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# FERTIGATION-CHEMIGATION IN PROTECTED AGRICULTURE

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**Abstract:** Fertigation-chemigation are regular and widely accepted practices for fertilization and plant protection under protected agriculture. With fertigation, the nutrients in the form of soluble fertiliser's anticipated to most crops needs according to their stage of development, are applied with the irrigation water. The application of plant protectants through irrigation system such as herbicides, fungicides, insecticides, nematicides, growth regulators and biocontrol agents has been also expanded rapidly during the last few decades. However, the application of any chemical to soil and crops may have environmental implications. In this work critical technical aspects, the current knowledge and future prospects of fertigation-chemigation for crops yield and improve quality on a degradation-free and sustainable basis, are presented.

## INTRODUCTION

The application of chemicals through the irrigation system became a common practice in modern irrigated agriculture (Bresler, 1977; Elfving, 1982, Harstone et al., 1981; Phene and Beale 1976; Phene and Sanders, Papadopoulos, 1985; 1986a; 1986b; 1987a; 1988a).

Application of chemicals, especially fertilizers, through irrigation systems is a practice of relatively long standing. However, fertigation-chemigation research and practical applications coupled with advances in irrigation and chemigation during the last few decades. Fertilizers were probably the first chemicals to be injected into modern irrigation systems. (Goldberg and Shmueli, 1969; 1970). Since these initial applications many types of chemicals have been injected into irrigation systems, including herbicides (Lange et al., 1974; Phene et al.; 1979), fungicides and insecticides (Phene et al., 1979; Zentmeyer et al., 1974; Potter, 1981, Young, 1980), nematicides (Chesness et al., 1976; Overman, 1975; 1978; Jonson, 1978) growth regulators (Btyan and Duggins, 1978), fumigants (Goldberg and Uzrad, 1976; Overman, 1976), and chlorine, acids and other chemicals to control clogging (Bucks et al., 1979; Ford, 1976; Ford and Tucker, 1975, Nakayama et al., 1977). This expansion of the use of chemigation to include the application of a board range of chemicals generated new terms as herbigation, fungigation, insectigation, nemagation to describe various types of chemigation.

Trickle (drip) irrigation system, which is highly efficient for water application, is also ideally-suited for fertigation and is practical to chemigating applied chemicals (Goldberg et al., 1976; Papadopoulos, 1985; Bresler, 1987). In this way, water soluble fertilizers at concentrations required are conveyed via the irrigation stream to the wetted volume of soil. Thus the distribution of chemicals in the irrigation water will likely place these chemicals in the desired location, the general root Papadoupouls, 1985; 1986a ; 1986 b ; Goldberg et al., 1979). Furthermore, with drip irrigation, the application of herbicides and pesticides for soil-borne diseases and pests due to the chemicals being more effective at lower concentrations (Gerst et al., 1981). In contrast to drip/trickle irrigation systems, spinkler Irrigation systems are exceptionally well suited to spray chemigation.

Some potential advantages of fertigation are improved efficiency of fertilizer recovery (Miller et al., 1981 ; Phene and Beale, 1976), minimal fertilizer losses due to leaching (Bresler, 1977; Klein et al., 1989; Papadopoulos, 1985; Stark et al., 1983), control of nutrient concentration in soil solution (Bar-Yosef, 1977; Papadopoulos, 1986a; 1986b; 1987b), control of nutrients form and ratio of the various forms particularly for N-fertilizers and flexibility in timing of fertilizer application in relation to crop demand based on development and physiological stage of crops (Snyder and Burt, 1976; Bresler, 1977; Kovach, 1983). Scheduling fertilizer applications on the basis of need potentially are reduced nutrient element losses associated with convention methods that depend on the soil as a reservoir for nutrients. In addition, fertigation reduces fluctuations of soil solution salinity due to fertilizers (Papadopoulos. 1985), thereby improving soil solution conditions particularly for salt sensitive crops (Papadopoulos, 1986b, 1987c), and conserves labour and energy. In general with fertigation, protection of soil and water from fertilizers on a sustainable basis can be achieved.

Possible disadvantages include unequal chemical distribution when irrigation system design or operation is faulty, over-fertilization in case that irrigation is not based on actual water requirements, or leaching if rainfall occurs at the time of fertilizer application, and chemical reactions in the irrigation system leading to corrosion, precipitation of chemical materials, and/or clogging of outlets.

The development, therefore, of balanced nutrient solutions to satisfy plant requirements for nutrients for high yield and quality without unduly raising soil salinity or causing fertilizer losses, is desired. However, to achieve this goal, the actual water requirements of the crops are needed, since two agricultural practices, irrigation and fertigation are becoming one unique agricultural practice called « fertigation ». No sound fertigation could be practiced if not based on sound irrigation.

The aim of this paper is to give a brief insight and review the application of this technique particularly for vegetables grown under cover at the farmers level and to summarize the present knowledge and future prospects in this field for practical application.

## FERTIGATION IN GREENHOUSES

In the greenhouse industry the nutrient status maintained in the root environment is usually higher than in the open field because of the greater, absorption by greenhouse crops. In this respect the amount and combination of the fertilizers is critical for both, yield production and protection of the environment.

### 1. Fertigation in greenhouse

In general, most of the fertilizers which are soluble in water or are already in liquid form can be used, provided they do not precipitate as insoluble salts by reacting with other fertilizers or ions present In the irrigation water. There is usually no solubility problem with nitrogen and some potassium compounds (Miller et al., 1975). Phosphorus may be added as potassium orthophosphate, as ammonium polyphosphate or as organic polyphosphate (Rauschkolb et al., 1976) and as phosphoric acid. The application of fertilizers according to their compatibility is an important parameter in order to avoid precipitant formation which may lead, among others, and to clogging of the irrigation systems. In general phosphate and sulphate based fertilizers should not be mixed with calcium based fertilizers. Magnesium is compatible with phosphates only at low concentrations and low pH (Nigel, 1983; Sonneveld, 1982). The solubility of common commercial fertilizers is given in Table 1.

**Table 1 : Solubility of some commercial fertilizers**

| Fertilizer | Solubility (Kg/100 L) |
|---|---|
| Liquid Fertilizers | highly soluble |
| Urea | 110 |
| Ammonium nitrate | 119 |
| Ammonium sulphate | 71 |
| Potassium nitrate | 32 |
| Potassium chloride | 28 |
| Potassium sulphate | 7 |
| Monoammonium phosphate | 23 |
| Diammonium phosphate | 58 |
| Magnesium sulphate | 71 |
| Monocalcium phosphate | Insoluble |
| Diclcium phosphate | insoluble |
| P-Acid | highly soluble |
| Urea-phosphate | highly soluble |

## 2. Distribution of fertilizers under trick fertigation

In greenhouses the fertilizer application through trickle-irrigation systems is the most common application of the chemical injection techniques. Trickle fertigation is an attractive concept, as it permits application of nutrients directly at the site of a high concentration of active roots and as needed by the crop.

However, following application through trickle irrigation, mineral nutrients move into the wetted volume in a manner consistent with the flux of the wetted volume in a manner consistent with the flux of the water in the soil, their solubility and / or reactivity with constituents in the soil solution, and their interaction, if any, with the exchange sites of the soil.

Since chemical characteristics of fertilizers differ, mineral nutrients are differently distributed in the soil when applied by trickle irrigation (Bar-Yosef, 1977; Goldberg et al., 1971, Papadopoulos, 1985). The nitrate form of nitrogen does not react with the soil exchange sites and is not held in soils. Nitrates move with other soluble salts to the wetted front. This is of particular interest since $NO_3$-N should always be applied with every irrigation and at that concentration needed by the fertigated crop, as to satisfy its requirement in N from one irrigation to the other (Papadopoulos, 1988a ; Hamdy, 1991). Theoretically, and this is in full agreement with experimental results, the distribution of NO3-N application the fertigated crops might be under the over-fertilization stress at the day of fertilizer application and under deficient stress due to leaching following the irrigation without fertilizer. The same applies, although at a lower degree, and for other nutrients that are not reacting with soil, and almost with all nutrients under pure sandy soils (Papadopoulos, 1988 b; 1991, 1992). The ammonium form of N derived from ammonium or urea fertilizers is not nearly so subject to immediate leaching losses because temporarily, depending on the soil, may be fixed on exchange sites in the soil. The behaviour of these fertilizers and their effect on yield and quality are further discussed in the following chapters. Nitrate status in soil at any time, will result from a dynamic equilibrium between addition by trickle irrigation and removal by the plant plus any losses from leaching or de-nitrification. The latter may occur in heavier soils, where oxygen tension may become limiting (Bar-Yosef and Sheikholslami, 1976). Hence, irrigation design as well as the irrigation scheduling program must be appropriate to maintain desired fertility level in the soil.

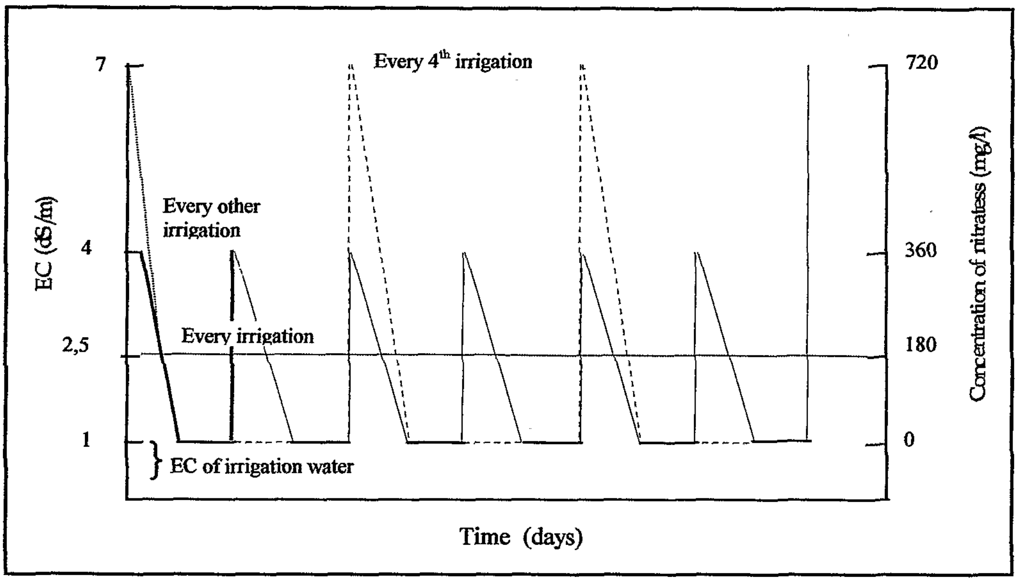


**Figure 1. Distribution of nitrates and salinity in soils following and irregular irrigations**

Potassium (K) is less mobile than nitrate (Goode et al., 1978), and distribution in the wetted volume may be more uniform due to interaction with soil binding sites (Kafkafi and Bar-Yosef, 1980 ; Uriu et al., 1980). Trickle-applied K moves both laterally and downward, allowing more uniform spreading of the K In the wetted volume of soil.

Phosphorus (P), contrary to N ad K, is readily fixed in most soils (Kafkafi and Bar-Yosef, 1980), although movement of applied P differs with soil texture. Commercial standard P-fertilizers may also precipitate in the irrigation lines in reaction with ions in the irrigation water such as Ca or Mg. Due to soil fixation of the applied P and problem of low solubility and precipitation of P in the irrigation system, it has been suggested that under such conditions P not be applied through irrigation systems. However, such an approach reduces the availability of P with consequent significant reduction in the yield. The phosphoric acid, is a useful source of P and in recent years widely used particularly in mini-sprinkler and drip fertigation.

### 3. Distribution of fertilizers under sprinkle-fertigation

The same principles applied for the movement and distribution of nutrients by trickle are valid to a large extent under sprinkle-fertigation. The nutrients, depending on their solubility and reactivity in the soil, will be distributed in the wetted soil, accordingly. However, with the sprinkler-fertigation (mini-sprinklers, and common sprinklers), some nutrients and particularly micro-nutrients may be absorbed directly from the wetted foliage. This might be of particular interest with certain crops in greenhouses with full foliage coverage of the soil. The minisprinkler-fertigation system could also be used successfully for plant protection purposes. Under such conditions a significant labour and energy saving can be achieved (Papadopoulos, 1989).

### 4. Nutrient uptake and fertilizer use effeciency

he nutrient-uptake efficiency with mineral-nutrient applications through the irrigation stream is increased substantially (Phene et al., 1979; Papadopoulos 1988 a). This is the case with all fertilizers; with highly soluble fertilizers not reacting with soil exchange, particularly under sandy soil conditions, due to decrease of leaching losses (Papadopoulos, 1988b) and with nutrients like P with high soil fixation potential due to less P fixation in soil. However, it is evident from Table 2 that depending on the form of the fertilizer, the same nutrient could be more efficient if applied with every irrigation or periodically The ammonium-nitrate was more effective when applied with every irrigation at 100 mg N/L, whereas, the urea was superior when applied with two third irrigation at 300 mg N/L, followed with two irrigations without N. Moreover, the form of the fertilizer combined with the frequency of application appear to be powerful means to improve also the quality of the product. The nitrate-N concentration in bean fruits, was less with the urea fertilizer irrespective of the frequency of application, whereas with the ammonium-nitrate was significantly higher but more controlled when its application was with every irrigation. It is, therefore, important during development of the fertigation recipes for the various crops that research should be directed not only to the concentration (amount) of the nutrients but also to the form of the fertilizers, and their frequency of application. The effect of N concentration in the irrigation water and the $NH_4/NO_3$ ratio on yield of strawberries are illustrated in Tables 3 and 4, respectively.

**Table 2: Yield and total-N and $NO_3$-N in French bean fruits as influenced by two forms of N-fertilizer applied with every or third irrigation**

| Treatment | Yield g/plot | Total % | $NO_3$-N mg/kg |
|---|---|---|---|
| $NH_4/NO_3$-every third irrigation (300 mg N/L) | 248 | 3.84 | 730 a |
| $NH_4/NO_3$-every irrigation (100 mg N/L) | 265 | 3.54 | 422 b |
| Urea-every third irrigation (300 mg N/L) | 275 | 3.74 | 227 c |
| Urea-every irrigation (100 mg N/L) | 233 | 3.72 | 245 c |

* Column means followed by the same letter are not significantly different at the 5 % level.

From Table ↄ the superiority of the P application through the irrigation system as compared to basal-P application, is obvious. Recent results with P-32 labelled fertilizers suggest that these differences in yield are associated with the high P efficiency applied continuously through the irrigation stream. In Table 5 the basal-P applied was equivalent to the 30 mg P/L applied with the Irrigation water. Similar to the P results have been also obtained with K-fertilization.

**Table 3 : Yield of strawberries as influenced by N concentration in the irrigation water**

| Level of N (mmol $l^{-1}$) | Number of fruits per plant | Yield (g/plant) | Mean (g/fruit) weight |
|---|---|---|---|
| 3.6 | 30.5b* | 405b | 13.3a |
| 7.2 | 35.5a | 465a | 13.1a |
| 10.8 | 31.3b | 376c | 12.0b |

*Means in the same column followed by the same letter are not statistically different at the 5 % level as determined by Duncan's Multiple Range Test.

**Table 4 : Yield of strawberries as Influenced by the N form, In irrigation water**

| NH4/NO3 ratio (mmol $l^{-1}$) | Number of fruits per plant | Yield (g/plant) | Mean weight (g/fruit) |
|---|---|---|---|
| 7/0 | 56.8a* | 650a | 11.5a |
| 3.5/3.5 | 47.5b | 547b | 11.5a |
| 0/7 | 48.8b | 568b | 11.6a |

*Means in the same column followed by the same letter are not statistically different at the 5% level.

**Table 5 : Yield of fresh bean as influenced by basal P application and three P-fertigation levels**

| Treatment | Yield (kg/plot) |
|---|---|
| 45 mg P/L | 5.49 a* |
| 30 mg P/L | 4.gg b |
| 15 mg P/L | 3.46 c |
| Basal - P | 2.43 d |
| Nil | 1.88 e |

*Column means followed by the same letter are not significantly different of 5 % level.

The superiority of fertigation in comparison with the equivalent application of all nutrients (N, P, K) by a granular form and two slow release fertilizers is shown in Table 6. Evidently, the nutrient uptake efficiency as indicated by the yield is higher with fertigation, which in extend means more environment friendly approach.

**5. Factors affecting the nutrient concentrations in fertigation recipes**

The objective of fertigation is an optimal supply of water and nutrients to the crops. According to Sonneveld et al., 1991 the concentrations of the various nutrient elements in the irrigation water necessary to achieve this objective which in extent is the main prerequisite to protect environment depend on the following factors:.

Crops grown, Crop yield, Growing stage, Quality demands, Nutrient status of the root environment, Microbial and chemical status of the root environment, Distribution of nutrients is the root environment, Chemical composition of the irrigation water, Transpiration rate of the crops and light intensity. Some of these factors are briefly discussed.

**Table 6: Yield of lettuce as influenced by continuous fertigation and soil application of two slow release fertilizers and a solid fertilizer**

| Treatment | Yield plot (5.4 $m^2$) | Wt/lettuce g |
|---|---|---|
| Fertigation | 76.8 A | 1066 A |
| Solid-powder | 25.3 B | 351 B |
| Paste I | 26.8 B | 373 B |
| Paste II | 26.8 B | 372 B |

- Column means followed by the same letter are not significantly different at the 1 % level

### Crops Grown

The nutrient absorption of different crops Is shown In Table 7. The data given for tomato concern a year round crop with a yield of 50 kg/m2. The roses were grown for more years and had a yield of 200 flowers/m2/yr. Tomato shows the highest nutrient uptake. Radish was grown year round, eight crops of 250 plantsim2. The K absorption are highest with 1600, 366 and 719 kg/ha for tomato, rose and radish, respectively. However, not only the quantities differ, but also the ratios between the elements. Tomato shows relatively high absorption for K, P and S.

### Growing Stage

Concentrations and ratios of nutrient elements have to be adjusted to the growing stage of crops. Young plants of fruits vegetable crops are often supplied with nutrient solutions of a high EC value to prevent lush growth and improve fruit setting. This is normal practice for both soil grown (Breimer et al., 1988) and substrate grown crops (Sonneveld, 1988), especially under poor light conditions. The ratios between the growing stage. For example, high absorption of K is noticed during heavy fruit loads of vegetable crops (Voogt, 1988a) and a massive stalk development of flower crops. In Table 8 a tomato recipe placed on plant growth stages is prevented.

**Table 7. Nutrient absorption of some greenhouse crops In relation to the water uptake, expressed as mmol/L. Water uptake is given in L/m$^2$.**

| Nutrient elements | mmol/L water absorbed | | |
|---|---|---|---|
| | Tomato | Rose | Radish |
| K | 6.3 | 2.2 | 4.6 |
| Ca | 2.0 | 0.8 | 1.5 |
| Mg | 0.6 | 0.4 | 0.5 |
| N | 9.9 | 5.2 | 8.6 |
| P | 1.4 | 0.4 | 0.4 |
| S | 1.3 | 0.5 | 0.4 |
| Water uptake | 650 | 425 | 400 |

**Table 8. General commercial tomato-fertigation under glass or plastic based on plant growth stages**

| Growth stage | Fertilizer | Application rate (g/l) |
|---|---|---|
| Starter fertilizer until the first truss | 15-30-15 + Mg | 1.0 |
| First truss set to first picking | 15-5-30 + Mg | 1.5 |
| First picking to end of season | 15-6-20 + Mg | 1.3 |

### Quality Demands

To obtain a high and stable quality of the produce, an optimal supply of nutrients is necessary. Deficiencies or near deficiencies often adversely affect quality Too low K supply, for example, is connected with a poor fruit quality of vegetables (Adams et al., 1978; Roorda van Eysinga, 1966).

Another important factor affecting quality is the ionic concentration in the root environment. A low osmotic potential (high EC value) in the soil solution or nutrient solution generally improves fruit quality of vegetables (Sonneveld and Welles, 1988 ; Mizrahi et al., 1988). High EC values for flower crops have no advantages for quality (Dekreij and Van Os, 1969; De Kreij and Van den Berg, 1991a) or even show negative quality aspects (De Kreij and Van den Berg, 1990b).

**Nutrient status of the root environment**

With fertigation the nutrient concentration of the irrigation water often has a greater effect on plant development than does the initial nutrient status of soil or substrate. This is especially the case with plants grown in small soil or substrate volumes or where spot irrigation is evident that the nutrient store available at the start of the cropping period is negligible in comparison with the total absorption. With spot irrigation, plant roots generally cover only a small part of the available soil volume, Watering with sprinkler irrigation systems on hand at start, since the roots will be distributed better in the available volume.

Microbial and Chemical Status of the Root Environment The N-source to be used in fertigation should be selected on basis of the microbial and chemical status of the soil or substrate in the root environment. In many substrates, $NH_4$ is only slowly converted to $NO_3$. $NH_4$ supplied in substrate systems may therefore be absorbed easily by crops, and addition of high quantities of $NH_4$ can be toxic (Barker and Mills, 1980). C; quantities below 15 % of the total N-supply often show favourable effects on plant development in substrate systems (Voogt 1987, Voogt 1988b). In greenhouse soils, $NH_4$ supplied is usually quickly converted to NO3 due to an abundant microbial, activity, stimulated by the high temperature. Thus, in soil cultures high quantities of $NH_4$ may be advantageous on calcareous soils for crops sensitive to iron or manganese chlorosis.

**Chemical composition of the irrigation water**

Most irrigation waters contain appreciable quantities of plant nutrients like Ca, Mg and $SO_4$. These quantities should be taken into account in adding the nutrient elements. Ionic concentrations higher than those absorbed by the crops cause salt accumulation in the root zone and necessitate leaching. This is the case especially with Na and CI. These ions are abundantly present in many irrigation wafers, but are little absorbed by crops (Sonneveld and Van den Burg, In press). Water supplies higher than the transpiration of the crop are also necessary to compensate for an uneven water distribution and an uneven water absorption by plants. In substrate systems this uneven distribution may result in the drainage water easily reaching 20~30 % of the supply (Sonneveld, 1988). This may lead to leaching of 50 % of the fertilizer (Verhaegh et al. 1990). In soil grown, crops leaching of fertilizers can also be voluminous.

**Transpiration rate of the crop**

The transpiration rate of the crop Is Important with respect to the ratio with which nutrients and water will be transported to the roots. In this regard, great differences occur between summer and winter grown crops. In Table 5 data are listed for radish crops grown under summer and winter conditions, in Netherlands. The growing period in summer was 25 days and in winter 75 days; the nutrient absorption of the crops were equal, but the water uptake differed by a factor of 4.5. Thus the ratio between nutrients and water absorption differed by the same factor. The nutrient concentration in the irrigation water should be adjusted for such differences.

## 6. Fertigation practices and recommendations

In fertigation both irrigation and fertilization affect plant behaviour, and adjustments In one factor can lead to limits imposed by another. For optimum plant performance under fertigation, all fertilization-irrigation-input factors must be balanced so that none is imposing significant limit.

**Table 9. Nutrient Absorption of Summer and Winter Grown Radish Crops in Relation to the Water Uptake, expressed as mmol/1 Water Absorbed (Water Uptake is given in L/m$^2$)**

| Nutrient elements | mmol/water absorbed | |
|---|---|---|
| | Summer | Winter |
| K | 2.9 | 12.8 |
| Ca | 0.9 | 4.1 |
| Mg | 0.3 | 1.4 |
| N | 5.4 | 23.8 |
| P | 0.2 | 1.1 |
| S | 03 | 1.2 |
| Water uptake | 75 | 17 |

However, to approach successfully, the actual water and nutrient requirements of the crops, together with a uniform distribution of both, water and nutrients, are important parameters in practising meaningful fertigation. In this respect extensive research in developing fertigation recipes has been undertaken and some tentative recipes developed in Cyprus and elsewhere are given in Table 10. Evidently, the real crop water requirements, particularly under plastic and greenhouse production, is the most critical link between irrigation and sound fertigation. In this respect, research priority should be attached.

The recipes suggested in Table 10, although good guidelines are not based on physiological growth stages of crops. In this respect substantial research is in progress since the crop demand to nutrients is a dynamic where not only the amount but also the form of the same nutrient and the ratio between the nutrients is changed. In Table 8 such a recipe for commercial tomato production is given.

## 7. Nutrient leaching and environmental impacts

A serious problem connected with fertigation in greenhouse industry is the leaching of nutrients to deep groundwater or surrounding surface water. In view of the high nutrient concentrations in soil and substrate solutions, it is not realistic to suppose that the drainage water will leave the root zone or the substrate system with ecologically acceptable concentrations. Restriction of leaching by a lower water supply is virtually.

Impossible, because of uneven distribution of water and nutrients in the root environment at low leaching fractions. That is why systems have been developed with which the drainage water is collected, sterilized and roused in the system.
In substrate systems, collection of drainage water can easily be practiced, but for crops grown in the greenhouse border soil it carries difficulties.

Therefore, a change from soil grown crops to substrate growing will be stimulated strongly in the Netherlands.

**Table 10. Recommended concentrations of nutrients in the irrigation water (g of nutrient per $m^3$)**

| Crop | N | P | K |
|---|---|---|---|
| Cucumber | 150-200 | 30-50 | 150-200 |
| Eggplant | 130-170 | 50-60 | 150-200 |
| Bell pepper | 130-170 | 30-50 | 150-200 |
| Tomato | 150-180 | 30-50 | 200-250 |
| Potato | 130-150 | 30-50 | 120-180 |
| French beans | 80-120 | 30-50 | 150-200 |
| Strawberries | 80-100 | 30-50 | 150-200 |
| Lettuce | 100 | 30-50 | 150 |
| Iceberg lettuce | 100 | 18 | 120 |
| Shamouti oranges | 35 | 3-5 | 8-10 |
| Banana | 15 | - | 45 |
| Cotton | 40-60 | 20-30 | 100 |
| Sunflower | 40-60 | 20-30 | 100 |

Reuse of drainage water requires water of good quality, especially with respect to Na and Cl contents. Full reuse of drainage water requires raw water with Na and Cl contents below the ratio of nutrient uptake/water uptake for these elements. This ratio differs for crops and growing conditions, but it is generally low. For Na it will amount to 1.0 mmol/l at best (Sonneveld and Van der Burg, press). Besides Na and Cl, other ions in the raw water may be a hindrance for recirculation of drainage water when their concentrations exceed the nutrient uptake water uptake ratio. For groundwater, such may be expected for Ca, Mg and $So_4$.

In this respect the « Taylor Make » fertilizer recipes which are based on both soil fertility and crop nutrient requirements are highly recommended.

## CHEMIGATION IN GREENHOUSES

The application by chemigation plant protectants such as herbicides, fungicides insecticides, nematicides and biocontrol agents has rapidly expandede during the last two decades. The terms herbigation, insectigation, fungigation, nemagation, entomopathogation, and mycoherbigation have been coined to describe various types of chemigation now in use to apply plant protectants. While a great deal of success has been experienced with chemigation of plant protectants, all available chemicals or chemical formulations have not yet been evaluated for this application technique. Likewise, some chemical formulations that have been evaluated have not produced effective or consistent results (Threadgill, 1992).

In general the application of most soil active chemicals via chemigation has given effective and consistent results. Soil active protectants include pre-emergence herbicides, some insecticides and fungicides, and most nematicides.
Chemigation or foliar active plant protectants such as post-emergence herbicides, most insecticides and fungicides, and most biocontrol agents has provided less consistent and effective results than chemigation of soil active materials. However, there have been many notable successes with foliar active materials. Factors such irrigation system type and component design, water application rate antecedent soil moisture, water quality, chemical formulation, chemical application rate and application frequency, and pest pressures all affect the efficacy of chemigated plant protectants. Significant advances in defining the effects of these factors and their interrelationships have been made in the last fifteen years.

## 1. Herbigation

In general, the application of pre-emergence herbicides through sprinkler irrigation systems has been proven to be very effective for a wide range of herbicides, weeds, crops, ad soil conditions. Although the herbigation of most conventionally formulated post-emergence herbicides has produced limited or inconsistent results, the addition of an oil, particularly non-emulsified oil conventional formulations of these herbicides shows great promise for achieving desired effectiveness.

Information about herbigation through drip/trickle irrigation systems that this technique for applying herbicides is generally effective in controlling weeds in only a portion of the area wetted by the irrigation water. This is particularly important for protected agriculture. While this limitation on the area within which weeds are controlled may be a significant disadvantage in humid climates, it may be of only limited significance in arid climates. Thus, herbigation through drip/trickle irrigation systems may have a higher degree of acceptability in arid climates and in greenhouses.

The non-uniformity of weed control through surface irrigation systems severely limits the practical application of herbicides with this technique (Pritchard, 1978)

## 2. Insectigation

Insectigation has proven to be a relatively effective technique for control of insects. Insectigation with conventional formulations generally provides reasonable but sometimes inconsistent pest control and should be practiced with a minimum amount of water. The use of oil-formulated insecticides offers tremendous potential for enhanced insect control and can be applied in much higher water volumes than conventional formulations in particular, the formulation of technical insecticide materials in a non-emulsifiable oil provides very significant advantages. However, these formulations are not yet commercially available.

## 3. Fungigation

Fungigation is an established means of applying fungicides to crops. Substantial information is available for fungigation with irrigation systems. Fungigation has proven to be quite effective for preventing or controlling a wide range of foliar and soil borne diseases on a variety of crops. Fungigation has also proven effective for the soil application of the water soluble soil fumigant. Vapam. The effectiveness of fungigation through drip/trickle or surface irrigation systems has not yet been widely established.

### 4. Nemagation

The application via nemagation of both non-fumigant and fumigant nematicides through sprinkler irrigation systems has been proven effective for the management of several major nematodes. The quantity of irrigation water used during nemagation does not appear to be significant up to 2.5 cm/ha (1.0 in/ac). Also, application of nematicides via nemagation appears to offer the possibility of salvaging a crop in which nematodes are detected after the crop has been planted. This salvaging alternative is not usually practical with the application of nematicides by conventional methods. With the drip irrigation, however, nemagation under protected agriculture, in low tunnels and greenhouses, appears very promising.

### 5. Chemigation in relation to integrated pest management

Integrated pest management (IPM) is a pest management technique which combines a variety of pest control technologies to achieve an acceptable level of pest control while having little if any negative impact on the environment. IPM integrates the concepts of beneficial pests, biological control, chemical control, crop rotations, tillage systems, and nutrient and water management to maintain acceptable crop productivity while applying minimal chemical pesticides. IPM is heavily dependent upon effective scouting of pests and applying pest control techniques in a very timely fashion. Instead of stressing regularly scheduled applications of chemical pesticides, IPM focuses on using a pest control technique only when pest pressures warrant it.

One of the advantages of chemigation is timeliness of application, that is, pest control agents can be applied at any time the irrigation system can be operated in wet or dry weather and at any time of the day or night. Also, sprinkler irrigation systems can be used to practice total chemigation, that is the application of all chemicals required to produce a crop. Therefore, sprinkler irrigation systems are very well suited to integration into an IPM programme.

Chemigation with drip/trickle irrigation systems can also be conveniently integrated into an IPM programme for applying those chemicals which can be practically distributed through a drip/trickle irrigation system. Chemigation with surface irrigation systems would seem so have very limited application in an IPM programme.

The current interest in the development of biosensors which could be used to monitor pest populations in the field or greenhouses offer an exciting futuristic potential for further integration of chemigation into an IPM programme. Utilizing a microprocessor-based control system, these biosensors could be used to automatically schedule application of pest control agents. While such arrangements may seem to be far in the future at this time, this potential combination of irrigation, pest control, and sensing technology offers exciting possibilities (Threadgill, 1992).

## CHEMIGATION AND THE ENVIRONMENT

Chemigation has several environmental implications, both positive and negative. According to Threadgill (1992) the main categories of these potential environmental impacts are:

1. Potential backflow of chemicals to the irrigation water supply or to the soil surface around the chemigation system.
2. Potential positive and negative impacts on nonpoint source polluant potential of materials applied by chemigation.
3. Potential positive and negative impacts on operator safely and
4. Potential effects on chemical residues in food and fiber products.

The potential disadvantages of chemigation are substantially limited under protected agriculture. The appropriate design and the uniformity of the irrigation system together with the development of appropriate management practices for both irrigation and chemicals are critical prevequisites. With chemigation both success and adoption of appropriate legislation and regulations and the use of good management practices in each country which utilizes chemigation is essential for the protection of the environment, man and the quality of life, the technology is available. It must simply be put into practice.

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