## Macronutrients - Phosphorus

by Thomas D. Landis and Eric van Steenis

### Introduction

Of the three "fertilizer elements" (N-P-K), phosphorus (P) is found in the lowest concentration in plant tissue - only about 5% (Table 1). As a limiting factor, however, phosphorus is second only to nitrogen in terms of its importance to plant growth and development. Phosphorus is essential to all forms of life and it can be found in every cell in all living organisms. The element phosphorus is never found in nature but is always combined with other elements to form phosphates, for example calcium phosphate.

Nearly 80% of the phosphorus in animals is found in bones and teeth. Because of this, farmers historically used ground bones as fertilizer even though very little of this phosphorus is immediately available to plants. In 1808, Sir James Murray produced the first effective phosphorus fertilizer in Ireland by treating bones with sulfuric acid and creating water soluble phosphate. He later found that rock phosphate (calcium phosphate) could be treated similarly. Significant deposits of rock phosphate were discovered in New York and, by the late-1800s, America was producing 90% of the phosphate fertilizer in the world.

### Role in Plant Nutrition

**Phosphorus has several critical physiological and structural functions in plants.**

• Energy storage and release - All living things need a constant source of energy to survive and grow. The solar energy captured in photosynthesis is stored in the chemical bonds between phosphorus atoms in adenosine triphosphate (ATP) molecules (Figure 1). When triggered by an enzyme, the endmost phosphate group is cleaved from the ATP molecule and energy is released. Even more energy can be gained by breaking the second phosphate group. These chemical reactions are reversed when phosphate groups are reattached in the chloroplasts using the energy from photosynthesis. Thus, ATP molecules function like a "battery"- storing energy when it is not needed, but able to release it when it is. Uridine triphosphate, cytidine triphosphate, and guanosine triphosphate function similarly to ATP and together provide an energy storage and release system for almost all the metabolic reactions in plants.

**Table 1 - The three major macronutrients and their typical concentration in seedling tissue**

| Element | Symbol | % of Total Mineral Nutrients in Plants | Adequate Range in Tree SeedlingTissue % | | Where and When Published |
|---|---|---|---|---|---|
| | | | Bareroot | Container | |
| Nitrogen | N | 37.5 | 1.2 to 2.0 | 1.3 to 3.5 | Summer, 2003 & Winter, 2004 |
| Phosphorus | P | 5.0 | 0.1 to 0.2 | 0.2 to 0.6 | This issue |
| Potassium | K | 25.0 | 0.3 to 0.8 | 0.7 to 2.5 | To Do - Winter, 2005 |

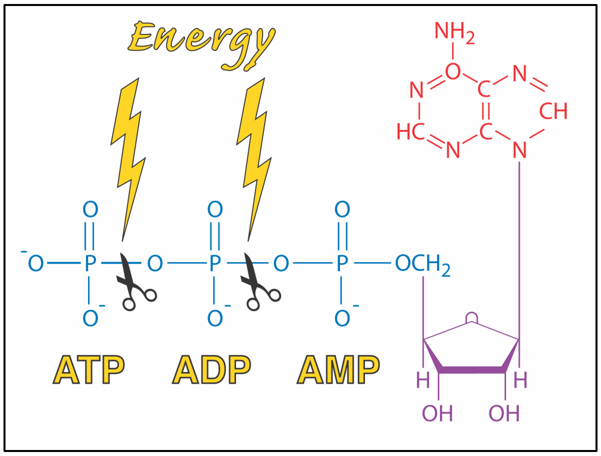



*Figure 1 - The chemical energy captured in photosynthesis is stored in the phosphate-to-phosphate bonds in adenosine triphosphate (ATP) molecules.*

- Component of nucleic acids - Nucleic acids are found in all plant cells and allow the replication and transcription of genetic information for reproducing and synthesizing compounds like proteins. Sugar phosphates form the double helix "backbone" for dioxyribonucleic acid (DNA) which contains the complete genetic blueprint of every organism. Phosphorus is also a constituent of ribonucleic acid (RNA) which serves as a chemical messenger, carrying genetic instructions through the plant.

- Structure and function of cell membranes - The membranes inside plant cell walls are composed primarily of phospholipids, long fatty acid chains which are attached to phosphate ions. The cell membrane could not perform its structural and chemical functions without phosphorus.

- Regulator of enzymes - Phosphorus helps regulate the activity of enzymes involved in critical metabolic processes such as starch synthesis.

- Cell buffer system - Phosphoric acid helps buffer cell pH and maintain homeostasis.

- Storage in seeds and fruits - Both contain high concentrations of phytin, which can be hydrolyzed to release phosphate for metabolism and cell wall formation. This ready source of stored phosphorus is critical during seed germination and emergence before the seedlings can begin to obtain phosphorus from the soil.

**Availability to plants.**

Phosphorus availability is radically different between field soil and artificial growing media.

*Soil* - Phosphorus is found in many organic and inorganic forms in soils but only a very small percentage is available for uptake by plant roots Calcium, magnesium, iron, and aluminum all chemically bond with phosphorus, and it is also found in minerals such as apatite. These unavailable forms are known as "nonlabile" phosphorus (Figure 2). Free phosphate ions ("labile P") are chemically adsorbed onto clay or organic particles and are gradually released into the soil solution. In addition, all organic matter contains a considerable amount of phosphorus. As it is decomposed by microorganisms and as these microorganisms themselves die, phosphorus is slowly released into the soil solution. Because the available forms of phosphate are negatively-charged anions, they are not held on soil cation exchange sites and can be easily leached from the root zone (Figure 2). Because of the very low concentration of soluble phosphorus in the soil, availability is highest when soil water is near field capacity. Due to the fact that the majority of soil phosphorus is so unavailable, nursery managers must supply it from fertilizers or green manure crops, and encourage beneficial microorganisms like mycorrhizal fungi.

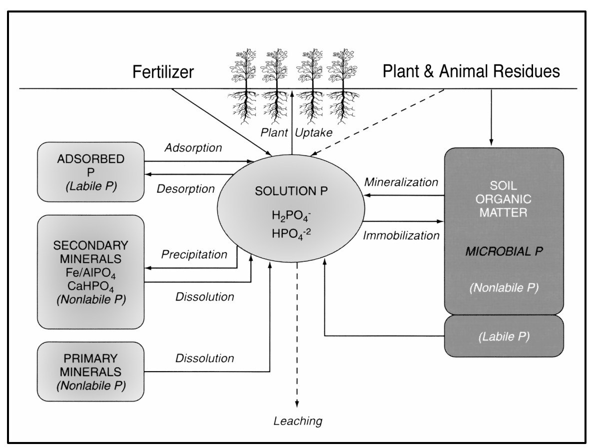



*Figure 2 - Phosphorus is found in both organic and inorganic forms in field soil and is slowly released to form the small percentage of available P in the soil solution. This situation does not apply to artificial growing media, however (modified from Havlin and others 1999).*

*Growing media* - Common artificial growing media contain very little phosphorus but do not chemically fix it like field soils. Although peat moss and vermiculite both have high cation exchange capacities, this does not affect the negatively-charged phosphate ions. There is some evidence that vermiculite has a limited anion exchange capacity. Therefore, a very high percentage of the phosphorus applied to container growing media remains soluble and available to plants. The down side is that this phosphorus is very easily leached by the high amounts of water used in container nurseries. Therefore, growers must continually supply phosphorus to achieve the rapid growth rates desired in container nurseries.

*Affects of pH* -The relative acidity or alkalinity of soils or growing media has a significant effect on the type of the orthophosphate ions and their availability. At lower pH, iron and aluminum form insoluble complexes with free phosphate ions whereas, at higher pH values, calcium ions tie-up the phosphate. The take-home lesson for nursery managers is that maintenance of a slightly acid pH is critical for optimum phosphate availability (Figure 3). Because artificial growing media do not contain these complexing agents, phosphorus availability in container nurseries is not limited by pH.

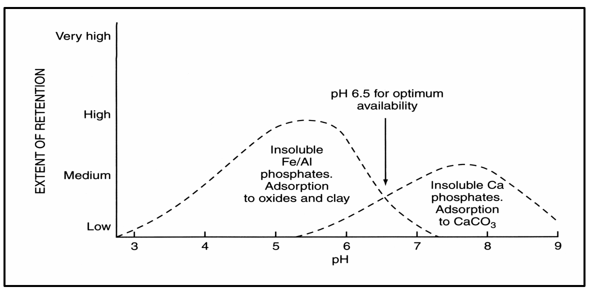



*Figure 3 - Maintenance of proper soil pH is critical to phosphorus availability in bareroot nurseries (modified from Havlin and others 1999).*

*Importance of mycorrhizal fungi* - Mycorrhizae are unique structures on plant roots which develop through a symbiotic association with specific fungi. One primary benefit of this symbiosis is that the presence of mycorrhizal fungi greatly increases phosphorus availability. As we have already discussed, the vast majority of soil phosphorus is unavailable to plants so mycorrhizae have a major role in phosphorus nutrition. In fact, mycorrhizae do not even form on seedling roots where phosphorus is readily available and this explains the difficulty of trying to inoculate with mycorrhizal fungi in nurseries where high fertilization rates are the rule. Studies have shown that the benefits of mycorrhizae are greatest when soil phosphorus levels are at or below 50 ppm and that inoculation is poor when levels exceed 100 ppm.

One of the classic symptoms of mycorrhizal deficiency in bareroot nurseries is a mosaic stunting pattern where patches of normal sized seedlings are interspersed with patches of stunted ones (Figure 4A). This typically occurs after soil fumigation has eliminated all the mycorrhizal fungi in the seedbeds, and the healthy patches are where random reinoculation has occurred. This same mosaic pattern can be seen in the “no phosphorus” treatment of a controlled fertilization study (Figure 4B), illustrating the strong link between mycorrhizae and phosphorus nutrition.

What does this mean to nursery managers? Should they restrict phosphorus fertilization to encourage mycorrhizal fungi? Phosphorus fertilizer is inexpensive and, if applied at the proper time and with the proper technique, can produce vigorous seedling growth whether mycorrhizae are present or not. Some species of fungi (*Rhizopogon* spp., for example) have been shown to be more tolerant of the high fertilization rates in nurseries. The real benefit of mycorrhizae come after outplanting and so nursery managers should encourage them during the hardening period when fertilization levels are lower and there are many sites on the roots available for infection.

**Uptake and mobility in plants**. Phosphorus is adsorbed by plants largely as the negatively charged orthophosphate ions ($H_2PO_4^-$ & $HPO_4^-$) which are present in the soil solution (Figure 2). The young, vigorous roots of nursery seedlings take up phosphate rapidly from the rhizosphere and so a strong gradient always exists between the rhizosphere and the soil solution. Therefore, most phosphorus absorption is active, requiring energy.

Phosphorus is very mobile in plants and can be translocated in either an upward or downward direction. Young rapidly growing leaves and meristems create a sink for phosphate and, if the supply from the roots is insufficient, phosphate can be remobilized from older leaves and transferred to new ones. During seed formation, phosphate is stored as phytin and is released for metabolic processes when the seeds germinate.

**Influences on Plant Growth and Development**

Phosphorus fertilization can have a profound influence on seedling performance during the various growth stages in nurseries:

**Establishment Phase.** Because of their rapid growth, young seedlings have a high requirement for phosphorus and take it up very rapidly. The stored phosphorus in the endosperm of the seed doesn’t last long and so germinants need to quickly find a source of phosphorus to support their high metabolic rates. To complicate things, the restricted root system of young seedlings

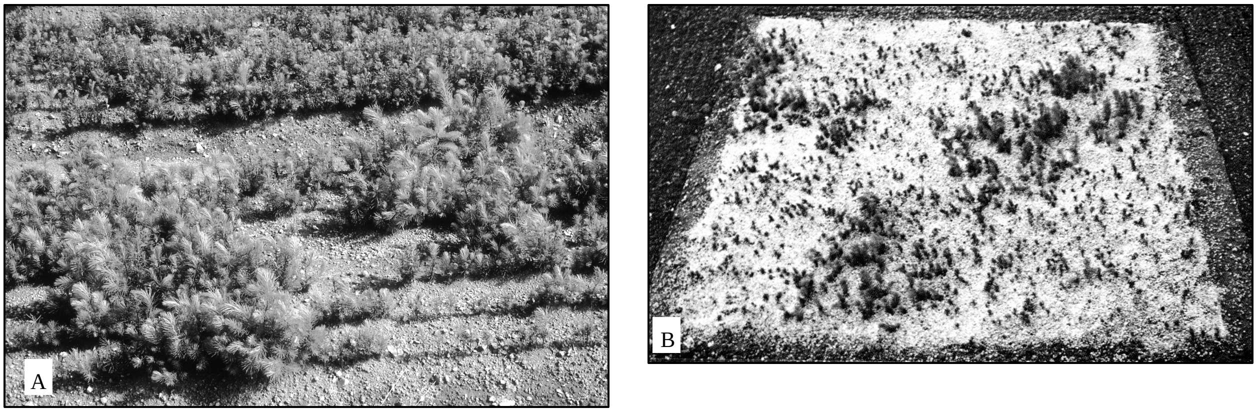



*Figure 4 - The strong influence of mycorrhizal fungi on phosphorus nutrition can be seen by this pair of photographs: A) the classic mosaic stunting pattern of mycorrhizal deficiency, B) the "no phosphorus" treatment in a controlled fertilizer study.*

**Phosphorus and Root Growth**

One of the traditional beliefs in nursery fertilization is that phosphorus stimulates root growth. There doesn't seem to be much published research to support this, however. With root crops where much of the photosynthate is channeled to the roots for storage, phosphorus fertilization has been shown to have a beneficial effect. On the other hand, in nursery crops where roots are primarily used for support and absorption, phosphorus does not seem to have any stimulating effect. In fact, adding phosphorus fertilizer to deficient plants has shown to promote top growth rather than root growth.

limits the soil volume that can be accessed. Finally, in bareroot nurseries and open growing compounds, low soil temperatures in the spring has been shown to retard phosphorus uptake.

**Rapid Growth Phase.** Seedlings in the exponential growth phase continue to have a high demand for phosphorus to support the high metabolism and rapid cell division. Bareroot nursery managers incorporate or band phosphorus fertilizers before sowing to make sure that it is available for uptake and utilization. Container growers keep phosphorus levels high in their fertigation formulas for the same reason.

**Hardening Phase.** As shoot growth has stopped and cellular metabolic rates slow down, phosphorus uptake has been shown to decline. At the same time, seedling root systems are more extensive and mycorrhizae are becoming established so seedlings are able to access phosphorus much more easily. It has been a traditional practice to increase the amount of phosphorus fertilizers applied to crops during the hardening phase with the objective of promoting root growth. This has not been substantiated by research, however (see sidebar), and may actually inhibit infection by mycorrhizal fungi.

**Monitoring Phosphorus**

Phosphorus nutrition can be monitored by chemical analysis of soils, growing media, or plant tissue but deficiency symptoms are not diagnostic.

**Deficiency Symptoms.** The visual symptoms of phosphorus deficiency are neither distinctive nor pronounced enough to be very diagnostic. Because phosphorus is needed for critical processes such as RNA synthesis and energy transfer, a deficiency has a pervasive effect on seedling physiology and growth is restricted. Therefore, the most common phosphorus deficiency symptom is stunted growth, especially in the root system (Figure 4). This is probably the reason why phosphorus is believed to promote root growth but reduced root growth is more a factor of restricted metabolic processes in the shoot rather than a phosphorus deficiency as such. Because it can be caused by so many factors, phosphorus deficiency often goes unnoticed as "hidden hunger".

There is no typical foliar symptom of phosphorus deficiency. The leaves of some crops show a darkish green color and others exhibit a reddish coloration from an enhanced production of anthocyanin pigment. For example, the foliage of western redcedar (*Thuja plicata*) seedlings exhibits a distinctive purpling or bronzing when phosphorus is deficient.

**Toxicity Symptoms.** High levels of phosphorus are more common in artificial growing media because it is chemically fixed so rapidly in soils. Experience with hydroponic crops relates that, if the phosphorus concentration of seedling foliage exceeds 1.00%, then problems may result. Although high phosphorus levels are not directly toxic, they can cause growth problems because of reduced uptake and utilization of several micronutrients including zinc, iron, and copper. These are know as “induced deficiencies” and zinc deficiency is usually the first to occur. A unique situation exists in Australia, New Zealand, and South Africa where plants have adapted to the extremely low soil phosphorus levels and native plants such as *Protea* and *Grevillea* show toxic reactions to even low phosphorus levels.

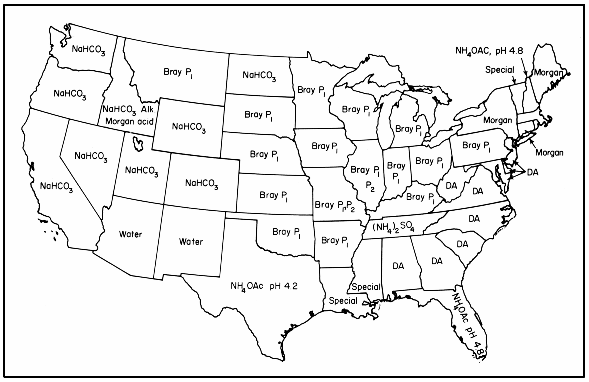
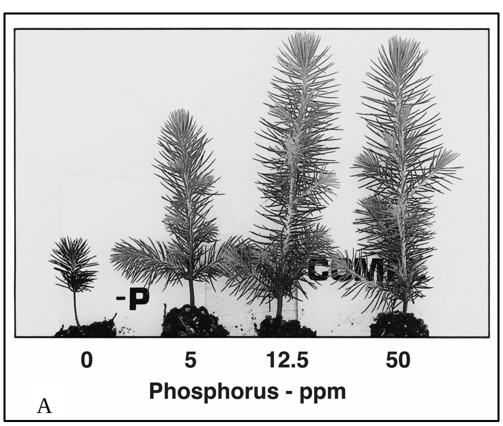



*Figure 5 - Soil tests for available phosphorus vary with soil types and so state testing laboratories have adopted different extraction procedures (modified from Donahue and others 1977).*

**Soil Tests.** Because of the many and varied ways in which phosphorus is bound in soils, creating a reliable test for available phosphorus has proven challenging. Different soils require different chemical extractants that simulate plant availability, and five extraction procedures are currently being used. In the more acidic soils of the northeastern states one of the Bray tests is used whereas, in the more alkaline soils of the western states, the Olson test using a $NaHCO_3$ extractant is preferred (Figure 5). Therefore, bareroot nurseries should use local soil testing labs to make certain that they are getting accurate information. Because soil test results can vary considerably between labs, it is a good idea to chose one lab and stick with them from year to year. A proficiency testing program of soil testing labs in the western US found that soil phosphorus results showed high variability.

**Artificial Growing Media Tests.** Although there are several techniques available, forest and conservation nurseries do not typically analyze their growing media for phosphorus. Instead, most growers have developed their fertilization regimes based on seedling growth response or foliar tests.

**Seedling Tissue Analysis.** Because of the difficulty in measuring available phosphorus in soils and growing media, tissue tests are generally considered to be the best way to monitor phosphorus nutrition (Figure 6A). A typical plant contains 0.20% P on a dry weight basis but this can vary 0.10% to 0.50% depending on species and age of tissue. For nursery stock, the adequate level for phosphorus is relatively low for a macronutrient - 0.10 to 0.20% for bareroot seedlings and 0.20 to 0.60 for container stock (Table 1). The phosphorus content of plants is generally considered deficient when it is below 0.10% and this threshold has been confirmed for a wide variety of conifer and broadleafed nursery stock (Figure 6B). For example, the foliage of western redcedar seedlings shows a distinctive purpling or bronzing below



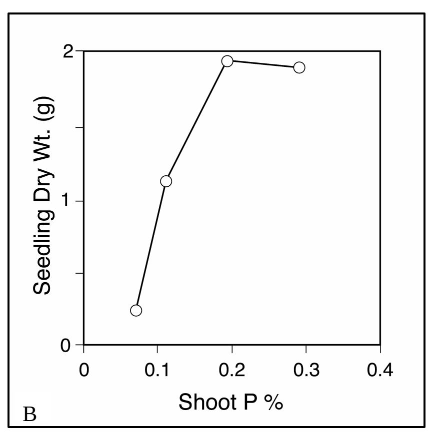




*Figure 6 - Seedling growth response is the best way to monitor phosphorus nutrition (A), and nursery stock can be considered phosphorus deficient when foliar concentrations decrease below 0.10 to 20% (B) (modified from van den Driessche 1984).*

0.10% but, when foliar concentrations exceed this level, the foliage is a normal green.

Foliar test results can vary from lab to lab so nurseries are encouraged to establish a relationship with one testing facility so that results will be comparable from year to year. Because of the considerable variation that occurs between species and at stages during the growing season, nurseries are encouraged to develop their own standards for tissue analysis.

**Phosphorus Management in Nurseries**

There are a few cultural practices that will increase phosphorus availability such as keeping soil moisture high and, as show in Figure 4, pH should be in the ideal 5.5 to 6.5 range. In particular, acidifying calcareous soils with sulfur or ammonium sulfate has proven effective. Organic matter contains relatively high levels of phosphorus and so organic amendments are a cheap and easy way to supply phosphorus, although the release rate is too slow to be practical in nurseries. The ratio of nitrogen to phosphorus is important: phosphorus keep the numerous metabolic processes going and nitrogen provides the building blocks for tissue growth and development. Nitrogen-to-phosphorus ratios are often calculated, and a 10:1 ratio is considered optimum.

**Fertilization.** Much of the phenomenal growth rates that are achieved in nurseries can be attributed to good fertilization practices and this is especially true for phosphorus. Therefore, nursery managers do not rely on reserves in the soil or growing media but add all the required phosphorus as fertilizer. Phosphorus fertilization has some unique considerations, however:

*Timing and Method of Fertilization* - The restricted root system of young seedlings means that growers must take special care to ensure that phosphorus is readily available early in the season. In bareroot nurseries, presowing incorporation into the seedbed and banding phosphorus fertilizers at the time of sowing have proven effective. Monoammonium phosphate and diammonium phosphate are recommended for banding because the presence of nitrogen is thought to increase phosphorus uptake. Because of its restricted movement in soils, top dressing of phosphorus fertilizers is not recommended.

In artificial growing media, phosphorus remains available but also leaches readily so growers must provide a continual supply. Starter fertilizer formulations and controlled release fertilizers have ample amounts of phosphorus but the challenge is ensuring even distribution of fertilizer between containers. Because of their restricted volume, this is more of a problem in small plug containers. Fertigation is a reliable way to achieve even distribution and provide a steady supply of phosphorus. Recommended phosphorus concentrations in fertigation solutions has traditionally been in the range of 30 to 100 ppm but this is much higher than shown to be necessary. Research trials have demonstrated that healthy seedlings can be grown with as little as 10 to 15 ppm phosphorus (Figure 6A). Growers who lower the pH of their irrigation water with phosphoric acid get the additional benefit of providing a steady supply of phosphorus from the very first irrigation.

*Types of Fertilizers* - The best phosphorus fertilizer for a given situation depends on many things, but the bottom line is crop response. In bareroot nurseries, you should learn the phosphorus-fixing ability of your soil and install some field trials. Controlled release fertilizers have special appeal for container growers because the can supply a steady supply of phosphorus to plants without the risk of leaching losses.

Due to an established labeling convention, the phosphorus in fertilizers is expressed as phosphate ($P_2O_5$) and fertilizer labels are required by law to state the N-P-K analysis as % N:% $P_2O_5$:%$K_2O$). To convert from % phosphorus to % phosphate multiply by 2.29; to convert from % phosphate to % phosphorus multiply by 0.43. The main sources of phosphorus container fertilizers is given in Table 2.

**Eutrophication of Surface Water.** Water quality has become one of the most important ecopolitical issues, and all types of agriculture are potential sources of fertilizer pollution. Phosphorus is considered a serious environmental pollutant because it promotes eutrophication of surface waters. Eutrophication can be defined as the excessive nutrient enrichment of water, which results in nuisance production of algae and other microscopic water plants. Because phosphorus is the primary limiting nutrient in freshwater systems, runoff from nurseries can lead to an explosive increase in algal growth called "blooms" on the water surface. Water quality progressively deteriorates as these plants decompose, creating taste and odor problems, and eventually killing fish and other aquatic organisms. To make matters worse, some species of algae release toxins into the water.

In bareroot nurseries, almost all of the fertilizer phosphorus is chemically fixed on soil particles and therefore surface runoff that carries suspended sediment is the primary culprit. With their artificial growing media, container nurseries have inherently high leaching rates of phosphorus. In one study, 16 to 64% of the applied phosphorus fertilizer was recovered in the leachate.

If excess irrigation and fertigation are allowed to run off

| Table 2 - Types of Phosphorus Fertilizers Commonly Used in Forest and Conservation Nurseries | | | | | | |
|---|---|---|---|---|---|---|
| **Fertilizer** | **Nutrient Analysis** | | | **Nursery Type** | **Application Method** | **Remarks** |
| | **% N** | **% $P_2O_5$** | **% $K_2O$** | | | |
| Milorganite® | 6 | 2 | 0 | BR | Incorporated | An organic fertilizer made from municipal sludge |
| Single superphospate | 0 | 16 to 22 | 0 | BR | Incorporated or Banded | Also contains 11 to 12% sulfur |
| Triple superphospate | 0 | 44 to 53 | 0 | BR | Incorporated or Banded | Also contains 1 to 2% sulfur |
| Diammonium phosphate (DAP) $(NH_4)_2HP0_4$ | 18 | 46 | 0 | BR | Incorporated or Banded | A dry granular or crystalline material |
| Monoammonium phosphate (MAP) $NH_4H_2PO_4$ | 11 | 52 | 0 | BR | Incorporated or Banded | A dry granular material |
| Potassium phosphates | 0 | 41 to 51 | 35 to 54 | BR or C | Fertigation | Water soluble with low salt index |
| Phosphoric acid (White or Food grade) | 0 | 54 | 0 | C | Fertigation | Nutrients are a by-product of the acidification of irrigation water |
| Plant Products 20-20-20 | 20 | 20 | 20 | C | Fertigation | Completely soluble, with micronutrients |
| Scotts Excel Cal-Mag 15-5-15 | 15 | 5 | 15 | C | Fertigation | Completely soluble, with calcium, magnesium, sulfur and micronutrients. |
| Scotts Peters Plant Starter 9-45-15 | 9 | 45 | 15 | C | Fertigation | Completely soluble, with high P for young plants. |
| Scotts Peters Foliar Feed 27-15-12 | 27 | 15 | 12 | C | Fertigation | Completely soluble |
| **Controlled-Release Formulations** | | | | | | |
| Osmocote Fast Start; 8 to 9 month release | 18 | 6 | 12 | C | Incorporation | Polymeric resin-coated prills |
| Osmocote High N; 8 to 9 month release | 24 | 4 | 8 | C | Incorporation | Polymeric resin-coated prills |
| Polyon 25-4-12; 8 to 9 month release | 25 | 4 | 12 | C | Incorporation | Polyurethane-coated prills |
| Nutricote 270; 8 to 9 month release | 18 | 6 | 8 | C | Incorporation | Thermoplastic resin-coated prills |

the nursery site, they can be considered point source pollution and subject to more and more legislation. Many container and even some bareroot nurseries are building constructed wetlands which collect all surface runoff and hold it until aquatic plants can remove the excess phosphorus. The surplus phosphorus is contained in the plant tissue and is removed from the system when the plants are harvested.

**Conclusions and Recommendations**

Phosphorus has critical physiological and structural functions in plants, and so phosphorus management is critical for promoting the rapid growth of nursery seedlings. Phosphorus availability is radically different between field soil and artificial growing media. In soils, the vast majority of phosphorus is chemically bound and unavailable and soil pH level is critical. With artificial growing media, phosphorus is readily available but is also subject to leaching. Phosphorus management is most critical during the establishment phase of seedling growth. Phosphorus nutrition can be monitored by chemical analysis of soils, growing media or plant tissue but diagnosis of phosphorus deficiency or toxicity using foliar symptoms is not recommended. Instead, chemical analysis of foliage has proven useful with 0.10% as the critical level below which growth rates will decline. Much of the phenomenal growth rates that are achieved in nurseries can be attributed to good fertilization practices and this is especially true of phosphorus. To achieve the rapid growth rates of nursery culture, nursery managers should not rely on reserves in the soil or growing media but add all the required phosphorus as fertilizer. In bareroot nurseries, incorporation or banding phosphorus into the seedbed prior to sowing has proven effective. With container crops, providing a low but continuous supply of phosphorus can be achieved by incorporation of controlled release fertilizers or as an added benefit using phosphoric acid to acidify irrigation water.

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