



Worldwide, economic and environmental pressures are leading to changes in the choice of materials for use in growing media. We review the principal organic constituents of media and their properties.

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# Organic Growing Media: Constituents and Properties

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Organic growing media are essentially bulk products. Availability in large quantity allied to its excellent air and water retention, low pH and salinity, and freedom from pests and diseases has led to peat being the dominant organic constituent of growing media in many parts of the world for the last 50 yr. The unique microporous properties of *Sphagnum* peat and its resistance to degradation are matched by few other growing media constituents. Nevertheless, local scarcity of *Sphagnum* peat and the expense of transport has led to the use of other materials in growing media. Notable among these is coir, which unlike peat, a CO<sub>2</sub> sink, is widely regarded as a rapidly renewable resource. Indeed, advances in processing and quality control in situ have led to a huge upsurge in the export and use of coir in growing media, particularly in Europe but also in the western United States. Locally available organic materials such as bark, composted materials including green (yard) wastes, municipal solid wastes, and even sewage sludge are also used in growing media. While possessing advantages such as the high air content of bark and nutrient supply of many composted materials, these media components may have disadvantages, from limited supplies due to bioenergy pulls and N lock-up in bark, to physical, chemical, and microbial contaminants in composts. Current innovative approaches involve increasing use of wood fiber in Europe, whole pine-tree thinnings in the United States, and realizing the use and transformation of composted wastes as next-generation constituents of growing media.

Abbreviations: CEC, cation exchange capacity; DBD, dry bulk density; EC, electrical conductivity.

Production of growing media, also known as plant substrates and defined as materials other than soils in situ (European Committee for Standardization, 1999), requires the provision of large quantities of constituents, whether inorganic or organic. Bulk materials for production of media, alone or in combination, must ideally be consistent in properties from batch to batch, particularly for use in the modern sophisticated seed and potting machinery used by professional growers. Plant propagation is routinely performed in many parts of the world by robotic systems, and automated techniques are also widely used with plants raised in pots or large containers. Materials need to be sought that enable constant provision of air, water, and nutrients (the latter usually applied as fertilizers) to roots and that are free from physical and chemical contaminants, weeds, pests, and diseases.

Globally, the total volume of materials used in growing media is difficult to estimate because recent data are not available for many areas of the world, including the Americas (both South and North), Australia, as well as Southeast Asia—where growing out of soil has expanded in recent years but mainly into hydroponic systems in China, Japan, Thailand, and Malaysia (Zhu and Wang, 2013; Nukaya, 2006; Montri and Wattanapreechanon, 2007). Schmilewski (2009) reported that >34 Mm<sup>3</sup> of growing media were manufactured per annum in Europe, of which ~92% was organic materials, with 77% (26.8 Mm<sup>3</sup>) of media constituents being peat. The principal users of these media were reported as Germany (~9 Mm<sup>3</sup>), Italy (~5 Mm<sup>3</sup>), the Netherlands (~4 Mm<sup>3</sup>), the United Kingdom (~3.3 Mm<sup>3</sup>) and France (~3 Mm<sup>3</sup>). In many countries growing media are primarily used by commercial growers, but in some the retail or hobby market consumes the bulk of growing media. In France and the United Kingdom, production for the hobby market has been reported as 64% (Schmilewski,

2009) and 70% (UK Department of Environment, Food and Rural Affairs, 2014), respectively, of the total for these countries. The Canadian Sphagnum Peat Moss Association, whose members supply most of the peat used in the United States, estimated in 2002 to 2003 that they supplied  $\sim 8.7 \text{ Mm}^3$  to the United States, with 70% going to professional growers.

## Principal Organic Constituents

### Peat

By virtue of its availability in large quantities in many boreal regions of the Northern Hemisphere, allied to its advantageous physical properties, peat is the principal organic component of growing media in many countries (Schmilewski, 2009). Peat is partially degraded organic material that accumulates over thousands of years within mires, the latter commonly defined as living peatlands (Rydin and Jeglum, 2013). Mires may develop in estuarine or floodplain areas where peat accumulation results from the partial degradation of marshland plants such as reeds, sedges, rushes, and other aquatic plants, but the most widespread and common peatlands are those derived from incomplete decomposition of bryophyte mosses, particularly those of the genus *Sphagnum* (Hammond, 1975). Lowland raised mires, consisting of partially degraded mosses that have accumulated over several millennia under acidic, waterlogged conditions below a living layer of *Sphagnum* are highly valued for extraction of peat both for horticultural and, in some countries, notably Russia, Belarus, Finland, and Ireland, for fuel.

Purpose-designed equipment has been developed for peat extraction. Milling machinery is now widely used to remove the surface layer of peat from drained peatlands, breaking up the semi-dried peat as it does so. This layer, often only 1 or 2 cm, may be allowed to dry further before aggregation into large windrows or piles, the latter then often covered with sheeting to prevent rewetting, and left in the field until required. However, much peat is removed



Fig. 1. Vacuum harvesting of peat.



Fig. 2. Peat sods.

from drained peatlands by direct vacuum harvesting (Fig. 1). Traditional cutting of peat into large (typically 25 by 10 by 10 cm) sods (Fig. 2), which are then air dried, is still extant because sods may be a better source of large particle size fractions than milled peat. Sod peat is less dusty and has a higher air content than the equivalent fractions (Fig. 3) derived from milled peat.

Peats vary in age and are commonly classified by the simple but very practical von Post scale developed in the 1920s (von Post, 1922), in which three categories of peat, viz. younger, undecomposed of low humification (H1–H3), partly decomposed (H4–H6), and older, highly decomposed (H7–H10), are identified. The test involves squeezing a small quantity of peat in the palm of a hand by drawing the fingers together to form a fist. The color of water expressed and the extent of peat extrusion between the fingers are used to define the degree of decomposition. Peats denoted H1 to H4 are often referred to subjectively as *white peat* and highly decomposed peats (H7 and above) as *black peat*. Indeed, attempts have been made to define peats more clearly based on measurements of color (Prasad and Maher, 2013). Black peats, typically from Lower Saxony, undergo freezing in winter, and this improves their air and water holding capacity.

### Coir

Coir is the material that forms the middle layers or mesocarp of coconut fruits (*Cocos nucifera* L.). These layers are composed of fibers embedded in the so-called coir pith. Coir is one of the most abundant plant-derived organic waste materials in many tropical and subtropical countries. Long fibers are extracted from the mesocarp after soaking and used for the production of matting, brushes, and insulating materials. The remaining material constitutes coir

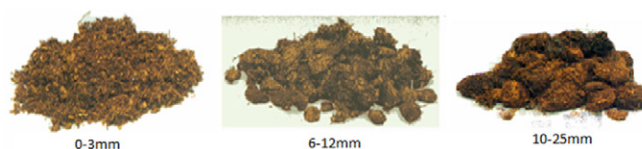


Fig. 3. Peat fractions.



pith, made up of short fibers and coir “dust.” Coir pith may contain high salt levels (predominantly Na, Cl, and K) and is washed with water or leached with solutions of, for example,  $\text{Ca}(\text{NO}_3)_2$  (so-called “buffered coir”), before preparation for horticultural use. After washing or leaching, the dried coir pith is compressed (ranging from 5:1 to 8:1 v/v) into blocks (~5 kg) or briquettes (~0.6 kg) for ease of transport (Fig. 4). These are then reconstituted with the addition of water, with an expansion ratio of 1:12 (w/v) or greater sought by manufacturers (Maher et al., 2008). In addition to coir pith, coir fibers (1–3 cm) are used to improve aeration in growing media. Coir chips (5–15 mm, Fig. 4), prepared from the hard outer husk of the coconut, are also used to enhance aeration, particularly with media for long-term nursery crops.

The production and use of coir in growing media has vastly increased in the decade 2004 to 2014. The principal areas of production are the Tamil Nadu and Kerala areas of India and Sri Lanka—these areas primarily supply coir to Europe and Australia—and Mexico, which exports coir to the United States. Exports of coir pith from Sri Lanka increased from 97 Gg (97,000 t, equivalent to 1.16  $\text{Mm}^3$  if reconstituted on a 1:12 w/v basis) in 2007 to 120 Gg (120,000 t, 1.44  $\text{Mm}^3$  if reconstituted) in 2010 (Sri Lanka Coconut Research Institute, 2011). Exports of coir pith from India, primarily for horticultural use, have increased markedly, from 86.6 Gg (86,000 t) in 2008–2009 to 271 Gg (271,000 t) in 2013–2014 (Coir Board of India, 2014); if reconstituted on a 1:12 (w/v) basis, this represents volume increases from 1.13 to 4  $\text{Mm}^3$ . Other areas of the world developing coir for horticultural use include the Philippines, Indonesia, Ivory Coast, Costa Rica, and Thailand (Abad et al., 2005).

## Bark

Bark from both hardwood and softwood species is a major component of growing media, particularly in areas where peat is scarce or expensive. In Europe, the principal users of bark are France, with >1.2  $\text{Mm}^3$  in 2005, principally from the maritime pine (*Pinus pinaster* Aiton), and Spain with 0.5  $\text{Mm}^3$  (Schmilewski, 2009). Bark from the Monterey pine (*Pinus radiata* D. Don) is the principal organic component of growing media in New Zealand (Fig. 5) and,



Fig. 4. Coir chips, coir blocks, and reconstituted coir.



Fig. 5. Composted *Pinus radiata* bark.

along with maritime pine and slash pine (*Pinus elliottii* Engelm.), is used in Australia, along with hardwood bark from *Eucalyptus diversicolor* F. Muell. and *E. calophylla* Lindl. (Handreck and Black, 2010). In the United States, the loblolly pine (*Pinus taeda* L.) in eastern states and Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] in the Pacific Northwest are the principal sources of bark for use in growing media (Bilderback et al., 2013).

Bark may contain phytotoxic materials (phenols and tannins) when freshly harvested, as well as, for some conifer species in northern Europe, Mn (Solbraa, 1979), although maritime pine has a lower Mn content than other barks, for example, *Pinus abies* L. Thus, although some barks may be used in growing media shortly after removal, shredding, and screening, bark may be aged, usually for 6 to 12 mo, or more commonly composted to eliminate potential problems of phytotoxicity arising from organic compounds (Solbraa, 1979).

## Compost

Composted materials per se are available in large quantities in many countries, but of all candidate materials for growing media, composts are the most variable: physically with respect to bulk density, air space, and water retention; chemically in terms of pH and nutrition; and also microbiologically (Raviv, 2011, 2013). For these reasons, composted materials (other than bark) are always used in combination with other materials. Composts produced from so-called green materials (prunings, shredded branches, plant debris, and waste from gardens and nurseries) (Fig. 6) are



Fig. 6. Green waste transformed into compost.



widely used as components of growing media in the Netherlands, United Kingdom, Italy, and Germany, primarily in media for the hobby market. Compost use in growing media in the Netherlands increased from 10,000 m<sup>3</sup> in 2001 to 65,000 m<sup>3</sup> in 2006 (Blok and Verhagen, 2009); in Italy, >0.25 Mm<sup>3</sup> was used in 2006 (Schmilewski, 2009) and in the United Kingdom, 0.31 Mm<sup>3</sup> of compost was incorporated into growing media in 2013 (UK Department of Environment, Food and Rural Affairs, 2014). Municipal wastes and sewage sludge are incorporated into growing media in some southern European countries, such as Spain (Abad et al., 2001; Moral et al., 2013) and also in Canada and the United States, where composts are widely used as components of media for the production of nursery stock (Chong, 2005; Bilderback et al., 2013). Strict quality control procedures are essential in preparing composts for use in growing media, with both the Waste and Resources Action Programme in the United Kingdom and the principal body monitoring growing media standards in Europe, the Netherlands-based RHP Foundation, outlining acceptable parameters for composts destined for use in growing media (UK Waste and Resources Action Programme, 2011; Wever and Scholman, 2011).

### Wood Fiber and Other Organic Materials

Other organic media components include wood fibers produced by mechanical defibrillation or more commonly steam-assisted thermal extrusion of virgin wood chips (Fig. 7). Wood fibers were developed as substrates in the 1970s and 1980s in Germany (Schmilewski, 2008) and have proved popular in France and from 2010 onward increasingly so in the United Kingdom, with volumes rising from 62,000 m<sup>3</sup> in 2007 (UK Department of Environment, Food and Rural Affairs, 2009) to 0.5 Mm<sup>3</sup> in 2013 (UK Department of Environment, Food and Rural Affairs, 2014). Other locally available organic materials may be utilized as constituents of growing media, again often for retail markets: examples include parboiled rice hulls (Fig. 8) in southern Europe (Schmilewski, 2009), grape marc (the skins and pips of grapes) in France and Australia (Handreck and Black, 2010), leaf mold in France (Schmilewski, 2009), and chipboard waste in the United Kingdom (Dickinson and Carlile, 1995).



Fig. 7. Wood fiber.

### Inorganic Materials

In addition to organic materials, inorganic materials derived from the thermal expansion of molten basalt and siliceous clays are used extensively in the production of growing media. Most notable is mineral wool produced by “spinning” molten basalt into threads and the compression and aggregation of these to form blocks or mats. Production of cucumber (*Cucumis sativus* L.), tomato (*Solanum lycopersicum* L.), and pepper (*Capsicum annuum* L. var. *annuum*) is principally undertaken with mineral wool mats, while perlite and vermiculite, produced from thermal expansion of volcanic aluminosilicate and phyllosilicate, respectively, are widely used in mixtures with organic materials. Inorganic media such as mineral wool and perlite have the advantage of low dry bulk densities (DBDs), often <100 kg m<sup>-3</sup>. Naturally occurring unprocessed inorganic materials including montmorillonitic clay, pumice, and siliceous sand are often added to organic growing media to improve wettability and buffer capacity, improve mechanical stability and aeration, and to aid “flowability” of media used in small modules, respectively.

### Physical Properties

Development of roots in a fixed volume of growing medium confined within a module, pot, or container requires a medium that can maintain air content and retain water during plant growth, as well as provide nutrients (Maher et al., 2008; Michel, 2010). The medium must also act as a physical support for plants, especially if these are large specimens grown over long periods.

Determination of the physical properties of organic media components requires definition of the origin, age, and especially the type and degree of processing performed with the material; some or indeed all of these criteria are frequently absent from the literature. Further, for comparative purposes, the use of an identical methodology is preferable; globally, there is considerable variation in analytical procedures used for both physical and chemical analyses of media. For example, air content is frequently expressed as air-filled porosity, and many researchers use the procedure devised by Byrne and



Fig. 8. Rice hulls.

Carty (1989), but container height, a major variable factor in this test, differs in Australia, the United States, and Europe (Handreck and Black, 2010) (Tables 1 and 2). Given these caveats, suggested ranges have been outlined within which growth of plants in media is acceptable; for example, Yeager et al. (2007) suggested total porosity values between 50 and 85% of media volume, air space of 10 to 30%, available water of 25 to 35%, and bulk density of 190 to 700 kg m<sup>-3</sup>, the latter according to the specific use of the medium.

### Bulk Density

For practical purposes of transport and handling, growing media should have a low bulk density, and many producers of growing media seek media with a bulk density <300 kg m<sup>-3</sup> in situ. In commercial practice, bulk density measurements are performed in situ on raw, processed, or reconstituted media components; considerable variation may thus occur, for example with peat, where the bulk density varies from year to year depending on the weather at harvest. Peat is often transported compressed into big bales. The ability to regain the original volume depends on several factors including moisture content, particle size, and degree of humification (Cattivello, 2013). The in situ bulk density of coir and composted materials depends on the efficiency of reconstitution from compressed blocks (Fig. 4) and the degree of processing, respectively.

Dry bulk density (Tables 1 and 2) gives an accurate comparative status of media components, and indeed some organic materials such as coir are transported in a dry state. Most peat-based growing media have a DBD of 40 to 200 g L<sup>-1</sup>, younger (H1–H3) peats being lighter in weight than more decomposed peats. Extruded

wood fibers may have a DBD even lower than that of young peats, but most other organic materials have DBDs greater than peats, with some composted materials possessing very high bulk densities due to the presence of inorganic material (Surrage and Carlile, 2008).

### Particle Size and Air and Water Holding Capacity

The particle size and shape of media components determines, to an extent, the degree of aeration and water holding capacity of the media and is influenced by processing and screening procedures. For example, milled peat may be used after rough screening (0–14/15 mm) to produce media for retail markets, but for professional markets, peat removed from the field may be screened to produce individual fractions (Fig. 3) for horticultural use: for example, 0 to 5 mm (referred to as fine) or even 0 to 3 mm (super-fine); 5 to 10 mm (medium); 10 to 20 mm (coarse); or >20 mm (very coarse). Not surprisingly, the physical characteristics of peats with different humification values, and especially fractions, differ.

Coir pith has a sponge-like structure, with particle size from most sources being on the order of 0.5 to 2 mm. Coir from some areas of the world is very variable, with physical and chemical properties (Table 2) linked to source and processing (Evans et al., 1996; Konduru et al., 1999; Abad et al., 2005). Coir chips prepared from sliced and crushed coconut husk can be screened to give particle sizes equivalent to those of peat fractions.

Peat and coir pith are superhydrophilic (Koch and Barthlott, 2009). Both are renowned for their ability to absorb and retain

Table 1. Physical properties of sphagnum-based peats and peat fractions used as components of growing media. Determinations of total pore space, air content, available water, and water buffering capacity were carried out according to European Committee for Standardization (2000) unless otherwise noted, with, in all cases, air content measured at 1-kPa suction.							
Origin	Von Post index	Particle size or fraction	Dry bulk density	Total pore space	Air content	Available water†	Source
		mm	kg m <sup>-3</sup>	% (v/v)			
Canada			84	94.2	41.2	26.9	Abad et al. (2005)‡
Latvia	H3	0–5	41	96.4	50.0	21.0	Amha et al. (2010)
Finland	H3	0–5	51	95.7	26.0	43.3	Amha et al. (2010)
Estonia	H5	0–5	98	93.7	13.9	39.6	Amha et al. (2010)
Russia	H2/H3	0–16	89	93.9	10.1	47	Bures et al. (1989)‡
Belarus	H3	0–20	105	93.4	6.8	45.3	Dubsky and Sramek (2009)
	H4	0–10	98.8	93.7	20.4	35.8	
	H4	0–3	118	94.4	13.7	42.3	
Ireland	H4	6–12	118	92.0	36.3	21.7	Prasad and Maher (1993)§
	H4	10–25	129	91.5	40.9	16.9	
	H7	3–6	263	83.8	42.6	8.1	
	H7	6–12	255	83.8	49.3	6.1	
† Available water at 1–10-kPa suction as defined by Handreck and Black (2010) as easily available water plus water buffering capacity.							
‡ Determinations of total pore space, air content, available water, and water buffering capacity were carried out using suction funnels with a porous plate as described by de Boodt et al. (1974).							
§ Determinations of total pore space, air content, available water, and water buffering capacity were carried out with sand boxes as described by Leijn-van Dijk and de Bes (1987).							

Table 2. Physical properties of coir, bark, composted materials, and wood fiber used as components of growing media. Determinations of total pore space, air content, available water and water buffering capacity were carried out according to European Committee for Standardization (2000) unless otherwise noted, with, in all cases, air content measured at 1-kPa suction.

Material	Origin	Particle size	Dry bulk density	Total pore space	Air content	Available water†	Source
		mm	kg m <sup>-3</sup>	% (v/v)			
Coir pith	Tamil Nadu, India	85% 0.25–2	56	96.3	41.2	28.1	Abad et al. (2005)‡
Coir pith	Sri Lanka	50% <1	74–81	94–96	13.5–29.4	23.8–37.8	Prasad (1997)§
Coir pith.	Mexico		61–72	95.2–95.9	43.7–57.8	19.9–25.8	Abad et al. (2005)‡
Coir chips			72–82	95	55	3	Aendekerck et al. (2000)‡
Fresh <i>Pinus pinaster</i> bark	France	7–15	197	87	53	4	Bos et al. (2003)
Aged spruce bark	Czech Republic	0–20	328	82.3	27.5	16.9	Dubsky and Sramek (2009)
Wood fiber, coarse	Germany	>50% >2	nd	93.2	51.9	19.4	Gruda and Schnitzler (2004)
Wood fiber, fine	Germany	>50% <1	nd	91.4	21.9	34.7	Gruda and Schnitzler (2004)
	United Kingdom	80% <4	554	73	9	nd	Maher et al. (2008)
Green compost	Ireland	50% <4	419	81	31	nd	Maher et al. (2008)
	Czech Republic	0–20	556	73.0	7.6	24.4	Dubsky and Sramek (2009)
Fresh <i>Pinus radiata</i> bark	Australia		250	70	30	9	Handreck and Black (2010)¶
Aged <i>Pinus radiata</i> bark	Australia		270	71	20	16	Handreck and Black (2010)¶
Fresh pine bark	United States		170	88.3	39.3	9.8	Bilderback et al. (2005)#
Aged pine bark	United States		190	87.3	27.2	26.3	Bilderback et al. (2005)#

† Available water at 1–10-kPa suction as defined by Handreck and Black (2010) as easily available water plus water buffering capacity.

‡ Determinations of total pore space, air content, available water and water buffering capacity were carried out using suction funnels with a porous plate as described by de Boodt et al. (1974).

§ Determinations of total pore space, air content, available water and water buffering capacity were carried out using sand boxes as described by Leijn-van Dijk and de Bes (1987).

¶ Handreck and Black (2010) outlined the procedures used in Australia for physical determinations, with air content measured at 6-cm (0.6-kPa) suction.

# Bilderback et al. (2005) used an in-house porometry system developed at the Horticultural Substrates Laboratory at North Carolina State University, with a mean suction of 3.8 cm (0.38 kPa).

not only water but also air, due primarily to their microporous nature (Tsuneda et al., 2001; Fornes et al., 2003). Scanning electron microscopy of coir reveals external circular pores ranging in diameter from 30 to 80 µm, leading to a relative surface porosity of around 49%; in contrast, sphagnum moss peat possesses small oval pores (20.5 by 11 µm) and a relative surface porosity of around 12%, although the internal porosity has been calculated at 51% (Fornes et al., 2003). Other researchers have described pores on peat surfaces of 10 to 20 µm (Koch and Barthlott, 2009). The greater frequency and larger size of pores on the surface of coir particles may explain the swifter uptake of water, as well as its equally rapid drainage and consequent higher air content than most peats (Fornes et al., 2003). Whereas water-absorbing polymers are frequently added to peat-based media to aid absorption after drying, these wetting agents are unnecessary in media that principally contain coir.

Media mainly composed of bark, wood chips, or wood fiber are characterized by high air content and low water retention (Lemaire et al., 1980), although bark particles can hold water internally and this can be accessed by plant roots (Pokorny and Wetzstein, 1984). Bark may be used raw, but in most cases bark is aged or more commonly composted to eliminate hydrophobicity, degrade antimicrobial compounds that may be present, and to reduce N

immobilization (Solbraa, 1979). Before composting, bark is usually hammer milled to a particle size of 10 to 20 mm (Maher et al., 2008). In terms of physical properties, aged or composted pine bark has a lower air content and is able to retain water better than fresh bark (Bilderback et al., 2005) (Table 2). The air content of wood fibers may be as high as 50%, but water retention at 1 to 10 kPa is relatively low (Gruda and Schnitzler, 2004). Processing and screening primarily determine the physical properties of composted materials used as components of growing media; fine-screened materials have a higher water holding capacity and lower air space than coarser materials (Table 2).

In addition to the inherent properties of a growing medium, container size and shape may have a marked influence on the air/water ratio of the substrate. In a pot or other container, a substrate moisture gradient exists where, due to gravitational effects, air content decreases and moisture increases from the top to bottom of the container (Fonteno, 1996; Owen and Altland, 2008). For example, in a 1:1 peat/vermiculite mixture filling containers 2.5 and 15 cm high, the air volume increased from 2 to 20% (Fonteno, 1988). Container geometry also influences air–water relationships. Bilderback and Fonteno (1987) reported that air volume increased by 25% and water volume decreased by 13% in tapered pots compared with cylindrical types.



Preservation of physical properties and especially air space within media during plant growth requires structural stability on the part of the medium. All organic-based growing media may undergo microbial degradation, and this combined with shrinkage and swelling (Michel, 2010) may have detrimental effects on structural stability. The extent of loss of stability varies greatly among components. Peats, notably decomposed *Sphagnum* types, are resistant to decomposition (Cattivello et al., 1997; Prasad and Maher, 2004). *Sphagnum* mosses do not possess lignin of the type found in vascular plants (Rydin and Jeglum, 2013) but lignin-like polymers form a major part of their cell walls. However, resistance to decomposition may be linked also to unique pectin-like substances (sphagnan) of the cell walls in *Sphagnum* mosses (Hajek et al., 2011). *Sphagnum* peats also contain phenolic antimicrobial substances (Thormann, 2010). Resistance to degradation of coir pith may be associated with lignocellulose complexes composed of cellulose, hemicellulose, and lignin linked through covalent and non-covalent bonds, which are highly resistant to degradation (Carr, 2012). Coir may also contain phenolic substances (Ma and Nichols, 2004). Other materials such as bark contain phenolic substances and levels of lignin (20–30%) comparable to those in peat and coir but are less stable (Maher et al., 2008). Degradation of bark and wood fiber may be linked to the ready decomposition of cellulose and easily hydrolyzable substances such as arabinoglucuronoxylans, present as the principal hemicellulose in coniferous wood and bark (Fengel and Wegener, 1989). Media prepared from less stable components may decompose in storage and use (Carlile, 2004; Prasad and Maher, 2004), resulting in shrinkage of media in pots and, in some cases, N immobilization (Dickinson and Carlile, 1995).

## Chemical Properties

In view of their low bulk density, almost all chemical analyses of growing media are reported on a weight per volume basis, reflected in standard analytical procedures of bodies such as the European Committee for Standardization.

### pH and Cation Exchange Capacity

Plants raised in growing media must be able to assimilate the same range of nutrients as those raised in soil. For this purpose,

the pH of media for most plants other than calcifuges needs to be in the range 5.5 to 6.5, some 0.5 to 1 units lower than for mineral soils (Lucas and Davis, 1961). At pH values >6.5, uptake of micronutrients, notably Fe and B, may be reduced in most organic growing media. The pH values within and among substrates may differ markedly (Table 3). Desirable pH levels are easily achieved with peat through the addition of lime, commonly as dolomitic limestone (which also provides Ca and Mg) at 2 to 3 kg m<sup>-3</sup> for less decomposed (H2–H3) peat and 3 to 7 kg m<sup>-3</sup> for more decomposed (H4–H6) peat (Maher et al., 2008). Coir pith generally has a pH of 5.5 to 7.0 (Evans et al., 1996); if coir is the major component of a medium, then lime is unnecessary but Ca must be provided, with gypsum recommended for this purpose (Handreck and Black, 2010). After composting pine and spruce bark, pH values range from 5.0 to 6.5 and lime may be added at 1 to 2 kg m<sup>-3</sup> for spruce bark, with higher rates added to pine-bark-based media (Jackson et al., 2009). Composted materials derived from green wastes, municipal solid wastes, and sewage sludge often have pH values well in excess of the range deemed optimal for growing media, with many instances of pH values of 7, 8, and even 9 being recorded (Surrage and Carlile, 2008; Vecchietti et al., 2013). Such composted materials are always used in mixtures with, for example, peat and bark, and in these combinations, reduction or even elimination of lime is possible (Warren et al., 2009).

Although the cation exchange capacity (CEC) of growing media constituents is frequently reported on a weight basis, because plants grow in a limited volume of media, usually of low bulk density, it is more appropriate (as with nutrient concentrations) to express CEC on a volume basis. If the bulk density of materials is known, then conversion from centimoles of charge per kilogram (meq [100 g]<sup>-1</sup>) to milliequivalents per liter is straightforward (Handreck and Black, 2010). Handreck and Black (2010) indicated that a moderate CEC of 50 to 200 meq L<sup>-1</sup> is desirable for most growing media. The CEC of peat has been recorded at 150 to 250 cmol<sub>c</sub> kg<sup>-1</sup>, the higher values associated with decomposed H4 to H6 peats (Puustjarvi and Robertson, 1975). These values approximate to 150 to 250 meq L<sup>-1</sup> (Landis, 1990) and endow many peats, particularly H4 to H6, with good buffering capacity, being resistant to pH changes brought

Table 3. Typical pH, electrical conductivity (EC) values and nutrient status of organic constituents of growing media.

Material	pH†	EC†	(NH <sub>4</sub> + NO <sub>3</sub> )-N	P	K	Source
		dS m <sup>-1</sup>	mg L <sup>-1</sup>			
Peat	3.9	0.2	48	1.6	4	Aendekerk et al. (2000), Handreck and Black (2010), Sonneveld and Voogt (2009)
Coir dust	6.2	0.9	31	3	55	Aendekerk et al. (2000), Bos et al. (2003)
Coir chips	5.7	0.5	3	5	57	Aendekerk et al. (2000)
Pine bark (composted)	4.0–4.3 (USA) 5.0–5.2 (Europe)	0.30	2 (no added N) 50–100 (urea added at 1 kg m <sup>-3</sup> )	13	290	Bunt (1988), Lemaire et al. (1980), Bures (1997), Leoni (2003), Handreck and Black (2010)
Wood fiber	4.8	0.2	3	3	35	Aendekerk et al. (2000), Lemaire et al. (2003), Domeno et al. (2010)
Green compost	7.5–8	1.0	100	28	900	Centemero (2009), Maher et al. (2008)

† Measurements based on 1:1.5 (v/v) substrate/water extracts.

about by alkaline water supplies (Maher et al., 2008), and minimize checks to plant growth from fertigation. Coir has a lower CEC than peat, with values ranging from 35 to 95  $\text{cmol}_c \text{ kg}^{-1}$  (approximately 70–150  $\text{meq L}^{-1}$ ) reported (Abad et al., 2002; Handreck and Black, 2010). Pine bark has a similar CEC, reported as between 58 and 74  $\text{cmol}_c \text{ kg}^{-1}$  (Daniels and Wright, 1988), which translates to 120 to 200  $\text{meq L}^{-1}$ . Composted bark is reported to have a higher CEC than fresh bark (Handreck and Black, 2010). The CEC of wood fiber is low, reported as 22  $\text{cmol}_c \text{ kg}^{-1}$  (Domeno et al., 2010), translating on a volume basis to a value of 20 to 30  $\text{meq L}^{-1}$ . Composted materials other than bark vary greatly in CEC; these materials, usually of high bulk density, include values for green compost at 22 to 44  $\text{cmol}_c \text{ kg}^{-1}$  (Hartz et al., 1996) and 75 to 100  $\text{cmol}_c \text{ kg}^{-1}$  (Smith and Hughes, 2004).

## Salinity

Components of the medium determine the starting level of salinity. Increases in substrate salinity may arise not only from the fertilizers added to growing media and salts present in irrigation water as soluble salts or slow-release compounds (Zaccheo et al., 2013) but also from salts present in irrigation water. In view of the plethora of methods used to determine salinity in growing media (listed in Handreck and Black, 2010), comparative values in Table 3 are presented using a 1:1.5 medium/water extract (European Committee for Standardization, 2011), widely used in Europe. The low salinity status (and high CEC) of peats allows the addition of liming materials and nutrients with little, if any, detriment to plant growth. The electrical conductivity (EC) of coir varies considerably, depending on source and treatment. Extensive washing will remove NaCl—commonly encountered in coir from coastal areas. Washing will also reduce K levels and hence salinity in coir, and in fact it may be further leached with  $\text{Ca(OH)}_2$  to give so-called *buffered coir*. Many manufacturers of growing media in Europe require reconstituted coir from imported blocks to have an  $\text{EC} < 0.3 \text{ dS m}^{-1}$  and a K content  $< 100 \text{ mg L}^{-1}$ . Low salinity values are associated with wood fiber (Lemaire et al., 2003) and most barks, with recommendations of  $< 0.5 \text{ dS m}^{-1}$  for composted bark destined for use in growing media (Yeager et al., 2007), but the salinity of composted materials is a frequent barrier to their use in growing media. Many have EC values in excess of  $1 \text{ dS m}^{-1}$  restricting their use in growing media to 20 to 40% (v/v) of the physical components (Spiers and Fietje, 2000; Prasad and Carlile, 2009).

## Specific Ion Content of Substrates

Low salinity values in *Sphagnum* peat are associated with a low ionic concentration (Table 3), and thus fertilizer incorporation requires no consideration of preexisting nutrients. In contrast, coir, while having low concentrations of N (both  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$ ) and P, frequently contains plant-available K of 50 to 200  $\text{mg L}^{-1}$  even when leached (Handreck, 1993a; Prasad, 1997). Many barks and wood fibers also contain K (Chong, 2005; Maher et al., 2008), and indeed the inherent plant-available K concentrations in coir, bark, and wood fiber may allow a reduction in base fertilization of this element. Green composts may contain

very high concentrations of K, often  $> 1 \text{ g L}^{-1}$  (Surrage and Carlile, 2008), contributing to their high salinity values.

Unwanted ions at undesirable concentrations may also be present in some components of growing media. While some components, notably peat, coir, and wood fiber, may be deficient in micronutrients such as Fe, Cu, B, Zn, Mn, and Mo and require their addition to formulated products, barks and other composted materials may have an excess of these trace elements as well as containing other elements to toxic levels. Barks, for example (Solbraa, 1979; Handreck and Black, 2010), may contain high concentrations of Mn ( $> 100 \text{ mg L}^{-1}$ ) that may exert phytotoxic effects if the media become acid ( $\text{pH} < 5$ ). Some composted materials, such as municipal solid waste and sewage sludge, may contain very high concentrations of Na and Cl, as well as Pb, Cd, and Ni (Perez-Murcia et al., 2006; López-Lopez and López-Fabal, 2013).

## Microbiology

Total viable counts (TVCs) of media constituents vary. The acidic, waterlogged conditions under which peat develops do not favor extensive microbial growth. Harvested peat, and indeed peat-based media at the point of manufacture, has a low microbial count; TVCs are often  $10^4 \text{ g}^{-1}$  dry weight or less (Kavanagh and Herlihy, 1975; Dickinson and Carlile, 1995). Coir-based growing media may have microbial counts as much as two orders of magnitude above that of peat (Prasad, 1997). As expected, composted materials including barks have much higher microbial counts than peat, often two to four orders of magnitude above that of peat (Dickinson and Carlile, 1995).

In growing media with easily degraded polysaccharide components such as hemicelluloses or cellulose, microbial growth may lead to immobilization of N added as part of base fertilizers. Nitrogen immobilization is particularly associated with wood fiber, bark, and other media constituents that may have been inefficiently composted, as well as bagged media that may be stored for long periods at retail outlets (Carlile, 2004; Handreck and Black, 2010). Predictions of N immobilization in growing media include the N drawdown index devised by Handreck (1993b) that involves incubating media with 75 or 150  $\text{mg N L}^{-1}$  and determining the amount of N left after 4 d.

Self-heating is a major problem in stored peat, whether on the bog or in transit, and is held to be microbially mediated (Tahvonon and Kemppainen, 2008). During self-heating, phytotoxic substances may be released (Wever and Hertogh-Pon, 1993); additionally, alterations in the physical, chemical, and microbiological properties may occur in self-heated peats (Cattivello, 2009), frequently rendering these unmarketable.

The microbial flora of growing media may contain fungi and bacteria including actinomycetes, and some are of significance for



human health (Carlile and Hammonds, 2008). Coliforms including *Escherichia coli* have been regularly isolated from composted green materials, municipal solid wastes, and of course sewage sludge. Strict limits have been suggested by authorities in some countries, such as those outlined by the UK Waste and Resources Action Programme (2011), where limits for *E. coli* in green compost destined for use in growing media have been set at  $10^3 \text{ g}^{-1}$  dry weight. Isolation of *Legionella longbeachae* from growing media based on composted bark in Australia (Steele et al., 1990) and its association with illness in users of such media has led to the insertion of printed warnings on bags of media sold through retail outlets. *Legionella longbeachae* has recently been detected in growing media, particularly those where peat has been diluted with other materials, in the United Kingdom and associated with illness among users (Currie et al., 2014). However, in both countries and the United States, risk assessments indicate that the likelihood of contracting legionellosis from growing media is very low.

While most growing media components, including composted materials (Noble and Roberts, 2003) are free of plant pathogens, these latter can spread very quickly in peat media, which may have a low content of antagonistic microflora (Carlile and Schmiewski, 2010). In contrast, many composted materials possess antagonistic microflora that can suppress pathogens (Hoitink et al., 1991). Although direct commercial application of the antagonistic properties of composted materials in growing media has proved difficult due its variable nature (St. Martin and Braithwaite, 2012), several antagonistic agents have been isolated, and microbial preparations are now marketed as additives to media not only for control of pathogens but also to accomplish biological control of insects. Preparations of *Trichoderma*, especially *T. harzianum* Rifai and *T. viride* Pers, are marketed in some countries for suppression and/or control of *Pythium* damping-off and vascular wilt diseases. Formulations of chlamydospores of *Metarhizium anisopliae* (Metsch.) Sorokin offer season-long control of *Otiorhynchus sulcatus* Fabricius (vine weevil) in growing media (Ansari et al., 2008; Bruck and Donahue, 2007).

Macroscopic growths arising from fungal hyphae have become common in recent years (Schlichte, 1997), and this may be associated with mixtures of components with peat and contact between media and surfaces where mycelia and spores may be present, such as benching or soil. Although not directly damaging to plants, these growths can be unsightly and interfere with irrigation and water uptake (Carlile and Schmiewski, 2010). Withdrawal of fungicides for control of these, principally basidiomycotina, pathogens may have contributed to their higher incidence. The development of biological preparations to control macroscopic fungi in growing media is highly desirable.

## Contaminants in Constituents

Wood fiber, bark, coir, and peat are generally homogenous, but composted waste materials, particularly municipal solid wastes

and sewage-derived materials, are by their very nature extremely heterogeneous and prone to contamination by metal, plastic, and glass objects. For acceptability as constituents of growing media, such materials must be efficiently sorted and contaminants screened out. This has led to the development of standards for compost destined for use in growing media, such as that of the Waste and Resources Action Programme in the United Kingdom (UK Waste and Resources Action Programme, 2011), which specifies an upper limit of 0.2% metal, 0.05% plastic, and 0.1% glass, all <2 mm in size.

Contamination of peat may come from weed seeds arising from plants growing on peat bogs or on bog margins (Keijzer and van Schie, 1997). The principal species involved are rushes (*Juncus* spp.) and sheep sorrel (*Rumex acetosella* L.). Control of these is usually performed on site by manual inspection and removal, with a particular focus of attention being the drainage ditches around peat extraction areas. Weeds and weed seeds are a potential hazard in composting systems, and their destruction is achieved by appropriate composting procedures involving aeration by turning (of windrows) or fan-driven systems to achieve temperatures where seeds and propagative vegetative organs are killed (UK Waste and Resources Action Programme, 2011). Such temperatures also serve to eliminate unwanted resting spores of diseases and eggs of insects and nematodes (Noble and Roberts, 2003). Reports of herbicide contamination of organic composted materials in the United States and United Kingdom by the persistent compound aminopyralid (4-amino-3,6-dichloro-2-pyridinecarboxylic acid) have prompted concerns about potential contamination of growing media and the need to assay candidate materials for potential growth retardation in plants (UK Waste and Resources Action Programme, 2009; US Composting Council, 2013).

## Formulation and Use

Growing media for professional use fall into three general categories: seedling, cutting, and young plant production; glasshouse pot plants; and outdoor container nursery stock (Table 4). Base fertilization of media for seedling modules or plugs is low at 200 to 500  $\text{g m}^{-3}$  of a low-N fertilizer, but the actual rate used varies with individual species. Media for pot plants have a higher concentration of base nutrients, usually 1 to 1.5  $\text{kg m}^{-3}$  of, for example, an 18:6:12 N–P–K fertilizer, but again with variations according to species. Growing media for large container plants may contain a similar level of base fertilizer, but this may be further supplemented with an appropriate controlled-release fertilizer. Of course, plants in growing media may be additionally or alternatively fertigated with an appropriate liquid feed.

Specialized uses of growing media include orchids (*Unident-Orchidaceae* spp.), bags and modules for strawberry (*Fragaria* × *ananassa* Duchesne ex Rozier) production under glass, and for use on green roofs. Pine bark of large particle size (20–50 mm) is used for orchids. Diversion of strawberry cultivation away from soil in recent years has led to a vast increase in the use of peat-and

coir-filled modules and trays. Expansion in green roof cultivation and the establishment of vertical gardens (Bures, 2013) has led to the development of mixtures of organic, largely coir, and inorganic materials for use as growing media in these emerging environmental-architectural developments.

Quality control of organic growing media for retail use has not generally been as stringent as for professional markets, but in the United Kingdom and elsewhere, consumer groups are undertaking independent testing of media for hobby gardeners, and these frequently show wide variation in performance (Which?, 2013).

For many purposes, peat is still the principal organic medium used in soilless growing of young plants; other constituents are often incorporated into potting media, and media for large containers may be further peat-diluted within the United States and Australia, with mixes based entirely on bark and other, often locally available, non-peat materials being used. Inorganic materials are frequently combined with organic substrates,

particularly pumice, vermiculite, and perlite, to produce media with the desired physical characteristics.

## Environmental Pressures and Change in Patterns of Use

The use of peat is held to be unsustainable by many environmental groups, and major campaigns against its use have been mounted in several countries, especially the United Kingdom (Carlile, 1999; Carlile and Waller, 2013). Notwithstanding critical evaluations of peat sustainability (Quantis, 2012; Carlile and Coules, 2013) and major programs of peatland restoration in Ireland, Canada, Germany, and Scandinavia, some national governments in Europe have announced their intention to reduce or phase out peat as a growing medium constituent. Indeed, in the United Kingdom, a progressive phase-out of peat in retail markets by 2020 and professional markets by 2030 is now government strategy (Carlile and Waller, 2013). Bark, both in Europe

Table 4. Organic-based growing media: principal types and typical constituents from three countries (Italy, the UK, and the United States).

Growing medium and use	Country	Physical constituents†
Seed plugs	Italy, UK	milled peat (0–5 mm) or coir dust
	USA	50% peat (0–5 mm) + 50% vermiculite
Cutting	Italy, UK, USA	50% milled peat (0–5 mm) + 50% perlite (1–3 mm)
	Italy	coir dust + perlite (1–3 mm)
Multipurpose (professional)	Italy, UK	50% milled peat (5–10 mm, H2/H3) + 50% milled peat (5–10 mm, H4/H6)
	Italy, UK	milled peat (5–10 mm, H2/H3) + coir dust
	UK	70% milled peat (5–10 mm, H2–H5) + 30% wood fiber
Multipurpose (retail)	Italy, UK	60–80% milled peat (0–10 mm, H2–H5) + 20–40% compost
	Italy, UK	50–70% milled peat t (0–10 mm, H2–H5) + 30–50% coir dust
	UK	60–80% milled peat (5–10 mm, H2–H5) + 20–40% wood fiber
Pot plant (small pot <12–14 cm)	Italy	sod peat (5–10 mm) + pumice (3–8 mm)
	UK	80% milled peat (5–10 mm) + 20% wood fiber
	USA	70% milled peat + 30% perlite
Pot plant (large pot >14 cm)	Italy	sod peat (10–20 mm) + pumice (7–12 mm)
	UK	50% milled peat (5–10 mm) + 50% milled peat (10–25 mm)
	USA	70% milled peat + 30% perlite
Outdoor container	Italy	sod peat (10–25 mm) + pumice (7–12 mm)
	Italy	sod peat (10–25 mm) + coir chips
	USA	60–80% pine bark + composted materials
Acidophilic plants	Italy	milled peat (5–10 mm, H2–H6) or milled + sod peat (10–30 mm, H2–H6)
Modules for strawberries	Italy	coir dust + perlite (3–6 mm)
	UK	peat (5–10 mm, H2–H6) + perlite (3–6 mm)
	UK	coir
Orchid media		coarse pine bark or sod peat (20–30 mm, H2–H4) + coir chips
Organic media	Italy	50–100% sod + milled peat + 50–0% green compost
Landscape media	Italy	60–80% milled peat (0–5 mm, H2–H6) + 20–40% sand
Media for green roofs	Italy	sod peat (5–10 mm, H3–H6) + pumice + lapilli

† Percentages are volumetric.



and the United States, is increasingly used as fuel in programs of “sustainable” energy production, affecting its availability for horticultural use (Bilderback et al., 2013). Materials such as peat and coir are expensive to transport to consumers remote from their sites of production.

As a consequence of all the above, research into locally available organic and indeed inorganic materials continues apace. Innovative approaches include the use of alternative biomass such as whole pine trees derived from plantation thinning and waste or “slash” from forest residues in the United States (Bilderback et al., 2013; Fields et al., 2014), the manufacture of wood fiber from the oversize fraction of green waste composting in the United Kingdom (Carlile and Waller, 2013), solid digestate from biogas plants (Do and Scherer, 2012; Crippa et al., 2013), and the use of biochar (Altland and Locke, 2013; Zaccheo et al., 2014). Worldwide, much research is focused on the transformation of agricultural, industrial, and municipal wastes (Evans et al., 2011; Raviv, 2013; Moral et al., 2013) into resources that can be used in growing media, with the benefit of diverting wastes from landfills and land spreading, and this approach seems likely in the future to provide large quantities of organic growing media, particularly in arid and semiarid regions of the globe.

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