

Section 3: Substrates

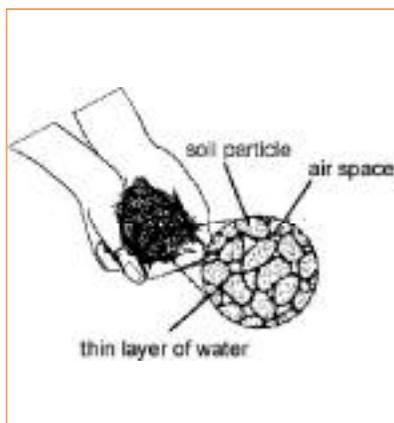
Most nurseries use mixtures of topsoil with organic and inorganic additions. However, these don't always allow the development of a good fibrous root system. In this chapter, we discuss what makes a good substrate and describe a variety of organic and mineral substrates suitable for agroforestry nurseries in the tropics.

Good plant development depends to a large part on the growing medium used. If a plant develops a good root system in a well-balanced substrate, this does not mean that the plant is pampered and will not adapt to the harsh life outside a nursery. In fact, the opposite applies. To survive in the harsh environment of a field, often without additional watering and fertilizing, a plant needs a well-developed and strong root system. The development of a healthy root system depends not only on the genetic properties of the plant but to a large extent on the physical and chemical properties of the substrate used.

Physical and chemical properties

A substrate should:

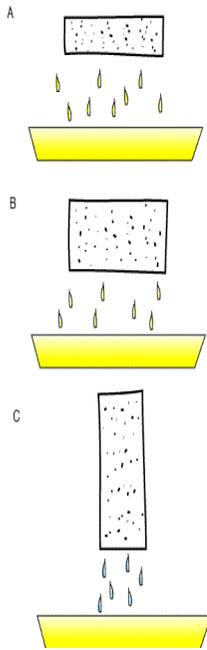
- be light in weight to ease transport to the planting site
- hold cuttings or seedlings firmly in place
- retain enough moisture to avoid need for frequent watering
- be porous enough for excess water to drain easily
- allow sufficient aeration of the roots
- be free from seeds, nematodes and diseases
- be able to be sterilized without changing its properties
- have enough nutrients for a healthy initial development of plants
- not have a high salinity level
- have a suitable pH
- be stable and not swell or shrink excessively or crust over in the sun.



The substrate properties that influence seedling growth can be divided into physical properties (water-holding capacity, porosity, plasticity and bulk density) and chemical properties (fertility, acidity and buffer capacity).

<p>Physical properties</p> <p>water-holding capacity</p> <p>porosity</p> <p>plasticity</p> <p>bulk density (weight per volume)</p>	<p>A substrate that allows a large amount of water to be held without waterlogging does not need frequent irrigation. The water-holding capacity is also a function of the container used. In shallow containers the substrate has a higher water-holding capacity than in deep containers (see box on p. 32).</p> <p>A good porosity is needed to allow sufficient oxygen to reach the roots to prevent rotting. All living cells, including plant roots, need oxygen for respiration and growth, and they give off carbon dioxide. To maintain adequate oxygen and carbon dioxide levels in the substrate, gas exchange with the atmosphere must be guaranteed. An oxygen content of below 12% in the substrate inhibits new root initiation; between 5 and 10% the levels are too low for established roots to grow; and at levels below 3%, roots do not function and eventually they die. Desirable total porosity values which maintain oxygen levels above 12% are around 50–80% by volume. Clay soils, which are unsuitable for seedling production, can have values of 40% or lower.</p> <p>A substrate that shrinks and cracks when drying, such as a clayey soil, damages the plants by shearing off roots.</p> <p>A substrate that has a light weight is easier to transport to the field. However, containers have to be sufficiently heavy so that they do not get blown over in the wind.</p>
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**Water-holding capacity**

Use an ordinary sponge to show how container height affects the water holding capacity: saturate the sponge and hold it flat over a tray (A). When the sponge stops dripping, turn it on its side — more water will drip out (B). When it stops dripping, stand it on end and more water will drain into the tray (C). Each time the height of the water column in the sponge increases, the amount of water it can hold decreases. In other words, deeper containers hold proportionally less water than the same amount of substrate in a shallow container. This explains why native soils, when put into a container, are often waterlogged: their depth has been reduced from metres to a few centimetres.

Calculating water-holding capacity and porosity

You can calculate the water-holding capacity and porosity of a substrate by the following steps:

1. With drainage holes sealed in an empty container, fill the container with water and record the volume required to fill the top of the container. This is the **container volume**.
2. Empty and dry the sealed container and fill it with dry substrate.
3. Using a measured volume of water, irrigate the substrate in the container slowly until it is saturated with water. This might take several hours. The saturation point is reached when water stays visible on the surface. Note how much water you have used. The volume of water needed to reach this point is called the **total pore volume**.
4. Remove the seal from the drainage holes and catch the water as it runs out. Wait several hours until all water has dripped out. Record the volume collected — this is the **aeration pore volume**.
5. Calculate total porosity, aeration porosity and water-holding porosity using the following equations:
Total porosity = total pore volume / container volume
Aeration porosity = aeration pore volume / container volume
Water-holding porosity = total porosity – aeration porosity.
 A good growing medium for most agroforestry trees has a total porosity of above 50% of which 30–50% is aeration porosity.

Chemical properties**fertility**

As soon as a seedling has used up the nutrients provided by its cotyledons (about two weeks after germination), it needs nutrients from the growth medium. The basic nutrients, of which plants require relatively large amounts, are nitrogen (N), phosphorus (P) and potassium (K). Plants also need very small amounts of other nutrients ('micronutrients') and deficiencies in micronutrients can occur in the nursery. The micronutrients that agroforestry trees are most often lacking are iron (yellow, 'chlorotic' leaves), especially in soils with a high pH or those derived from limestone, and boron (shoot tip dries out), especially in soils from igneous rocks.

acidity

The right substrate pH is very important for healthy plant development. The reason for this is that nutrients become available for plants at different pH levels. The optimum is around 5.5 for organic soils and around 6.5 for mineral soils. Most plants grow best in a medium with near-neutral pH (5.5–6.5), although some plants are particularly tolerant of acidity (for example *Inga edulis*, *Casuarina junghuhniana*) or alkalinity (for example *Prosopis chilensis*, *Tecoma stans*).

cation exchange capacity

The cation exchange capacity (CEC) is the ability of a material to adsorb positively charged ions ('cations'). It is one of the most important factors affecting the fertility of a growth substrate. The main cations involved in plant nutrition are calcium, magnesium, potassium and ammonium, listed in order of decreasing retention in the substrate. Many micronutrients are also adsorbed, such as iron, manganese, zinc and copper. These nutrients are stored on growth medium particles until they are taken up by the root system.

In practical terms, the CEC indicates the fertilizer storage capacity of the substrate and indicates how frequently fertilizer needs to be applied. Some soils contain high amounts of clays which absorb cations so strongly that they become unavailable for plant nutrition (mineral 'fixation'). These soils are unsuitable for nursery purposes.

Although the CEC of some soil-less substrates is very high, anions get washed out easily and need to be replenished frequently. This is particularly important for phosphorus and for nitrogen in the form of nitrate. Mixing a slow-release P-fertilizer, such as rock phosphate, into the substrate before planting can help alleviate this problem.

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Bulk densities and CEC for various growth substrates

CEC is traditionally measured on a weight basis for field soils, but CEC per volume is more meaningful for container growth media, because of the relatively low bulk density of most media and the small volumes of the containers. CEC values for some typical growth medium components are compared below. Vermiculite and peat moss have the highest CEC values, whereas materials such as perlite and sand have very low CEC values.

substrate	approximate dry bulk density (g/L)	CEC meq/L
perlite	ca 100	1.5–3.5
sand	1400–1700	45–105
pine/fir bark	200–300	ca 100
vermiculite	ca 120	110–198
peat	ca 110	

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Soil and soil-less media

All nursery managers have their own favourite growth substrate. These vary depending on availability, but in developing countries they are mainly soil from agricultural or forest areas, sometimes mixed with sand and/or manure.

Forest soil is often a main component of potting mixtures. Soil is usually a mixture of mineral components from weathered parent rock and of organic components from decomposed litter. Whereas the topsoil (the top 10–20 cm) can be very rich in nutrients, subsoil from deeper layers is often very poor and depleted. When using soil as a potting substrate it is advisable to use only forest topsoil. Topsoil usually has a good CEC. Its pH is largely determined by the parent rock and the plant composition (soil under conifers tends to be more acidic). However, nurseries requiring large volumes of substrate need to consider the damage soil mining does to the forest floor.

As a rule of thumb when soil is to be part of the growing medium, use the following mixtures (topsoil : fine gravel : well-decomposed organic matter such as manure or compost):

- for heavy (clayey) soils 1 : 2 : 2
- for medium (loamy) soils 1 : 1 : 1
- for light (sandy) soils 1 : 0 : 1

A common problem in the nursery is the variability of the substrate used. If forest soil is used, once a good source is depleted, soil is obtained from a neighbouring plot, usually without paying attention to changes in soil properties. If organic substrates are used, the source material for these may vary in quality, influencing the quality of the final potting mixture. When using soil is it advisable to have a chemical analysis done on each batch so that supplementary fertilizer can be applied if necessary. In fact, most large container nurseries never include soil in their substrate.

As an alternative to native soil, organic and inorganic soil-less substrates have been receiving increased attention in tropical nurseries. There are two main reasons for this: firstly, the soil-less materials have, in appropriate mixtures, optimal physical and chemical properties, and secondly, they do not contain weed seeds, fungal spores or insects, or they can be heat sterilized without losing their properties, whereas soil changes its physical and chemical properties under high temperatures — for example, toxic levels of manganese can occur.

The two major groups and components of soil-less media are:

- **inorganic:** for example, gravel, sand, vermiculite, perlite, tuff and pumice, polystyrene.
- **organic:** for example, peat, charcoal, softwood and hardwood barks, compost, rice hulls, sawdust and other organic waste products.

The choice for substrate components will depend on the location of the nursery, the resources available and plant requirements. For example, vermiculite is mined in South Africa and Kenya and is therefore comparably cheap in these locations, and peat is found in large quantities in Kalimantan, so it is a major ingredient of soil-less media in Indonesian nurseries. In many countries, bark is available as a by-product of sawmills and can be obtained cheaply.

perlite	Perlite is a siliceous material of volcanic origin, mined from lava flows. The crude ore is crushed and heated to about 760°C, causing the enclosed water to vaporize and expand the particles like a sponge. It is very light (80–100g/L), can hold 3–4 times its own weight in water and has a near neutral pH but a very low CEC, and it contains no mineral nutrients. It is most useful to increase aeration in a mix and it is, in combination with peat moss, a very popular substrate for cuttings in the USA.
tuff (pumice)	Tuff is produced from ash and rock fragments ejected during volcanic eruptions. Some particles melt together in the heat. The material is very porous and consists of mostly silicon dioxide and aluminium oxide with small amounts of iron, calcium, magnesium and sodium. After mining, it is screened to different sizes but is not heat treated. It increases aeration and drainage in a propagation mix.
polystyrene	Expanded polystyrene flakes and other synthetic plastic aggregates are often added to improve drainage and aeration, and to decrease the bulk density of the substrate. They are inert (do not add nutrients), do not decay and do not absorb water.

Organic components

The organic components improve the physical structure of the substrate by reducing weight and increasing its water-holding properties. They are also resilient to compaction. Organic matter has a high CEC and can store nutrients until needed by the plants. Some organic materials, such as compost, can contain considerable amounts of nutrients. Peat is the most popular organic component, but because of the destruction of valuable biotopes for the harvest of peat, alternative materials with similar physical and chemical properties are sought.

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Organic components**peat**

Peat is plant material that has decomposed under partial exclusion of oxygen. These anaerobic conditions slow down bacterial and chemical decomposition and often peat is many thousand years old. Tropical peat originates from younger deposits with varying properties. Peat from different sources varies greatly in the vegetation from which it originated, the state of decomposition and mineral content. All peats have good water-holding capacity, high CEC, low level of nutrients and low pH (around 3–4.5). The most common peat is sphagnum peat, a slightly decomposed peat from *Sphagnum* mosses. It has a high water holding capacity of 15–30 times its dry weight and contains small amounts of nitrogen (0.6–1.4%). Its dry bulk density is around 110 g/L. This particular material originates mainly in Canada, Ireland and Germany. In tropical countries other less decomposed peats can be substituted for it.

charcoal

Charcoal dust or small pieces help to improve the CEC of a substrate. Charcoal is readily available everywhere.

shredded bark

Softwood or hardwood bark are good alternatives to peat moss with much the same properties. Bark is a cheap by-product of many sawmills. It can be used from softwood (cedar, pine, fir) or hardwood species; the bark of tree ferns is also recommended. There is only limited information about the suitability of tropical tree species. Bark should be hammer milled (shredded) through a 2–3 cm screen and then composted for 4–6 months because fresh bark can contain tannins, phenols, resins or terpenes which are toxic to plants unless they are broken down. The higher temperatures of composting also help reduce insect and pathogen levels. When bark is not completely composted, plants grown in this medium may suffer from nitrogen deficiency because the composting bacteria need nitrogen to break down the organic matter. Please note that in areas with severe shortages of firewood, bark might be used for this purpose by the population, and the nursery should find alternative materials so that their operations do not compete for this scarce resource.

<p>compost</p>	<p>Composting is the physical and chemical breakdown of materials that liberates nutrients available to plants. Micro-organisms (fungi and bacteria) digest the material during decomposition. Compost from green material generally has a high nutrient level and a good CEC. Producing a consistently good compost takes practice and it may be worthwhile to conduct studies to learn how different species react to the addition of compost to their potting medium, and to make adjustments if necessary. Any organic material can be composted; a mixture of materials is best (see box). Compost is a very important ingredient in nurseries on coral atolls in the Pacific.</p>
<p>other materials</p>	<p>Coconut husks, rice hulls, sugar cane bagasse, coffee shells, old sawdust and other waste materials can be used similarly to the materials listed above. New materials will doubtless be found through continuous research. Most soil-less substrates can be used alone or added to soil to improve its properties.</p>

Producing compost

Each nursery site can have unique materials for composting because all that is needed is a very large supply of low cost vegetative material (green matter shrinks to only a fifth of its original volume during the composting process). For compost production the only machine needed is a straw cutter, cheap and available in any agricultural community. This is needed because the vegetative material must be chopped to fairly uniform small sizes. The compost heaps will be above the ground and can be either in the open during the dry season or under shelter from rain.

Good compost requires careful management of the micro-organisms which digest the vegetative material — their diet is best fed with vegetative material having a C:N ratio of 25–30 (see examples on p. 40). They also require moisture and oxygen. Heaps should not be wet — the best moisture level is 55%. Initially there will be adequate oxygen but as the micro-organisms function

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To make good compost you need material with a C:N ratio of 25-30. Keep the heap at 55% moisture and at a temperature of about 60°C.

this will be used up in the process of digestion. In addition, the temperature of the heap will quickly increase due to the activity of the micro-organisms. Two types of micro-organisms are present in the compost-making process: (1) the 'normal' type, which occurs in abundance during normal decomposition; (2) 'thermophilic' (temperature loving) micro-organisms. The normal micro-organisms quickly raise the temperature of the heap to 40°C. At this temperature they die, leaving the thermophilic micro-organisms to continue digestion. These heat-loving organisms operate very quickly, raising the temperature considerably and using up oxygen rapidly. They die if the temperature exceeds 65°C, the oxygen supply fails or the heap becomes either too dry or too wet.

C:N values for some materials

Material	C:N ratio
cow manure	18
horse manure	25
young hay clippings	12
cut straw	48
rotted sawdust	208–210
raw sawdust	400–511
sugarcane trash	50
fruit wastes	35
cabbages	12
tobacco	15
potato tops	25
pine wood	723

Nitrogen requirements for composting sawdust and bark:
 sawdust: 0.5–1.1 kg N/m³
 bark: 0.2–1.9 kg N/m³

Thus the art of making good compost quickly lies with the care of the thermophilic micro-organisms. Nursery managers must monitor the C:N ratio, chop up vegetable matter into small pieces of similar sizes, ensuring adequate but not excessive moisture, supply enough oxygen and ensure that the temperature does not exceed 60°C. Temperature and oxygen control are linked because, by lifting and turning the heap, temperature is reduced and oxygen is supplied. The compost is ready when it looks brown — it should have the consistency of coarsely ground coffee. You can determine whether the compost

is ready by placing two handfuls of the material into a plastic bag and leave the bag sealed for 24 hours in a dark place. If you open it and no odour or heat is noticeable, the compost is ready. The ready compost can then be removed from the bed and stored for another four months to mature. If you put a plastic sheet with fine holes over the heap this will allow the compost to breathe but will prevent weed seeds from entering.

Suggested mixes

For any species, research is needed to find out the optimal substrate. When mixing, it is important that all components are finely ground and sieved through a 5 mm sieve to remove excessively large particles. When mixing by hand, the components are placed in layers on a heap and then turned thoroughly with a shovel. Alternatively, a cement mixer or a drum can be used. When peat or shredded bark is part of the mixture, it is very important that the material is wetted **before** mixing. Although the literature often recommends the addition of wetting agents, this is not necessary when special attention is given to thorough wetting of the mixture during the mixing process.

Calculating the amount of substrate needed

Before mixing, you need to know roughly how much substrate you will need. Start with the container volume and the number of containers to fill. To calculate volume you can seal the drainage holes of the container and fill it with water from a measuring cylinder, noting how much water you filled. Or you can calculate it by measuring the height and diameter of the container, assuming it is cylindrical:

$$\text{volume} = \text{hr}^2 \\ (\text{height} \times \frac{1}{2} \text{ diameter squared} \times 3.1416).$$

Once you know the volume of the container, multiply this by the number of containers needed. For example: volume = 500 ml; 10 000 seedlings needed. Total volume needed is $500 \times 10\,000 = 5\,000\,000$ ml or 5000 litres or 5 m^3 . Then calculate the amount of each component needed.

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<p>Suggested mixes</p> <p>germination</p> <p>husks</p> <p>cuttings</p> <p>recommended in the rooting stage, and once rooted the cuttings can be transferred to other substrates with in the in- g moulds</p> <p>container seedling production</p> <p>various proportions, and fertilizers. For tropical countries such as coconut husks, rice hulls</p>	<p>Often fine, washed quartz sand (0.5-1mm) is adequate. However, it needs constant monitoring as sand dries out easily. If easily available, fine grade vermiculite, vermiculite mixed with peat or hammer-milled and composted bark, or composted coconut are good alternatives.</p> <p>Depending on the species' moisture requirements, fine, washed quartz sand, sand mixed with fine gravel at various ratios or composted sawdust, bark or vermiculite is used. When starting with a new species, the best bet is usually sand (2 mm fraction), and research at a later stage will determine if any of the other media are better.</p> <p>Sterile media without nutrients are usually recommended in the rooting stage, and once rooted the cuttings can be transferred to other substrates with in the in- g moulds</p> <p>Alternatively, cuttings can also be rooted in substrates treated with fertilizers, which will avoid the transplanting step. However, in substrates containing fertilizer, infection of the cuttings with bacterial and algae growth are more prevalent. It is very important that cuttings should not be set in soil or media containing soil because these substrates usually do not have the required high porosity for sufficient gas exchange, which can lead to rotting of the cuttings. Exceptions are stakes of easy-to-root species (such as <i>Gliricidia sepium</i>) that can be directly struck at the final field location.</p> <p>There are probably as many recommended potting mixtures as there are nurseries. Global recommendations do not exist. Usually the mixtures contain vermiculite, peat or hammer-milled bark in various proportions, and fertilizers. For tropical countries alternative substrates, and compost have given good results with various species. Although the use of many different mixtures in a nursery is not feasible, simple screening experiments testing three or four mixtures can easily be carried out for each species.</p>
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Although many soil-less media do not contain nutrients, they are very popular in commercial plant propagation. This is mainly because the fertilizer schedule for the plants can be individually tailored to each species and development stage. Compost, on the other hand, is popular because it is usually so rich in nutrients that it can be used as a substrate which at the same time has good fertilizer properties.

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