Managing Irrigation and Fertilizer

In hydroponic crop production systems, water application is integrated with fertilizer feed application. The management of fertilizer application to the plants is therefore integrated with the management of watering. The management of watering and nutrition is focused on the optimal delivery of water and nutrients over the various growth stages of the plant to maximize yield through the changing growing environment over the production year.

Water

Water quality

Plants are comprised of 80 to 90 per cent water, and the availability of adequate quality water is very important to successful crop production. Water quality is determined by what is contained in the water at the source (well, dugout, town or city water supply) and the acidity or alkalinity of the water.

Water is a solvent, and as such, it can contain or hold a certain quantity of soluble salts in solution. Fertilizers, by their nature, are soluble salts, and growers dissolve fertilizers in water to obtain nutrient solutions to provide the plants with adequate nutrition.

Before using any source of water for crop production, it is important to have the water quality tested. Water quality tests determine the amount of various salts commonly associated with water quality concerns. The maximum desirable concentrations, in parts per million (ppm), for specific salt ions in water for greenhouse crop production are presented in Table 3.

Table 3. The maximum desirable concentrations, in parts per million (ppm), for specific salt ions in water for greenhouse crop production.

Element	Maximum Desirable (ppm)
Nitrogen (NO_3 - N)	5
Phosphorus (H_2PO_4 - P)	5
Potassium (K^+)	5
Calcium (Ca^{++})	120
Magnesium (Mg^{++})	25
Chloride (Cl^-)	100
Sulphate (SO_4^-)	200
Bicarbonate (HCO_3^-)	60
Sodium (Na^{++})	30
Iron (Fe^{+++})	5
Boron (B)	0.5
Zinc (Zn^{++})	0.5
Manganese (Mn^{++})	1.0
Copper (Cu^{++})	0.2
Molybdenum (Mo)	0.02
Fluoride (F-)	1
pH	7.5
E.C.	1.0 mmho

Parts per million are one unit of measurement of the amount of dissolved ions, or salt in water, and are also used to measure the level of dissolved fertilizer salts in nutrient solutions. The level of nutrients as dissolved ions in water can also be reported in milligrams/Litre of solution. There is a direct relationship between milligrams/Litre (mg/L) and ppm, where 1 mg/L = 1 ppm. Another common unit of measure for dissolved fertilizer salts is the millimole (mM). The concept of millimoles and the relationship between millimoles and ppm is explained in the "Feed Targets and Plant Balance" section. Water quality tests will also report the pH, the acidity or alkalinity of the water.

Once the water source has been determined to be suitable for greenhouse crop production, it is also important to have the water tested routinely to ensure any fluctuations in quality that may occur do not compromise crop production.

Electrical Conductivity of Water

Water quality analyses also report the electrical conductivity or E.C. of the water. The ability of water to conduct an electrical current depends on the amount of ions or salts dissolved in the water. The greater the amount of dissolved salts in the water, the more readily the water will conduct electricity.

Electrical conductivity is an indirect measure of the level of salts in the water and can be a useful tool for both determining the general suitability of water for crop production and for the ongoing monitoring of the fertilizer feed solution. Using electrical conductivity as a measure to maintain E.C. targets in the nutrient solution and the root zone can be a management tool for making decisions regarding the delivery of fertilizer solution to the plants.

Electrical conductivity is measured and reported using a number of measurement units including millimhos per centimeter (mmho/cm), millisiemens per centimeter (mS/cm) or microsiemens per centimeter (μS/cm). Water suitable for greenhouse crop production should not have a E.C. of more than 1.0 mmho/cm.

1 mmho/cm = 1mS/cm = 1000 μs/cm

pH

The relative acidity and alkalinity of the water is expressed as pH, and is measured on a scale from 0 to 14. The lower the number, the more acidic the water or solution; the higher the number, the more alkaline. The pH scale is a logarithmic scale, meaning that every increase of one number, i.e. 4 to 5, represents a tenfold increase in alkalinity. Conversely, every single number decrease, i.e. 5 to 4, represents a tenfold increase in acidity.

Most water supplies in Alberta are alkaline, with typical pH levels of 7.0 to 7.5. Alkalinity of the water increases with increasing levels of bicarbonate. The pH measurement reflects the chemistry of the water and nutrient solution. The pH of a fertilizer solution has a dramatic determining effect on the solubility of nutrients and how available nutrients are to the plant.

The optimum pH of a feed solution, with respect to the availability of nutrients to plants, falls within the range of 5.5 to 6.0. The pH of a solution can be adjusted through the use of acids, such as phosphoric or nitric acid, or potassium bicarbonate, depending on which direction the feed solution needs to be adjusted. When acids or bases are used to adjust the pH of the feed solution, the nutrients added by the acid (nitrogen, phosphorus) must be accounted for when the feed solution is calculated. Most water supplies in Alberta are basic in pH and require the use of acid for pH correction.

The amount of acid required to adjust the pH usually depends on the bicarbonate (HCO_3-) level in the water. The amount of bicarbonate in the water supply can be determined by a water analysis and is reported in parts per million (ppm). A good target pH for nutrient feed solutions is 5.8, and as a general rule, this pH corresponds to a bicarbonate level of about 60 ppm. If the incoming water has, for example, a pH of 8.1 and a bicarbonate level reported at 207 ppm, then 207 ppm - 60 ppm = 147 ppm of bicarbonate, which needs to be neutralized by acid to reduce the pH from 8.1 to 5.8.

To neutralize 61 ppm or 1 milliequivalent of bicarbonate, it takes about 70 ml of 85 per cent phosphoric acid, or about 76 ml of 67 per cent nitric acid per 1,000 litres of water. To neutralize 147 ppm of bicarbonate, the following approach could be used:

Using 85% phosphoric acid:

140 ÷ 61 = 2.3 milliequivalents of bicarbonate to be neutralized.
2.3 milliequivalents x 70 ml of 85% phosphoric acid for each milliequivalent = 2.3 x 70 ml = **161 mls** of 85% phosphoric acid for every 1,000 litres of water.

Using 67% nitric acid:

2.3 milliequivalents of bicarbonate to be neutralized.
2.3 milliequivalents x 76 ml per milliequivalent = 2.3 x 76 ml = **175 mls** of 67% nitric acid for every 1,000 litres of water.

These calculations have to be made for each water sample based on the results of a water analysis reporting the level of bicarbonates. In addition to phosphoric and nitric acid, sulfuric and hydrochloric acids can also be used to adjust the pH of the water down.

Acids are corrosive. Special care and attention must be used when handling them for pH correction. The common acids used to lower the pH are phosphoric acid (85 per cent) and nitric acid (67 per cent). Of these two, nitric acid is the most corrosive and must be handled very carefully. Acid resistant safety glasses, rubber gloves and a rubber apron should be the minimum safety equipment used when handling acids.

Mineral Nutrition of Plants

To support optimum growth, development and crop yield, the fertilizer feed solution has to continually meet the nutritional requirements of the plants. Although the mineral nutrition of plants is complex, experience in crop culture has determined basic requirements for the successful hydroponic culture of plants.

There are 12 mineral elements considered essential for plant growth. Water (H_2O) and carbon dioxide (CO_2) are also necessary for plant growth and supply hydrogen, carbon and oxygen to the plants, bringing the total to 15 essential elements.

A criterion to determine whether an element is essential to plants is to determine if the plant cannot complete its life cycle in the complete absence of the element.

Other elements, although not necessarily considered universally essential, can affect the growth of plants. Sodium (Na), chloride (Cl) and silicon (Si) are in this category. All three of these nutrients either enhance the growth of plants or are considered essential nutrients for some plant species.

The essential nutrients can be grouped into two categories that reflect the quantities of the nutrients required by plants. Macronutrients, or major elements, are required by plants in larger quantities than the amounts of micronutrients, or trace elements, required for growth (Table 4).

Another useful grouping of the mineral nutrients is based on the relative ability of the plant to translocate the nutrients from older leaves to younger leaves. Mobile nutrients are those that can be moved readily by the plant from older leaves to younger leaves. Nitrogen is an example of a mobile nutrient. Calcium is an example of an immobile nutrient, one which the plant is not able to move after it has initially been translocated to a specific location.

The discussion of plant nutrients only as elements does not allow for a more complete discussion of how plants access the elements from the root environment and how hydroponic growers ensure their crop plants are adequately supplied with nutrients. The term "element" can be defined as a substance that cannot be broken down into simpler substances by chemical means; the basic unit of an element is the atom. With the simplest or purest form of plant nutrients being the atom, nutrients are often not available to plants in their purest form. Pure nitrogen is an example of a nutrient element represented by its atom.

Table 4. Essential mineral elements for plants.

Element	Symbol	Type	Mobility in Plant	Symptoms of Deficiency
Nitrogen	N	macronutrient	mobile	Plant light green, lower (older) leaves yellow.
Phosphorus	P	macronutrient	mobile	Plant dark green turning to purple.
Potassium	K	macronutrient	mobile	Yellowish green margins on older leaves.
Magnesium	Mg	macronutrient	mobile	Chlorosis between the veins on older leaves first, turning to necrotic spots, flecked appearance at first.
Calcium	Ca	macronutrient	immobile	Young leaves of terminal bud dying back at tips and margins. Blossom end rot of fruit (tomato and pepper).
Sulfur	S	macronutrient	immobile	Leaves appear light green.
Iron	Fe	micronutrient	immobile	Yellowing between veins on young leaves (interveinal chlorosis), netted pattern.
Manganese	Mn	micronutrient	immobile	Interveinal chlorosis, netted pattern.
Boron	B	micronutrient	immobile	Leaves of terminal bud becoming light green at bases, eventually dying. Plants "brittle."
Copper	Cu	micronutrient	immobile	Young leaves dropping, wilted appearance.
Zinc	Zn	micronutrient	mobile	Interveinal chlorosis of older leaves.
Molybdenum	Mo	micronutrient	immobile	Lower leaves pale, developing a scorched appearance.

When the atoms of different elements combine, they can form other substances that are based on a particular combination of atoms, substances based on molecules. Nitrate (NO_3-), is a molecule based on nitrogen and oxygen atoms; nitrate is absorbed by plant roots as a source of nitrogen. Nitrate is an "available" form of nitrogen (Table 5). The nitrate molecule has an overall negative charge, which causes the molecule to be fairly reactive chemically and therefore more available.

The availability of nutrient elements to plants is generally based on the existence of the nutrient element as a charged particle, either a charged atom or charged molecule. An atom or molecule that carries an electric charge is called an ion. Positively charged ions are called cations, while negatively charged ions are called anions. The nitrate molecule (NO_3^-) is an anion, while the iron atom can exist as the Fe^{+2} (ferrous) or Fe^{+3} (ferric) cations. Plants are able to acquire the essential mineral elements via the root system utilizing the chemical properties of ions. In particular, to acquire negatively charged anions, the plant roots have sites that are positively charged. The plant is also able to attract positively charged cations to negatively charged sites on the root.

Water is a very important component in the plants acquisition of nutrient elements because the nutrient ions exist only when they are in solution, when they are dissolved in water. As solids, the ions generally exist as salts; a salt can be defined as any compound of anions and cations. In the absence of water, the nutrient ions form compounds with ions of the opposite charge. Anions combine with cations to form a stable solid compound.

For example, the nitrate anion (NO_3^-) commonly combines with the calcium (Ca^{+2}) or potassium (K^+) cations forming the larger calcium nitrate $Ca(NO_3)_2$ or potassium nitrate (KNO_3) salt molecules. As salts are added to water, they dissolve, or dissociate, into their respective anion and cation components. Once in solution, these components become available to plants.

Table 5. Forms of nutrient elements commonly available to plants.

Element	Symbol	Available as	Symbol
Macronutrients:			
Nitrogen	N	Nitrate ion	NO_3^-
		Ammonium ion	NH_4^+
Phosphorus	P	Monovalent phosphate ion	$H_2PO_4^-$
		Divalent phosphate ion	HPO_4^{-2}
Potassium	K	Potassium ion	K^+
Calcium	Ca	Calcium ion	Ca^{+2}
Magnesium	Mg	Magnesium ion	Mg^{+2}
Sulfur	S	Divalent sulfate ion	SO_4^{-2}
Chlorine	Cl	Chloride ion	Cl^-
Micronutrients:			
Iron	Fe	Ferrous ion	Fe^{+2}
		Ferric ion	Fe^{+3}
Manganese	Mn	Manganous ion	Mn^{+2}
Boron	B	Boric acid	H_3BO_4
Copper	Cu	Cupric ion chelate	Cu^{+2}
		Cuprous ion chelate	Cu^+
Zinc	Zn	Zinc ion	Zn^{+2}
Molybdenum	Mo	Molybdate ion	MoO_4^-

An important point to remember is that different salts have different solubilities; that is, some salts dissolve readily in water (highly soluble), and some salts do not. Calcium sulfate ($CaSO_4$) is a relatively insoluble salt and would be a poor choice as a fertilizer because very little of the calcium would go into solution as the calcium cation (Ca^{++}) and be available to plants. Fertilizer salts, by their very nature, are useful because they go into solution readily. In hydroponic culture, greenhouse growers formulate and make a water-based nutrient solution by dissolving fertilizer salts.

In addition to existing as salts, some of the micronutrients (iron, zinc, manganese and copper) exist in chelates. A chelate is a soluble product formed when certain atoms combine with certain organic molecules. The sulphate salts of iron, zinc, manganese and copper are relatively insoluble, and chelates function to make these mineral nutrients more readily available in quantity to the plants.

Fertilizer Feed Programs

Fertilizer nutrient solutions are formulated to meet the needs of the plants using a combination of component fertilizer salts. The amounts of the various fertilizers used depend on target levels that have been determined to be optimal for the crop in question.

Although there is considerable similarity between fertilizer programs for the various vegetable crops, there can be some differences reflecting the different crop requirements. In any event, when mixing fertilizer solutions, only high quality, water-soluble fertilizers should be used.

The required nutrient levels, or target nutrient levels, of the various essential elements are often expressed as the desired parts per million (ppm) in the final nutrient solution. The recommended nutrient fertilizer feed targets for greenhouse peppers are listed in Table 6.

Table 6. Nutrient feed targets (ppm) for greenhouse sweet peppers grown in sawdust.	
Nutrient	Target (ppm)
Nitrogen	200
Phosphorus	55
Potassium	318
Calcium	200
Magnesium	55
Iron	3.00
Manganese	0.50
Copper	0.12
Molybdenum	0.12
Zinc	0.20
Boron	0.90

Even though all 12 mineral elements are essential for plant growth and development, nutrient targets for sulfur and chlorine (not considered universally essential) are not listed. The reason for this omission is that adequate amounts of sulfur are obtained from the use of sulfate fertilizers, potassium sulfate or magnesium sulfate. Chloride is assumed to be present in adequate amounts as a contaminant in a number of fertilizers.

As the purity of fertilizers has improved, growers will have to pay more attention to ensuring these other elements, particularly chloride, are present in adequate amounts. Once the recommended nutrient targets are known, calculations are made to determine how much of each fertilizer is needed to meet these targets.

To make these calculations, some other basic information is required:

- the volume of water that will be used to make the feed solution.
- the types of fertilizers available and the relative amounts of each nutrient present in the fertilizer.

When considering what volume of water to use for the nutrient solution, it is first important to understand the delivery of the nutrient solution to the plants as discussed earlier in the "Irrigation and Fertilizer Feed" section.

Every greenhouse must be able to supply water and nutrients to the plants on an ongoing basis. During hot, dry Alberta summers, mature pepper plants can use approximately 3.5 to 4.0 litres of water per plant per day, while cucumbers can require over 6 litres and tomatoes up to 3 litres. This water always contains fertilizer, which is added as the water comes into the greenhouse, before it is pumped to the plants. Greenhouses may vary in their delivery systems, but some form of fertilizer injection system is used in all commercial scale greenhouses.

Feed targets and plant balance

The first approach to altering the feed solution in response to a crop that is overly vegetative is to increase the feed electrical conductivity (E.C.) to direct the plants to become more generative and set and fill more fruit. The feed E.C. can be increased from 2.5 mmhos to approximately 3.0 mmhos over the course of a few days.

Dialing up the feed E.C. increases the absolute amounts of fertilizer nutrients in the feed, but does not affect the ratio of the nutrient levels with respect to one another. Increasing the feed E.C. increases the level of fertilizer salts in the root zone, increasing the stress on the plant as it becomes more difficult for the plant to take up water. The plant responds to the stress by putting more emphasis on fruit production, a stressed plant begins preparations for the end by trying to ensure that the next generation will carry forward. The fruit holds the seed, and in plant terms, developing fruit means that the next generation will survive and carry on. Plants don't think these things out, but stressing the plant does direct the plant to set more fruit. There is a limit to how far growers can go with this technique because a successful crop requires having enough vegetative growth to continually fill a high volume of fruit consistently throughout the season.

Another option is available for affecting the vegetative/generative balance of the plants through manipulating the nutrient ratios, particularly the nitrogen-potassium ratio (Table 7).

Table 7. Typical absolute value and relative ration targets for N*, K*, and Ca* in vegetable feed programs (E.C. of 2.5 mmhos) for Southern Alberta production conditions.

	Nutrient Targets Crop			Nutrient Ratio (ppm)		
	N	K	Ca	N	K	Ca
cucumber	200	302	173	1.00	1.51	0.86
pepper	214	318	200	1.00	1.48	0.93

* N = Nitrogen, K = Potassium, Ca = Calcium

The N:K ratios presented in the table are all about 1:1.5. Increasing the level of potassium, with respect to nitrogen, and increasing the ratio to 1:1.7 will direct the plant to be more generative. The reason for this change is that nitrogen promotes vegetative growth while potassium promotes mature growth, generative growth. Calcium is also important for promoting strong tissues, fruit and mature growth. Shifting the feed program to favor potassium over nitrogen will direct the plant to be generative. Calcium is important in the equation in that it should always be approximately equal to the amount of nitrogen. A N:Ca ration of 1:1 works for both tomatoes and peppers, while a N:Ca ratio of 1:0.85 has shown to work well for cucumbers.

Changes to the N:K ratio should be made carefully. The above ratios come from the feed programs of successful Alberta growers and can serve as a guide. The place to start is to determine the ratios in the current feed program and examine the performance of the crop. If it is determined that there is room for improving the balance of the plants, alterations in the nutrient ratios can be undertaken.

Always be aware that many factors influence plant balance: day/night temperature split, 24-hour average temperature, relative humidity and watering. These factors should be optimized before feed ratios are changed. You have to know where the crop is in order for you to make sound decisions on where it should be and how to get there.

Due to the large volumes of fertilizer feed solution that can be required daily, it is impractical to make the fertilizer feed on a day-to-day basis. Instead, the required fertilizers can be mixed in a concentrated form, usually 100 to 200 times the strength delivered to the plants. Injectors or ratio feeders are then used to "meter-out" the correct amount of fertilizer into the water that make up the nutrient solution going to the plants.

By using concentrated volumes of the fertilizer feed held in "stock tanks," growers are able to reduce the number of fertilizer batches they have to make. Depending on the number of plants in the crop, the size of the stock tanks and the strength of the concentrate, growers may only have to mix fertilizer once every two to four weeks.

Designing a fertilizer feed program

The design of a fertilizer feed program is a relatively straightforward process once the nutrient target levels are decided and basic information about the water quality, feed delivery system and component fertilizers is known. Fertilizer targets and the component fertilizers used to make the fertilizer solution can change over the course of the year, depending on the crop and the knowledge of the grower. The changes are often slight adjustments in the relative proportion of the macronutrients from one to another, particularly the nitrogen/phosphorus/potassium (N:P:K) ratio.

Changes can also include the addition of alternate forms of a nutrient in question. A common example is the use of ammonium nitrogen (NH_4-N) in addition to nitrate nitrogen (NO_3-N) during the summer months. Ammonium nitrate is the common source of ammonium nitrogen, which is a more readily available form of nitrogen that works to promote vegetative growth. During the summer months, a target of approximately 17 ppm of ammonium nitrogen is recommended to help optimize plant balance and crop production.

Moles and millimoles in the greenhouse

Some greenhouse vegetable growers have been concerned about millimoles and moles. Not to worry, these growers are not referring to four-legged moles. Rather, they are using another unit of measure to discuss fertilizer feed targets and root zone targets.

A millimole is one thousandth of a mole, and a mole, is defined as the amount of a substance of a system that contains as many elementary entities as there are atoms in exactly 12 grams of Carbon 12. The concept of the mole has come out of stoichiometry, a branch of chemistry that studies the quantities of reactants and products in chemical reactions.

Chemists and physicists have argued for a long time over how to measure the masses of individual elements (some of those same elements that growers feed their crops in fertilizer feed solutions), and in 1961, they settled on using the mole.

A good way to understand what a mole is and why to use it is to relate it to the concept of a dozen. We understand that a dozen is twelve of something, be it cucumbers, eggs or whatever. A mole is 6.02×10^{23} of some entity, and chemists usually refer to actual molecules of a substance when they talk about moles, although you could have a mole of eggs or a mole of cucumbers.

You would be quite the grower to grow a mole of cucumbers, tomatoes or peppers. The number 6.02×10^{23}, which in longhand is 602 000 000 000 000 000 000 000, is called Avogadro's number after the nineteenth century chemist who did some pioneering work on gases and was largely ignored for his trouble.

Moles do relate to parts per million (ppm). Both concepts are ways to measure how much of a given nutrient we are dealing with in a fertilizer feed sample, leachate or tissue sample. The difference is that ppm is a measure of mass (e.g. 1 ppm = 1 milligram/litre) while moles measure amounts. One mole of any substance contains Avogadro's number of entities or basic units. Those entities, as mentioned earlier, can be atoms or molecules or whatever you want.

When we talk about one mole of nitrate nitrogen, NO_3, we are referring to 6.02×10^{23} molecules of NO_3, because the basic NO_3 entity is made up of one atom of nitrogen (N) and three atoms of oxygen (O). If we are talking about a mole of iron, Fe, we are talking about atoms, because the basic entity of iron is the iron atom.

All atoms and molecules have different basic weights, some being heavier than others. If we talk about 1 ppm of NO_3 versus 1 ppm of Fe, we are talking about the same mass of each, i.e., 1 milligram/litre. However, there will be a different number of basic entities or moles of NO_3 and Fe in a solution that contains 1 ppm each of NO_3 and Fe.

The atomic weights of all the elements can be found on the periodic table. The atomic weights of the elements are given in grams per mole. The molecular weight of oxygen is 16 grams/mole. This means that 6.02×10^{23} atoms of oxygen weights 16 grams. One mole of nitrogen weighs 14 grams. By combining all the atoms that make up molecules we can arrive at the molecular weights. Therefore, the molecular weight of NO_3 would equal $14 + 3(16)$ grams/mole or
62 grams/mole. One last thing to remember is that moles are related to millimoles in the same way that grams are related to milligrams. So if moles are related in the range of grams, millimoles are in the range of milligrams.

We know that 1 ppm is equal to 1 milligram/litre, so to convert ppm to millimoles, divide ppm by the molecular weight of the element you are working with. For example:

---

1 ppm of NO_3 = 1 mg/litre

1 mg/ litre of NO_3 ÷ 62 mg/mole = 0.016 millimoles of NO_3 in one litre.

1 ppm of Fe = 1 mg/litre

1 mg/litre of Fe ÷ 56 mg/millimole = 0.018 millimoles of Fe in one litre.

1 ppm of magnesium (Mg) = 1 mg/litre

1 mg/litre of Mg ÷ 24 mg/millimole = 0.041 millimoles of Mg in one litre.

As these examples show, a solution containing 1 ppm of various elements or molecules will contain different mole or millimole amounts of these same elements.

To convert millimoles to ppm:

ppm = millimoles/litre x molecular weight (mg/millimole)

Example:

ppm NO_3 = 0.016 millimoles of NO_3 in one litre x 62 mg/millimole

= 1 ppm NO_3

Once you can work back and forth between ppms and millimoles, you might be asking if there is any benefit to working in millimoles rather than ppm. If you are comfortable working with ppms and you are comfortable with designing and managing your fertilizer feed programs in ppms, stick to what you know. However, if you want to be working with actual amounts of atoms and molecules of the nutrients you are feeding, then you may want to work with millimoles. Whatever the case, with a little practice you can work with either unit.

Water volumes

Calculating the required amounts of the various fertilizers depends on the volume of water to be used. This figure is determined by the volume of the stock tank (e.g. 200 litres) multiplied by the injection ratio (e.g. 100:1 or 200:1). For example, using a 200 litre fertilizer concentrate stock tank and a 200:1 injection ratio, the volume of water that will be used to calculate the amount of fertilizer to add will be:

200 litres (stock tank volume) x 200 (injector ratio)
= 40,000 litres

Calculations in the following sections on fertilizer and water will be based on 200 litre stock tanks and a 1:200 injection ratio.

Accounting for nutrients in raw water

Assuming the water quality analysis has determined the water is suitable for greenhouse crop production, the first step is to account for the nutrients already contained in the water. This information comes directly from the water analysis report.

Accounting for nutrients provided by pH adjustment of water

Next, determine if the pH needs adjusting, and if so, decide on the amount of acid (or base) required to meet the target pH of 5.8. Once the amount of acid to be added has been determined, the levels of nutrients present in the acid have to be accounted for.

Using the example in the previous section on pH, where it was determined that 161 ml of 85 per cent phosphoric acid would be required to adjust the pH from 8.1 to 5.8 for every 1,000 litres of water, the amount of acid required for 40,000 litres would be (161 ml/1,000 litres x 40,000 litres =) 6,440 mls. Knowing the volume of acid required and the specific gravity of the acid makes it is possible to calculate the weight of acid that will be used.

6,440 mls (85% phosphoric acid) x 1.41 grams/ml
= 9,080 grams of phosphoric acid

Table 8. The specific gravity of 85 per cent phosphoric acid and 67 per cent nitric acid.

Phosphoric acid (85 per cent)	1.14 grams/ml
Nitric acid (67 per cent)	1.28 grams/ml

Having the weight of the acid, it is now possible to determine the amount of phosphorus contributed to the pH-adjusted water by 85 per cent phosphoric acid. One more piece of information is required; phosphoric acid contains 32 per cent available phosphorus, which is also referred to as the fertilizer grade of the acid.

Table 9. Fertilizer "grades" of phosphoric and nitric acid.

Phosphoric acid	32 per cent available phophorous (PO_4-P)
Nitric acid	22 Per cent available nitrogen (NO_3- N)

Now, using the following formula:

Formula 1 (from Mirza and Younus, 1994)

$$\text{ppm} = \frac{\text{grams of acid x grade of acid x 10}}{\text{litres of water}}$$

the amount of phosphorus (in ppm) contributed by 7,857 grams of 85% phosphoric acid

$$= \frac{9{,}080 \text{ grams x } 32\% \text{ x } 10}{40{,}000}$$

= 73 ppm of phosphorus, actual "P"

This same sequence of calculations can be used to determine the amount of nitrogen contributed if 67 per cent nitric acid was used. In this example, 49 ppm of nitrogen would be contributed if 67 per cent nitric acid was used.

Determining fertilizers amounts to meet feed targets

For the purposes of this discussion of designing a fertilizer program, only component fertilizers will be considered. A list of the common component fertilizers for greenhouse crop production is presented in Table 10. The fertilizers are identified by their chemical name and their fertilizer number designation, i.e. 0-53-35 for monopotassium phosphate. The "grade" of the fertilizer with respect to the different nutrients supplied by the fertilizer is also provided.

It is important to know that the three-number designation of the fertilizer represents the percentages or grade of nitrogen (N), phosphorus (P) and potassium (K), in that order, present in the fertilizer. However, it is very important to note when the percentages for phosphorus and potassium are used, the number on the bag represents the percentages of phosphate (P_2O_5) and potash (K_2O) and not actual phosphorus and potassium. Phosphate is only 43 per cent actual phosphorus and potash is only 83 per cent actual potassium. For this reason, monopotassium phosphate, 0-53-35, is listed as containing 23 per cent phosphorus (53 per cent x 0.43 = 23 per cent), and 29 per cent potassium (35 per cent x 0.83 = 29 per cent).

Blended or premixed fertilizers are also used by some growers. A common premixed fertilizer is 20-20-20. If these fertilizers are used, it is important to account for all the nutrients provided in the fertilizer, both macro and micronutrients. As well, although the fertilizer 20-20-20 contains 20 per cent nitrogen, for the purposes of calculating actual phosphorus (P) and actual potassium (K), 20-20-20 should actually be considered as 20-8.6-16.6.

In determining the amount of fertilizer to add, it is important to remember that as salts, fertilizers often contain more than just one plant nutrient. For example, calcium nitrate ($Ca(NO_3)_2$) provides both calcium and nitrogen. Calcium nitrate is commonly used in commercial vegetable greenhouses as the only source of calcium. The amount of calcium nitrate added depends on how much is required to meet the calcium target.

However, since nitrogen is also present in calcium nitrate, it is important to keep track of how much nitrogen is contributed. After all, there is also an optimum target for nitrogen. Calcium nitrate is 19 per cent calcium and 15.5 per cent nitrogen, so for every 100 grams of calcium nitrate, there will be 19 grams of calcium and 15.5 grams of nitrogen.

The percentage of the relative nutrient components of a fertilizer is also sometimes referred to as the "grade." As the fertilizer calculations are made, an ongoing tally is kept on what nutrients are being supplied by the various fertilizers until all the feed targets have been met.

With the information of stock tank size, injector ratio and the nutrients contributed by each fertilizer, the same relatively simple formula (Formula 1) can be modified and used to determine the amount of each fertilizer required to meet the parts per million (ppm) feed targets of the essential nutrients.

Formula 2 (from Mirza and Younus, 1994)

$$\text{grams of fertilizer required} = \frac{\text{ppm desired x litres of water}}{\text{grade of fertilizer x 10}}$$

This formula can be rearranged to calculate ppm if the amount of fertilizer added is known.

$$\text{ppm} = \frac{\text{grams of fertilizer x grade of fertilizer x 10}}{\text{litres of water}}$$

Assumptions with the example include using 200 litre stock tanks, a 200:1 injector ratio, meeting a calcium target in the nutrient solution of 180 ppm and obtaining all the calcium from calcium nitrate. The formula can be used to determine the amount of calcium nitrate required to meet the calcium target, as well as determining the levels of nitrogen (in ppm) contributed by the calcium nitrate.

Calcium required = 180 ppm, from calcium nitrate, 19% calcium, 15.5% nitrogen.

grams of calcium nitrate required =

$$\frac{180 \text{ ppm} \times (200 \times 200) \text{ litres of water}}{19\% \times 10}$$

$$= \frac{180 \text{ ppm} \times 40{,}000 \text{ litres of water}}{190}$$

$$= 37{,}894 \text{ grams}$$

$$= 37.9 \text{ kilograms}$$

The amount of nitrogen contributed:

$$\text{ppm of nitrogen} = \frac{37{,}894 \text{ grams} \times 15.5\% \times 10}{40{,}000 \text{ litres}}$$

$$= 146.8 = 147 \text{ ppm of nitrogen}$$

By repeating this type of calculation using the various component fertilizers, including the micronutrient chelates, all the individual nutrients coming from each fertilizer can be accounted for until all the nutrient targets are met and balanced in the final feed program.

Table 10. Some component fertilizers for formulating nutrient feed programs for hydroponic greenhouse vegetable crops.

Element			Element		
Macronutrients	Fertilizer	Nutrients	Macronutrients	Fertilizer	Nutrients
Nitrogen	Calcium nitrate 15.5-0-0	15.5% nitrogen (NO_3 - N) 19% calcium	**Calcium**	Calcium nitrate 15.5-0-0	19% calcium 15.5% (NO_3 - N)
	Potassium nitrate 13-0-44	13 % nitrogen (NO_3 - N) 37% potassium		Calcium chloride $CaCl_2$ - $2H_2O$	27% calcium 48% chlorine
	Ammonium nitrate 34-0-0	17% nitrogen (NO_3 - N) 17% nitrogen (NH_4 - N)	**Magnesium**	Magnesium sulfate $MgSO_4$ - $7H_2O$	10% magnesium 13% sulfur
Phosphorus	Monopotassium phosphate 0-53-35	23% phosphorus 29% potassium		Magnesium nitrate Mg $(NO_3)_2$- $6H_2O$	10% magnesium 11% nitrogen (NO_3 - N)
Potassium	Potassium nitrate 13-0-44	37% potassium 13% nitrogen (NO_3 - N)	**Sulfur**	Magnesium sulfate $MgSO_4$ - $7H_2O$	10% magnesium 13% sulfur
	Potassium sulfate 0-0-50	41.5% potassium 17% sulfur		Potassium sulfate 0-0-50	41.5% potassium 17% sulfur
	Monopotassium phosphate 0-53-35	23% phosphorus 29% potassium	**Chlorine**	Calcium chloride $CaCl_2$ - $2H_2O$	48% chlorine 27% calcium
	Potassium chloride 0-0-60	49% potassium 26% chlorine		Potassium chloride 0-0-60	26% chlorine 49% potassium
Micronutrients	Fertilizer	Nutrients	Micronutrients	Fertilizer	Nutrients
Iron	Iron chelate	13% iron	**Zinc**	Zinc chelate	13% zinc
Manganese	Manganese chelate	13% manganese	**Molybdenum**	Sodium molybdate	39% molybdenum
Copper	Copper chelate	14% copper	**Boron**	Borax	15% boron

Rules for Mixing Fertilizers

Once the amounts of the various fertilizers have been determined, the next step is to mix the fertilizers in the stock tanks. Most commercial vegetable greenhouses use a two-stock-tank system for mixing fertilizers, although some systems involve three stock tanks with the third tank containing the acid or bicarbonate for pH adjustment.

Before mixing fertilizers, ensure that a dust mask and gloves are worn to avoid inhaling the fertilizer dusts or coming into contact with the fertilizer concentrates.

The first rule in mixing fertilizers is to always use high quality, water soluble "greenhouse grade" fertilizers. Second, when working with stock tank concentrates, never mix calcium containing fertilizers (e.g. calcium nitrate) with any fertilizers containing phosphates (e.g. monopotassium phosphate) or sulfates (e.g. potassium sulfate, magnesium sulfate). When fertilizers containing calcium, phosphates or sulfates are mixed together as concentrates, the result is insoluble precipitates of calcium phosphate and calcium sulfate. Essentially, the calcium combines with the phosphate or sulfate in the solution and comes out of the solution as a solid. This solid forms a "sludge" at the bottom of the fertilizer tank, which can plug the irrigation lines.

This reaction between calcium, phosphate and sulfate can be avoided if a one-times strength fertilizer is being mixed, as it is considerably more dilute. However, mixing fertilizers to make a one-times strength fertilizer solution is impractical for a commercial greenhouse operation since it would mean that someone would be mixing fertilizers almost continuously.

The third rule for mixing fertilizers is to dissolve the fertilizers for each tank together in hot water. The components of tank one are dissolved together as are the components of tank two. The micronutrients are added to the tanks when the solution is warm, not hot. The fourth rule is to continually agitate the solution in the stock tanks as the fertilizers are being added.

Using the two-stock tank system, the fertilizers should be mixed as follows:

Using the two-tank stock tank system, the fertilizer should be mixed as follows:

Tank A	Tank B
calcium nitrate	potassium nitrate (one half the total amount)
potassium nitrate (one half the total amount)	magnesium sulfate
iron chelate	monopotassium phosphate
	potassium sulfate
	manganese chelate
	zinc chelate
	copper chelate
	sodium molybdate
	boric acid

If other fertilizers are used, ensure that mixing calcium-containing fertilizers with phosphate or sulfate-containing fertilizers is avoided. Generally, other nitrate fertilizers can be added to the "A" tank, while with all others mixed in the "B" tank. Note that iron is always added to the "A" tank to avoid mixing it with phosphate fertilizers, which can cause the precipitation of iron phosphates, resulting in iron deficiency in the plants. If acids are used for pH correction, they can be added to either the "A" or "B" tank, or they can be added to a third stock tank, a "C" tank. If potassium bicarbonate is required for pH correction, it should be added to a third tank, the "C" tank, to avoid the risk of raising the pH in the other stock tanks, which could result in the other fertilizers coming out of solution.

The fertilizer feed program is designed to supply specific quantities of the nutrient elements to the plants per every unit volume of nutrient feed delivered to the plant. The absolute quantities of these nutrients is measured by the parts per million (ppm) targets. In addition to the absolute quantities of the nutrients in the feed, the relative ratios of one nutrient to another (particularly the N:P:K ratio) are also an important component of the feed program.

Direct measurement of the various component nutrients contained in the feed solution and the determination of the relative ratio of the nutrients comes from a lab analysis of the feed solution. It is useful to have the feed solution tested regularly to monitor the actual nutrient levels being delivered to the plants. Lab analysis of the feed solution takes time, and it is also important to be able to monitor the feed on a ongoing basis throughout the day. Measuring the electrical conductivity (E.C.) of the feed solution is a very useful tool in the day-to-day management of the fertilizer feed solution.

Measuring the E.C. of the fertilizer feed solution delivered to the plants can be used as an indirect measure of the level of nutrients reaching the plants. The feed program contains the appropriate quantities of dissolved fertilizer salts required to meet the nutrient requirements of the plants, and this solution has a corresponding E.C. In fact, the corresponding E.C. of most feed solutions delivered to the plants, when based on a nitrogen target of 200 ppm, is about 2.5 mmho. Of course, the other nutrients are present in their relative amounts with respect to nitrogen. Once the feed solution has been mixed to meet the targets, measuring the E.C. of the one-times strength solution can serve as the point of reference for delivering the nutrients to the plants.

The day-to-day management of the delivery of feed to the crop can vary and is based on the salt level of the feed solution. The feed solution can be used as a management tool to direct the development of the crop towards a vegetative or generative direction. The basis for this approach is that the higher the level of salts delivered to the root zone, the more stress is placed on the plants. The more stress the plant is under, the more emphasis the plant puts on producing fruit and the less emphasis on stems and leaves.

There are limits to the salt stresses that can be placed on the plants while still maintaining optimum production, as a high sustained yield is obtained through a balance of leaves and fruit throughout the season. However, using the feed solution to help optimize plant balance is a management tool. On cloudy days, plants can make use of higher fertilizer levels, more so than on sunny days when the plant has greater demands for water. Raising the feed E.C. (0.3 mmho) on a cloudy day will provide more nutrients to the plants; lowering the fertilizer E.C. on a sunny day will provide a greater relative proportion of water to the plants. The saltier the fertilizer solution, the harder the plant has to work to extract the water from the root zone.

Management of the daily application of fertilizer to the crop is based on varying the E.C. of the feed solution. The general rules for managing the feed E.C. and the total amount of nutrient solution volume delivered to the crop on a daily basis is presented in the next section.

Fertilizer and water application

Water and fertilizer are delivered simultaneously to the crop through the nutrient solution, and the amounts of water and fertilizer delivered vary with the changing requirements of the plants. The plants requirements change as they develop from seedlings to mature plants and in accordance with the day-to-day changes in the growing environment. To manage the delivery of nutrients and water to the plant, it is important to have a way of determining the crop's requirements for fertilizer and water.

Feed monitoring stations are established throughout the crop. One or two stations per every 0.4 hectare (1 acre) of greenhouse area are usually sufficient, but having one monitoring station for every watering "zone" of the greenhouse is a good idea. The purpose of the monitoring station is to measure the volume of feed delivered to the individual plants and to determine the volume of feed solution leachate, or "overdrain," flowing past the plants and out of the root zone over the course of the day. The E.C. and pH of the feed solution are taken on a daily basis, as are the E.C. and pH of the leachate (Figure 15).

Figure 15. Typical fertilizer feed system with two fertilizer stock tanks and computerized control of pH and E.C.

The daily monitoring of the percentage of feed solution volume flowing through the root zone environment, the sawdust bags or rockwool slabs, etc. is used to adjust the volume of feed solution delivered to the plants. The E.C. of the leachate is used to make adjustments to the feed solution E.C. Monitoring the pH of the feed and leachate helps to ensure the correct pH is being fed to the crop. It also gives an indication of what is happening in the root zone with respect to pH.

Optimum feed pH is approximately 5.8, and this pH optimum also applies to the root environment as well. Generally, the activity of the roots tends to raise the pH in the root environment, and feeding at a lower pH can help counteract this rise in pH.

The amount of nutrient solution delivered to the plant on a daily basis can be determined by the percentage overdrain or leachate recovered from the plants over the course of the day. Leaching, or allowing a certain percentage of nutrient solution applied to the crop to pass through the root system, allows for a flushing of the root zone to avoid the accumulation of salts.

Generally, when the plants are young, a percentage leachate of 10 to 15 per cent is a good target. As the plants develop, the amount of water required to attain this overdrain target increases. As the season progresses and the light levels increase and the plants mature and begin to bear fruit, the overdrain targets increase to 20 to 30 per cent. Generally, these higher overdrain targets apply as the high light period of the year begins, usually in June. As the percentage overdrain decreases, the leachate E.C. increases, that is, the amount of salts in the root zone increases. The general rule for managing the level of salts in the root zone is that the root zone E.C. should not be greater than 1.0 mmho above the feed E.C.

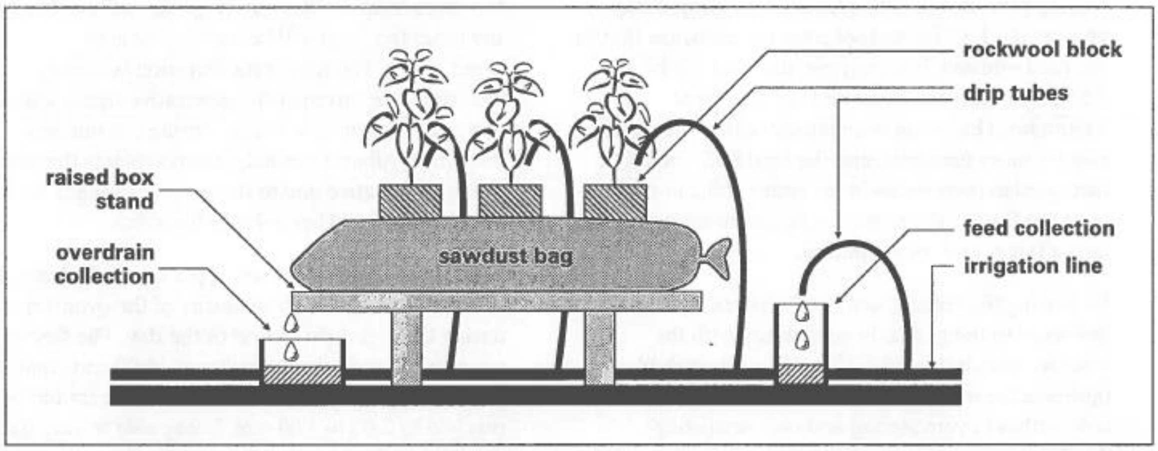

Figure 16. General schematic of a nutrient feed monitoring station

It is not a good idea to feed at a pH of lower than 5.5 when attempting to lower the pH in the root zone. In addition to feeding at a pH of 5.5, ammonium nitrate at 2 to 5 ppm of ammonium nitrogen (NH_4 - N) will help lower the pH of the root zone, due to the acidifying effect of this fertilizer.

A schematic of a typical feed monitoring station is presented in Figure 16. In addition to monitoring the feed and leachate, recording the leachate percentage, feed and leachate E.C. and pH can be used as a tool to chart the performance of the crop with respect to these recorded values over time and in relationship to other parameters, including the amount and intensity of available light.

Feed solution design is based on delivering adequate nutrition to the plants, and these feed programs usually have an E.C. 2.5 mmho (this largely depends on the E.C. of the irrigation water). With the optimum feed solution E.C. at approximately 2.5 - 3.0 mmho, the salt levels in the root zone should be maintained at around 3.5 - 4.0 mmho.

Early in the crop cycle, the salt levels in the root zone can be maintained at the proper target fairly easily by increasing the volume of nutrient solution delivered to the plant to ensure a 10 to 15 per cent overdrain. As the season progresses and the water has been increased so that the upper limit of 30 per cent overdrain has been reached, and the E.C. of the overdrain continues to climb above the target of 3.5 - 4.0 mmhos, the E.C. of the solution can be dropped.

The reduction in feed solution E.C. is accomplished in stages, with gradual, incremental reductions in feed E.C. in the order of 0.2 mmho every two to three days. It is never advisable to apply straight water to the plants to lower the root zone E.C. since the rapid reduction in root zone E.C. and increased pH can compromise the health of the roots and reduce the performance of the crop.

During periods when the plants are in a rapid stage of growth, the E.C. in the root zone can be below that of the feed solution. For example, the feed can be at 2.5 mmho while the leachate E.C. may be at 2.0 mmho. This result is an indicator that the plants require more nutrients, and the feed E.C. should be increased in increments in the order of 0.2 mmho/day until the E.C. in the root zone begins to approach the upper target limit of 4.0 mmho.

By varying the volume and E.C. of nutrient solution delivered to the plants, in accordance with the leachate overdrain and E.C. targets, it is possible to optimize the delivery of water and nutrients to the crop without overwatering and over-fertilizing. Applying too much or too little water can compromise the health and performance of the crop.

Water delivery to the plants occurs over the course of the entire day. Watering can be scheduled by using a time clock, or in more sophisticated systems, watering can be triggered by the amount of incoming light received by the greenhouse. In general, the greater the ability to control the delivery of water, the greater the ability to maximize crop performance.

A starting point for watering the crop early in the crop cycle would be to apply water every half hour from one half hour after sunrise to approximately one hour before sunset. The amount of water required to meet the overdrain target is divided among the waterings, based on the duration of the individual waterings.

For example, if a 40-second watering delivers 100 ml of water, then 10 watering events are required to deliver 1 litre of water. When more than a litre of water is required in one day, the duration of the individual watering events can be increased, or the number of watering events can be increased or both.

Generally, as the crop matures, it is better to increase the frequency of watering events than the duration of each event. If the watering system allows the variation of the frequency and duration of the watering events over the course of the day, then it is possible to increase the frequency and/or duration of the watering events during the high light period of the day, without necessarily increasing the duration of the early morning or late afternoon watering events.

Watering frequency can be used to help direct the vegetative/generative balance of the plant. For any given volume of water that is delivered to the plants, the more frequent the waterings throughout the day, the more the plant will be directed to grow vegetatively. The longer the duration between waterings, the stronger the generative signal sent to the plant. Frequent watering during the summer months in Alberta can help balance plants that are overly gener-ative due to the intense sunlight, high temperatures and low relative humidity.

With regard to the concept of per cent overdrain, it is preferable to obtain the majority of the overdrain during the high light period of the day. The first of the overdrain should start to occur at 10:00 a.m., and the greater part of the daily overdrain target should be reached by 2:00 to 3:00 p.m. Being able to vary the duration of the watering events over the course of the day allows for more nutrient feed being delivered to the plants between 10:00 a.m. and 2:00 to 3:00 p.m.

The use of overdrain targets is one way to ensure the plants are receiving adequate water throughout the day. A strong indicator of whether or not the plants have received adequate water during the previous day is whether the growing points or the tops of the plants have a light green color early in the morning. Over the course of the day when the plant is under transpiration stress, the color of the plants will progress from a light green to a darker blue- green. If the plants have received adequate water throughout the previous day, the light green color will return overnight as the plant recovers and improves its water status.

If the plants remain a darker bluish-green in the early morning, the amount of water delivered the previous day was inadequate. Usually, this result means that the overdrain targets for the previous day have not been met, and the amount of nutrient solution delivered to the plants has to be increased.

During the summer months, under continuous periods of intense light, the plants may not have recovered their water status overnight even when the daily overdrain targets have been met. The plants begin the day a dark blue-green color, an indication that they are already under water stress, even though the day has just begun. Under these circumstances the overdrain targets for the day could be increased, but there is the associated risk of overwatering and decreasing root health and performance.

In these cases, it is advisable to consider one or two night waterings, one at approximately 10:00 p.m. or one at 2:00 a.m. or both. Usually, the night waterings are the same length of time as the minimum watering duration applied during the day. Night watering can also help increase the rate of fruit development, but there is an associated risk of fruit splitting if too much water is applied at night. The night waterings should not be continued indefinitely, and the decision to use night watering events and to continue with night watering has to be based on the assessed needs of the crop.

Management of the feed solution and its delivery to the crop has to be relatively flexible to meet the changing crop needs. With experience, growers gain more confidence and skill in meeting and anticipating the changing crop needs throughout the crop cycle and through periods of fluctuating light levels. The general information presented in this section serves as a starting point. By following the principles of overdrain management, electrical conductivity and pH monitoring and correction, a successful strategy for water and nutrient delivery can be established.

As with many things, there is no one "right" way to apply water and nutrients to the crop. The use of leaching, although ensuring that salt levels do not accumulate to high levels in the root zone, does result in some "waste" of fertilizer solution as runoff.

Strategies can be employed to minimize the waste associated with leaching. Collection and recirculation of the leachate, with an associated partial sterilization or biofiltration of the nutrient solution, is one approach. The sterilization or biofiltration steps are required to minimize the disease risk associated with recycling nutrient solutions. Some estimates place the fertilizer cost savings at between 30 to 40 per cent when recirculation is used. In addition to being economical, recycling nutrient solutions is an environmentally sound practice.

There is a limit to how long nutrient solutions can be recirculated, because prolonged recycling of the same solution can negatively affect growth and yield. This result is primarily associated with the accumulation of sulfate ions in the solution. In addition to sulfates, chlorides and bicarbonates also have a tendency to accumulate and can influence crop growth. The progressive accumulation of sulfates in recirculating solutions requires occasional "refreshing" of the solution, where the solution would have to be allowed to leave the greenhouse as waste.

Conclusion

Commercial greenhouse management in Alberta growing conditions requires knowledge and the use of particular systems. Since greenhouse systems are complex, many growers simplify the many decisions they must make by using specific indicators.

Indicators quickly reveal changes in the greenhouse that may require changes in management strategies. Knowing and understanding these basic indicators will help in three ways:

- to evaluate the greenhouse environment
- to implement ways to enhance the greenhouse environment
- to achieve optimum crop performance

Anticipating crop needs and responding effectively to crop changes will lead to successful greenhouse crop production.