Plant Nutrition and Fertilization

12

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Plants require adequate quantities of mineral nutrients in the proper balance for basic physiological processes, such as photosynthesis, and to promote rapid growth and development. Without a good supply of mineral nutrients, growth is slowed and plant vigor reduced. Young plants rapidly deplete mineral nutrients stored within their seeds, and cuttings have limited nutrient reserves. Therefore, nursery plants must rely on root uptake of nutrients from the growing medium. When nutrients are supplied in proper amounts and at the proper time, nursery plants can achieve optimum growth rates.

This chapter describes the importance of nutrition to plant growth development and details typical fertilization practices for producing plants in tropical nurseries.

Facing Page: *Topdressing native sandalwood (*Santalum *species) seedlings with controlled-release fertilizer at Waimea State Tree Nursery in Hawai'i. Photo by Douglass F. Jacobs.*

Basic Principles of Plant Nutrition

A common misconception is that fertilizer is "plant food" (figure 12.1A), but the basic nutrition of plants is very different from that of animals. Using the green chlorophyll in their leaves, plants make their own food in the form of carbohydrates from sunlight, water, and carbon dioxide in a process called photosynthesis (figure 12.1B). These carbohydrates provide the plant energy, and when combined with mineral nutrients absorbed from the soil or growing medium, carbohydrates are used to synthesize proteins and other compounds necessary for basic metabolism and growth.

Thirteen mineral nutrients are considered essential to plant growth and development and are divided into macronutrients and micronutrients based on the amounts found in plant tissue (table 12.1). Some mineral nutrients have a structural function. For example, nitrogen is an integral part of plant proteins, and nitrogen and magnesium are structural components of chlorophyll molecules needed for photosynthesis (figure 12.2). Understanding these basic functions has practical applications because a deficiency of either nutrient causes plants to be chlorotic (that is, yellowish in color). Other mineral nutrients have no structural role, but potassium, for example, is functionally important in causing the stomata in leaves to open and close.

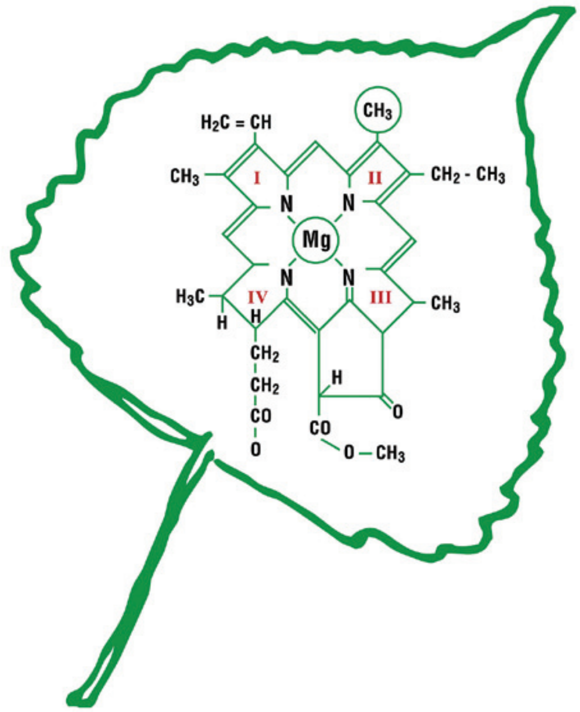

Figure 12.2—Mineral nutrients such as nitrogen and magnesium are important components of chlorophyll molecules that give leaves their green color and are essential for photosynthesis. Illustration from Dumroese and others (2008).

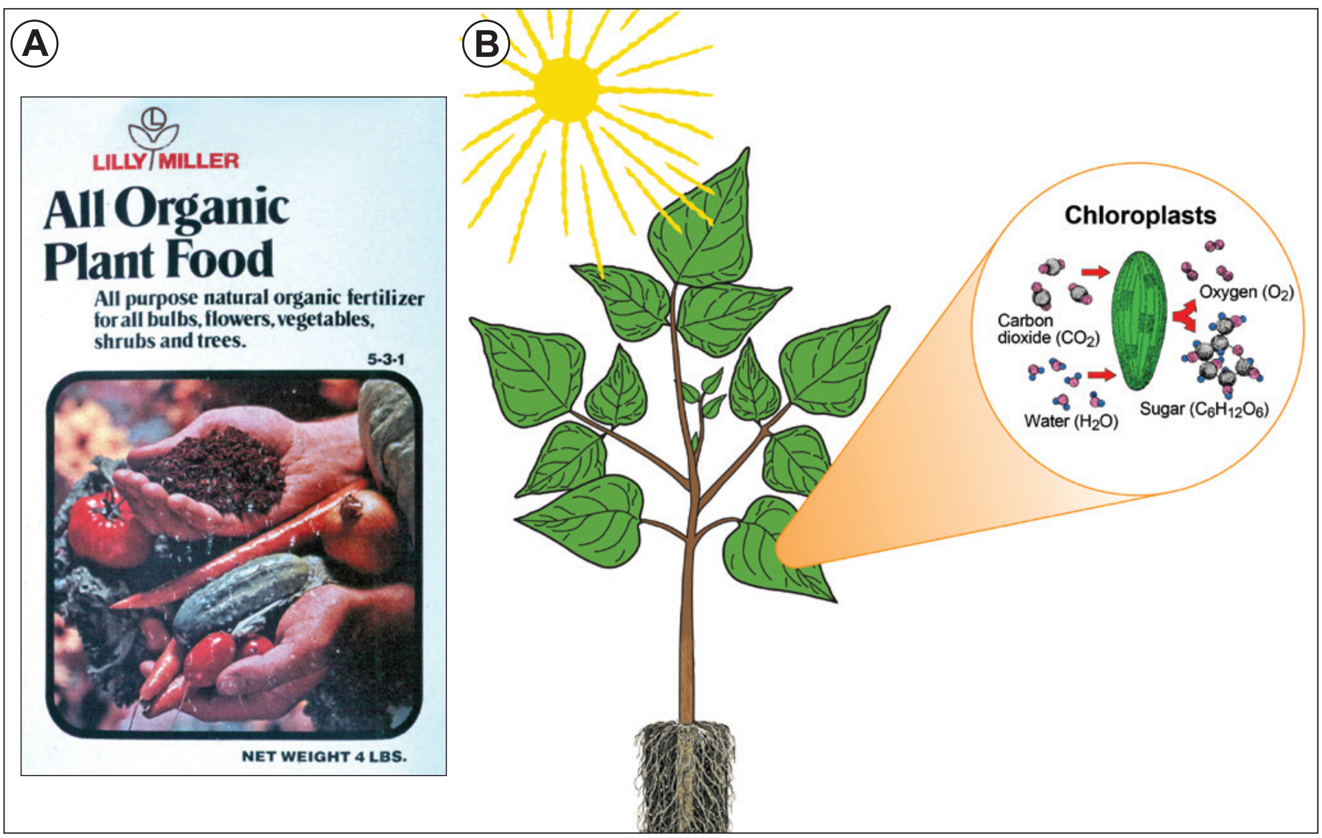

Figure 12.1—Although some fertilizers are advertised as "plant food" (A), plants actually create their own food through the process of photosynthesis in their green leaves (B). Photo A by Thomas D. Landis, and illustration B by from Dumroese and others (2008).

Table 12.1*—The 13 essential plant nutrients (divided into macronutrients and micronutrients). Nitrogen, phosphorus, and potassium are the most common fertilizer elements.*

Name (symbol)	Percent of plant tissue (oven dry weight)	Structural functions	Physiological functions	Deficiency symptoms (general)
Macronutrients				
Nitrogen (N)	1.5	Component of chlorophyll, amino acids, proteins, and nucleic acids	Vital to all physiological processes through roles in enzyme systems.	Old leaves turn yellow (chlorosis), plant growth stunted; small leaves. Differs from iron chlorosis because older foliage is affected first.
Phosphorus (P)	0.2	Component of cell walls and nucleic acids	Energy storage and release, functioning of cell membranes, regulates enzyme and cell buffering.	Some plants show purpling, but stunting is most common.
Potassium (K)	1.0	None	Osmotic adjustment. Important in maintaining cell turgor, phloem transport, cell growth.	Necrosis of leaf margins, stunting.
Calcium (Ca)	0.5	Component of cell walls	Facilitates cell division, stabilizes cell membranes, inhibits fungal infections and toxins.	Disintegration of cell walls, inhibition of meristems and especially root tips, increased susceptibility to fungal attack.
Magnesium (Mg)	0.2	Component of chlorophyll	Regulates cellular pH and ionic balance, energy transfer, enzyme stabilization.	Interveinal chlorosis or yellowing of needle tips, symptoms may occur in patches.
Sulfur (S)	0.1	Maintain protein structure, component of vitamins, and coenzyme A	Amino acids formation, protein synthesis, ion transport across membranes.	Light green foliage leading to chlorosis, often visible on younger foliage, stunting.
Micronutrients				
Iron (Fe)	0.01	Critical to manufacture of chlorophyll	Catalyst to several enzymes systems, especially for photosynthesis.	Chlorosis of newer foliage; in severe cases leaves turn whitish.
Manganese (Mn)	0.005	Structural component of ribosomes	Critical to Hill Reaction in photosynthesis, carbohydrate and nucleic acid synthesis, and lipid metabolism.	Chlorosis similar to iron deficiency except severe cases lead to necrosis.
Zinc (Zn)	0.002	Component of several enzymes	Enzyme catalyst for carbohydrate metabolism, protein synthesis, and auxin production.	Reduced internode elongation ("rosetting") and stunted foliage ("littleleaf"). Chlorosis or bronzing of younger leaves.
Copper (Cu)	0.0006	Constituent of proteins and enzymes	Photosynthetic functioning; phenol, carbohydrate, and nitrogen metabolism.	Chlorosis, tip dieback, twisted, needle tips.
Molybdenum (Mo)	0.00001	Component of several enzyme systems, notably for nitrogen uptake	Essential for reducing nitrate ions to ammonium after uptake; critical for nodule function in legumes.	Chlorosis and necrosis of leaf tissue.
Boron (B)	0.002	None	Involved in cell division and elongation, lignification of cell walls, synthesis of amino acids and proteins.	Distortion and discoloration of shoot and root tips, short shoot internodes producing a bushy or rosette appearance.
Chloride (Cl)	0.01	None	Osmosis and ion balance within cells; photosynthetic oxygen evolution.	Rare. Wilting of leaf margins and restriction of root elongation.

An important nutrition concept is Liebig's Law of the Minimum, which states that plant growth is controlled by the mineral nutrient in shortest supply. See Chapter 5, Propagation Environments, for more discussion about limiting factors. A good way to visualize the concept of limiting factors is a wooden bucket with staves of different lengths. If water is poured into the bucket, it can be filled only to the height of the shortest stave—the limiting factor. Nitrogen is nearly always limiting to plant growth in nature, which is the reason why nitrogen fertilizer is frequently applied in nurseries (figure 12.3).

Just as important as the absolute quantities of nutrients available to plants is the balance of nutrients. The proper nutrient balance is relatively consistent among plant species and can be expressed as Ingestad's Ratios. Healthy plant tissue contains approximately 100 parts of nitrogen to 50 parts of phosphorus, to 15 parts of potassium, to 5 parts of magnesium, to 5 parts of sulfur. On a practical basis, most tropical plant nurseries use complete fertilizers that contain a balance of all mineral nutrients.

Mineral nutrients are absorbed by root hairs as two types of ions: cations and anions. Cations have an electrically positive charge, while anions are negatively charged. Particles of soil, compost, and artificial growing medium are also charged, so nutrient ions attach to sites with an opposite charge. Roots typically release a cation (often H^+) or an an ion (for instance, HCO_3^-) when taking up a nutrient ion of the same charge from the soil or growing medium (figure 12.4). See Chapter 6, Growing Media, for more information on this topic. Fertilizers applied in the nursery break down into soluble nutrient ions, which are then taken up by plant roots.

Sources of Mineral Nutrients

Plants produced in container nurseries may acquire nutrients from several different sources, including the growing medium, irrigation water, beneficial microorganisms, and fertilizers. Many tropical nurseries use artificial growing media that are essentially infertile, which enables growers to apply the right type of fertilizer, in the right amount, and at the right time. Levels of mineral nutrients in a commercial growing medium are generally very low, which is why they are often amended with a "starter dose" of fertilizer. Native soils and composts contain higher nutrient concentrations than commercial growing media but rarely enough for the fast growth rate and nutrient balance desired in nurseries. If soil or other homemade growing media will be used, a soil test can be done to determine which nutrients are lacking (see the section on testing in the following paragraphs).

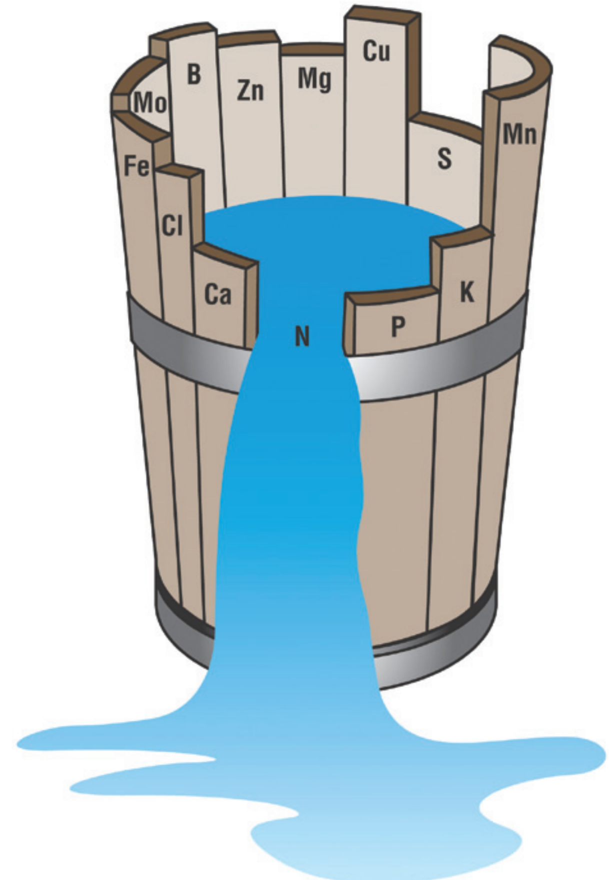

Figure 12.3—The concept of limiting factors can be illustrated by a wooden bucket that can be filled with water only to the shortest stave. In this example, nitrogen (N) is the most limiting, which is typical in nurseries. Illustration from Dumroese and others (2008).

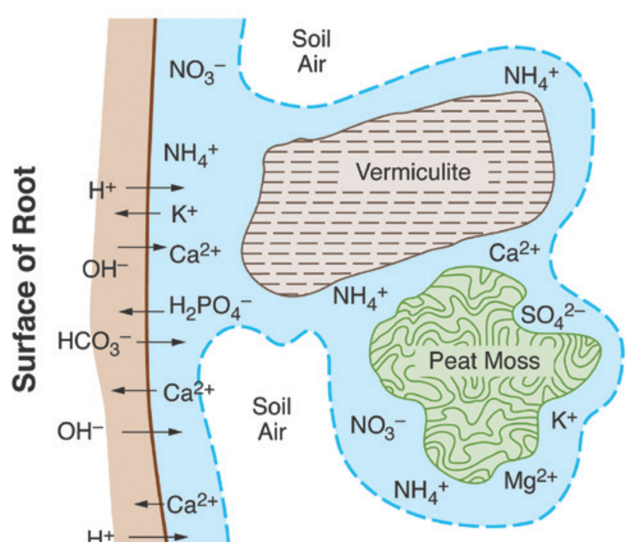

Figure 12.4—Nutrient cations and anions are extracted by plant roots through an exchange process with soil, compost, or artificial growing media. Illustration from Dumroese and others (2008).

Another potential source of mineral nutrients in nurseries is irrigation water. "Hard water" often contains enough calcium and magnesium for good plant growth. Sulfur is another nutrient often found in water sources. Beneficial microorganisms may provide an important source of nitrogen for some species, such as legumes, as detailed in Chapter 13, Beneficial Microorganisms.

To achieve the desired plant growth and health, fertilizers are the most common source of mineral nutrients in tropical plant nurseries. Growers need to have a good understanding of types of fertilizers and how and when to apply them. Many different types of fertilizers are used in tropical plant nurseries and vary according to their source materials, nutrient quantities, and mechanisms of nutrient delivery. The two main fertilizer categories are organic (figure 12.5A) and synthetic (figure 12.5B).

All commercial fertilizers are required by law to show the ratio of nitrogen to phosphorus to potassium (actually the oxides of phosphorus and potassium; $N:P_2O_5:K_2O$) and the complete nutrient analysis on the label (figure 12.5C). Some fertilizers contain only one mineral nutrient whereas others contain several. Examples of single-nutrient fertilizers include ammonium nitrate (34-0-0) or concentrated superphosphate (0-45-0). Fertilizers may be blended or reacted to supply two or more essential nutrients. An example of a blended fertilizer is a 12-10-8, which was formed by adding triple superphosphate (0-46-0), potassium magnesium sulfate (0-0-22), and ammonium nitrate (34-0-0). An example of a multiple-nutrient fertilizer is potassium nitrate (13-0-44).

Some tropical plant nurseries prefer organic fertilizers because they are less likely to burn crops if too much is applied and have lower risk of water pollution. If inoculating with beneficial microorganisms, organic fertilizers are generally preferred. The main drawbacks of organic fertilizers are that they are more expensive, and their lower nutrient content and solubility result in slower plant growth. Most of the research in tropical plant nurseries has

A

B

C

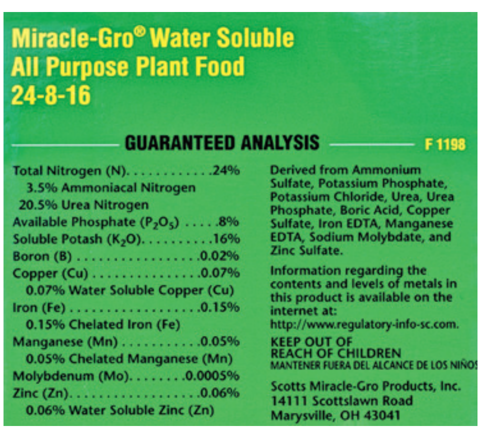

***Figure 12.5**—The two main types of commercial fertilizers are organic (A), and synthetic (B). All fertilizers must show the nitrogen-phosphorus-potassium ratio on the label, and most also give a complete listing of mineral nutrients (C). Photos by Thomas D. Landis.*

been done with synthetic fertilizers because they are inexpensive, readily soluble, and quickly taken up by crops. Synthetic fertilizers are popular with growers because they stimulate the rapid growth rates desired in nursery culture.

Organic Fertilizers

Until the early 20th century, nearly all fertilizers used in agriculture, including nurseries, were organic. The shortage of Chilean nitrate, a major source of organic nitrogen, led to development of the Haber-Bosch Process, which converts the abundant nitrogen gas in our atmosphere into ammonia. This ammonia can then be chemically converted into a vast array of synthetic fertilizers. After the Second World War, these synthetic, ammonia-based fertilizers became cheap and readily available, and use of organic fertilizers dropped from 91 percent in the early 1900s to 3 percent by the 1950s. In recent decades, however, organic farming has seen a resurgence because of changes in public values. In tropical areas, concern about the environmental and economic implications of manufacturing, transporting, and using synthetic fertilizers is rising. In response to this increasing demand, a wide variety of organic fertilizers have been developed, and many have potential in tropical plant nurseries.

Defining organic fertilizers can be a complicated and confusing subject, and much of this confusion comes from terminology. For our purposes, organic fertilizers can be defined as materials that are naturally occurring and have not been synthesized, and we recognize two general categories: animal or plant wastes and natural minerals (figure 12.6).

Animal or Plant Wastes

These materials are what most people consider to be organic fertilizers and can be applied to crops directly or developed into a wide variety of other processed fertilizers. One of the attractions of these types of organic fertilizers is they are renewable and widely available.

Unprocessed Organics

This category is by far the largest and most complicated because nearly any type of animal or plant waste can be used as a fertilizer, including animal manure, sewage sludge, and peat moss. In tropical areas, guano is an excellent organic fertilizer and consists of the accumulated excrement of seabirds or bats. Guano has high levels of phosphorus and nitrogen and does not have any noticeable odor. One of the largest mining operations occurred on the small South Pacific island of Nauru where centuries of deposition by seabirds created vast reserves of mineralized guano.

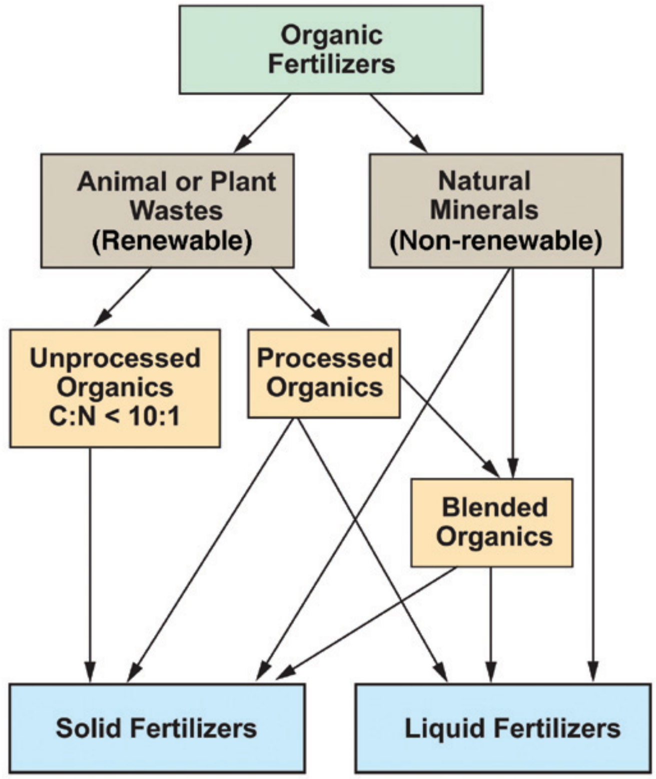

***Figure 12.6**—The terminology of organic fertilizers is complicated, but various types can be illustrated in this flow chart from Landis and Dumroese (2011).*

The best criterion for determining which types of unprocessed organic matter are suitable fertilizers is the carbon-to-nitrogen (C:N) ratio. Organic materials with a C:N less than 10:1 are considered to be fertilizers. Unprocessed organics can be challenging to use because of their high potential for water pollution.

Processed Organics

This category includes any organic material that has been processed in some manner before being used as a solid or liquid fertilizer, and includes composts, blood meal, bone meal, and materials such as feather meal and kelp extracts (table 12.2). Manure is a good source of nutrients but will always need to be composted first so it will not damage plants or pollute water. One way to test if the manure is composted enough to use as fertilizer is to place a few handfuls into a plastic bag and seal it for 24 hours; if the material does not smell bad or give off heat at the end of the test period, it is ready to use; otherwise, it will need further composting. Nearly any organic waste matter can be composted and the composting process has been well documented. See Chapter 6, Growing Media, for more information on composting. Many new processed organic fertilizers are now available from horticultural supply sources.

Table 12.2—Percentages of nitrogen, phosphorus, and potassium supplied by a variety of organic materials. Adapted from Diver and others (2008).

Organic fertilizers	N	P	K
Bat guano (fresh)	10	3	1
Bat guano (old)	2	8	0
Blood meal	10	0	0
Bone meal (steamed)	1	11	0
Cottonseed meal	6	2	1
Eggshells	1.2	0.4	0.1
Fish emulsion	4	1	1
Fish meal	5	3	3
Greensand	0	0	7
Hoof and horn meal	12	2	0
Kelp meal	1.5	0.5	2.5
Soybean meal	7.0	0.5	2.3
Worm castings	0.5	0.5	0.3
Manure			
Cow	2	2.3	2.4
Horse	1.7	0.7	1.8
Pig	2	1.8	1.8
Sheep	4	1.4	3.5
Poultry	4	4	2

N = Nitrogen, P = Phosphorus, K = Potassium

Anyone considering the use of processed organic fertilizers needs to test them first to decide if a need exists for composting, determine proper application rates, and identify potential nutrient toxicities or deficiencies. It is also wise to initiate small-scale tests with any new fertilizer product to avoid possible problems and determine plant growth rates.

Natural Mineral Fertilizers

This second major category of organic fertilizers includes minerals and other materials that come directly from the earth (figure 12.6). Minerals like sodium nitrate are commonly used in many blended organic fertilizers because they are soluble and have a high nutrient content. Like all types of mining, however, obtaining natural minerals is an extractive process and nonrenewable in the long term.

Rock Phosphate

Natural deposits of fluoroapatite are the raw material of most phosphate fertilizers and are currently mined in North Africa, the former Soviet Union, and in Florida, Idaho, Montana, Utah, and Tennessee. The raw ore contains 14- to 35-percent phosphate (P_2O_5) and is processed by grinding and washing into a fine granular fertilizer. Rock phosphate is very insoluble in water and makes an effective slow-release granular fertilizer. Because of its low solubility, rock phosphate has been recommended as an ideal phosphorus fertilizer to encourage mycorrhizal development.

Sodium Nitrate

This salt ($NaNO_3$) is commonly known as Chilean or Peruvian saltpeter because of the large caliche mineral deposits found in both countries. Although this fertilizer has been used in organic farming for many years, several organic certifying agencies have concluded that mined mineral fertilizers conflict with basic organic principles. For example, the USDA National Organic Program currently restricts use of sodium nitrate to less than 20 percent of total annual applied nitrogen and requires that growers phase out its use over time.

Magnesium Sulfate

This mineral ($MgSO_4$) comprises Epsom salts or Kieserite. Although more widely used for medicinal purposes, magnesium sulfate is a very soluble source of magnesium and sulfur and has been used in the formulation of liquid fertilizers for container tree nursery crops.

Sul-Po-Mag

Technically known as sulfate of potash-magnesia or langbeinite, this salt is mined from marine evaporite deposits and is a common component in many blended organic fertilizers. It was originally discovered in Germany and contains soluble nutrients in the following ratio: 22-percent potassium, 22-percent sulfur, and 11-percent magnesium. Another common trade name is K-Mag Natural, an ideal product for supplying potassium and sulfur without any accompanying nitrogen.

Blended Organic Fertilizers

This category of organic fertilizers includes a wide variety of products containing a mixture of processed organic plant or animal wastes supplemented with natural minerals (figure 12.7). It is easy to identify blended organic fertilizers by checking the ingredients on their labels.

Solid Organic Fertilizers

Powdered or granular fertilizers can be derived from unprocessed organics, processed organics, natural minerals, or blended organics (figure 12.6). Solid organic fertilizers have not been widely used in forest or native plant nurseries. Biosol® (6-1-3) is a solid organic fertilizer that is supplemented with Sul-Po-Mag, however, and has potential for nursery use.

Liquid Organic Fertilizers

This category of organic fertilizers can be derived from processed organics, natural minerals, or blended organics (figures 12.5A, 12.6). Ingredients might include fertilizers such as fish waste, soybean meal, kelp, recycled foodstuffs, bat guano, sulfate of potash, feather meal, blood meal, steamed bone meal, or any number of ingredients. Many products are targeted to specific crops but others are for more general use. Some liquid organic fertilizers contain suspended material and must be filtered or continually agitated during fertigation to prevent the material from plugging nozzles.

Synthetic Fertilizers

The most important synthetic fertilizers are made using the Haber-Bosch process in which atmospheric nitrogen is converted into ammonia under high temperature and pressure. Having been called the most important invention of the 20th century, this industrial process produces 500 million tons of artificial fertilizer per year. Synthetic fertilizers are popular because they are relatively inexpensive, readily available, and have high nutrient content compared with organic products. In populated tropical areas, synthetic fertilizers can be found at garden supply shops and through horticultural dealers, but inaccessibility and transport costs may be a limitation in remote areas. In the humid tropics, storage of synthetic fertilizers becomes a challenge because they readily absorb moisture from the air.

Synthetic fertilizers can be divided into two classes: (1) soluble products that release nutrients quickly when dissolved in water and (2) slow-release or controlled-release fertilizers that release nutrients slowly over time. Both types have their advantages and disadvantages, which need to be considered before deciding upon a fertilization system (table 12.3). Other types of granular fertilizers that are used on lawns or in agriculture are not recommended for tropical plant nurseries.

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B

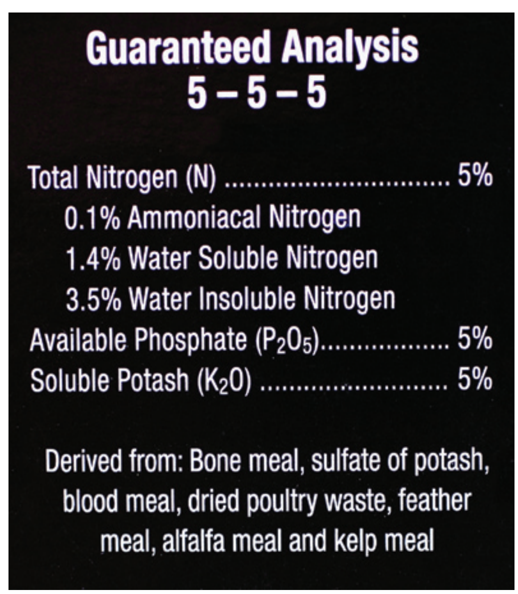


Figure 12.7*—Blended organic fertilizers (A) contain processed organic materials and natural minerals, such as sulfate of potash (B). Photos by Thomas D. Landis.*

Table 12.3—Comparison of advantages and disadvantages of two major types of synthetic fertilizers used in tropical plant nurseries.

Factor	Soluble fertilizer	Controlled-release fertilizer
Nutrient release rate	Very fast	Much slower—dependent on type and thickness of coating, as well as temperature and moisture
Number of applications	Multiple—must be applied at regular intervals	Usually once per season, but additional top-dressing is an option
Uniformity of application	Good, but dependent on irrigation coverage	Can be variable if incorporated, resulting in uneven growth
Adjusting nutrient rates and ratios	Easy and quick	Difficult
Nutrient uptake efficiency	Poorer	Better
Leaching and pollution potential	Higher	Lower
Potential for fertilizer burn (salt toxicity)	Low if applied properly	Low, unless prills damaged during incorporation or following high temperatures
Product cost	Lower	Higher
Application costs	Higher	Lower

Soluble Fertilizers

Soluble synthetic fertilizers come in either granules or water-soluble crystals (figure 12.8A). Soluble fertilizers are typically injected into the irrigation system, a process known as fertigation (see the discussion in the following section). Their popularity stems from the fact that the application rates can be easily calculated, distribution is as uniform as the irrigation system, and, if properly formulated and applied, the chance of fertilizer burn is very low (table 12.3). Because they are immediately soluble, the nutrients in these fertilizers are quickly available for plant uptake and it is easy to adjust nutrient levels and ratios, which gives the grower great control of plant growth rates. When growing a variety of plant species in the same area, it is necessary to separate them based on relative growth rates so that different fertilizer mixes can be applied. The major drawback to using soluble fertilizers is their relatively low nutrient uptake efficiency and subsequent high leaching rate. Because they are soluble, some nutrients that are not used by plants or are held on the cation exchange sites of the growing medium, leach out with each irrigation. Fixed overhead irrigation systems apply fertilizer solution to the aisles as well as to the plants, so all these nutrients run off and can cause pollution.

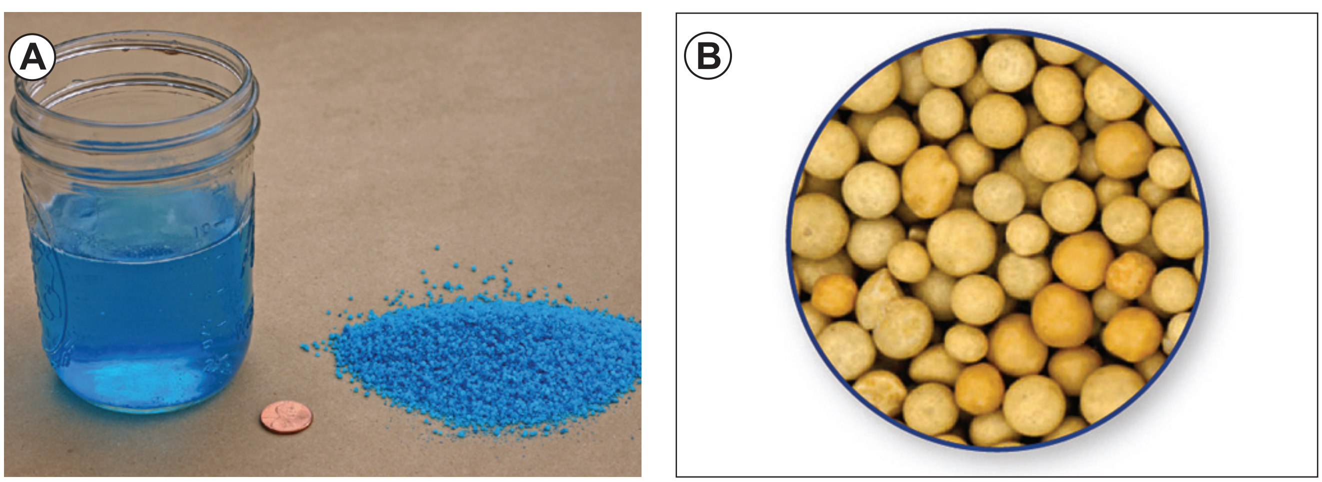


Figure 12.8—The two major types of synthetic fertilizers used in native plant nurseries are soluble crystals that dissolve completely in water (A), and polymer-coated controlled-release fertilizers, which are soluble fertilizers inside a thin plastic shell. These "prills" come in a variety of sizes, nutrient formulations, and release rates (B). Photo A by Thomas D. Landis, and photo B by Douglass F. Jacobs.

Special types of water-soluble fertilizers are sometimes applied to stimulate uptake through the foliage ("foliar feeding"). Although this method seems to be a good way to fertilize, remember that all leaves are covered with a water-repelling cuticle, so foliar uptake is very inefficient. More nutrient uptake actually occurs through the roots as a result of the fertilizer solution washing down into the soil or growing medium rather than through the foliage itself. Special care must be taken to prevent salt damage to foliage, so we do not recommend foliar feeding for smaller nurseries.

Controlled-Release Fertilizers

Coated fertilizers consist of a water-soluble fertilizer core covered with a less-soluble barrier, which affects the nutrient release rate. The most common coatings for controlled-release fertilizers (CRF) are sulfur or a polymer material. The major advantage of CRFs is that the gradual nutrient release results in higher nutrient uptake efficiency and less pollution potential (table 12.3). Often, CRF needs to be applied only once. Using CRF enables growers to supply nutrients for an extended duration without the specialized equipment needed to apply water-soluble fertilizers. Popular brands of polymer-coated fertilizers include Osmocote®, Nutricote®, and Polyon®, which have a variety of formulations for different plant species and growing cycles. Some release rates are so slow that they can provide an added benefit after outplanting.

Polymer-coated CRFs are widely used in tropical plant nurseries. The round, polymer-coated "prills" (figure 12.8B) have a more uniform nutrient release than sulfur-coated products. In addition, the prills can be formulated to contain both macronutrients and micronutrients (table 12.4), whereas sulfur-coated products generally supply only nitrogen.

Nutrient release from polymer-coated CRF is a multistep process. During the first irrigation, water vapor is absorbed through microscopic pores in the coating. This process creates an osmotic pressure gradient within the prill, causing the flexible polymer coating to expand. This expansion enlarges the tiny pores and allows the mineral nutrients to be gradually released into the soil or growing medium (figure 12.9). Besides water, temperature is the primary factor affecting the speed of this process. Nutrient release generally increases with increasing temperature. In warm, tropical climates, growers can expect CRFs to release more quickly than indicated on the label. The manufacturer adjusts the release rates of polymer-coated products by altering the thickness and nature of the polymer material, and longevities vary from about 3 to 18 months.

***Table 12.4**—Nutrient analysis of 15-9-12 Osmocote® Plus controlled-release fertilizer. Adapted from Everris Company (2012).*

Nutrient	Percentage
Macronutrients	
Nitrogen (7% ammonium; 8% nitrate)	15
Phosphorus (P_2O_5)	9
Potassium (K_2O)	12
Calcium	0
Magnesium	1.3
Sulfur	5.6
Micronutrients	
Iron (0.09% soluble, 0.01% chelated)	0.46
Manganese	0.06
Zinc	0.05
Copper	0.05
Boron	0.02
Molybdenum	0.02

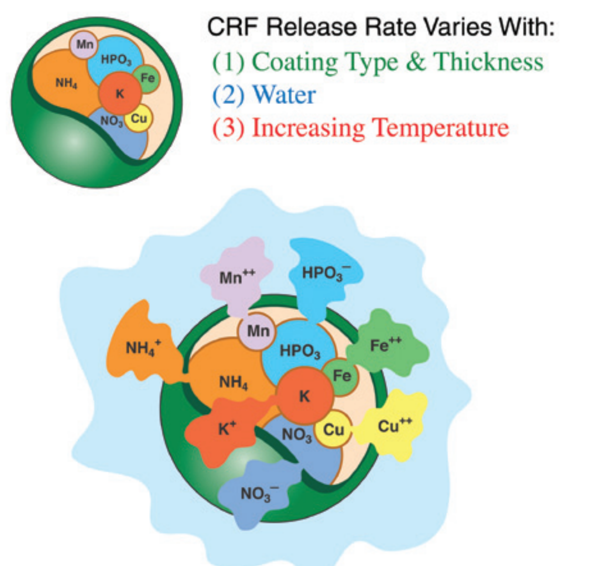


***Figure 12.9**—Nutrient release from polymer-coated fertilizers occurs after water vapor is absorbed through the prill membrane, creating an osmotic pressure gradient that expands the pores within the coating and allows fertilizer nutrients to pass through to the growing medium. Illustration from Dumroese and others (2008).*

Other types of CRFs are nitrogen-reaction products, such as ureaform and IBDU Micro Grade Fertilizer. These fertilizers are created through a chemical reaction of water-soluble nitrogen compounds, which results in a more complex molecular structure with very limited water solubility. The rate of nutrient release of ureaform is controlled by many factors, including soil temperature, moisture, pH, and aeration, while IBDU becomes available primarily through hydrolysis. These materials are rarely used in tropical native plant container production but are sometimes applied at outplanting.

Comparison of Organic Versus Synthetic Fertilizers

Because of the variability involved, it is difficult to compare organic and synthetic fertilizers but some generalizations can be made (table 12.5).

Mineral Nutrient Analysis

Nearly all organic fertilizers have relatively low mineral nutrient analyses. The nitrogen percentage is rarely above 15 percent and more typically in the range of 5 to 10 percent (figure 12.7B). Higher analysis products are usually supplemented with natural minerals such as sodium nitrate. Organic fertilizers often contain all 13 mineral nutrients. Synthetic fertilizers can be specially formulated to contain only a few macronutrients or a range of all mineral nutrients.

Table 12.5*—Comparison of organic and synthetic fertilizers.*

Factor	Organic	Synthetic
Mineral nutrient analysis	Low	High
Range of mineral nutrients	All	One to many
Nutrient release rate	Slower	Faster
Compatibility with beneficial microorganisms	Yes	At low levels
Cost	More	Less
Handling	Bulkier	More concentrated
Ecological sustainability	Yes	No
Water pollution risk	Low	High
Other benefits	Improves soil texture and encourages soil microbes	Better for research

Nutrient Release Rate

One of the major differences between organic and synthetic fertilizers is how fast their nutrients become available to plants. Soluble synthetic fertilizers are formulated as salts and are readily available, whereas a range of release rates exist for synthetic CRF, depending on coating thickness. Unprocessed organic fertilizers must first be broken down into smaller particles by soil microorganisms and then converted to a soluble form. Even processed organics contain a large percentage of insoluble nitrogen that must undergo microbial decomposition before being available for plant uptake. Liquid organic fertilizers have the benefit of being already in solution, or at least, in aqueous suspension.

Compatibility With Beneficial Microorganisms

Perhaps one of the most underappreciated benefits of organic fertilizers is that they promote the growth of beneficial soil microorganisms, including mycorrhizal fungi and nitrogen-fixing bacteria because nutrients are released slowly and the organic component improves soil conditions. Research has shown that high levels of soluble synthetic fertilizers, especially nitrogen and phosphorus, can inhibit the establishment and development of mycorrhizal fungi. This is particularly evident in the soilless growing media of container seedlings where applications of soluble, synthetic fertilizers are common.

Cost

A comparison of fertilizer costs is difficult because each fertilizer contains different percentages of nutrients and values must be compared on a per-weight or per-volume basis. Although they can be more expensive strictly on a per nutrient basis, both processed and unprocessed commercial organic fertilizers provide many other benefits that are hard to valuate, including adding organic matter and stimulating soil microorganisms (table 12.5). Synthetic fertilizers also have hidden costs, such as the carbon emissions during their manufacture and the ecological effects of increased potential for water pollution. For tropical growers, the potential to reduce transport costs by sourcing local commercial or homemade organic fertilizers may be attractive. In the final analysis, fertilizers represent only a very small percentage of the cost of producing nursery stock, so price may not be a deciding factor on the type of fertilizer to use.

Handling and Application

Because of their bulkiness and low nutrient analysis, unprocessed organic fertilizers are more expensive to ship, store, and apply compared with synthetic fertilizers. Conversely, synthetic fertilizers are more uniform in quality, have a high nutrient analysis per unit weight, and are much easier to apply to crops.

Ecological Sustainability and Water Pollution

One of the real benefits of organic fertilizers is that they are kinder to the environment and many can be obtained from recycled materials. Not only can nurseries recycle their cull seedlings, weeds, and other organic materials through composting, but they can also serve to recycle leaves, yard clippings, and other such organic wastes from the local community that would otherwise go to landfills (Morgenson 1994).

Nutrients in organic fertilizers are much less susceptible to leaching than those in synthetic fertilizers. Both processed and unprocessed organic fertilizers release their nutrients slowly and in a form that remains in the soil profile. Synthetic fertilizers, especially soluble formulations, often release their nutrients much faster than plants can use them, with the excess nutrients potentially polluting surface or ground water.

Fertilizer Application Rates and Methods

Fertilizer application rates depend on the growing environment and other cultural factors such as container volume, type of growing media, and irrigation frequency. In particular, the size of the growth container has a profound effect on the best application rate and timing. Very small containers require lower rates applied frequently whereas larger containers can tolerate high application rates applied less frequentlyFor most fertilizer products, manufacturers provided general recommended application rates for container nursery plants on package labels. In addition, experimentation, consultation with other growers and development of propagation protocols (see Chapter 4, Crop Planning: Propagation Protocols, Schedules, and Records) will help refine fertilizer application rates for tropical native plant species.

Fertigation for Applying Soluble Fertilizers

Some tropical plant nurseries apply soluble fertilizers through their irrigation systems, a process known as fertigation. The best fertigation method varies depending on the type of irrigation and the size and sophistication of the nursery. The simplest method is to mix soluble fertilizers and water in a watering container or use a hose injector, and water plants by hand. This method can be tedious and time consuming, however, when fertigating a large quantity of plants. On the other hand, this method may be appropriate for smaller nurseries growing many different species with different fertilizer needs.

Fertilizer injectors are a much more precise way to apply soluble fertilizers, especially when growing large numbers of plants with the same fertilizer requirements. The simplest injectors are called siphon mixers (figure 12.10A) and the Hozon™ and EZ-FLO® are common brands and range in cost from $20 to $200. Siphon injectors are attached to the water faucet and have a piece of rubber tubing inserted into a concentrated fertilizer solution (figure 12.10B). When an irrigation hose is attached to the other end and the water is turned on, the flow through the hose causes suction that pulls the fertilizer solution up and mixes it with the water at a fixed ratio. For example, the Hozon™ injects 1 part of soluble fertilizer to 16 parts of water, which is a 1:16 injection ratio. Note that this injector requires a water pressure of at least 30 pounds per square inch (lb/in^2 [psi]) (0.207 MPa) to work properly whereas the EZ-FLO® functions at water pressures as low as 5 psi (0.034 MPa).

More complicated, but more accurate, fertilizer injectors cost from around $300 to more than $3,000. For example, the Dosatron® is a water pump type of injector that installs directly into the irrigation line and pumps the fertilizer solution into the irrigation pipe at a range of injection ratios (figure 12.10C). Among the most technologically advanced fertigation systems is the automated hydraulic boom, which provides very consistent and uniform coverage of water and fertilizer to the crop. The relatively high price of irrigation booms, however, makes them cost prohibitive for most tropical plant nurseries. Any injector must be calibrated after it is installed to verify the fertilizer injection ratio and then must be checked monthly to ensure that it is still working properly.

Some nutrients, notably calcium and magnesium, are very insoluble in water and can even cause solubility problems in concentrated fertilizer solutions. If they are not present naturally in the irrigation water, calcium and magnesium must be supplied in a separate fertilizer solution or in a dolomitic limestone amendment to the growing medium.

Caution: Every fertilizer injector must be installed with a backflow preventer to eliminate the possibility that soluble fertilizer could be sucked back into the water line and contaminate drinking water.

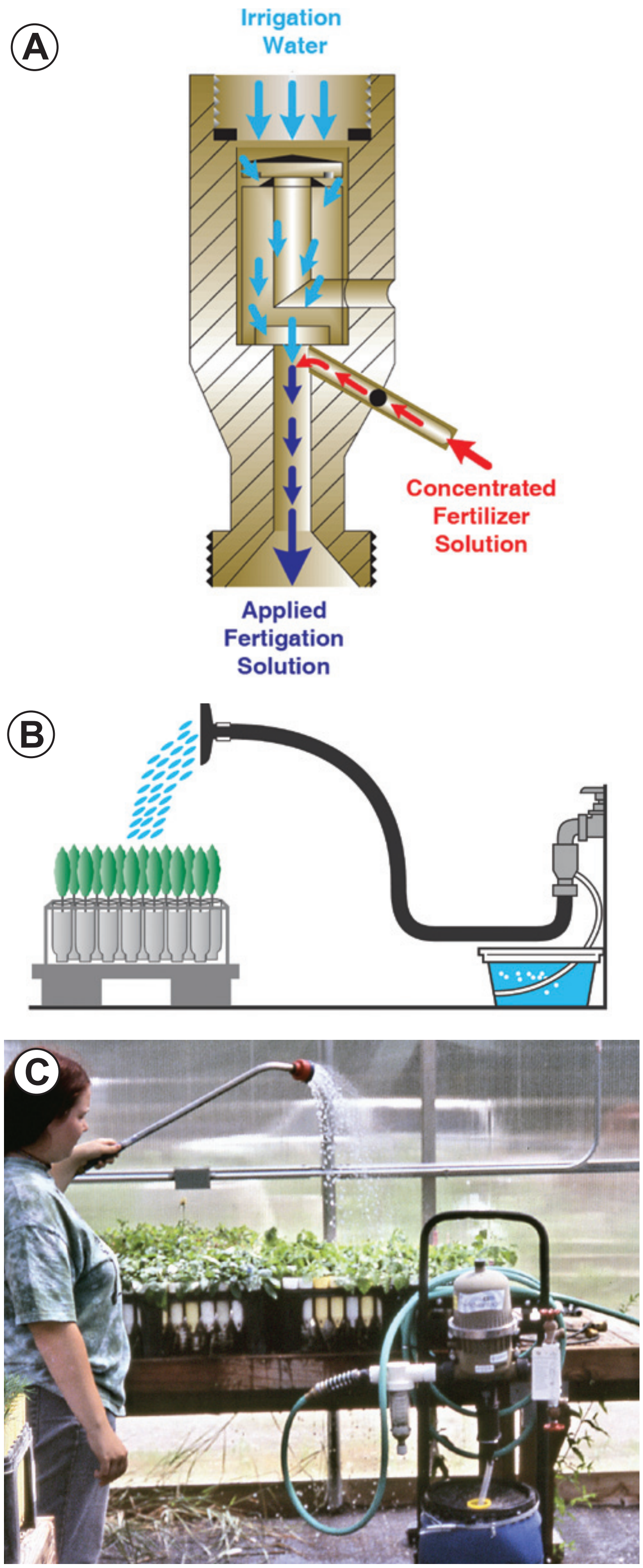


***Figure 12.10**—Soluble fertilizers can be mixed with water and applied to the crop, a process called "fertigation." A siphon injector (A) sucks up concentrated fertilizer solution, mixes it with irrigation water, and the fertigation solution is then applied with a hose (B) or other irrigation system. The Dosatron® injector (C) allows for more precise control of injection ratios. Illustrations A and B courtesy of Hummert™ International, and photo C by Tara Luna.*

Applying Controlled-Release Fertilizers

CRF can be topdressed (sprinkled into the top of the container), if care is taken to ensure that each container or cell receives an equal number of prills (figure 12.11A, table 12.6). A special drop-type application wand can be used to topdress larger (>1 gal [4 L]) containers because a measured dose of fertilizer can be applied to the base of each plant. This method avoids the potential of fertilizer granules being lodged in foliage and burning it as soon as the crop is watered.

Another option for applying CRF is to incorporate it into the growing medium (figure 12.11B, table 12.6). If growers mix the growing medium on site, CRF can be incorporated but special care must be taken to ensure uniform distribution (figure 12.11C) and to prevent damage to the prill coating. If the coating is fractured, then the soluble fertilizer releases immediately, causing severe salt injury. Nurseries can purchase growing media with CRF that have already been evenly incorporated with special, commercial mixing equipment. Purchased medium

***Table 12.6**—Manufacturer's recommendations for applying 15-9-12 Osmocote® Plus controlled-release fertilizer. Adapted from Everris Company (2012).*

Temperature		Longevity (months)	
ºF	ºC		
60	15	4 to 5	
70	21	3 to 4	
80	26	2 to 3	
90	32	1 to 2	
Units	Incorporation rates		
	Low	Medium	High
lbs per yd^3	3.0	8.0	12.0
kg per m^3	1.8	4.7	7.1
g per L	1.8	4.7	7.1
Topdressing (grams per container)			
Container volume	Low	Medium	High
1 qt (946 cm^3)	2	4	6
1 gal (4,546 cm^3)	6	17	26
5 gal (22,730 cm^3)	26	70	105

needs to be handled carefully and not stored for long because much of the nutrients can be released because of prill breakage or high temperatures.

Growers can use the general recommendations provided by manufacturers if they classify their crops by relative nutrient uses: low, medium, or high (table 12.6). Of course, these applications rates should be used conservatively until their effect on individual plant growth and performance can be evaluated. Because CRF nutrient release is so affected by temperature, growers need to be cautious about using CRF label recommendations. Manufacturers base their release rates on an average temperature of about 70 °F (21 °C), and those release rates increase by about 25 percent for every 9 °F (5 °C) increase in temperature (table 12.6). As with all nursery practices, growers should always initiate small scale trials before adopting any new fertilizer treatment.

Applying Organic Fertilizers

Composts could be incorporated into growing media but they must be fully mature to prevent fertilizer burn. One of the challenges of using liquid organic fertilizers is how to achieve the high soluble nitrogen levels necessary for rapid growth rates. High-quality nursery crops can be grown with organic fertilizers but, because their nutrient analysis is relatively low (figure 12.7B), production schedules may have to be adjusted.

Determining When to Fertilize

Because artificial growing media such as peat-vermiculite media are inherently infertile, fertilization should begin as soon as the seedlings or cuttings become established. Some brands of growing media contain a starter dose of fertilizer, however, so be sure and check the label. Homemade soil mixes that have been amended with compost or other organic fertilizers may not need fertilization right away but observe plant growth and establish small trials to be certain.

In nurseries, plant growth rates can be controlled by fertilization levels, especially nitrogen. As plants take up more nutrients, their growth rate increases rapidly until it reaches the critical point. After this point, adding more fertilizer does not increase plant growth but can be used

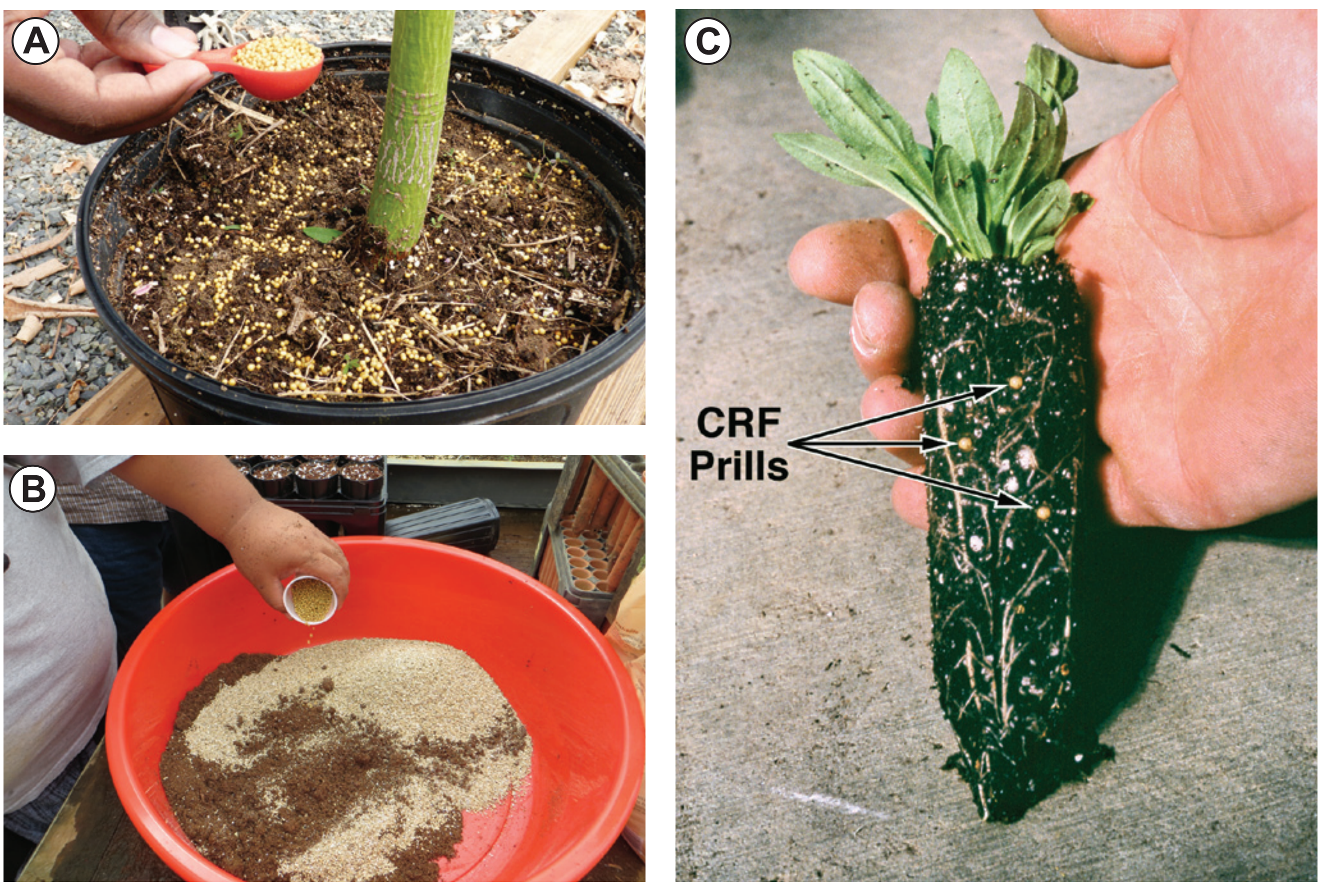
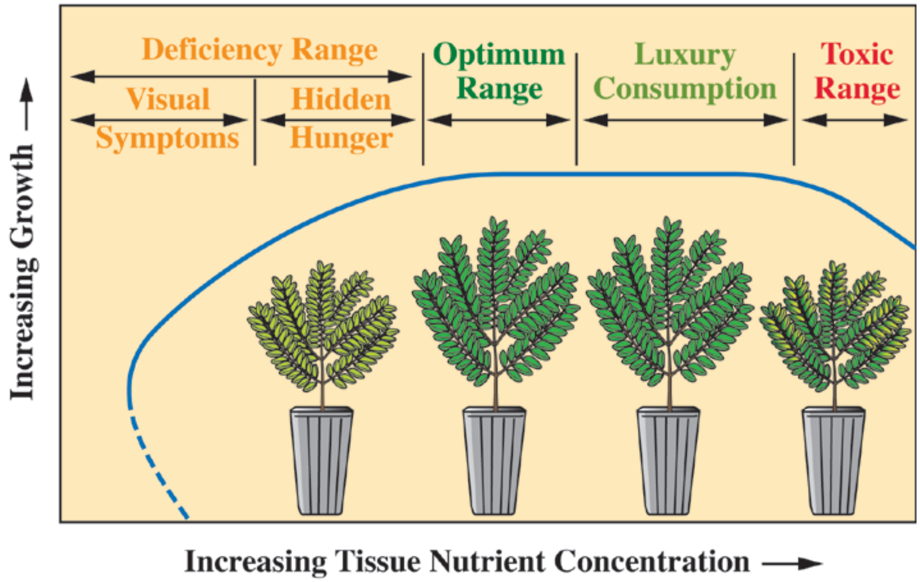


Figure 12.11—Controlled-release fertilizers can be applied directly to containers ("topdressing") if care is taken to achieve uniform application (A). Incorporating controlled-release fertilizers when the growing medium is mixed (B) helps to achieve even distribution of prills in small containers (C). Photo A by Brian F. Daley, photo B by Diane L. Haase, and photo C by Tara Luna.

Figure 12.12—*Fertilization is one of the most effective ways to increase plant growth, which follows a characteristic pattern. As nutrient content increases in plant tissue, growth increases and deficiency symptoms are abated but fertilization beyond the optimum range is not always beneficial. Illustration by Jim Marin.*



to "load" nursery stock with extra nutrients for use after outplanting. Beyond a certain point, however, excessive fertilization can cause a decline in plant growth and eventually results in toxicity (figure 12.12).

Some tropical plant species require very little fertilizer while others must be "pushed" with nitrogen to achieve good growth rates and reach target specifications. Small-seeded species expend their stored nutrients soon after germination whereas those with large seeds contain greater nutrient reserves and do not need to be fertilized right away. Excess fertilization early in the growing season can be detrimental to legumes and other natives, which must establish nitrogen-fixing bacteria or mycorrhizal fungi on their root systems before outplanting. Experience in growing a particular species is the best course of action to develop species-specific fertilizer prescriptions.

Tropical native plant growers should never wait for their crops to show deficiency symptoms before fertilizing. Plant growth rate will slow down before visible symptoms appear. Even after fertilization, it can take weeks before growth will resume following a deficient condition. Evaluating symptoms of nutrient deficiencies based on foliar characteristics can be challenging even for experts because different nutrient deficiencies have similar characteristic symptoms and considerable variation in these symptoms may occur among species. In addition, typical foliar symptoms, such as chlorosis, could be caused by something other than nutrient stress, such as heat damage or root disease. The position of the symptomatic foliage can be somewhat diagnostic. For instance, nitrogen is very mobile within the plant and will be translocated to new foliage when nitrogen is limiting. Therefore, nitrogen deficient plants show yellowing in the older rather than the newer foliage (figure 12.13A). Conversely, iron is very immobile in plants, so deficiency symptoms first appear in newer rather than older foliage (figure 12.13B). Keep in mind that excessive fertilization can cause toxicity symptoms (figure 12.13C). So,

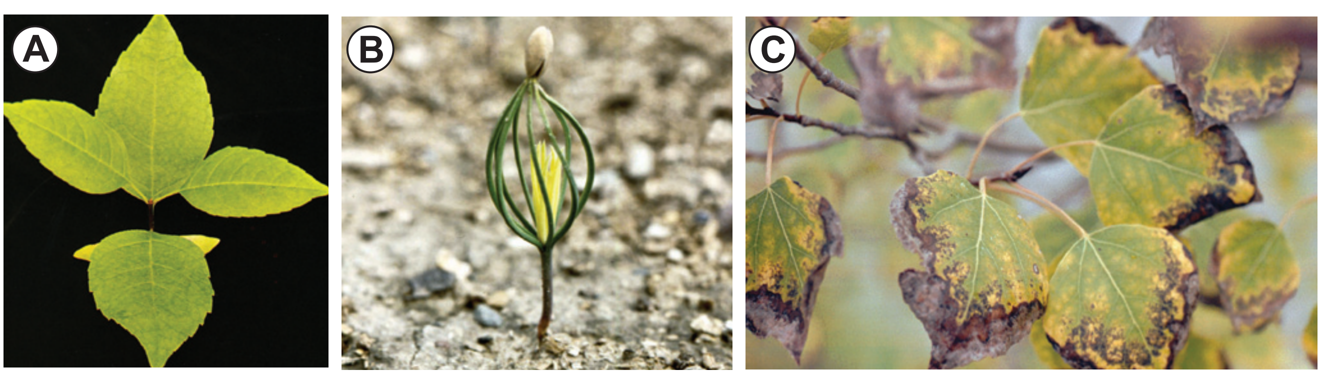


Figure 12.13—*Nutrient deficiency symptoms such as chlorosis (yellowing) are common but can be caused by several different nutrients. Nitrogen chlorosis is seen first in older foliage (A), whereas iron chlorosis occurs in newer needles or leaves (B). Excessive fertilization can cause toxicity symptoms, such as necrosis along the leaf margin caused by boron toxicity (C). Photo A from Erdmann and others (1979), and photos B and C by Thomas D. Landis.*

the take-home message is: foliar symptoms can be an indicator of nutrient (or other) problems but should never be used as the sole guide to fertilization. Crop monitoring and testing, experience, and knowledge about the growth phases are the best guides for determining fertilizer timing and rates.

Fertilization During Plant Growth Phases

Growers need to be aware of the different nutrient requirements during each growth phase and adjust fertilizer prescriptions accordingly (table 12.7). These adjustments are particularly important for nitrogen (especially the ammonium form of nitrogen), which tends to be a primary driver of plant growth and development (figure 12.14).

Establishment Phase

Fertilization needs to begin as soon as plants have emerged and have become established. Small plants are very succulent, however, and are particularly vulnerable to root damage from high salt concentrations. In addition, high nitrogen has been shown to increase the risk for damping-off fungi and other pest problems. Therefore, we recommend fertilizing with a low to moderate level of nitrogen (25 to 75 ppm) during this period.

Rapid Growth Phase

This phase is the period when plants attain most of their shoot development, and high levels of nitrogen (100 to 150 ppm) tend to accelerate this growth. In addition to nitrogen, fertilizers need to include adequate levels of all the other mineral nutrients. Growers must closely monitor plant growth and development during the rapid growth phase, however, to ensure that shoots do not become excessively large or top heavy.

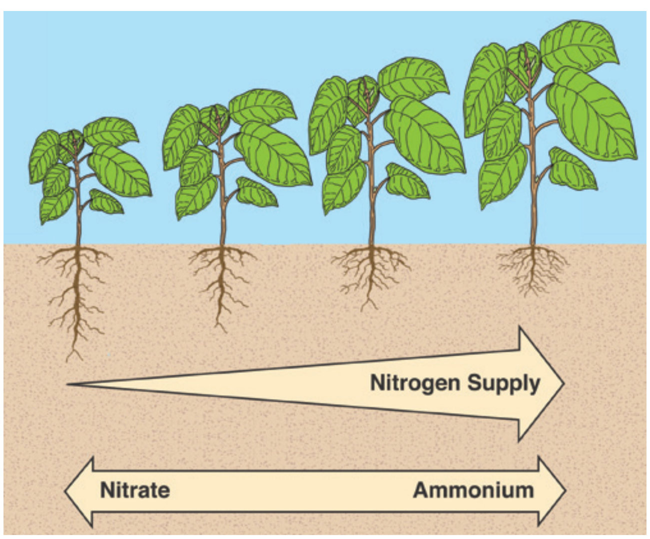


Figure 12.14*—Because nitrogen is so critical to seedling physiology, nitrogen fertilization can be used to control the shoot-to-root ratio. It is also used to speed up or slow down plant growth. Fertilizers with the nitrate form of nitrogen are recommended during the hardening phase to slow shoot growth while stimulating roots; ammonium nitrogen is recommended during rapid growth. Illustration adapted from Dumroese and others (2008).*

Table 12.7*—Examples of fertilization regimes adjusted for plant growth phases.*

Growth phase	Nitrogen	Phosphorus	Potassium
Establishment	Medium	High	Low
Rapid growth	High	Medium	Medium
Hardening	Low	Low	High

Hardening Phase

The objective of the hardening phase is to prepare plants for the stresses of shipping and outplanting by slowing shoot growth while simultaneously promoting stem and root growth. See Chapter 15, Hardening, for a complete description of this topic. High nitrogen levels stimulate plant growth, so reducing the amount of nitrogen (25 to 50 ppm) helps them to begin hardening. A lower ratio of nitrogen to that of phosphorus and potassium typically is helpful (table 12.7). In addition, changing to fertilizers containing the nitrate form of nitrogen (as opposed to ammonium) is helpful because nitrate-nitrogen does not promote shoot growth. Calcium nitrate is an ideal fertilizer for hardening because it provides the only soluble form of calcium, which has the added benefit of helping to promote strong cell wall development. It is important to distinguish granular calcium nitrate from liquid calcium ammonium nitrate, which does contain ammonium. A good rule of thumb for many tropical plants is that hardening should begin when shoots have reached 75 to 80 percent of the target size. Plants take a few weeks to respond to this change in fertilization and will continue to grow after nitrogen fertilization has been reduced. Leaching the growing medium with several irrigations of plain water is a good way to make certain that all excess nitrogen is eliminated from the growing medium.

Monitoring and Testing

We recommend monitoring the electrical conductivity (EC) of fertilizer solutions and performing chemical analysis of plant foliage to determine if fertilization is sufficient, to prevent problems from developing, and to diagnose any deficiencies or toxicities if they do develop.

EC Testing

Because all fertilizers are taken up as electrically charged ions, the ability of a water solution to conduct electricity is an indication of how much fertilizer is present. Growers who fertigate need to periodically check the EC of the applied fertigation water and the growing medium solution. Measuring the EC of fertigation water as it is applied to the crop can confirm that the fertilizer solution has been correctly calculated and that the injector is functioning.

Simple handheld EC meters (figure 12.15) are fairly inexpensive and are very useful for monitoring fertigation. The EC reading indicates the total amount of fertilizer salts and natural salts present in the water source. Normal readings in applied fertigation should range from 0.75 to 2.0 uS/cm. Measuring the EC of water leached from containers can also help pinpoint problems of improper leaching and salt buildup within the growing medium. Measuring the EC of the solution in the growing medium, however, provides the best estimate of how much fertilizer is available to plant roots. The typical range of acceptable EC values in the growing medium for most tropical plant species is about 1.2 to 2.5 uS/cm. If the EC is more than 2.5, it is a good idea to leach out the salts with clean irrigation water. See Chapter 11, Water Quality and Irrigation, for more information about EC measurements, guidelines, and units.

Foliar Testing

The best way to monitor plant nutrition and responses to fertilization is to test plant foliage for an exact measurement of nutrients that the plant has acquired. By examining tissue nutrient concentrations and simultaneously monitoring plant growth, it is possible to identify if and when specific nutrients are deficient or excessive/toxic (figure 12.12). Little published information is available for ideal mineral nutrient levels in tropical nursery plants so we recommend small trials to develop guidelines for your own species. Foliar samples must be collected in a systematic manner and sent to a reputable laboratory for processing (recommendations may be available through local extension agents). The analyzed nutrient concentration values are then compared with some known set of adequate nutrient values to determine which specific elements are deficient (table 12.8). The cost to analyze these samples is relatively inexpensive considering the potential improvement in crop quality that may result from having data to guide fertilizer regimes.

***Figure 12.15**—An electrical conductivity meter used to estimate fertilizer salt concentrations in irrigation water, fertigation water, or saturated media extract. Photo by Douglass F. Jacobs.*

Growth Trials

Small growth trials are another good way to monitor plant nutrition and fertilization needs. These trials are especially informative for tropical plant species because so little published information is available. Detailed

***Table 12.8**—Estimated ranges of foliar nutrient levels for healthy tropical plants (based on data compiled by Drechsel and Zech [1991] on field-grown, broad-leaved, tropical tree species). Nutrient ranges can vary greatly among species. Nursery trials are recommended to determine the best ranges for specific species.*

Nutrient	Range of foliar levels in healthy plants
Macronutrients	**(%)**
Nitrogen	1.5 to 3.5
Phosphorus	0.10 to 0.25
Potassium	0.60 to 1.8
Calcium	0.50 to 2.5
Magnesium	0.15 to 0.50
Sulfur	0.10 to 0.30
Micronutrients	**ppm (parts per million)**
Iron	50 to 250
Manganese	35 to 250
Zinc	10 to 40
Copper	5 to 20
Boron	15 to 50
Molybdenum	0.10 to 1.0

documentation of growing conditions, fertilizer inputs, and resulting plant response can help to formulate future fertilizer prescriptions for a specific species within a nursery. See Chapter 20, Discovering Ways to Improve Nursery Practices and Plant Quality, for more information on how to make these discoveries through trials and experiments.

Reducing the Environmental Effects of Fertilization

Regardless of the method of fertilizer application or the type of fertilizer used, runoff of excess fertilizers is a major environmental concern. Nutrient ions, notably nitrate and phosphate, leach easily from container nurseries, and can pollute groundwater or adjacent streams. Many areas have laws and regulations limiting runoff and groundwater nitrate levels. Growers need to choose types of fertilizers and schedule their applications to minimize potential pollution concerns. Because nitrate and phosphate are so soluble in water, growers need to irrigate only when necessary and apply only enough water so that only small amounts drain out the bottom of the containers. This approach also makes sense from an economic standpoint, because the desire is to have most of the applied fertilizer taken up by crop plants rather than lost in runoff.

Reducing, eliminating, and managing environmental effects of fertilization in the nursery include these practices:

1. Apply fertilizer as part of a designed nutrient and irrigation program. The goal is never to push plants as quickly as possible through all phases of growth; instead, crops should be cultured to produce balanced, healthy plants for the best results after outplanting.
2. Consider using slow-release and controlled-release fertilizers in addition to, or instead of, highly soluble liquid fertilizers.
3. Select organic fertilizers that have less leaching potential.
4. Explore options to recycle or reuse irrigation water, including subirrigation systems or catchment ponds where runoff can be collected, treated, and reused.
5. Learn about water conservation and responsible management and reuse of runoff water, as discussed in Chapter 11, Water Quality and Irrigation.

A combination of these steps as appropriate for your nursery will help to minimize nutrient leaching and reduce the effects of fertilization on the environment.

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