Chapter 2

Design and Preparation of Nutrient Solution Used for Soilless Culture of Horticultural Crops

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/59478

1. Introduction

Hydroponic systems include all systems that deliver the nutrients in a liquid form, with or without an aggregate medium to anchor the plant roots. Hydroponic systems in controlled environments can produce high quality plant free from accidental adulteration by weeds, soil or environmental toxins such as heavy metals in soils. In some species it may be possible to optimize for higher yields of target organs [1].

2. Mineral nutrition required for plants growing in soilless hydroponics

2.1. Nitrogen (N)

Nitrogen is the most frequently limiting nutrient. Within the plant, nitrogen serves in the same ways it does in other organisms—as a component of amino acids and nucleic acids. Nitrogen also plays a critical role in the structure of chlorophyll, the primary light harvesting compound of photosynthesis. This, along with its structural role in amino acids, explains why plants require large amounts of nitrogen, and thus why it is often the limiting nutrient for plant growth. The largest natural source of nitrogen is the Earth's atmosphere, which is roughly 78% gaseous nitrogen, an inert and essentially biologically unavailable form of the element. Its biological unavailability is because the two nitrogen atoms form an extremely stable bond, which is not easily broken. Apart from human industrial processes that fix nitrogen gas to solid or liquid forms, the primary means of nitrogen fixation are through the high temperature and energy of lightning strikes and biological nitrogen fixation by bacteria. These processes produce nitrogen in three main forms, each of which is available to plants: nitrate, nitrite, and ammonium. Nitrogen deficiency is commonly revealed by chlorosis. In the case of nitrogen-deficient chlorosis, the effects are first seen in the more mature leaves and tissues. The plant will preferentially export nitrogen to actively growing tissues, leaving the more mature parts of the plant to show signs of deficiency first. Nitrogen deficiency affects not only the leaves of the plant, but all living cells that have high nitrogen demands for amino and nucleic acids, reducing overall productivity and plant vigor. Generally, nitrogen-deficient plants also exhibit the spindly growth of an etiolated habit [2].

2.2. Phosphorus (P)

Phosphorus is frequently a limiting nutrient, particularly in tropical regions, where the soil chemistry differs from temperate soils, or in highly weathered soils, where phosphorus has long since leached away. Phosphorus is one of the three main elements in commercial lawn fertilizers, though there is mounting evidence that many lawns and green areas already have ample phosphorus, and thus it is being phased out of some commercial fertilizers. The ultimate source of virtually all terrestrial phosphorus is from the weathering of minerals and soils in the Earth's crust. Phosphorus is generally available as phosphate, an anion that is not bindable by the cation exchange complex and thus can be easily leached from the soil by rain or runoff. Phosphorus plays the same chemical and biochemical role in plants as it does in all other organisms. It is the main element involved in energy transfer for cellular metabolism and it is a structural component of cell membranes, nucleic acids, and other critical materials. Plants lacking sufficient phosphorus are frequently characterized by phenomena that appear as wound-responses in leaves, such as production of pigmented compounds resulting in darkening or purpling of the leaves. Stunting can also occur, as well as necrotic lesions and other symptoms [2].

2.3. Potassium (K)

Potassium is the primary osmolyte and ion involved in plant cell membrane dynamics, including the regulation of stomata and the maintenance of turgor and osmotic equilibrium. It also plays important roles in the activation and regulation of enzyme activity. Potassium is a soil exchangeable cation and is actively absorbed by plant roots. It is a major component of many soils and is ultimately derived from the weathering of soil parent materials such as potassium-aluminum-silicates in the soil. Potassium though a part of the cation exchange complex, is only weakly held to the soil particles and is highly leachable. Due to plants and other organisms holding potassium as free ions in their cells, once an organism dies, its potassium quickly reenters the soil solution. If other organisms do not quickly take up potassium, it is easily lost from the soil due to leaching and runoff. A loss of potassium is a common result of forest fires, clear-cut harvest methods, and other major disturbances that cause runoff and erosion. Potassium-deficient plants generally form necrotic lesions or more generalized leaf necrosis after a relatively short period of chlorosis. In severely limiting conditions, there can be general bud death. As with nitrogen deficiency, symptoms of potassium deficiency first tend to appear in more mature leaves, as the plant will move potassium to actively growing, younger tissues. Most plants require potassium in fairly high concentration, and as a result, potassium is a common major constituent of commercial fertilizers,

http://dx.doi.org/10.5772/59478

particularly in agricultural systems where the removal of plant parts (e.g., fruits) from the site strips potassium from the local cycling system. Sodium, another monovalent cation, can sometimes substitute for potassium in certain plants [2].

2.4. Sulfur (S)

Sulfur is another biologically ubiquitous element, playing critical structural roles in several amino acids and in compounds involved in electron transfers in photosynthesis and respiration. Sulfur is also a structural component of specialized enzymes and related molecules. Sulfur is found in the soil primarily as sulfate and is derived from the weathering of parent soil materials or from byproducts of the human combustion of fossil fuels, which produce the sulfur containing gases hydrogen sulfide and sulfur dioxide. These gases are converted to the sulfuric acid of acid rain. Plants lacking sufficient sulfur often show symptoms such as chlorosis and spindly or stunted growth. Unlike plants deficient in nitrogen or potassium, sulfur-deficient plants generally first show signs of deficiency in the younger, developing tissues because sulfur is not easily translocated within the plant [2].

2.5. Calcium (Ca)

Calcium is a divalent cation that plays important roles in cell wall structure, cell membrane relations, and signal transduction in the plant. Most of these functions are essentially extracellular, occurring in the cell walls rather than within the cell membrane, though calcium's role in cell membrane integrity extends to the intracellular membranes as well. Calcium is derived predominantly from geologic sources from the weathering of soil materials—and is a major ion in the cation exchange complex of the soil. It is fairly uncommon for soils to be deficient in calcium, and most plants seem to grow under conditions with a surfeit of calcium. In plants with insufficient calcium, developing buds, young leaves, and root tips either fail to grow or die, most likely due to cell wall related defects. Calcium is generally made unavailable to plants at low pH (higher acidity), so acidic soils often contribute additional symptoms to the calcium deficiency; many metals become mobile at low pH and are toxic (e.g., aluminum) [2].

2.6. Magnesium (Mg)

Magnesium is another divalent cation but, unlike calcium, its roles are more intimately related to intracellular functions than the predominantly extracellular roles of calcium. Magnesium is the most import mineral in the activation of enzymes. Magnesium is also the central structural element of chlorophyll, and it is involved in the synthesis of nucleic acids. The primary source of magnesium is the weathering of parent materials in soils and, like calcium, it is generally found as a common part of the cation exchange complex or in the soil solution. The solubility of magnesium decreases with increasing acidity and at high pH (alkaline) as well. In the case of low pH, magnesium deficiency will likely occur in conjunction with metal toxicity, due to the increased solubility of metals at low pH. As magnesium plays such a critical role in so many aspects of plant cell biochemistry, there is no single pattern of symptoms for magnesium deficiency. Since magnesium is a necessary component of chlorophyll, plants that have insufficient magnesium often exhibit chlorosis. The symptoms of magnesium deficiency tend to appear first in more mature tissues because magnesium is translocatable within the plant [2].

2.7. Iron (Fe)

Iron is a divalent or trivalent heavy metal, depending on the reduction-oxidation conditions in the soil. It is intimately involved as a structural component of heme-type and other proteins, plays roles in the activation of some enzymes, and is involved in the synthesis of chlorophyll. Iron is found in the soil as various oxides and also in association with various organic molecules. Iron can be limiting in the natural environment due to the unavailability to the plant of the oxide forms of the element. Plants overcome the limitations of iron absorption by both lowering the pH of the soil and increasing the iron solubility and the production of specialized iron-scavenging compounds called siderophores. Siderophores move into the soil, bind with the available iron, and are then reabosorbed by the plant. Once inside the plant, the siderophore is stripped of the iron and then sent back into the soil to secure more iron.

Plants deficient in iron show interveinal chlorosis, first appearing in the younger tissues because iron is not easily translocated within the plant body. In extreme deficiency, even the tissue around the veins becomes chlorotic, and the entire leaf may look pale yellow or white [2].

2.8. Sodium (Na)

Sodium is a micronutrient only for those plants that undergo C4 or CAM photosynthesis rather than C3 photosynthesis. C4 is a specialized form of photosynthesis that is more efficient in hot, dry weather. CAM is a specialized form of photosynthesis that greatly reduces transpirational water loss, typical of cacti and other desert plants. C3 is the most common type of photosynthesis, typical of plants such as maple trees and soybeans. Sodium can also substitute for potassium to a variable degree, depending on the plant species (generally, species that are salt-tolerant can endure a greater rate of substitution). As a monovalent cation, it is a part of cation exchange complex and thus is available in the soil solution. The original source for some sodium is sea salt, but most of the sodium in the soil solution is from salts in the parent soil material. Sodium deficiency is characterized by an inability to photosynthesize properly. In most soils and conditions in the field, a surfeit rather than a dearth of sodium is likely to be the case. Sodium in high concentration in the soil can upset the water potential of the soil solution compared to the roots and thus limit water flow into the plant [2].

2.9. Chlorine (Cl)

Chlorine is necessary for splitting water in photosynthesis, the step that generates oxygen gas breathed by animals. Chlorine is a monovalent anion found largely in soil derived from salts in the parent soil material. It is highly leachable, but is nonetheless available in large amounts, and thus chlorine deficiency is virtually unknown. In the laboratory, it is characterized by the formation of blue-green, shiny leaves that eventually turn a bronze color. In extreme cases, plants wilt or become severely stunted, in addition to having significant chlorosis and necrosis [2].

2.10. Boron (B)

Boron is a neutral micronutrient element, generally present in the soil solution as boric acid. The precise functions of boron in the plant are unknown. It is suggested to have a role in nucleic acid synthesis and general membrane function, as well as in cell wall structural integrity. Plants deficient in boron show general organ brittleness and the apical meristems often die. Roots can also die or become brittle. Such damage often leads to infection by pathogenic organisms, which have little trouble colonizing the already weakened plant [2].

2.11. Manganese (Mn)

Manganese is a heavy metal micronutrient, the functions of which area fairly known. It is involved in the oxygen-evolving step of photosynthesis and membrane function, as well as serving as an important activator of numerous enzymes in the cell, a role it can also share with magnesium in some cases. The symptoms of manganese deficiency largely depend on the species of plant in which the deficiency occurs. In general, manganese-deficient plants form chlorotic and necrotic lesions on the leaves, fruits, or seeds. The distribution of symptoms, whether on younger or older tissues, is dependent on the plant in question [2].

2.12. Zinc (Zn)

Zinc is another heavy metal micronutrient that plays critical roles in many enzymes, often appearing either at the active site of the enzyme or in a position that regulates the enzyme structure. Lack of zinc results in the inability of the plant to make sufficient quantities of these proteins, and thus general growth and extension are limited. Zinc may also be involved in chlorophyll synthesis in some species, and in the synthesis of proteins from DNA. The effects of zinc deficiency are both well known and dramatic. Specifically, plants deficient in zinc often show symptoms known as little leaf and/or rosette growth. In the case of little leaf, the leaves fail to expand to their normal, mature size. Rosette plants are those in which elongation of the stem is almost eliminated, so that all leaves appear to grow from the same place at the base of the stem. Zinc deficiency can also result in stunted growth forms [2].

2.13. Copper (Cu)

Copper is a micronutrient that is heavily involved in electron transfers in energy exchange reactions within the cell, due to its variable oxidation states. It is a component or activator of some enzymes. Copper is a heavy metal found in the soil in association with various other molecules. When found in the plant body, it is typically bound to special molecules within the plant to limit or prevent toxic effects that can arise from high concentrations. Plants deficient in copper often show symptoms of chlorosis or leaf rolling, though there is species-related variability. Woody species sometimes have bark that is blistered, and young shoots may experience dieback [2].

2.14. Molybdenum (Mo)

Molybdenum is a micronutrient specifically for plants that form root nodules with nitrogen-fixing bacteria, though plants that do not form nodules also use trace amounts of it in a protein involved with nitrogen metabolism and uptake. In the case of root nodule–forming species, however, molybdenum plays a structural role in the nitrogen-fixing enzyme nitrogenase. The symptoms of molybdenum deficiency in plants that don't form root nodules include interveinal chlorosis, leaf rolling, and sometimes necrosis. In plants that do form root nodules, molybdenum deficiency results in a loss of productive nitrogen fixation, due to the bacterial need for the element [2].

2.15. Silicon (Si)

Some scientists consider silicon (Si) a micronutrient. Though it not known to be essential, it is accumulated by plants and used in the plant body at a fairly high concentration [2].

2.16. Cobalt (Co)

Cobalt (Co) is an essential micronutrient for plant species that form root nodules [2].

2.17. Nickel (Ni)

Nickel (Ni) is a micronutrient that, while essential, is virtually never limiting or deficient in the natural world. In the rare cases when it is limiting, symptoms include reduction in leaf size, cupping of the leaf, and reduced vegetative growth. It is also a component of a single enzyme, urease. When grown without nickel, plants fail to produce urease in sufficient quantity and can suffer effects of accumulating toxic quantities of urea in the cells [2].

3. Nutrient solutions and its management under soilless hydroponics

Nutrient solutions are critical parts of plant nutrition research. Hydroponics is the science of growing plants in liquid media, rather than in pots of soil [3]. For a hydroponic solution to sustain plant growth, it must provide the required nutrients at appropriate concentrations, and in the correct forms that are available to the plant. Developing a useful hydroponic solution can be a time consuming process. Different plant species may require nutrients in different concentrations, ratios, or chemical forms for efficient absorption [4]. Most plant nutrient solutions, whether used in hydroponics or for watering plants in pots, often employ nutrients at much higher concentrations than they would find in natural soil. The main reason for this approach is to save time in the lab. For example, if there is a high concentration of nutrients present, the solution may need to be changed only once a week instead of once a day, saving considerable time, particularly in an experiment with 500 beakers of plants/ nutrient solution.

Nutrient solutions for growing of some horticultural plants are listed in below.

Total	**Cl**	**SO_4**	**PO_4**	**NO_3**	**meq. L^{-1}**
4.6			0.8 0.6	3.2	K
0.2	0.2				Na
5.2				5.2	Ca
1.5		1.5			Mg
0.1				0.1	NH_4
1.9			1.6 0.3		H
13.5	0.2	1.5	3.3	8.5	Total

Table 1. Nutrient solution for growing cucumber [4].

Total	**Cl**	**SO_4**	**PO_4**	**NO_3**	**meq. L^{-1}**
5.8			0.8 0.6	4.4	K
0.2	0.2				Na
5.2				5.2	Ca
1.5		1.5			Mg
0.1				0.1	NH_4
1.9			1.6 0.3		H
14.7	0.2	1.5	3.3	9.7	Total

Table 2. Nutrient solution for growing Aloe [1, 3].

Total	**Cl**	**SO_4**	**PO_4**	**NO_3**	**meq. L^{-1}**
4.6			0.8 0.6	3.2	K
0.2	0.2				Na
5.2				5.2	Ca
1.5		1.5			Mg
0.1				0.1	NH_4
1.9			1.6 0.3		H
13.5	0.2	1.5	3.3	8.5	Total

Table 3. Nutrient solution for growing garden cress [5, 6]

Total	Cl	SO_4	PO_4	NO_3	meq. L^{-1}
1.8			0.4 0.3	1.1	K
0.1	0.1				Na
2.6				2.6	Ca
0.7		0.7			Mg
0.5				0.5	NH_4
0.95			0.8 0.15		H
6.65	0.1	0.7	1.65	4.2	Total

Table 4. Nutrient solution for growing basil [5].

Total	Cl	SO_4	PO_4	NO_3	meq/l
2.4			0.8 0.6	1.0	K
0.1	0.1				Na
2.0				2.0	Ca
1.5		1.5			Mg
0.5				0.5	NH_4
1.9			1.6 0.3		H
8.4	0.1	1.5	3.3	3.5	Total

Table 5. Nutrient solution for growing anthorium.

4. Preparation of hydroponic nutrient solution for horticultural crops

Hydroponics is a common culture method for production of herbs, vegetables and other crops such as strawberry. It is necessary to determine optimal ranges of elements in nutrient solutions. There are different basic nutrient that was used in soilless culture all around the world. We prefer Quick nutrient solution because this nutrient solution design is simple and easily we are able to changed macronutrient and nutrient solution pH. In below we explain how design a nutrient solution and how prepare stock and nutrient solution.

Step 1.*Research review and total nutrient content selection.*

At the first we have to search about our plant and read all document available. This stage is very important and helps us to design the best nutrient solution. If you don't find any document for your plant then searched for other plant from your plant family that have the highest similarity to your plant. We continue this section with an example (Cucumber). Research review indicated that this plant need high nutrient element with high nitrate to ammonium ratio. So we select 13.6 meq per liter of nutrient solution as total nutrient content (Table 6). In below table each column was related to one anion and each row is related to one cation. So in next step each number was related to one salt that produce from one onion and one cation.

Total	**Cl**	**SO_4**	**PO_4**	**NO_3**	**meq/l**
					K
					Na
					Ca
					Mg
					NH_4
					H
13.6					Total

Table 6. Total nutrient content in Quick table.

Step 2. *Total N and NO_3 to NH_4 ratio selection*

After total nutrient selection you have to select total N and NO_3 to NH_4 ratio (Table 7). In some cases it is important to change this level during plant growth especially in different environmental condition like light and temperature. In this step like previous step other researcher published document help you. In cucumber we select total N and NO_3 to NH_4 ratio 8.7 and 86, respectively so our Quick table filled as below.

Total	**Cl**	**SO_4**	**PO_4**	**NO_3**	**meq/l**
					K
					Na
					Ca
					Mg
0.1					NH_4
					H
13.6				8.6	Total

Table 7. Ammonium concentration design in nutrient solution

In this step we have to select our nitrogen salt according our availability (Table 8). If potassium nitrate, calcium nitrate and ammonium nitrate were available so our table filled as below:

Total	Cl	SO_4	PO_4	NO_3	meq/l
				3.2	K
					Na
				5.3	Ca
					Mg
0.1				0.1	NH_4
					H
13.6				8.6	Total

Table 8. NO_3 concentration design in nutrient solution.

In fact we select calcium concentration. As you know if concentration of calcium select 2 times more that potassium in nutrient solution they concentration in plants were be equal.

Step 3.*K and pH selection*

After N we must optimize K concentration in our nutrient solution. If we use KH_2PO_4 and K_2HPO_4 we have an opportunity to optimize nutrient pH in our nutrient solution. By increasing KH_2PO_4 concentration the nutrient solution pH decreased. So our table was completed as see in Table 9.

Total	Cl	SO_4	PO_4	NO_3	meq/l
4.6			0.8 0.6	3.2	K
					Na
5.3				5.3	Ca
					Mg
0.1				0.1	NH_4
			1.6 0.3		H
13.6				8.6	Total

Table 9. K and pH design in nutrient solution

In upper table we write 2 numbers for potassium phosphate. If you notice we also have two numbers for H that indicated first number is related to salt with the higher H so the top and below numbers are related to KH_2PO_4 and K_2HPO_4, respectively.

Step 4.*Optimization of other element concentration*

Finally we must select SO_4, Mg, Na and Cl concentration in our table. In below we complete our Table (Table 10).

Total	Cl	SO_4	PO_4	NO_3	meq/l
4.6			0.8 0.6	3.2	K
0.2	0.2				Na
5.3				5.3	Ca
1.5		1.5			Mg
0.1				0.1	NH_4
1.9			1.6 0.3		H
13.6	0.2	1.5	3.3	8.6	Total

Note 1: Micro nutrient have to select separately in another table.

Note 2: Total anion and total cation concentration are equal.

Table 10. Completion of nutrient solution preparation design.

5. Preparation of stock nutrient solution

At first we must calculate our needed salts. In this reason we need molecular weight of each salt. Molecular weight was divided to active capacity of salt. For example active capacity is 2 and 1 for K_2HPO_4 and KH_2PO_4, respectively. The result finally multiplied by table level. In below I calculated each salt concentration.

Nutrients	Conversion	Amount (mg/L)
Macro		
KNO_3	3.2×101	323
$Ca(NO_3)_2$	5.3×82	434.6
NH_4NO_3	0.1×80	8
KH_2PO_4	0.8×136	109
K_2HPO_4	0.6×87	52
$MgSO_4/7H_2O$	1.5×123	184.5
NaCl	0.2×58.5	11.7
Micro		
$(NH_4)_6Mo_7O_{24}/4H_2O$	-	0.05
H_3BO_3	-	1.5
$MnSO_4/4H_2O$	-	2
$CuSO_4/5H_2O$	-	0.25
$ZnSO_4/7H_2O$	-	1
Sequestered Fe 136	-	10

Table 11. Nutrient calculation as mg/L

All macronutrient and micronutrient that listed in Table 11 were prepare separately as stock solution and were used in irrigation solution.

It is better to separate Ca salt and Fe salt from others. So we have 4 stock solutions as below.

1. Stock A = 1/2 KNO_3 + $Ca(NO_3)_2$ + NH_4NO_3
2. Stock B = 1/2 KNO_3 + other macronutrient salts
3. Stock C = Fe salt
4. Stock D = other micronutrient

6. Conclusion

As describe in this chapter nutrient solution is one of the most important step in soilless culture of horticultural crop. By using Quick table we are able to design and change nutrient element in solution. In other hand by using different kind of salt we are able to change pH of nutrient solution. In stock preparation we separate Ca and Fe salts from others kind of salts. It is also possible to separate any salt that not solved completely in stock solution so this is better to test all salts in a small level then prepare stocks solution.

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