of the system. The use of urea for fertigation with such water induces the precipitation of $CaCO_3$ because the urea increases the pH of the solution. Besides, irrigation water temperature and pH also affect the solubility. It may be necessary to lower the pH of the irrigation water to about 5.5 to keep P in the solution during the fertiliser injection, and to prevent blockage of the emitters. P application as phosphoric acid is preferable during the cold weather. It serves to remove precipitates and to supply P to the slow growing roots.

NH_4/NO_3 ratio and other nutrient uptake: The main factor affecting pH in the rhizosphere is NH_4/NO_3 ratio in the irrigation water, especially in sandy soils with low buffering capacity. The N form absorbed by plant affects the production of carboxylates and the cation-anion balance in the plant. When NH_4 absorption is predominant, the plants absorb more cations than anions, and excrete H^+ ions through roots in the soil which decreases the rhizosphere pH. Due to ammonium or nitrate nutrition a fluctuation of the order of 1.5 units in the pH of soil volume around the roots has been reported (68). According to Ganmore-Neumann and Kafkafi (69, 70), NH_4 is an undesirable source of N for tomato and strawberries when the temperature in the root zone is greater than 30°C, because it adversely

affects the root growth and plant development. Uptake of NH_4 as nitrogen source by plants decreases the uptake of other cations like Ca^{2+}, Mg^{2+} and K^+. Some plants such as tomato are very sensitive to high ammonium concentration near the roots; therefore nitrate rich solutions should be selected (71). At elevated root zone temperature, ammonium might damage the roots by competing with the sugar needed for root respiration. However in cold root zones, the ammonium is a safe N source since less sugar is consumed for respiration by root cells (70).

When NO_3^- anion is absorbed, the plant takes up more anions than cations and the excess of anions is palliated by a greater synthesis of carboxylates. During the carboxylation process, dicarboxylic acids (citric, malic, etc.) and OH^- are produced. Both the carboxylates and the hydroxyls can be exuded by the roots into the soil. The exuded OH^- increases the pH of the rhizosphere. Carboxylate exudation by the roots increases P availability by releasing the phosphate specifically adsorbed on iron oxides and clays micelles in the soil solution. The carboxylates can also increase the availability of Fe and P through chelation, for example, citrate forms a chelate with Ca and releases P from calcium phosphate (72, 4).

Therefore, NO_3^- nutrition should be preferred over ammonium nutrition due to greater organic acid synthesis and enhanced anion uptake. However, nutrition with 100% nitrates would increase rhizospheric pH to undesirable levels - values of more than 8 have been registered - and this would decrease the availability of P and micronutrients by precipitation (4). Therefore, it is recommended to use N as mixture with 80% as NO_3^- and 20% as NH_4^+ for optimal results. Plant sensitivity to the N form increases particularly, during the fruiting stage (73).

Water quality, crop susceptibility and fertiliser selection: Crops vary widely in their tolerance to salts. Fertilisers being salts, increase the E-C of the irrigation water. When brackish waters having EC > 2 dS/m with high salinization hazard are used for irrigation in crops sensitive to salinity, the amount of accompanying ions added with the N or K must be decreased (4). For example in crops sensitive to chloride, KNO_3 is preferred over KCl as a source of K to avoid chloride accumulation in the soil solution. Similarly in the greenhouse crops grown in containers with very restricted root volume, fertilisers with low salt index should be used. Sodium fertilisers ($NaNO_3$ or NaH_2PO_4) are unsuitable due to an adverse effect of Na on the hydraulic conductivity of the soil and toxic effect on plant growth and development.

Subsurface Drip Irrigation and Fertigation

Yield responses from various crops indicate that crop yield under subsurface drip was greater than or equal to that obtained with other irrigation methods, including surface drip. Laterals can be installed at depths ranging from 0.02 to 0.70 m and lateral spacing range from 0.25 to 5.0 m. The deep position of tricklers significantly increases the P and K contents at the center of the root zone. The enhanced concentration apparently stimulates plant rooting, which together with the higher nutrient activity in the soil solution, increase P and K uptake rates, which in turn facilitate greater dry matter production and commercial yield than that, obtained with surface trickler placement (74). Thompson *et al* (25) found that for broccoli production with subsurface-drip irrigation on sandy loam or finer soils, fertigation can be applied as infrequently as monthly, without compromising crop yield or quality, or causing excessive N losses. In addition to cost effectiveness and energy saving, the subsurface drip fertigation has added agronomic advantages over the surface drip fertigation including higher NUE and reduced evaporation and weed germination as the surface 4-5 cm soil layer remains dry.

Fertigation in Greenhouse Crops

When vegetables are grown in greenhouses, fertigation remains the most effective way of water and nutrient application not only for agronomic benefits but also for technical feasibility. In greenhouses growing plants in containers allows the collection of the leaching water and its comparison with the applied fertigation solution. The measurement of pH, electrical conductivity (EC) and nutrient concentration in the leached solution indicates whether the fertiliser applied is in optimum, excess or lower quantity, and therefore allows for the consecutive correction of the fertigation regime (4). It is recommended to collect the leached solution from the containers and the solution that leaves the drippers to compare the pH and EC of both the solutions on a daily basis. Automatic computerized devices that measure pH and EC of both solutions can be used to automatically correct the next irrigation solution according to optimal values entered beforehand.

Electric Conductivity: A higher value of EC in the leached solution than in the applied solution indicates that the plant absorbs more nutrients than water, therefore we must apply greater amount of water to the plant. If the difference between the EC of the leached solution and the fertigation solution is more than 0.4-0.5 dS/m, we must apply a leaching irrigation in order to wash the excess salts (4).

Chlorides: An impaired management of the irrigation regime may lead to an unwanted accumulation of Cl ions in the irrigation water. If the Cl concentration in the leachate is higher than the Cl concentration in the incoming solution >50mg/L, it

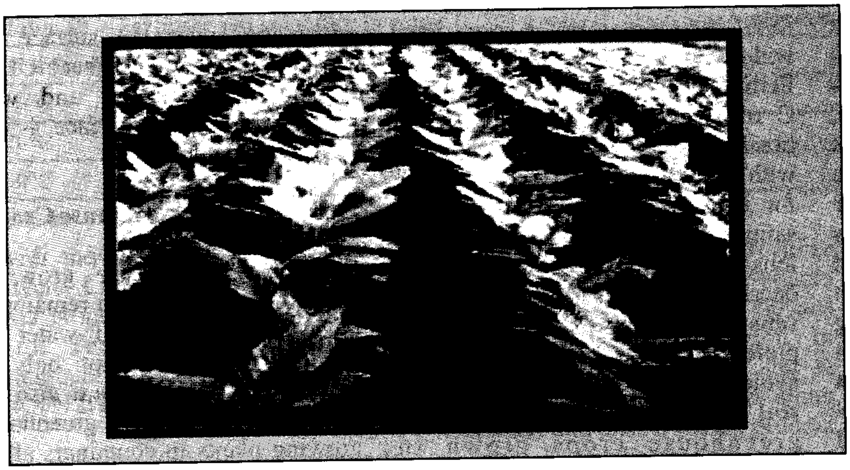

Figure 3 - Cost reduction in drip lay out with micro tubes in the turmeric crop

indicates a chloride accumulation in the root zone. It requires applying irrigation without fertilisers to leach the chlorides below root zone.

pH: The optimum pH of the irrigation solution must be around 6 and the pH of the leaching solution should not exceed 8.5. An alkaline pH of the leaching water indicates that pH in the root zone reached a value that would cause P precipitation and decrease micronutrient availability. When pH of the leachate water is higher than 8.5, it is essential to adjust the NH_4/NO_3 ratio of the fertigation solution by increasing slightly the proportion of NH_4 over NO_3.

Methods of Fertigation

Four methods of fertigation used are:

1. Continuous application: Fertiliser is applied at a constant rate from start to the end of the irrigation cycle. The total amount of fertilisers is injected regardless of water discharge rate.

2. Three-stage application: Irrigation starts without fertilisers. Injection begins when the ground is wet. Injection is stopped before the irrigation cycle is completed. Remainder of the irrigation cycle allows the fertiliser to be flushed out of the system for the system cleansing.

3. Proportional application: The injection rate is proportional to the water discharge rate, e.g. one liter of fertiliser solution is mixed into 1000 litres of irrigation water. This method has the advantage of being extremely simple and allows for increased fertigation during the periods of high water demand and when most amounts of nutrients are required.

4. Quantitative application: Nutrient solution is applied in a calculated amount to each irrigation block, e.g. 20 litre to block A, 40 litres to block B. This method is suited to automation and allows the placement of the nutrients by controlling precisely.

Constraints and their Solution for Successful Adoption of Fertigation

The high cost of establishing fertigation systems : Has confined this irrigation method to locations where labour is expensive, water is scarce, and the crops grown have a rich market that can cover high investment. This has prevented a large scale adoption of this technology in countries like India where majority of farmers are resource poor.

The high cost of fertigation through drip system can be brought down by adopting the cost reduction measures like use of micro tubes **(Figure 3)** and adoption of paired row system and through other innovative approaches. Under paired row system one drip line is laid out in between two rows of the crop. Besides, the government might enhance the amount of subsidy given particularly to small and marginal farmers.

Clogging of lines: Precipitation of insoluble di-calcium phosphate, di-magnesium phosphate and calcium carbonate, could develop when high pH water is used. Iron phosphate, originating from wells containing divalent iron, might precipitate in drip lines even at low water pH. Water containing high concentration of Mg ions might cause ammonium magnesium phosphate precipitation in the fertiliser tank. Fertigation increases the quantity of nutrients present in an irrigation system and this can lead to increased bacteria, algae and slime in the system which can cause clogging of the system.

In the case of clogging of the drip system by bicarbonate precipitation, the use of fertilisers with acid reaction partially corrects this problem. However, acid fertilisers cause corrosion of the metallic components of the irrigation system and damage the cement and asbestos pipes. Therefore, a periodic injection of acid in the fertigation system is recommended to dissolve the precipitated material and unclog the drippers. The acids like phosphoric, nitric, sulphuric and chlorhydric acid can be used for this purpose. However, HCl is preferred due to its low cost. Acid injection through the system will also remove bacteria, algae and slime. The irrigation and injection system should be carefully washed after the injection of the acid.

Bacteria, algae and slime in the system can be removed at regular intervals by injection of chlorine or acid through the system. Chlorine injection should not be used while fertiliser is being injected into the system as the chlorine may tie up these nutrients making them unavailable to the plant. Systems should always be flushed of nutrients before completion of irrigation. Before commencing a fertigation programme, fertiliser compatibilities and solubility should be checked.

Salt injury: The salts accumulated at the wet zone periphery can reach very high levels and a single flush of rain could wash this salt into the root zone and cause considerable damage to plants. In an arid climate zone, where the evaporation rate is high, mobile nutrient anions (NO_3^- and Cl^-) together with the cations Na^+ and Ca^{2+} may accumulate around the wet zone periphery on the soil surface. This zone of highly concentrated soluble salts is detrimental to young seedlings because their restricted root system might be exposed to high salt concentrations, even with good quality water.

A correct irrigation management under saline conditions includes water application over the evaporation needs of the crop so that there is excess water to pass through beyond the root zone and carrying away the salts with it. This leaching prevents excessive salt accumulation in the root zone and is referred as leaching requirement (75). Further, there is a competitive antagonistic effect between NO_3^- and Cl^- anions; the presence of Cl^- ion reduces the absorption of NO_3^- and vice versa (76). Therefore, under saline conditions, the damage by salinity can be reduced by fertilizing with NO_3^-. The NO_3^- ions will be preferably absorbed over the Cl^- ions.

Nutrient deficiency: On heavy clay soils, a zone of water ponding might develop under the trickler outlets. In this wet soil volume, at high soil temperature, local anaerobic conditions might cause severe nitrate-N loss by denitrification (77). Under such conditions, plants might suffer from N deficiency even if they receive regular N supply through fertigation. In such cases, low concentration of N in the form of urea or ammonium sources in the irrigation solution might prevent N loss by denitrification and the resulting N deficiency. The rate of water discharge from a dripper should not exceed the rate of water entry into the soil from a point source. The hydrolysis of applied urea can result in ammonia toxicity and loss of N as NH_3 volatilization but acidification of the irrigation water prevents loss of N from urea by ammonia volatilization.

Oxygen deficiency: Maintenance of the water potential by frequent irrigation at continuous low water tension, especially in clay soils might lead to a sub-optimal supply of oxygen in the root zone (78). Roots respond within minutes to a reduction in oxygen supply by cessation of root extension, and the elongation zone of a cotton root, for example, dies after only 30 minutes without oxygen (79). Under drip irrigation, oxygen might be excluded from the saturation zone when there is a continuous supply of water at higher regime in the wet soil volume. Therefore, to safeguard the plants against sub-optimal O_2 supply, the delivery of optimum amount of H_2O through drip system is essential.

FUTURE NEEDS

There is need to develop recommendations for the most suitable fertiliser formulations including the basic nutrients (NPK) and microelements according to the local soil type, climate, crops and their physiological stages, and other factors like nutrient mobility in the soil and salinity. Further, there is need to work on reducing the initial cost of establishment through continuous research and development in technology which suits best to Indian conditions.

CONCLUSIONS

Fertigation provides a variety of benefits to the users like high crop productivity and quality, resource use efficiency, environmental safety, flexibility in field operations, effective weed management, and successful crop cultivation on fields with undulating topography. Fertigation is considered eco-friendly as it avoids the leaching of nutrients especially N-NO_3 (80). Fertigation has been found as one of most successful way of water and nutrient particularly N, K and micronutrient application through drip system. Yield advantages have been reported across the wide range of crops under diverse agro-climatic situations. Vegetables have been found particularly responsive to fertigation due to their wide spacing nature, continuous need of water and nutrients at optimal rate to give high yield with good quality, high capital turn over to investments and may be their cultivation by more skilled farmers. Eventhough the initial cost of establishing the fertigation system is higher but in long term basis it is economical compared to conventional methods of fertilisation as it brings down the cost of cultivation. However, to get the desired results it requires higher management skills at operator level like selection of fertilisers, timing and rate of fertiliser injection, watering schedule, as well as the maintenance of the system. Users may face some practical problems in the field like clogging of emitters, salt injury to the plants, and wilting of individual plants due to nutrient deficiency and restricted root respiration because of water logging particularly in heavy clay soils. But such problems can be overcome through effective management skills of the users which build up over the time with the use of the system. Therefore, to make the agriculture sustainable and economically viable and to ensure food and nutritional security of the burgeoning population there is need to promote the fertigation at large scale by the concerned stakeholders.

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