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Citrus Chemigation

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ABSTRACT

Advances in microirrigation techniques have facilitated greater adoption of chemigation in citrus production. Citrus chemigation is the application of liquid chemicals, i.e., fertilizers, pesticides, and/or herbicides to citrus groves through irrigation systems. This article reviews citrus chemigation; it discusses chemigation management, chemigation system components, and chemigation efficiency under citrus production systems. Pressurized irrigation systems, e.g., overhead sprinklers, microsprinklers, and/or drip systems have successfully been used to carry out citrus chemigation. Through chemigation practices, citrus growers have been able to control the timing and the amount of chemical application to their groves. Selection of suitable irrigation system, use of efficient injection devices, and compatibility of chemicals are crucial for an efficient chemigation operation. Combined use of incompatible chemicals could form insoluble compounds and/or precipitates that may clog the chemigation system.

Keywords: chemical injectors, chemical precipitates, chemigation calculation, chemigation efficiency, chemigation equipments, chemigation systems, chemigation uniformity, citrus chemigation, fertigation, fertilizer solubility, irrigation systems, soil pH, system clogging

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INTRODUCTION

Chemigation refers to the application of chemicals including fertilizers, insecticides, pesticides, fumigants, nematicides, soil amendments, and other compounds through irrigation water (Burt *et al.* 1998). Terms such as fertigation, insectigation, herbigation, nemagation, and fungigation have been widely used to describe various types of chemigation (Threadgill *et al.* 1990). Applications of fertilizers (Harrison 1974; David 1975; Greef 1975; Bester *et al.* 1977; Bredell and Barnard 1977), herbicides (Lange *et al.* 1974; Phene *et al.* 1979), fungicides and insecticides (Phene *et al.* 1979; Young 1980; Potter 1981), nematicides (Chesness *et al.* 1976; Overman 1975; Jonson 1978; Overman 1978), growth regulators (Bryan and Duggins 1978), and fumigants (Goldberg and Uzrad 1976; Overman 1976) through irrigation water have also been reported in the literature.

Of various types of chemigation, fertigation is the most widely used term as it facilitates the supply of right amount of nutrients at the right time as compared with the conventional dry fertilizer broadcasting method (Syvertsen and Sax 1999; Boman and Obreza 2002). Koo (1980) and Burt *et al.* (1998) described the common advantages of fertigation: 1) considerable savings in the costs of fertilizer application and labor; 2) fertilizers are already in solution form and thus, immediately available to the plants throughout the root

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zone; 3) the high flexibility in irrigation timing makes it easier to schedule fertilization; 4) minimized soil compaction by avoiding heavy equipment traffic through the field to apply fertilizers; and 5) careful regulation and monitoring of nutrient supply, for instance, small doses of fertilizers are applied when needed to prevent leaching of water-soluble nutrients during periods of excessive rainfall or over-irrigation (Boman and Obreza 2002). If fertilizers are applied through irrigation systems, savings of 29-78% in application costs may result (Csinos *et al.* 1986) due to the improved efficiency of fertilizer application (Phene and Beale 1976; Miller *et al.* 1981), low fertilizer leaching (Bresler 1977; Stark *et al.* 1983; Papadopoulos 1985; Klein *et al.* 1989), precise nutrient application (Bar-Yosef 1977; Papadopoulos 1986a, 1986b, 1987), and right amount and right time of fertilizer application (Snyder and Burt 1976; Bresler 1977; Kovach 1983). Although the practice of applying plant nutrients dissolved in irrigation water began centuries ago with the dumping of livestock manure in irrigation canals (Threadgill *et al.* 1990), mechanized chemigation was only reported a few decades ago in modern irrigated agriculture (Phene and Beale 1976; Phene and Sanders 1976; Bresler 1977; Hairston *et al.* 1981; Elfving 1982; Papadopoulos 1985, 1986a, 1986b, 1987, 1988), as well as for young citrus trees cultivation (Boman 1995). Chemigation also appears to be a promising alternative tool for applying all other agrochemicals (Bryan and Thomas 1958; Goldberg and Shmueli 1970; Vieira 1994) in areas susceptible to surface runoff (Basinal *et al.* 2005).

Chemigation is particularly useful in establishing young citrus (Koo 1980), apple (Kipp 1988), and peach (Bussi *et al.* 1991) trees. Although, no significant increase in crop yield has been reported (Oliveira *et al.* 1995; Paramasivam *et al.* 2001; Alva *et al.* 2005), major plant nutrients, i.e., NPK (nitrogen, phosphorous, potassium, respectively), uptake is particularly higher with chemigation than with conventional methods (Phene *et al.* 1979; Smith *et al.* 1979; Uriu *et al.* 1980; Dasburg *et al.* 1988; Papadopoulos 1988). Chemigation has resulted in a variety of effects on fruit quality in mature trees. Goode *et al.* (1978) and Delver (1984) studied the quality of apples from orchard supplied, with and without chemigation, at harvest and at several stages of apple storage. In addition to enhancing nutrient uptake, these studies reported the improved storage of apples. Smith *et al.* (1979), Koo (1980), and Dasburg *et al.* (1988) reported on minor improvements in citrus fruit quality when chemigation was compared with a conventional method of surface broadcasting. Marsh and Stowell (1993) conducted a 3-year field trial on kiwifruit (*Actinidia deliciosa*) vines that received 40% of their nutrient requirements by chemigation and the rest as solid fertilizer at equal amounts of N (58 kg ha^{-1}) and K (294 kg ha^{-1}). They reported that plots receiving nutrients through chemigation showed no improvement in fruit quality or storage as compared with the plots receiving a conventional solid fertilizer application. Boman (1996) conducted a 4-year field experiment with grapefruit trees (‘Ruby Red’) in Florida to compare conventional fertilizer broadcasting with the combined application of fertilizers via surface broadcast and fertigation. Their fertilization treatments included 1) three broadcast applications per yr and 2) the combination treatment with a broadcast application of 33% of the annual N and K_2O, followed fertigation at 2-week intervals with the remainder 67% nutrients. In this field experiment, Boman (1996) found an average increase in fruit yield by 4150 kg ha^{-1} yr^{-1} for the combined treatment compared with conventional broadcasting. Chemigation studies concerning optimum N application rates for maximum citrus fruit yield components, plant nutrient uptake, and minimized nutrient leaching have been reported in the literature (Paramasivam *et al.* 2001; Thompson *et al.* 2002; Alva *et al.* 2003; Schumann *et al.* 2003; Alva *et al.* 2005; Kusakabe *et al.* 2006).

In this review paper, we summarize the current available information on various aspects of citrus chemigation. We discuss 1) best irrigation systems for chemigation, 2) chemigation management, 3) chemigation system components, and 4) chemigation efficiency in addition to few short- and long-term chemigation studies regarding the response of citrus fruit yield, plant nutrient uptake, and nutrient leaching. The information provided in this review should prove valuable to scientists, professionals, and growers for the evaluation and improvement of their citrus chemigation systems to meeting their specific goals. Future needs for improving citrus chemigation systems have also been emphasized.

BEST IRRIGATION SYSTEMS FOR CHEMIGATION

Citrus groves are irrigated with microsprinklers and drip systems (Paramasivam *et al.* 2001, 2002; Alva *et al.* 2005; Kusakabe *et al.* 2006) as well as with surface flooding (Sauls 2008). Irrigation systems are selected based on their water use efficiency that varies with the soil properties and crop characteristics rather than the application system itself. Irrigation systems are categorized by their irrigation efficiency that is defined as the volume of water beneficially used by the plants relative to the volume delivered from an irrigation system (Jensen 2007). Sprinkler and drip systems have substantially high irrigation efficiencies (60-70%, 80-90%, respectively) than that (50-60%) of the traditional surface flooding (Nir 1982; Smajstrla *et al.* 1991). Flood irrigation techniques utilize more water as compared with low volume pressurized irrigation systems. In flood irrigation techniques, the irrigation water is directed and controlled by constructing basins, borders, and/or furrows. During flood irrigation, the applied water percolates through the plant root zone resulting in leaching losses of the applied nutrients. On the other hand, the low volume irrigation systems apply water to the soil around the plants; therefore, the agrochemicals can effectively be applied with such irrigation systems. Since the infiltrating water dispenses the fertilizer in soil, fertilizer distribution depends on the water flow patterns in soil (Hanson *et al.* 2006). Under flood irrigation, most of the water movement is under gravity resulting in excessive drainage. More nutrients may be needed for flood-irrigated groves than for low volume systems (Thompson *et al.* 2000) that retain the applied water, hence nutrients, in the plant root zone (Fares *et al.* 1997).

Pressurized irrigation systems offer the ability to use high frequency chemigation (Marler and Davies 1990; Smajstrla *et al.* 1991; Willis *et al.* 1991; Tucker *et al.* 1995; Boman 1996; Alva and Paramasivam 1998; Alva *et al.* 1998; Boman and Obreza 2002). Chemigation through these systems have been reported in a number of studies (Bresler 1977; Del Amor *et al.* 1981; Gerstl and Albasel 1984; Papadopoulos 1985; Ogg 1986; Gerstl and Yaron 1993). Selection of irrigation systems for their potential use in chemigation is critical as the applied chemicals are distributed in field based on the application uniformity of these systems. Drip irrigation systems uniformly distribute the applied chemicals in the target locations around plant roots (Papadoupouls 1985, 1986a, 1986b). High irrigation application efficiency of water associated with negligible deep percolation applied by drip system makes this system ideal for chemigation. Since the drip irrigation system applies the controlled and precise amount of water to the field, the negative impacts, i.e., surface runoff, soil erosion, deep percolation, or nutrient loss are avoided. Prescribed chemical application, reduced application costs, minimum operator hazards, no soil compaction, and less tree injury are among the important advantages of chemigation through drip irrigation system over ground sprays (Vieira and Sumner 1999). Quiñones *et al.* (2003) used flood and drip irrigation systems to compare N uptake efficiency in citrus trees [*Citrus sinensis* (L.) Osb.] grown on Carrizo citrange rootstock (*C. sinensis* × *Poncirus trifoliata Raf.*). Their results showed that the drip irrigation system was more efficient for improving water use efficiency and plant N uptake from the applied fertilizer, thus potentially enhancing plant growth and reducing N leaching losses.

CHEMIGATION MANAGEMENT

Types, sources, and compatibility of citrus nutrients

Some of the information presented in this subsection is adopted from Boman and Obreza (2002).

Nitrogen and nitrogen sources

Nitrogen (N) is an essential pre-requisite for citrus plants and is ideal for chemigation due to its complete dissolution in irrigation water. Urea, ammonium nitrate (NH_4NO_3-H_2O), calcium nitrate ($5Ca(NO_3)_2$-NH_4NO_3-$10H_2O$), potassium nitrate (KNO_3), and ammonium sulfate ($(NH_4)_2SO_4$) are some of the examples of N containing sources. The N fertilizers are extensively used to prepare single- or multi-nutrient fertilizer solutions. Generally, pH neutral N sources (i.e., $Ca(NO_3)_2$, KNO_3) are used as N fertilizer materials in chemigation practices. For high pH soils, acidic sources are useful because they have the potential of reducing soil pH. Common N content sources are given below.

Ammonium nitrate solution (20-0-0) [NH_4NO_3-H_2O]:
Ammonium nitrate fertilizer is one of the most common and widely used N sources used to supply N contents to citrus trees. It can be dissolved in water at a density of 1.26 kg L^{-1} (10.5 pounds per gallon).

Urea-ammonium nitrate solution (32-0-0) [$(NH_2)_2 2CO$-NH_4NO_3]:
This source of N is manufactured by combining urea (46% N) and ammonium nitrate (35% N) on equal N content basis. Of the available N sources, urea-ammonium nitrate has the highest N concentration. Calcium nitrate is not generally used with urea-ammonium nitrate source so as to prevent the formation of insoluble, milky white precipitates that potentially could clog the chemigation systems.

Calcium nitrate (15.5-0-0-19 Ca) [$5Ca(NO_3)_2$-NH_4NO_3-$10H_2O$]:
Calcium nitrate is a rich in nitrate N (NO_3-N) with 1 % of ammonium-N (NH_4-N) and calcium (Ca). Calcium nitrate can be mixed with NH_4NO_3, magnesium nitrate ($Mg(NO_3)_2$), KNO_3, and muriate of potash (KCl). However, this product should not be mixed with any products containing phosphate, sulfates, or thiosulfates to avoid the formation of insoluble precipitates that may result in plugging problems in low volume drip, trickle, or micro-jet irrigation systems.

Ammonium thiosulfate (12-0-0-26) [$(NH_4)_2S_2O_3$]:
Ammonium thiosulfate (ATS) is used as an acidulating agent. When ATS is applied to the soil through chemigation, sulfur oxidizing bacteria, *Thiobacillus* spp, oxidize free sulfur (S) to form sulfuric acid (H_2SO_4). Gypsum is formed upon mixing ATS with a lime-rich calcareous soil. Gypsum helps maintain good soil structure. ATS can be mixed with neutral or alkaline phosphate liquid fertilizers or with other N fertilizers. However, it should not be mixed with acidic compounds due to the fact that it will decompose into elemental S and $(NH_4)_2SO_4$. Application of this fertilizer to neutral or acidic soils may result in drastic decreases in soil pH over time. The extent of pH drop varies with soil types and with amount of the fertilizer applied.

Phosphorus and phosphorus sources

Citrus plants generally need phosphorous (P) early in their life cycle, which makes P an important pre-plant amendment if already deficient in soil. Later stage application of P via chemigation is adopted if P deficiency symptoms appear in plants any time during the growing season. Phosphorous is the most critical element used in chemigation regarding its solubility in water especially in presence of other nutrients, e.g., calcium (Ca). Most of the commercially available fertilizers contain phosphoric acid (P_2O_5) as water soluble and citrate soluble phosphate. Since P is not easily dissolved in irrigation water, it is less likely to leach through many soils. Phosphorous, attached to eroded soil particles, is usually transported via surface runoff. It is important to know that injection of P fertilizers into irrigation system may cause emitter plugging due to the formation of precipitates when P is mixed with certain fertilizers. For Ca and Mg (magnesium) rich irrigation water, solid precipitation in the irrigation lines is expected if P is used in chemigation. Most of the dry phosphorus fertilizers (e.g., ammonium phosphate ($(NH_4)_3PO_4$) and superphosphates) are not injected with irrigation water due to their low solubility in the water. The P fertilizers, such as mono-ammonium phosphate (MAP), di-ammonium phosphate (DAP), mono basic potassium phosphate, P_2O_5, liquid ammonium polyphosphate, and urea phosphate, are water soluble and can be used in chemigation.

Phosphoric acid (0-54-0):
Phosphoric acid is a water soluble syrupy liquid that is used with many formulations of N, P, and potassium (K) mixtures, but not with any of the Ca fertilizers. The use of Ca fertilizer with P_2O_5 results in the formation of insoluble calcium phosphate ($Ca_3(PO_4)_2$), which can plug irrigation pipes, emitters, and drippers of the irrigation system.

Potassium and potassium sources

Potassium is one of the major nutrients for citrus plants. Major K sources include potassium chloride (KCl), potassium nitrate (KNO_3), and potassium sulfate (K_2SO_4). When mixed with other fertilizers, K may generate solid precipitants. Since the solubility of K_2SO_4 is very low, it is therefore seldom used in chemigation. Potassium thiosulfate is another common source of K which can be mixed with urea and ammonium polyphosphate solutions in absence of acidic fertilizers. The major K sources are presented below along with their merits and demerits.

Potassium chloride (0-0-62) [KCL]:
Potassium chloride is one of the least expensive, most popular, and highly water soluble fertilizer source for K nutrients. However, KCl is not useful if the irrigation water contains high salinity levels.

Potassium nitrate (13-0-46) [KNO_3]:
Potassium nitrate is an expensive fertilizer component compared with other K sources. It is an excellent choice of potassium fertilizers for areas of high saline irrigation water. Potassium nitrate is less soluble than KCl, but more soluble than K_2SO_4.

Potassium sulfate (0-0-52) [K_2SO_4]:
Potassium sulfate is one of the best alternatives to KCl in high salinity areas and simultaneously presents a source of sulfur content. It is less soluble than both KCl and KNO_3.

Potassium thiosulfate (0-0-25-17) and (0-0-22-23) [$K_2S_2O_3$]:
Potassium thiosulfate, usually available in two grades, is a neutral to basic, clear, liquid solution. This fertilizer can be blended with other fertilizers, except acidic blends (i.e., pH < 6.0). In order to avoid the formation of precipitates, it is always useful to conduct small blending jar tests prior to final injection.

Other nutrients and their sources

Calcium:
Calcium is seldom applied via chemigation. If used in chemigation, the entire system (i.e., tanks, pumps, filters, and all tubings) needs to be flushed thoroughly prior to its injection to avoid the formation of precipitates. Ca fertilizers are not injected with phosphate or sulfate fertilizers because

of their potential to form precipitates with these compounds.

Micronutrients:
The majority of metal micronutrients are not used in chemigation due to their low solubility in water. Thus, micronutrients, including copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn), are applied as surface broadcast.

Urea:
Urea is commonly available as a dry solid fertilizer (46-0-0) and/or as a liquid urea (23-0-0) solution. Commercially available urea contains about 2.25% biuret, a byproduct that is formed during the manufacturing process. For foliar application, urea with less than 0.25% biuret is recommended as a higher percentage of biuret can inhibit plant growth.

Urea sulfuric acid [$CO(NH_2)_2.H_2SO_4$]:
This is an acidic fertilizer that combines urea and sulfuric acid. When urea is applied to soil, it increases the soil pH and enhances N losses via ammonia volatilization. Combined application of urea and sulfuric acid reduces both ammonia volatilization and soil pH, and thereby reduce ammonia damage to plant roots that occurs when only urea is used as a nutrient source. Urea sulfuric acid is safer to use than sulfuric acid alone as the latter can acidify irrigation water to minimize system clogging.

Compatibility of different chemicals is a major concern during chemigation management and is directly related to fertilizer solubility in irrigation water or in any of the fertilizer solutions. Solubility depends on a number of factors, the most important being pH, solution temperature (discussed in a later section), and the concentrations of the soil solution. Some fertilizers do not dissolve in irrigation water and adversely affect the ability of the resultant solution to dissolve the internal or external solution components. For example, the mixture of $(NH_4)_2SO_4$ and KCl considerably reduces the solubility of the mixture due to the formation of K_2SO_4. Other non-compatible mixtures include 1) $Ca(NO_3)_2$ with any phosphates or sulfates, 2) $MgSO_4$ with DAP or MAP, and 3) P_2O_5 with Cu, Fe, Zn, and manganese sulfates (Wolf *et al.* 1985). The compatibility of chemical solutions with the irrigation water and with any other chemicals to be used in chemigation injection should be tested to avoid the formation of chemical precipitates in the irrigation system. Since Mg is one of the more difficult elements to dissolve in the chemical solutions, $Mg(NO_3)_2$, a source of Mg, is not used in the presence of P and nitrate (NO_3) to avoid their reaction and the subsequent formation of insoluble magnesium ammonium phosphate ($(NH_4)MgPO_4 \cdot 6H_2O$), which may clog the irrigation equipment (Koo 1980).

Chemigation calculations

Basic chemigation calculations involve determining the velocity of a water soluble chemical that is directly related to the velocity of the irrigation water in the system. Chemigation time is therefore related to the time needed by irrigation water to travel from the injection point to the furthest emitter. Thus, the total travel time for a chemical is taken from the injection point to the last emitter. Chemical travel time is calculated as $T = D/v$, where D is the distance travelled by the dissolved nutrient or the length of pipe through which the irrigation water flows and v is the velocity of irrigation water. Chemical travel time is used to calculate chemical injection rate (CIR) for a particular irrigation system. For a microsprinkler system, CIR can be calculated based on the following relationship (Boman *et al.* 2004):

$$\mathrm{CIR} = \frac{\mathrm{A} \times \mathrm{Q}}{\mathrm{F} \times \mathrm{T} \times \rho} \times 100,$$

where A is the area to be irrigated (ha), Q (kg ha^{-1}) is the quantity of chemical to be applied per hectare, F is the chemical fraction (fertilizer per liter of fluid injected, %), ρ (kg L^{-1}) is the chemical solution density. Using the above relationship, a quantity of 6 kg ha^{-1} of N is applied to a 50 ha citrus block with a 10-0-10 5 kg L^{-1} dense fertilizer solution that is injected for 2 hr at the injection rate of 300 L hr^{-1}. Since the microsprinkler irrigation systems do not irrigate the entire soil surface, the fertilizer applied, using these systems, is delivered only to the irrigated portion of the soil surface. For a simple case of 50% irrigated soil surface, the N application rate in the irrigated zone, using above information, will be 12 kg ha^{-1}. Because the microirrigation systems do not apply water and chemicals to the entire soil surface, chemical applications to micro-irrigated crops are often made on individual plant/tree basis, rather than on a gross area basis. The above relationship for CIR on number of tree in an area basis becomes (Boman *et al.* 2004):

$$\mathrm{CIR} = \frac{\mathrm{A} \times \mathrm{Q_p} \times n}{\mathrm{F} \times \mathrm{T} \times \rho} \times 100,$$

where Q_p (kg $tree^{-1}$) is the quantity of fertilizer to be applied per tree, n is the number of trees per ha, and all other variables are same as previously defined. In a 20 ha grove of young citrus trees, the quantity of 0.05 kg of N from a 5 kg L^{-1} dense 8-0-8 solution, at 2 hr chemigation time for 200 trees ha^{-1} grove will require 250 L hr^{-1} CIR.

The duration of injection should be greater than the time the chemical needs to travel from the point of supply tank to the most distant emitter of dripper or sprinkler in the field. Flushing time is also an important consideration to completely clean the system and it should also be same as the time of duration of fertilizer injection; nonetheless, excessive flushing time may lead to leaching loss of nutrients.

Chemical solubility and soil pH modification

Chemical solubility refers to the complete dissolution of a solid chemical (i.e., fertilizer) in irrigation water. Fertilizers including NH_4NO_3, KCl, KNO_3, K_2SO_4, urea, MAP, and DAP are among the highly soluble fertilizers and thus are ideal for chemigation. Since the chemical solubility increases with increase in temperature (Wolf *et al.* 1985; **Table 1**), the manufacturers of chemigation systems recommend dissolving chemicals in hot water prior to their use in chemigation system (Hanson *et al.* 2006). Once dissolved in water, the amount of chemicals in a solution is recognized by the solution density, which refers to the weight of the known volume of solution compared with the non-chemical solution volume.

Neutral substances (e.g., KCl, KNO_3, K_2SO_4) do not affect soil pH; however, the basic fertilizers (e.g., $Ca(NO_3)_2$ and sodium nitrate ($NaNO_3$)) increase and the acidic fertilizers (e.g., NH_4NO_3, $(NH_4)_2SO_4$, DAP, MAP, and urea) decrease soil pH (Hanson *et al.* 2006). Neutral irrigation solutions with pH $\cong$ 6 are ideal for chemigation. Alkaline solutions with pH > 7.5 cause the precipitation of P and thus decrease the availability of nutrients to the plant. Chemical solutions that decrease soil pH may increase the salt load beneath drip or sprinkler emitters (Haynes and Swift 1987). To avoid these problems, base dressings are suggested with the some of the basic chemicals (Marsh and Stowell 1993).

Acidic fertilizers are usually corrosive in nature; they therefore pose many health hazards especially to the skin and eyes of the individuals who handle chemigation equipments. This necessitates periodical and prior-to-use inspections of all system components, including pumps, injection devices, lines, filters, and tanks. Effective chemigation requires the fundamental knowledge and general understanding of soil chemical properties (e.g., soil pH, soil particle

Table 1 Temperature dependence of chemical solubility.

Temperature (°C)	Chemical solubility, g/100 g of water				
	NH_4NO_3	KCl	KNO_3	K_2SO_4	Urea
10	158	31	21	9	84
20	195	34	31	11	105
30	242	37	46	13	133

Source: Wolf *et al.* 1985

surface properties that affect nutrient solubility and mobility), chemistry of fertilizers and chemicals (e.g., possible reactions among compounds, mixing compatibility, precipitation, clogging and corrosion nature), crop parameters (e.g., plant nutrient requirements at different growth stages, plant rooting system and root growth stages), irrigation system including irrigation scheduling, and water quality factors (pH, salt and other dissolved nutrients, and general water quality for agricultural use).

Chemical system clogging

Alkaline water forms insoluble compounds and thus is not favorable for use in the chemigation operation. Alkalinity of the water is especially crucial when P is used in chemigation as the added P forms insoluble tri-basic calcium phosphate that can clog irrigation equipments (Rauschkolb *et al.* 1976). This necessitates the continuous monitoring of pH of the P carrying solutions flowing in the irrigation equipment (Koo 1980). Since MAP and DAP are excellent sources of P and N, these compounds are commonly used for enhanced citrus yield. There is a high possibility of precipitation of insoluble P, if MAP or DAP is mixed with high Ca or Mg carrying irrigation water. The precipitates formed in the irrigation equipment during the chemigation processes can be dissolved and cleared off with the use of acidic fertilizers (Ford and Tucker 1975; Ford 1976; Nakayama *et al.* 1977; Bucks *et al.* 1979). Although the acidic fertilizers are corrosive to the metallic components of the chemigation system and potentially damage the cement and asbestos pipes, they dissolve the precipitates and help to unclog the system emitters/drippers. Periodic injection of phosphoric-, nitric-, sulfuric- or chlorohydric acids into the chemigation system can remove bacteria, algae, and slime trapped in the system.

Clogging is particularly crucial for drip systems because of their small orifices in the emitters (Koo 1980). Several studies (Abbott 1985; Gilbert and Ford 1986; Nakayama and Bucks 1991; Boman and Ontermaa 1994) have identified various factors (e.g., solids, iron, calcium, phosphate, sulphate, algae, and hydrogen sulphide-oxidising bacteria) that are responsible for emitter clogging. Chemical solutions or low quality brackish water can also cause emitter clogging (Bucks *et al.* 1982). Very few reports on clogging of sprinklers during or after chemigation operation have been reported in literature. Koo (1980) did not experience emitter clogging while using solution fertilizer in over head sprinkler systems. However, he reported very little difference in the incidence of clogging between pre- and post-chemigations. Various researchers (Ford and Tuckler 1975; Parchomchuk 1979; Gilbert *et al.* 1981) have reported on emitter clogging and described methods of identifying and/or reclaiming the clogged emitters. The use of acid fertilizers temporarily unclogs the system emitters. The irrigation and chemical injection systems should be thoroughly washed/flushed with fresh water especially after the acid injection into the systems.

CHEMIGATION SYSTEM COMPONENTS

A chemigation system comprises an efficient irrigation system, a chemical reservoir or supply tank, chemical injection devices, and a backflow prevention mechanism. Irrigation systems have already been discussed; the other components of the chemigation system are discussed in the following sections.

Chemical reservoir or supply tank

Chemical reservoirs commonly called as supply tanks are usually made of polyethylene or fiberglass materials. Tank size is an important consideration for a chemigation system. Tank size should be large enough to contain the chemicals sufficient for at least one chemigation operation. Tank volume, V (L), is determined as $V = (R \times A) / (C \times \rho)$; where R is the chemigation rate (kg ha^{-1}), A is the area to be chemigated (ha), C is the concentration of chemical source (e.g., N-P-K, decimal), ρ is the chemical solution density (kg L^{-1}). To fertigate a 50 ha citrus block at the N chemigation rate of 10 kg ha^{-1}, the 10.6 kg L^{-1} dense 9-2-9 chemical solution of NH_4NO_3, KCl, and H_3PO_4 (i.e., 9% N fraction) will require a tank of a 524 L volume. To avoid overflow and to accommodate dead storage, it is always recommended to consider a 10% extra volume of the tank. The size of the tank can be doubled, tripled or folded to any size depending upon the number of chemigations planned between tank refilling.

Chemical injectors and injection techniques

Chemigation injection devices work either on piston flow (positive displacement pumps) or on vacuum generation (suction or negative pressure, venturi-type) principles. Positive displacement pumps include proportional injectors, rotary pumps, and peristaltic pumps. The injection energy for positive displacement pumps is provided by an electric, gasoline, or hydraulic motor. Accurate chemical application and easy adaptation for automation are among the major advantages of positive displacement pumps. Although these injection devices have been successfully and extensively used, there are disadvantages associated with their design characteristics and their high initial cost. A huge proportion of their internal area is exposed to a range of nutrients that may corrode the surfaces of the device. Moreover, it is not easy to set the pump stroke length to obtain a desired injection rate.

Rotary and peristaltic pumps are used to transfer chemicals from the supply tank to the irrigation system; the former transfer the solution through the action of rotating gears, while the latter transfer the solution due to the creation of partial vacuum. A more or less constant chemical flow is generated and the chemical injection rate is not affected by the change in irrigation application rate. Peristaltic pumps are used to inject chemicals in microsprinklers. The required chemical injection is achieved by the squeezing action of the rotating rollers on a flexible tube. Since the injected chemical passes through a tube and does not touch the inner components of the pump, the peristaltic pump material is protected against any corrosive impact caused by the chemical.

Since the injectors based on venturi principle utilize the differential pressure generated across the device (**Fig. 1**), the rate of chemical injection varies with the generated differential pressure. Chemical injection rate is influenced by the pressure drop; the larger the pressure drop, the higher the injection rate. Proper operation of these devices requires a pressure drop across the venture; some minimum pressure for even a low rate of chemical injection is required. This constraint results in poor chemical injection efficiency and problems in quantitative chemigation.

Most of the centrifugal pumps work on vacuum genera-

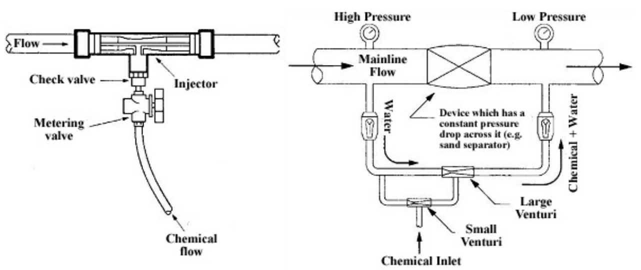

Fig. 1 Chemical injectors based on small venturi metering valve (left) and a large venturi (right) to create adequate pressure differentials for efficient chemical injection. (From Burt C, O'Connor K, Ruehr T (1998) Fertigation. San Luis Obispo, CA: Irrigation Training and Research Center, California Polytechnic State University, CA, with kind permission of Irrigation Training and Research Center, California Polytechnic State University, San Luis Obispo, CA 93407, US).

tion principles. Advantages of vacuum injection method include 1) simple operation and no moving parts, 2) easy installation and maintenance, 3) better control on injection rates, 4) ideal for dry formulations, and 5) no power or fuel needed for pump operation. For this injection method, it is necessary that the pressure produced by the centrifugal pump be higher than the pressure in the irrigation line. The flow rate of the chemical from the pump, however, depends on the pressure in the irrigation mainline. The higher the pressure, the smaller the flow rate from the injection pump. Hence, centrifugal pumps require periodical calibration that is recommended in order to precisely control the injection rates (Boman *et al.* 2004).

Ideal and efficient chemigation equipment can 1) facilitate large scale chemigation, 2) control the duration and proportion of chemical application, and 3) ensure on-time start and completion of the chemigation process. The injection method should be compatible with the irrigation system and the type of crop (i.e., fruit trees or regular field crops). Incompatible chemical injectors may damage the irrigation system itself and reduce system application efficiency and/ or chemigation efficiency. Details on different types of injection devices including proportional injectors, and centrifugal and positive displacement pumps can be found elsewhere (Boman *et al.* 2004).

Backflow prevention mechanism for chemigation safety

A safe chemigation operation requires the system components (i.e., supply tank, injection devices, and irrigation system) to be connected securely and properly. The supply tank is connected to the irrigation system via a supply pipeline. Two small open-ended tubes are placed in the supply pipeline; the end of one tube faces upstream, while the end of the other tube faces downstream. The water that flows through the supply tank displaces the chemical stored in the tank and the displaced chemical is forced into the irrigation supply line. The water pressure causes water to flow into the upstream tube and the chemical out of the downstream tube, as result of differential pressure between up- and downstream ends. The water pressure can be controlled using a pressure-reducing valve that is installed between the inlet and outlet ports in the supply pipeline. There is a high risk of contamination if a proper backflow prevention mechanism is not maintained. Possible contamination causes include discontinuation in water supply and the simultaneous operation of chemical injection unit. This situation worsen if the irrigation water flows back through the injection unit into the chemical storage tank causing the tank to overflow. Check valves (in the mainline and in the injection line), vacuum relief valve, low pressure drains, and interlocking circuits are among useful backflow prevention devices and are described in **Table 2**.

Chemigation systems are calibrated for specific chemical concentrations, irrigation system types and their application efficiency. Change in any of above scenarios necessitates recalibration of the systems. Calibration procedures vary depending upon the injection method used and the specific design of the injection equipment. Commercially available, properly calibrated chemigation systems eliminate many steps of calibration, including weighing of fertilizers, determining the required nutrients concentration, manually setting the knobs for the required concentration, and calculations of irrigation application rates. Boman *et al.* (2004) suggested that commercially available calibration should be verified by using a chemical flow meter or by using volumetric measurement for the accuracy of rate injected.

CHEMIGATION EFFICIENCY

Since non-efficient chemigation can cause poor plant growth (Mortvedt 1997), chemigation is aimed to efficiently apply plant chemicals (i.e., fertilizers) to the wetted and active root area. Koo (1980) highlighted the importance of a minimum coverage of 60-70% of the ground surface area by irrigation water for uniform nutrient application and high plant nutrient uptake. Chemigation uniformity is related to chemigation efficiency that optimizes the amount of the required chemicals and thus, the production costs, and minimizes the risk of potential groundwater degradation. Two types of application uniformity include 1) field uniformity: even distribution of fertilizer throughout the field; and 2) localized uniformity: chemical distribution around the system dripline (Hanson *et al.* 2006). Chemigation efficiency is judged from the major benefits accrued, which include 1) regulated and well monitored application of chemicals, 2) energy and labor savings, 3) better resource management, 4) continuous dry crop foliage that prevents leaf burn and the establishment of plant pathogens, 5) control and flexibility in time of nutrient application, 6) application of chemicals under certain restricted conditions, e.g., when crop or soil conditions would otherwise prohibit the workers' entry into the field, and 7) possibility of use of precise, complex and/ or readily mixed solution compounds.

Although chemigation efficiency is related to irrigation efficiency and chemigation system design, best management practices (BMPs) are necessary to ensure high chemigation efficiency. Low irrigation efficiency systems can not uniformly apply fertilizers to citrus groves. Koo (1980) evaluated fertilization of citrus through sprinkler irrigation systems and reported no difference in the mineral content of leaves, fruit quality and fruit production between the conventionally applied dry fertilization and liquid fertilization through overhead sprinkler systems. Boman (1996) reported a higher fertilizer use efficiency by the combined use of dry (dry fertilizer broadcasted in the beginning of the cropping season) and liquid fertigation (as remainder applications) as compared with conventional broadcast application of dry fertilizer application only throughout the cropping season.

Management practices for high chemigation efficiency

Other than the irrigation systems and chemigation system design, the chemigation efficiency depends on factors, including soil type, crop stage, chemical type, chemigation time, and irrigation water quality. Soil types, along with the physical and chemical characteristics of the soil (i.e., texture, pH, or percentage of Na, Ca and other elemental composition that enhance adsorption of the applied nutrients), influence the performance of chemigation operation. For example, sandy soils require frequent chemigation in small doses than clay loams. Soils with P fixation characteristics also require frequent and small doses of P applications. Similarly, if the soil has high pH, the application of NH_3 fertilizer will result in loss of NH_3 via volatilization. Plant nutrient requirements vary with plant phenological growth stages; less nutrients are required at initial stages of growth than at later growth stages. Therefore, chemigation is gene-

Table 2 Backflow prevention devices and their description.

Devices	Description
Mainline check valve	It is installed upstream from the injection point to prevent water stored in the pipelines from flowing back into the well after the pump shuts off.
Injection line check valve	It prevents water from flowing into the chemical tank if the injection pump unexpectedly shuts off.
Vacuum relief valve	It is installed between pump and check valve to prevent a vacuum from developing in the pipeline after the pump is shut off.
Low pressure drains	These are installed between the check valve and pump to drain any water leaking past the check valve.
Interlocking circuits	The circuits turn off the electrical injection equipment if the irrigation pump unexpectedly shuts off.

rally more effective at high growth and development stages than at low, slow or no growth stages.

Chemigation is usually performed during day hours; however, when NH_3 fertilizer is used with a sprinkler system, chemigation is performed under the lowest possible temperature conditions to minimize potential NH_3 volatilization. Since NH_3 volatilization can be higher during sunny and windy conditions especially in alkali soils, chemigation is usually not conducted under these weather conditions. In the case of high saline irrigation water, it is preferable to inject small amounts of chemical. High irrigation water pH (e.g., > 7.5) adversely affects the solubility of certain fertilizers; the use of buffers or mild acids is suggested under such conditions. Hard water that contains a high content of Ca and Mg facilitates the formation of precipitates of P. Additionally, remnants of N fertilizers in the irrigation systems due to improper system flushing can contribute to algae or microbial growth that potentially can cause system clogging. Under these circumstances, frequent injection of chlorine could minimize plugging problems.

Chemigation frequency

High nutrient application rates, low plant nutrient uptake, and shallow citrus root zone (Marler and Davies 1989; Paramasivam *et al.* 2000; Kusakabe *et al.* 2006) pose a potential risk of nutrient leaching losses upon excessive irrigation or heavy rainfall events (Syvertsen and Smith 1995; Kusakabe *et al.* 2006). Due to the shallow rooting system of citrus trees, e.g., more than 80% of roots are within the top 30 cm soil layer (Paramasivam *et al.* 2000), it is important to lower the fertilizer rates and increase chemigation frequency to minimize nitrate leaching (Willis *et al.* 1990; Alva and Paramasivam 1998; Alva *et al.* 1998; Kusakabe *et al.* 2006). Light and frequent chemigation generally increase the fertilizer uptake efficiency of plants (Malo 1974; David 1975). Frequent application of N may result in on-time N availability to the citrus trees and storage of excessive N in plant tissues (Weinbaum *et al.* 1984; Kato 1986) for later use. Frequent chemigation is reported to increase the growth of young citrus trees (Willis *et al.* 1990), improve plant N uptake (Legaz and Primo-Millo 1988), and minimize NO_3 leaching (Willis and Davies 1990).

Studies on citrus chemigation frequency have been extensively reported in the literature (Marler and Davies 1990; Willis *et al.* 1991; Syvertsen and Smith 1995; Tucker *et al.* 1995; Boman 1996; Alva and Paramasivam 1998; Alva *et al.* 1998). Willis *et al.* (1990) recommended a weekly or bi-weekly chemigation. The University of Florida reduced the recommended fertilizer rates to 50% for the first 3 years after the planting of young citrus trees (Tucker *et al.* 1995). Syvertsen and Sax (1999) conducted chemigation frequency tests on lysimeter-grown citrus trees that were weekly and bi-weekly N fertigated with microsprinklers. They recommended that the young citrus trees can be grown in sandy soils with minimum N leaching if annual rates of N application are conducted in split applications. Thompson *et al.* (1999) evaluated the effects of chemigation frequency on the yield and fruit quality of microsprinkler-irrigated grapefruit to develop best management guidelines for N fertigation. Their treatments included weekly, monthly, and tri-monthly chemigation frequencies; the former two treatments were reported to increase fruit yield. Banňuls *et al.* (2003) conducted a field experiment using nutrient application at 1, 2, 4, and 8 week intervals in drip-irrigated orchard of Clementine (*Citrus clementina* Ort. ex. Tan) grafted on Troyer citrange (*C. sinensis* × *Poncirus trifoliata*) rootstock in the Valencian Citrus area of Spain. They reported that the application frequency did not have any consistent effect either on fruit yield and quality or on concentrations of macro- and micronutrients in plant leaves. Arpaia and Lund (2003) reported no difference in N uptake in citrus trees between one time N application via surface broadcast and frequent chemigation, i.e., during every irrigation event applied from winter to summer. Little or no relationship between citrus yield and chemigation has also been reported in literature (Hanson *et al.* 2006; Kusakabe *et al.* 2006).

CITRUS CHEMIGATION STUDIES

Historical advancement in pressurized irrigation (Calvert and Reitz 1965; Bester *et al.* 1977; Koo 1980; Smarjstrla *et al.* 1991) and availability of soil water content measuring devices (Fares and Alva 2000) have made chemigation adaptable to a wide range of annual (Thompson *et al.* 2002; Darwish *et al.* 2003) and perennial crops (Marsh and Stowel 1993) including citrus (Alva and Paramasivam 1998; Paramasivam *et al.* 2001, 2002; Alva *et al.* 2005; Kusakabe *et al.* 2006). This section summarizes a few short- and long-term studies on the effect of chemigation on citrus tree growth, fruit yield and quality, plant nutrient uptake, and nutrient leaching.

Short-term studies

Willis *et al.* (1991) studied the growth parameters of 'Hamlin' orange trees on 'Sour Orange' rootstock grown on a Kanapaha fine sand (loamy, siliceous, hyperthermic, Grossarenic Paleaquults) in Florida. They used two N rates (i.e., 0.06 and 0.11 kg N $tree^{-1}$ yr^{-1}) applied as dry granular broadcast (5 applications yr^{-1}) and as chemigation (i.e., 5, 10, or 30 applications yr^{-1}). They reported that neither the tree height nor the trunk diameter was significantly influenced by either N application methods or chemigation frequency for any of the N rates used.

Thompson *et al.* (2000) conducted field studies on 5-year old 'Newhall' navel orange trees on 'Carrizo' citrange rootstock on a Gilman loam soil in Maricopa County, Arizona. Three rates of N (i.e., 68, 136, and 204 g N $tree^{-1}$ yr^{-1}) were used with 3 application frequencies (i.e., weekly, monthly and 3 application yr^{-1} [27, 7, or 3 applications yr^{-1}]). Results of this study indicated that increasing N rates significantly increased the leaf N concentration, particularly at the 136 and 204 g N $tree^{-1}$ rates, compared with that of the trees which were unfertilized. The results further demonstrated that weekly application of either 68 or 136 g N $tree^{-1}$ yr^{-1} significantly increased the fruit yield compared with that of trees which were unfertilized. Another parallel study (Weinert *et al.* 2002), with experimental conditions similar to Thompson *et al.* (2000), reported that only 25% of N fertilizer was taken up by the trees; therefore, a non-significant effect of N rates and/or of application frequency is justified.

Schumann *et al.* (2003) reported on 2 years of data on the response of 7-8 year old 'Hamlin' orange trees (*Citrus sinensis* [L.] Obs.) on Swingle citrumelo (*Citrus paradise* Macf. × *Poncirus trifoliate* [L.] Raf.) grown on a Candler fine sand (hyperthermic, coated Typic Quartzipsamments) in Polk County, Florida. Water soluble granular (WSG; 4 equal split dose applications yr^{-1}), fertigation (FRT; 15 application yr^{-1}), or controlled release fertilizer (CRF; one application yr^{-1}) for 4 N application rates (i.e., 78, 134, 190, and 246 kg ha^{-1} yr^{-1}) were evaluated. The authors found that at the optimal N rates, the peak fruit yield was 20 Mg ha^{-1}

Table 3 Yield parameters of 7 and 8-year old 'Hamlin' orange trees on 'Swingle' citrumelo rootstock grown on a Candler find sand in Florida as affected by fertilizer sources (i.e., water soluble granular and fertigation). Yield response data are cumulative for the year 7 and 8.

Yield parameters	Dry granular	Fertigation	% Reduction with fertigation
Soluble solids (Mg ha^{-1})	175	145	21
Fruit yield (Mg ha^{-1})	150	135	11
Juice yield (Mg ha^{-1})	160	130	23
Tree canopy (m^{-3} $tree^{-1}$)	190	150	27
Fruit numbers (fruits ha^{-1})	230	160	44
Leaf N concentration (g kg^{-1})	230	195	18

Source: Data extracted from Schumann *et al.* (2003).

for WSG source, while it was close to 25 Mg ha^{-1} for the FRT source. Similarly, the optimal N rates for juice yield were close to 15 and slightly less than 12 Mg ha^{-1} for FRT and WSG, respectively (**Table 3**).

Kusakabe *et al.* (2006) conducted a 3-year field experiment in central Arizona to evaluate the effects of various N rates and chemigation frequencies on fruit yield and quality, leaf N concentration, and residual soil N of 'Newhall' navel oranges (*Citrus sinensis*) on 'Carrizo' citrange (*Porcirus trifoliata x Citrus sinensis*) rootstock grown on a Gilman (coarse-loamy, mixed, superactive, calcareous, hyperthermic Typic Torrifluvents) fine sandy loam. Their experiment included unfertilized control plots and the combinations of three chemigation frequencies (27, 9, and 3 applications yr^{-1}) and three N rates (68, 136, and 204 g N $tree^{-1}$ yr^{-1}). The authors reported that 1) the maximum yields occurred at N rates of 105 to 153 g N $tree^{-1}$ yr^{-1}, 2) the optimal N rates were equivalent to 17 to 34% of currently recommended N rates for citrus grown in Arizona, 3) fruit and juice quality did not show significant response to N rate or chemigation frequency, 4) leaf N concentrations at optimum N rates were above the critical leaf tissue N range of 25 to 27 mg g^{-1}, and 5) higher residual soil NO_3 concentrations were resulted from the highest N rate. They concluded that the optimum N rates for microsprinkler-irrigated 'Newhall' navel oranges in Arizona are lower than the currently recommended N rates.

Long-term studies

Paramasivam *et al.* (2001) and Alva *et al.* (2005) reported the findings of a 6-year field experiment that was conducted in a Tavares fine sand (hyperthermic, uncoated Typic Quartzipsamments) in central Florida using 25+ year old 'Hamlin' orange trees on 'Cleopatra mandarin' rootstock (286 trees ha^{-1}) to evaluate the effects of various rates and sources of fertilizers on fruit yield and fate of N in the soil. Three years mean fruit yield response to N rates in the range of 112 to 336 kg ha^{-1} as WSG (4 applications yr^{-1}) and in the range of 112 to 280 kg ha^{-1} as FRT (18 applications yr^{-1}) was quadratic with optimum N rate 260 kg ha^{-1} for both sources of fertilizer application. There were no significant differences between the WSG and FRT sources across the range of N rates used in this study. However, their highest N application rate (i.e., 336 kg ha^{-1}) was only evaluated for the WSG. With regards to fruit yield response, the authors concluded that, chemigation failed to demonstrate significant yield advantage over the WSG broadcast application.

For the fate of the applied N in the soil, irrigated using under the tree microsprinkler irrigation system and fertilized with 112 to 168 kg N ha^{-1} as CRF (1 application yr^{-1}) and above reported WSG and FRT, the cumulative leaching loss of NO_3-N below 240 cm soil depth was observed. Similar to the yield response to various sources of N application, chemigation also failed to reduce leaching losses below the root zone compared to that of WSG or CRF. The authors attributed this finding to unexpected rainfall following certain chemigation events.

Alva *et al.* (2003) conducted a nutrient management practice demonstration project using two identical (32 ha each) citrus blocks of 34+ years old 'Valencia' orange trees on 'Rough lemon' rootstock planted (286 trees ha^{-1}) in an Astatula fine sand in Highlands County, Florida. Both blocks were irrigated using under the tree low volume sprinklers with one emitter per tree and a delivery rate of 96 L hr^{-1} and wetting area of 28 m^2 $tree^{-1}$. During 1993 and 1994, both blocks were on similar management practices, including fertilizer application of 197 and 209 kg N ha^{-1}, respectively. Dry granular sources of N, P, and K were used with the annual rates split in 3 broadcast applications (i.e., Jan/Feb, May/Jun, and Sep/Oct). For the next 4 years, the two blocks received different fertilizer management combined with irrigation management, while keeping all other tree management practices similar across the two blocks. Nitrogen rate was about 180 kg ha^{-1} for both blocks. For one block, dry granular product along with P and K sources (in a NPK blend of 1:0.5:1) were broadcasted 3 times a year (i.e., Jan/Feb, May, and Sep). While the second block received the same annual N rate except that NPK blend was applied in 18 fertigations $year^{-1}$ (i.e., Jan/May and Sep/Oct). No fertilizer was applied during June through August due to heavy rainfall (60% of total annual precipitation). The results showed that the cumulative fruit yield over the 4-year period increased by 11%, while total soluble solids (TSS) increased by 16% with FRT compared to that of WSG.

In the same project study, the NO_3-N concentration in the surficial aquifer was monitored by sampling four monitoring wells in each block. Surficial aquifers are separated from regional confined aquifer systems and are generally under unconfined water table conditions. Surficial aquifer system consists of mostly beds of unconsolidated sand, shelly sand, and shell that lie typically 15–30 m underground. Surficial aquifer is mainly used for domestic, commercial, or small municipal supplies. Surficial aquifer NO_3-N concentration before the start of this project was above the maximum contaminant limit (MCL) of 10 mg L^{-1} in both citrus orchards. As the study progressed, the NO_3-N concentration in the groundwater decreased well below the MCL in the orchard that was under chemigation. These NO_3-N concentrations were significantly lower than those in the groundwater underneath the citrus orchard which received broadcast application of dry granular fertilizer. In the citrus orchard that received WSG treatment, the surficial aquifer NO_3-N concentrations generally remained above the MCL. This long-term study demonstrated, for the first time, the beneficial effects of fertigation in decreasing NO_3-N loading into the surficial aquifer underneath citrus groves in sandy soils under high summer rainfall conditions.

FUTURE RESEARCH

Long-term citrus field studies in Florida successfully demonstrated the substantial benefits of N chemigation in terms of fruit yield and quality and also in reducing NO_3-N leaching to the groundwater. Based on the recent research developments and the advancements in technology, there is an urgent need for continuous evaluation of developed citrus BMPs to enhance water- and nutrient use efficiency in citrus orchards. Developed BMPs can be fine tuned by automating and integrating chemigation systems to minimize nutrient losses for better economic returns to the citrus-based community and industry, as well as for the sustainability of chemigated groves.

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