Global Aspects of Fertigation Usage

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Abstract

Shortage of water for desert agriculture was the first stimulus for the development of drip irrigation in Israel in 1960. Incorporation of fertilizers and clogging problem led to the development of the second generation of drippers, which featured turbulent flow. Within 40 years the principle of delivering water and nutrients to a specific zone near the plant roots has spread all over the world, and is now applied to greenhouses, row crops, vegetables and plantations. Computer-controlled irrigation and fertilization led to savings in labor costs and to accurate timing of irrigation. The flexibility of the fertigation system, at all scales from the individual small farmer using gravity driven irrigation to huge plantations and field areas, is one aspect that has quickly led to world-wide acceptance. The shortage of irrigation water worldwide is another factor that drives the expansion of fertigation, as well as the ability to safely use recycled sewage water for agriculture.

Keywords: crops, development steps, global expansion, nutrients supply rate, N form, subsurface drip irrigation.

Introduction

An old proverb says: “Necessity is the mother of all inventions”.

Subsurface trickle irrigation using a system of canvas tubes was tried by Robey (1934). In Israel, where water scarcity was the main stimulus, adoption of drip irrigation started from zero in 1960 and reached 6,000 ha by 1974; practical acceptance proceeded faster than research (Ravitz and Hillel, 1974). Flood and canal irrigation methods date back thousands of years in Egypt, Mesopotamia, India and China, and are still in use. Irrigation of small plots with water carried by hand in buckets is still practiced in many countries.

The worldwide irrigated areas are presented as percentages of the total land area in a map produced by the FAO (Siebert *et al.*, 2005). The most heavily irrigated areas are in China and India, the world's most populated countries. Drip irrigation of closely spaced row-planted crops such as wheat and rice is not economic, therefore, the sprinkler or flood systems are common. Today, leisure industries and facilities such as football pitches, golf courses and tennis courts have adopted subsurface trickle irrigation systems to extend their availability, albeit at high costs.

"Fertigation" – "fertilization" plus "irrigation" – was applied to tomatoes grown on sand dunes in a field experiment performed in 1969 (Sagiv *and Kafkafi*., 1974), and Goldberg *et al.* (1971) reported the distribution of minerals and nutrients from a point source of irrigation to roots. Fertigation has now spread all over the world.

Benefits of drip irrigation and fertigation

Technological turning points in drip irrigation development in Israel

1960 Use of a perforated rubber tube for subsurface irrigation (Blass, 1964).

1965 First plastic linear-flow dripper produced by Netafim was used in the field in the southern Negev. Precipitated chemicals blocked the flow, which resulted in the development of the turbulent flow dripper (1970).

1976 Pressure-regulated dripper is developed, allowing constant flow in spite of pressure fluctuations of 3.5 atmospheres. It provides regulated flow and self cleaning.

1980 First use of drip irrigation in large areas of corn and cotton fields. Increases yields by ~25-35%.

1983 Enclosure of the dripper within a smooth tube is developed, to enable mechanical rolling and spreading (multi-season pressure regulation).

1990 Special stick-in drippers developed for greenhouse use.

2000 New family of integral drippers, especially suited for subsurface drip irrigation.

Expected benefits from fertigation

1. Improved nutrient availability.
2. Enhanced plant nutrient uptake.
3. Reduced fertilizer application rates and water requirements.
4. Minimized nutrients losses through leaching.

5. Prevents salt injuries to roots and foliage.
6. Reduced soil compaction, because of reduced surface traffic.
7. Decreased weed infestation.

Under-plastic-cover fertigation

1. Saves water by reducing direct evaporation from soil surface.
2. Prevents salinity buildup on soil surface.
3. Prevents weed infestation.
4. Reduces herbicide use.
5. Increases soil temperature if a clear plastic cover is used.
6. Reduces soil temperature if a reflecting cover is used.

Subsurface drip irrigation (SDI)

1. Increases water use efficiency by elimination of evaporative water losses.
2. Enables the use of recycled sewage water, by preventing plants exposure to pathogens.
3. Enables plants to escape morning frost damage.
4. Reduces fruit diseases by keeping the soil beneath the growing fruit dry.

Efficient use of water

The ultimate efficiency of water and fertilizer use can be achieved by matching the daily supplies of water and nutrients to demand, according to the plant development stage, with zero evaporation. André *et al*. (1978a, b) monitored daily demands for water and nutrients throughout the corn development cycle. When drip irrigation was applied in the field it was shown that plants took up all the daily supply and left nothing to neighboring plants (Abura and Kafkafi, 2002), which was evident from the sharp boundaries between treatments.

Fertigation, in any trickle irrigation technology, involves the injection of soluble fertilizer solutions into the irrigation systems via any dosing apparatus: dilution tanks, Venturi-type suction or by calibrated injection pumps. Commercial firms all over the world supply such equipment in all forms and sizes. The corrosive nature of fertilizers prevented the use of fertigation when aluminum or zinc-plated metal pipes were used for irrigation, but the introduction of plastics for containers, drip lines, pumps and connections enabled accurate fertilizer application through the irrigation lines. The fertilizer industry has adapted itself to field demands by introducing clean and soluble – albeit more expensive – fertilizers: soluble, acidic phosphate and potassium fertilizers with wide ranges of NPK ratios (IFA, 2005). The time pressure and the work load on the farmer arising from the need to prepare fertilizer solutions led to the development of services supplying liquid fertilizer blends according to specific recipes, as ordered by growers to meet specific plant demands, matched to particular growing stages and climatic conditions (Prenger *et al.*, 2001). In the highly sophisticated industry of greenhouse cultivation, clean acid and bases are stored, and the instantaneous supply of nutrients to the irrigation line is controlled continuously, on site, by computer.

The conventional method of fertilizer application before planting becomes ineffective with drip irrigation systems. Growing tomatoes on sand dunes without a daily supply of P in the trickle line resulted in a complete exhaustion of P within a radius of 10 cm around the plants by the time it was needed for the developing fruits, but injection of a complete NPK fertilizer into the trickle line increased the yield by 30% (Ben Asher *et al.*, 1974). An adequate supply of nutrients and water to satisfy plant demands from a limited soil root volume can be achieved only by matching the supplies of water and nutrients to plant needs during the various growth stages. Fertigation enables accurate supply of water and nutrients to the individual plant, whether it is a corn or a cotton plant in the field, or a single tree within an orchard. The daily application rate of fertigation changes during the growing season and is planned to follow plant daily demand according to its nutrients uptake strategy. Therefore, the units used in calibrating fertigation are milligrams of nutrient supplied per day per plant rather than kg/ha. Likewise, the unit for water supply is changing from the regular millimeters to liters per day per plant. Scaife and Bar-Yosef (1995) reported the daily consumption of water and nutrients by crops.

The fertigation technique has rapidly spread all over the world in the last 40 years, and irrigation controllers are available commercially that compensate for humidity, temperature and wind effects. In dealing with factors that modify temperature and humidity, a solar integrator can automatically increase the frequency of irrigations in sunny, hot dry weather and reduce it in dull, cool, damp weather. A rain override could also be used for outdoor crops: such a controller may initiate a single irrigation station as a trigger and then sequentially activate many other stations. All these instruments are based on physical measurements, but no easy-to-use, reliable, chemically activated automatic controllers are yet available for open-field crops or orchards. The quick development of trickle irrigation and fertigation systems in many parts of the world followed the demands to minimize water use in agriculture, which arose from the shortage of water caused by increasing urban demands. Development was also driven by increasing labor costs, demands to prevent pollution and to minimize soil erosion, increasing reliance on saline water sources, and unfavorable soil quality and wind conditions.

Fertigation reduces the amount of heavy work and minimizes the number of man hours involved in traditional methods of irrigation, such as furrow irrigation or flood irrigation. The ability to deliver an exact amount of nutrients and water to a specific plant in the field, at an exactly specified time under the remote control of a computer offers many advantages. It saves labor, avoids traffic movements on wet soils, thereby preventing compaction, saves water by avoiding delivery of water to unplanted areas such as traffic lanes and wide spaces between rows, minimizes evaporative water loss from bare soil by applying fertigation beneath plastic mulch. These advantages have made this system acceptable at all scales of agriculture production systems, from small-holdings to huge plantations. The ability to irrigate undulating soil surfaces enabled vineyards and tree plantations to be established in areas that were not accessible to agriculture before. However, the high costs of trickle systems have confined this irrigation method to locations where labor prices are high, water is scarce, and quality crops have a rich market that can cover the high investment costs.

The use of recycled sewage water

A particular development of surface and subsurface trickle irrigation is related to the increasing use of recycled sewage water for agriculture. Two main factors drive this development: 1) water shortage – sewage treatment systems and collecting dams for irrigation are already in use; and 2) because of environmental considerations, industrial effluents are reused and currently form about 70% of the water used in Israel's agriculture (Arlozoroff, 1996). Agricultural water use and comparisons with water resources worldwide were reported by the FAO (2005): the various regions differ markedly in their percentages of renewable water resources, in the decending order: Near East and North Africa – 51%, South Asia – 36%, East Asia – 8%, 90 developing countries – 8%, sub-Saharan Africa – 3%, and Latin America – 1%. Withdrawal of water for irrigation was estimated to account for only 8% per cent of the total renewable water resources of the 90 developing countries. However, there are wide variations between regions in the percentages of water used for irrigation: the Near East and North Africa use 53% of their water resources for irrigation, whereas Latin America uses barely 1%. The variations between individual countries are even wider: in 2000, ten countries used more than 40% of their water resources for irrigation, a situation which can be considered critical. An additional nine countries used more than 20% of their water resources for that purpose, a situation that may indicate that they are on the threshold of impending water scarcity. For several countries, relatively low national figures may give an overly optimistic impression of the level of water stress: China, for instance, is facing severe water shortage in the north, whereas the south still has abundant water resources. Already by 2000, two countries, Libya and Saudi Arabia, used volumes of water for irrigation which were several times larger than their annual water resources. Local groundwater mining also occurs in several other countries of the Near East, South and East Asia, Central America and the Caribbean, even if at the national level the water balance may still be positive.

Advantages of fertigation over fertilization

Fertigation has specific advantages over band placement or broadcast fertilization.

- Frequent supply of nutrients reduces fluctuations of nutrient concentration in the soil solution.
- Efficient and precise application of nutrients that matches changing plant physiological demands.
- Fertilizers are supplied only to the irrigated soil volume.
- Nutrients can be applied to the soil to compensate for nitrogen (N) leaching caused by excessive rains, when soil or crop conditions would prohibit entry into the field with conventional equipment.

Drip fertigation has further advantages (Haynes, 1985) over other methods of fertigation such as sprinkle irrigation.

- Increased fertilizer use efficiency, because nutrients are applied only to the active root zone, which reduces losses of nutrients through leaching or soil fixation.
- The crop foliage remains dry, thus reducing incidence of pests or diseases, and avoiding foliage burn.
- Fertigation can be applied under all weather conditions; it is unaffected by wind, and is free of the runoff associated with sprinkler irrigation.
- It is the most suitable method for protected and plastic-covered crops.

Drip fertigation systems

Each drip fertigation systems is designed for a specific combination of crop, climate and soil, and comprises the following components in conjunction with a drip irrigation system.

Fertilizer delivery

There are two main methods. 1 – Fertilizer dilution tanks, which are usually used in small plots, are connected to the head of the irrigation line, and deliver predetermined quantities of fertilizer during the irrigation cycle. 2 – External pumps, which are used to cover large areas, inject the fertilizer solution under positive pressure (usually that of the water supply) directly into the irrigation line. The latter method is supposed to deliver a constant concentration of fertilizer during the irrigation cycle.

Filtration

Filtration is a prerequisite in drip irrigation, to avoid clogging of drip lines and emitters, and to maintain the uniformity of water and fertilizer application. The type of filtration system depends on the quality and source of the water supply, and the water quality and composition must be taken into consideration at the planning stage of the fertigation systems, especially when a subsurface installation is considered. In the case of deep well water sources the system should remove gravel, sand or suspended materials. Open surface waters (ponds, rivers or lakes) may contain organic matter and algae that must be removed before entry to the lines. In fertigation systems a second filtration step after the fertilizer container is necessary, to remove any particulate matter or precipitates from the fertilizer mixtures. Deep well water sources may contain soluble divalent iron, which, on contact with phosphate, may produce a gel-like precipitate that can block the tricklers and filters.

Distribution of water and nutrients in soil

Water flow

Two main forces – gravity and capillarity – govern the movement of water in the soil.

In drip irrigation, water spreads from a dripper in three dimensions and creates a wetted front of various shapes (Bressler, 1977), depending on the soil type and the water discharge rate. When the trickle discharge rate is higher than the soil infiltration rate, lateral water movement dominates and shallower penetration is to be expected albeit with larger wetted soil surface area with a given amount of water.

Nutrient movement

Strongly sorbed ions, such as phosphate, are less mobile in soils than non-sorbed ions, such as nitrate or chloride (Kafkafi and Bar Yosef, 1980). During repeated fertigation cycles there is a balance between the lateral spread of water and evaporation, as a result of which soluble salts might accumulate at the border between the dry and the wet zones, especially in hot dry areas with no dry-season rainfall (Kafkafi and Bar Yosef, 1980). The salt 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.

Plastic covers

To avoid soluble salt accumulation on the soil surface because of evaporation, irrigation under a plastic cover is used, especially when saline water is the only source for irrigation. In an arid climate zone, where the evaporation rate is high, mobile nutrient anions (NO_3^-, 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.

Selection of fertilizers

Most water-soluble and liquid fertilizers are suitable for fertigation. In selecting a fertilizer four main factors should be taken into consideration.

1. Plant type and stage of growth.
2. Soil conditions.
3. Water quality.
4. Fertilizer composition and price.

Type of plant

Plant sensitivity to the form of N increases during the fruiting stages (Xu *et al.*, 2001). Some plants, such as tomato, are very sensitive to high ammonium concentration near the roots, therefore, nitrate-rich nutrient solutions should be selected (Kafkafi *et al.*, 1971).

Soil and water conditions

At elevated root-zone temperatures ammonium might damage the roots by competing with the sugar needed to root respiration. Local high ammonium concentration can result in ammonia toxicity to root cells. In cold root zones ammonium is a safe N source, since less sugar is consumed for respiration by root cells (Ganmore-Newmann and Kafkafi, 1983).

On heavy clay soils, a zone of water ponding might develop under the trickler outlets. In this wet soil volume, at high soil temperatures, local anaerobic conditions might cause severe nitrate-N losses to the atmosphere, as N_2 or N_2O. Under such conditions the plants might suffer from N deficiency in spite of receiving a nitrate supply through the irrigation line. In such cases, low concentrations of N in the form of urea or ammonium sources in the irrigation solution might prevent the N losses and deficiency caused by denitrification. In heavy clay soils, the ammonium concentration in the soil solution will always be below the root-damaging level, because of preferential sorption to soil surfaces. It may be necessary to lower the pH of the irrigation water to about 5.5, in order to keep the phosphorus (P) in the solution during the fertilizer injection, and to prevent blockage of the tricklers. Phosphorus application as phosphoric acid is preferable during cold seasons; it serves to remove precipitates and to supply P to the slow-growing roots. If micro-nutrients are needed, their soluble chelated forms are less subject to precipitation in the irrigation lines, and they move in the soil with the water towards the roots.

Fertilizer characteristics

Solid fertilizers vary in their dissolution rates and in the amount that can be dissolved in a given volume of water at a specific temperature. The solubility generally decreases when two or more fertilizers are mixed together. This characteristic is crucial to the fertilizer choice. Solubility generally increases with temperature, but because of their endothermic reaction, nitrate salts lower the solution temperature. When the fertilizer tank is placed in an open field low ambient temperatures could cause solid precipitation in the tank and could block the drippers. The diverse solubility characteristics of the various fertilizers, and the problems they cause in field operations stimulated the establishment of "fertilizer dilution services", which provide a nutrient cocktail according to the farmer’s order, to meet the specific crop needs at the appropriate times throughout the growing season.

Another approach to solving the solubility problem was adopted in the advanced greenhouse industry, where separate tanks of nutrient sources, acids and bases are used. With the help of a computer it is possible to calibrate the appropriate dose of each nutrient element to be pumped into the irrigation line, so that the concentration of the mixture remains low and precipitation is prevented. This technology is too expensive to operate in large open fields and plantations, where Venturi-type or proportional pumps are used to inject the dose of fertilizer solution from a storage tank into the irrigation line.

Urea, ammonium nitrate, calcium nitrate, potassium nitrate and ammonium phosphate, are soluble in water and are used extensively to prepare single- or multi-nutrient fertilizer solutions. Mono-ammonium phosphate, phosphoric acid and urea phosphate are also water soluble, but they may precipitate when injected at high rates into “hard” water, i.e., containing high concentrations of calcium and magnesium carbonates. All potassium fertilizers are water-soluble but vary in their rates of dissolution and their sensitivity to temperature; KCl is the most widely used potassium fertilizer for field crops.

Compatibility of fertilizers

Mixing two fertilizers can sometimes result in precipitation. For example, injection of a calcium salt with phosphate or sulfate may increase the likelihood of calcium phosphate or calcium sulfate precipitation, even at low pH. The pH of the irrigation solution should be within the range 5.5 to7.0. Too high a pH will reduce the availability of P, Zn and Fe, and may result in precipitation of Ca and Mg phosphates or carbonates in the irrigation lines. Too low a pH is detrimental to roots and may increase Al and Mn concentrations in the soil solution. Nitric (HNO_3) or phosphoric (H_3PO_4) acids are used to lower the pH level in fertigation. Their advantage, besides dissolution of basic precipitates in the line, is that they also supply the plants with the essential nutrients, and thereby replace N and P fertilizers. In saline waters and calcareous clay soils nitric acid increases Ca dissolution and thereby minimizes salinity injury, because of Ca/Na competition, and reduces the chloride salinity in the root zone, because the nitrate counterbalances excess chloride (Xu *et al.*, 2000).

Precipitation in the irrigation 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 pH water. Water containing high concentrations of Mg ions might cause ammonium magnesium phosphate precipitation in the fertilizer tank. Avoiding the use of ammonium fertilizer in such conditions can avoid the risk of blocking the emitters. Using K_2SO_4 or $(NH_4)_2SO_4$ with water containing high concentrations of calcium might result in $CaSO_4$ (gypsum) precipitates that could clog the drip lines.

Scheduling fertigation

Nutrient elements are taken up according to plant demands at a specific development stages (André *et al.*, 1978 a, b). Fertigation, i.e., injecting fertilizer into a drip irrigation system, offers the benefits of supplying the correct amounts of nutrients to the crop at the times when they are most needed by the plants, directly into the root zone. Fertigation scheduling depends upon climatic factors, soil type and the fertilizer requirements of the growing plants. The uptake rates of nutrients (N, P and K) during growth of field and vegetable crops were summarized by Bar Yosef (1999). Climatic conditions, soil type, system design, and length of the growing season and other plant characteristics determine the frequency of fertilizer application. In plants grown on sand dunes, several irrigations per week might be needed, whereas on clay soils one or two irrigations per week might be sufficient. The smaller the root volume, the higher the necessary frequency of fertigation.

Nutrients behavior in soil

Soil chemical properties are an important factor in planning fertigation. The pH strongly influences the availability of residual nutrients in the soil and also of those added via fertigation. The balance between the uptake of cations and of anions by the plant affects the pH in the rhizosphere (Marschner, 1995). Nitrate and ammonium are the main forms of N available for plant uptake. When a plant takes up more nutrient cations than anions, as occurs when NH_4^+ is the main N source, protons are exuded by the roots and acidify the rhizosphere. If the anion uptake is predominant, as when NO_3^- is the main source of N, the roots exude OH^- or HCO_3^-, which results in a pH rise in the rhizosphere. The rhizosphere pH varies with the form and concentration of the N fertilizer, but the extent of the pH change in the zone around the root depends on the buffer capacity of the soil.

The cation exchange capacity of the soil is an important consideration in determining the amount of cations to be added during fertigation, and the frequency of addition. In most agricultural soils and irrigation waters, calcium and magnesium are present in larger quantities than needed by any crop, and their supply to the plants is usually satisfied by water mass flow (Barber, 1962). Potassium is the main cation that must be supplied with the irrigation water, and in order to ensure the maintenance of an acceptable concentration of potassium in the soil solution, a soil with a low cation exchange capacity (CEC) must receive fresh supply of potassium more frequently than one with a high CEC, that can hold higher quantities of potassium. Fertigation is most practicable in sandy soils and those in dry and arid regions that have low CEC, since these soils need frequent irrigation and quick replenishment of nutrients. Old farming practices regarded sand dunes as non-agricultural soils, but the introduction of fertigation turned desert sand dunes into productive agricultural soils (Kafkafi, 1994). The most important aspect of fertigation, globally, is that it offers the possibility to expand human activities into areas never before used for irrigation. The need to saving water in the traditional areas of irrigation, and the loss of existing productive fields in the face of urban growth could provide the stimulus to move water and agricultural production to desert areas.

Nitrate (NO_3^--N) is highly mobile and is more likely to be lost through surface runoff, denitrification during flood irrigation, and leaching. In trickle irrigation, ponding under the tricklers, especially in clay soils, creates an oxygen-deprived space in which denitrification is observed during the irrigation cycle (Bar Yosef, 1999). The rate of water discharge from a dripper should not exceed the rate of water entry into the soil from a point source. Hydrolysis of applied urea can result in ammonia toxicity and losses in the form of gaseous NH_3, but acidification of the irrigation water prevents such direct losses of ammonia from urea fertilizers.

Added phosphate is adsorbed or precipitated in the soil, leading to a rapid decline in the water-soluble phosphate concentration in the soil solution. Movement of phosphate is impeded because of retention by soil oxides, carbonates and clay minerals. Application of P via drip irrigation is more efficient than via sprinkler irrigation or broadcasting, because fertigation supplies P directly into the active roots zone, which enables its immediate uptake, before it undergoes drying and irreversible fixation in the soil.

Root growth

To achieve optimum plant growth, the root zone must be well supplied with water, nutrients and oxygen, and must suffer minimal soil compaction. 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 (Silberbush *et al.*, 1979). 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 min without oxygen (Klepper, 1981). Under drip irrigation, oxygen might be excluded from the saturation zone when there is a continuous supply of water at high rates, but a slow flow rate may maintain optimal moisture and oxygen regimes in the wet soil volume.

The nitrate-to-ammonium ratio affects the development of the root system: high concentrations of ammonium are deleterious to root growth, especially when soil temperatures are high, i.e., under plastic or in growth containers. At high root temperature sugar in the root cells is required for respiration and for ammonium metabolism. If the supply of sugar from the leaves, lags behind it's consumption in root cells, the resulting temporary excess of free ammonia kills the root cell (Ganmore-Newmann and Kafkafi, 1983). At high temperatures around the roots, especially under soilless cultivation conditions, nitrate-N is a safer N form during fertigation. At low root temperature NO_3^- accumulates in the roots, resulting in N deficiency (Ali *et al.*, 1994). Thus, the concentration and form of N applied in fertigation should be adapted to the differing conditions of the winter and summer seasons, and according to specific crops demand and sensitivity. In general, monocotyledon roots are less sensitive to ammonium in solution than dicotyledon ones (Moritsugo *et al*., 1983).

Subsurface drip irrigation and fertigation (SDI)

Seasonal installation and removal of drip lines increase production costs in wide-row field crops. Subsurface drip irrigation became a common practice in the USA following its introduction about 1960, but interest in the technology has greatly expanded since the early 1980s. Yield responses for over 30 crops indicated that crop yield for subsurface drip was greater than or equal to that obtained with other irrigation methods, including surface drip, and required less water in most cases. Laterals are installed at depths ranging from 0.02 to 0.70 m, and lateral spacings range from 0.25 to 5.0 m. Injection of nutrients, pesticides, and other chemicals to modify water and soil conditions is an important aspect of subsurface drip irrigation. Irrigation water use for corn can be reduced by 35-55% by using SDI, compared with traditional forms of irrigation (Camp, 1998). The deep position of the tricklers significantly increased the P and K contents at the center of the root zone. The enhanced concentration apparently stimulated plant rooting which, together with the higher nutrient activity in the soil solution, increased P and K uptake rates, which, in turn, facilitated greater dry matter production and commercial yield than were obtained with surface trickler placement (Hernandez *et al.*, 1991). Slow-release chemicals embedded in filters prevent root entry and clogging of the drippers. In addition to cost effectiveness and energy saving, subsurface drip fertigation has added agronomic advantages over surface drip fertigation: 1) placement of nutrients in the region where root activity is maximal and the daily and seasonal temperature fluctuations are low; and 2) the top 4-5 cm soil layer remains dry, thereby reducing the evaporation losses and inhibiting weed germination.

References

Abura, L., and U. Kafkafi. 2003. Global food security and the role of sustainable fertilization, 26-28 March 2003, IFA/FAO, Rome. http://www.fao.org/ag/agl/aglw/aquastat/water_use/index5.stm.

Ali, I., U. Kafkafi, Y. Sugimoto, and S. Inanaga. 1994. Response of sand-grown tomato supplied with varying ratios of NO_3/NH_4 at constant and variable root temperatures. Journal of Plant Nutrition 17:2001-2024.

André, M.D., D. Massimino, and A. Daguenet. 1978a. Daily patterns under the life cycle of a maize crop. I. Photosynthesis, transpiration, respiration. Physiologia Plantarum 43:397-403.

André, M.D., D. Massimino, and A. Daguenet. 1978b. Daily patterns under the life cycle of a maize crop. II. Mineral nutrition, root respiration, and root excretion. Physiologia Plantarum 44:197-204.

Arlozoroff, S. 1996. Managing scarce water: “recent Israeli experience". *In:* Between war and peace (dilemmas of Israeli security) E. Karsh (ed.). Frank Cass and Co., London.

Barber, S.A. 1962. A diffusion and mass flow concept of soil nutrient availability. Soil Science 93:39-49.

Bar Yosef, B. 1999. Advances in fertigation. Advances in Agronomy 65:1-77.

Ben Asher, J., B. Bar Yosef, and U. Kafkafi. 1974. Application of an irrigation model and fertilization considerations in growing tomato on a sand dune. *In:* Plant analysis and fertilizer problems. Proc. 7^{th} IPNC, Hanover, Germany. Vol. 1. J. Whermann (ed.). International Plant Nutrition Colloquium.

Blass, S. 1964. Subsurface irrigation. Hassadeh 45:1. (in Hebrew).

Bressler, E. 1977. Trickle-drip irrigation: principles and application to soil-water management. Advances in Agronomy 29:343-393.

Camp, C.R. 1998. Subsurface drip irrigation: A review. Transactions of the ASAE 41:1353-1367.

Ganmore-Newmann, R., and U. Kafkafi. 1983. The effect of root temperature and NO^{3-}/NH^{4+} ratio on strawberry plants. I. Growth, flowering and root development. Agronomy Journal 75:941-947.

Goldberg, D., B. Gornat, and B. Bar Yosef. 1971. The distribution of roots, water and minerals as a result of trickle irrigation. Journal of the American Society for Horticultural Science 96:645-648.

Haynes, R.J. 1985. Principles of fertilizer use for trickle irrigated crops. Fertilizer Research 6:235-255.

Hernandez, J.J.M., B. Bar Yosef, and U. Kafkafi. 1999. Effect of surface and subsurface drip fertigation on sweet corn rooting, uptake, dry-matter-production and yield. Irrigation Science 12:153-159.

IFA. 2005. (http://www.fertilizer.org/ifa/publicat/html/pubman/manual.htm)

Kafkafi, U. 1994. Combined irrigation and fertilization in arid zones and protected agriculture. Israel Journal of Plant Science 42:301-320.
Kafkafi, U., and B. Bar Yosef. 1980. Trickle irrigation and fertilization of tomatoes in high calcareous soils. Agronomy Journal 72:893-897.
Kafkafi, U., I. Walerstein, and S. Feigenbaum. 1971. Effect of potassium nitrate and ammonium nitrate on the growth, cation uptake and water requirement of tomato grown in sand soil culture. Israel Journal of Agricultural Research 21:13-30.
Klepper, B. 1991. Crop root-system response to irrigation. Irrigation Science 12:105-108.
Marschner, H. 1995. Mineral nutrition of higher plants. 2nd ed. Academic Press, London.
Moritsugo, M., T. Suzuki, and T. Kawasaki. 1983. Effect of nitrogen source on growth and mineral uptake under constant pH and conventional culture conditions. Berichte des Ohara Institute fur landwirtschftliche Biologie, Okayama University 18:(3,S)125-144.
Prenger, J.J., R.C. Hansen, C. Glynn, and D.A. Herms. 2001. Computer-controlled delivery of five levels of nutrients to container-grown willow. Paper 018013, ASAE Annual Meeting.
Ravitz, E., and D. Hillel. 1974. The progress and problems of drip irrigation in Israel. *In:* Proceedings of the 2nd International Drip Irrigation Congress 74. San Diego CA USA.Library of congress catalog card Number 74-15261.
Robey, O.E. 1934. Porous hose irrigation. Michigan State College Extension Bulletin 133. 22 pp.
Sagiv, B., and U. Kafkafi. 1976. Fertilization and manuring of pepper plants in sandy soils. Hassadeh, 56(10):1726-1730 (in Hebrew).
Scaife, A., and B. Bar Yosef. 1995. Fertilizing for high yield and quality vegetables. IPI Bulletin 13, Basel, Switzerland.
Siebert, S., P. Doell, S. Feick, and J. Hoogeveen. 2005. Global map of irrigated areas version 3.0. Johann Wolfgang Goethe University, Frankfurt am Main, Germany / FAO, Rome, Italy.
Silberbush, M., M. Gornat, and D. Goldberg. 1979. Effect of irrigation from a point source (trickling) on oxygen flux and on root extension in the soil. Plant and Soil 52:507-514.
Xu, G.H., H. Magen, J. Tarchitzky, and U. Kafkafi. 2000. Advances in chloride nutrition of plants. Advances in Agronomy 68:97-150.
Xu, G.H., S. Wolf, and U. Kafkafi. 2001. Effect of varying nitrogen form and concentration during growing season on sweet pepper flowering and fruit yield. Journal of Plant Nutrition 24:1099-1116.