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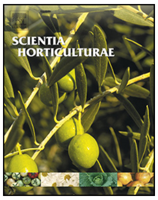

Review

Achieving environmentally sustainable growing media for soilless plant cultivation systems – A review

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ABSTRACT

Soilless cultivation is recognized globally for its ability to support efficient and intensive plant production. While production systems vary, most utilize a porous substrate or growing medium for plant provision of water and nutrients. Until relatively recently, the main drivers for the selection of the component materials in growing media were largely based on performance and economic considerations. However, increasing concern over the environmental impacts of some commonly used materials, has led researchers to identify and assess more environmentally sound alternatives. There has been an understandable focus on renewable materials from agricultural, industrial and municipal waste streams; while many of these show promise at an experimental level, few have been taken up on a significant scale. To ensure continued growth and sustainable development of soilless cultivation, it is vital that effective and environmentally sustainable materials for growing media are identified. Here we describe the factors influencing material selection, and review the most commonly used organic materials in relation to these. We summarise some of the renewable, primary and waste stream materials that have been investigated to date, highlighting the benefits and challenges associated with their uptake. In response to the need for researchers to better identify promising new materials, we present an evidence-based argument for a more consistent approach to characterising growing media and for a clearer understanding of the practical and economic realities of modern soilless cultivation systems.

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1. Introduction

Soilless plant culture is any method of growing plants without the use of soil as a rooting medium (Savvas et al., 2013). This relatively simple definition encompasses a diverse range of plant growth systems which generally involves containerization of plant roots within a porous rooting medium known as a ‘substrate’ or ‘growing medium’. Compared with soil-based cultivation, soilless production can be more cost-effective (Grafiadellis et al., 2000), producing higher yields and prompter harvests from smaller areas of land (Raviv and Lieth, 2008; Nejad and Ismaili, 2014). Soilless systems also have generally higher water and nutrient use efficiencies (van Os, 1999; Savvas, 2002). As a result, they have become increasingly important globally over the last 50 years (Schmilewski, 2009).

Containerised plant production presents two fundamental challenges for healthy root growth. First, unlike a normal soil profile, a container environment provides a very shallow layer of growing medium which becomes quickly saturated during irrigation. Secondly, small container volume provides limited capacity for water storage between irrigation events (Bunt, 1988). Essentially, an effective growing medium must have a physical structure that is capable of sustaining a favourable balance between air and water storage both during and between irrigation events in order to prevent root asphyxia and drought stress (Fonteno, 1993; Caron and Nkongolo, 1999). The inability of soil to provide this balance at such small volumes is a key driver in the development of soilless growing media. Indeed, these media have been a pivotal innovation, allowing growers to carefully control water, air and nutrient supply to the plant roots whilst excluding soil borne pathogens (Raviv et al., 2002). The definition of an ‘effective growing medium’ is context specific however, there are some general considerations that apply to all soilless growing media. As well as an appropriate physical structure, a growing medium must provide a suitable biological and chemical environment in which plant roots can effectively access nutrients. It also needs to meet the practical and economic requirements of the grower; in short it must be affordable, easy to obtain and manageable.

Historically, drivers for the selection of soilless growing media have been based predominantly on performance and economic cost. However, societies, are becoming more environmentally aware (van Os, 1999), and sustainable practices are increasing globally (Greendex, 2014). In turn, there is an intensifying pressure on legislators, retailers and ultimately growers to reduce the environmental impact of plant production (Carlile, 1999, 2004a; Alexander et al., 2008; Schmilewski, 2014). This change in societal attitude is well exemplified by the drive to reduce the reliance of the northern hemisphere on peat-based growing media (Schmilewski, 2008a, 2008b; Wallace et al., 2010). In terms of performance and economic considerations, peat is in many ways an ideal constituent of soilless growing media (Bragg, 1990; Schmilewski, 1996, 2008a). It is low in plant nutrients but able to adsorb and release them when added as fertilizer (Bragg, 1991, 1998; Robertson, 1993; Maher et al., 2008). Widespread reserves of peat exist in the northern hemisphere, making it a readily available and relatively cheap resource (Robertson, 1993; Maher et al., 2008). Consequently, it has become the material of choice throughout plant production systems from propagation to saleable ‘finished plant’ material (Bragg, 1991). However, the extraction of peat has well documented negative impacts on the environment (Alexander et al., 2008); arguably the most important of these is the release of stable, sequestered carbon into the active carbon cycle, thereby exacerbating climate change (Cleary et al., 2005; Dunn and Freeman, 2011). During the last 20 years, peat extraction has come under increasing scrutiny throughout Europe and particularly in the UK (Carlile and Coules, 2013; Siegle, 2014; Alexander et al., 2008; Alexander and Bragg, 2014). This has generated an abundance of studies examining a diverse range of alternative materials (Raviv et al., 2002; Bragg and Brough, 2014). In the selection of new materials, environmental considerations have become as important as performance and economic cost. In this context there has been a justifiable emphasis on organic materials derived from agricultural, industrial and municipal waste streams (Chong, 2005; Raviv, 2013). The disposal of such materials already presents an environmental problem, and their re-use as growing media might provide a convenient solution. Yet despite this work, few of these materials have been widely adopted by the horticultural industry. There appear to be three main reasons for this; first, the alternative materials studied, have been selected predominately with environmental drivers in mind with significantly less consideration given to performance and economic cost. Secondly, the characterisation of these materials is carried out using a wide variety of approaches; this produces results that are difficult to compare and interpret among different materials. Finally, few researchers consider the commercial realities of growing media manufacture such as whether the volume of material available is sufficient to meet demand, or whether there are any legislative constraints which might impede uptake.

As the importance of soilless plant culture is likely to rise in the years to come, it is essential that researchers work with growing media manufacturers towards identifying new materials that are environmentally sustainable, commercially viable and able to perform as well as those they are replacing. This review seeks to critically evaluate the drivers that influence material selection for soilless growing media and explain why relatively few organic materials are in current common use. It then provides an overview of the diverse range of novel growing media materials that have been investigated, and highlights the challenges associated with their uptake. It concludes with an assessment of how a more consistent approach to material characterisation, and an improved understanding of the practical and economic realities of modern soilless cultivation systems, should enable researchers to identify promising new growing media materials.

2. Factors influencing the selection of materials for soilless growing media

Commonly used soilless materials vary both locally and globally and can be organic or inorganic in nature. Many of these materials have been previously reviewed in detail (Bragg, 1998; Handreck and Black, 1994; Maher et al., 2008; Papadopoulos et al., 2008) and it is beyond the scope of this review to describe all of them. To elucidate why some materials have been taken up and used widely, while others have not, it is useful to examine the drivers which determine material selection for soilless growing media. These can be broadly divided into three categories; performance, economic and environmental. When considering these drivers it is also important to understand the growing media supply chain, and the parties making the decisions involved in raw material selection. While historically growers have manufactured their own growing media, increasing labour costs and larger production scales mean that most growers now purchase 'ready-to-use' soilless growing media (McCann, 2015; pers. comm, 20th Nov.). Growing media manufacturers, working in cooperation with their grower customer base are therefore the primary decision makers with regard to the selection of one raw material over another.

2.1. Performance drivers

An effective growing medium must perform well in two key areas. First, it must possess the physical, chemical and biological properties necessary to support healthy root growth in the challenging environment of a container. Secondly, it must meet the practical requirements of the production system in which it is being utilized. The physical, chemical and to a lesser extent biological characteristics of growing media materials have been investigated quite extensively over the last 40 years; whereas practical considerations have received relatively little research focus.

2.1.1. The physical, chemical and biological properties that determine growing medium performance

Effective soilless growing media must have a physical structure that creates an appropriate balance of air and water for healthy root development. This balance must be maintained over an entire crop production cycle, which can last from several weeks to more than a year. Growing medium structure is determined by the size, shape, texture and physical arrangement of the particles from which it is composed (Bilderback et al., 2005). Variables which describe this physical structure (e.g. bulk density, particle size distribution and pore space) have been reviewed extensively across a broad range of organic and inorganic growing media components (Bunt, 1988; Argo 1998a; Blok and Wever, 2008; Wallach, 2008). Other authors have focused on the measurement of hydraulic properties; these describe how water is absorbed, held and released by the growing media (Fonteno, 1993). Particular attention has been paid to the ability of a growing medium to store water or its 'water retention characteristic' (Fonteno, 1993). Based on work by de Boodt and Verdonck (1972), a number of methods have been devised to describe the water- and air-holding capacities of different materials; these include: easily available water (de Boodt and Verdonck, 1972; Bunt, 1983; Verdonck et al., 1983), air-filled porosity (Waller and Harrison, 1986; Bragg and Chambers, 1988; Byrne and Carty 1989), container capacity (Bunt, 1988; Fonteno and Harden, 2003; Bilderback, 2009) and water holding capacity (Handreck and Black 1994; Handreck, 2011). The aforementioned studies have led to generalised (Verdonck et al., 1983; Bunt, 1988; Bilderback et al., 2005) and sector-specific (Bragg and Chambers, 1988) recommended ranges for the air and water content of horticultural growing media. The practical application of these ranges to novel materials is somewhat limited. The methods used to obtain them vary, and different definitions and terminology are frequently used. For instance, the volume of a material made up of air, after it has been fully saturated with water and then allowed to drain under gravity, is commonly termed its air-filled porosity (AFP); it is also referred to as airspace, aeration, air capacity and air content. It can be measured simply by saturating a column of material and then allowing it to drain (e.g. Byrne and Carty 1989; Fonteno and Harden, 2003; Bilderback, 2009) or by imposing increasingly negative water potential using more specialised equipment (de Boodt et al., 1974; BSI, 2011a). Even for the relatively simple gravimetric approaches, AFP values obtained for the same material can vary quite widely, according to the size and geometry of the container used to make the measurement (Handreck, 2011). These diverse approaches present a significant challenge to comparing data among different published studies; interpretation very much depends on a detailed understanding of the methods used and how they vary (Schmilewski and Günther, 1988).

An effective growing medium must also provide a suitable environment for efficient plant nutrient provision. Chemical properties (pH, electrical conductivity, cation exchange capacity and nutrient availability etc.) have been measured across a diverse range of growing media and are extensively reviewed (e.g. Lemaire, 1995; Argo, 1998b; Silber, 2008). However, due to the diversity of analytical methods and units of measure reported, the optimal ranges quoted for chemical variables can vary quite extensively throughout the literature. Unlike physical properties, chemical properties can be manipulated to a large extent by the grower (Handreck and Black, 1994; Silber and Bar-Tal, 2008). If nutrient provision is low, the use of additives such as fertilizers is relatively straightforward (Bragg, 1998; Handreck and Black, 1994). However, some materials, possess intrinsic chemical properties that make them particularly well suited for use as a growing medium, which impacts both on their cost and manageability. For instance, most plant nutrients tend to be available within a relatively narrow pH range of 5.0–5.5 (Lucas and Davis, 1961). A growing medium material, such as peat, that naturally possesses a similar pH range, will provide a relatively optimal availability of nutrients with minimal intervention from the manufacturer. In contrast, composted materials, may contain high levels of soluble salts which are complicated and expensive to remedy (Rainbow and Wilson, 1998).

Biological properties are an important consideration for organic materials, as they can have large impacts on growing medium performance (Carlile and Wilson, 1991; Carlile, 2004b; Alsanius and Wohanka, 2009). These impacts can be broadly categorised into three main areas of concern; pathogens/weeds, biological stability and nutrient immobilization or 'draw-down'. First and foremost, growers require confidence that organic growing media are free of any organisms that might harm plant development or human health, including disease causing pathogens (Carlile and Hammonds, 2008; Waller et al., 2008; Noble et al., 2009; Wever and Scholman, 2011), plant pests (Carlile and Schmilewski, 2010; Kühne and Heller, 2010) and weed seeds (Carlile and Schmilewski, 2010; Wever and Scholman, 2011). Secondly, organic materials are subjected to variable rates of microbial decomposition which can cause undesirable physical changes in the resultant growing medium (Nash and Laiche, 1981; Prasad and Maher, 2004; Jackson et al., 2009a). For instance, organic media may shrink (or 'slump') within the container (Särkkä et al., 2008; Cattivello et al., 1997) leading to reduced air-holding capacity (Aendekerk, 1997), and excessive water retention (Nash and Pokorny, 1990). These problematic changes in growing media properties during plant production are generally referred to as 'instability' (Verhagen, 2009). Thirdly, as microbes decompose carbon compounds in organic material they consume plant available nutrients. This microbial uptake of nitrogen (Handreck, 1992a) and to a much lesser degree phosphate (Handreck, 1996) can detrimentally affect plant performance if not appropriately compensated for (Carlile and Wilson, 1991; Handreck, 1993).

The degree to which an organic growing medium might suffer from instability and nutrient draw-down depends on a variety of factors including the biochemical structure of component materials, climatic conditions and moisture availability (Carlile and Wilson, 1991; Thomas and Spurway, 1998). The relative instability of different growing media has been assessed through the direct measurement of microbial activity; e.g. CO_2 evolution (Aendekerk, 1997; Prasad, 1997; Verhagen, 2009), dehydrogenase activity (Carlile and Dickinson, 2004) or O_2 uptake (NiChualain and Prasad, 2009; Verhagen, 2009). Nitrogen draw-down capacity has been evaluated by applying known concentrations of nitrate or ammonium to different organic materials and then measuring the relative immobilization rate (Handreck, 1992a,b; Sharman and Whitehouse, 1993; Bragg and Whiteley, 1995; Jackson et al., 2009b). These methods provide a useful comparison of the potential problems among different organic materials under controlled conditions. However, they cannot predict how a growing medium will perform under all the diverse conditions that occur on a commercial nursery. While some of the leading problems can be overcome by blending with more stable components, by adding additional nitrogen (Gruda et al., 2000) or by secondary processing (e.g. composting, Guster et al., 1983), these approaches inevitably represent additional costs for the growing media manufacturer which may not be feasible. Predicting and correcting for potential issues with biological properties of organic materials still presents somewhat of a challenge both for growing media manufacturers and growers (Verhagen, 2009).

2.1.2. Practical considerations for determining growing media performance

Whilst measurement of the properties of a material may give a good indication of its suitability as a growing medium, the ultimate test is how these factors combine to influence plant growth. A common approach to evaluating novel growing media is to conduct experiments in which the performance of a test plant species is compared to those grown in a conventional or ‘industry standard’ medium. Plant performance is determined in a number of ways, from subjective visual assessments (Alexander et al., 2013) to quantitative measures of plant growth; e.g. growth index (Scheiber and Beeson, 2006), leaf area (Herrera et al., 2008) and biomass (Hernández-Apaolaza et al., 2015). Experimental set-ups vary from small laboratory-based studies with one ‘test’ plant species to large-scale commercial trials with multiple ‘test’ species. Whilst the impact of a growing medium on plant performance is crucial, it does need to be evaluated in the context of a commercial plant production system. An effective growing medium from a grower’s perspective is one that performs well within the practical constraints of their particular operation.

For most commercial growers the production of large quantities of healthy and uniform plants to precise time-scales is critical. Predictability, consistency and confidence are key factors for any growing medium used in this setting (Ball, 1998; Schmilewski, 2008a). In Northern Europe, where peat has traditionally been the dominant material in growing media, mechanised horticultural production has been optimised accordingly. Switching to an alternative material can be extremely costly and complicated if it doesn’t possess very similar properties to peat. For instance, a material with a significantly different particle size distribution may damage or impede automated potting equipment designed for peat. While peat has excellent capillarity and can be watered from the top or bottom of a container, other materials might not redistribute water evenly and could perform poorly in such systems. A major challenge of incorporating a more diverse suite of materials into growing media comes then, from the need for more flexible mechanised production systems.

Where living plants are sold to consumers within containers (e.g. ornamental plants, living herbs or salads), the appearance of the growing medium also becomes important. In the UK, where peat-based media have been the norm, the use of alternative materials which may look quite different, can impact negatively on the saleability of container plants.

2.2. Economic drivers

The performance of a soilless growing medium must be balanced against its cost. This includes the market value of the material per unit volume, transport costs (Lu et al., 2006) and the cost of any secondary processing required for its effective use.

A material’s market value is dynamic and determined by two factors: supply (i.e. availability) and demand (i.e. competition from other users). Secondary processing refers to the investment required by the growing media manufacturer after initial purchase of the raw material, to produce a saleable, consistent growing medium. The degree of secondary processing applied can vary quite widely from simple fertilizer addition, grading or milling to complete transformation via composting or pyrolysis. Generally, the more modifications required the higher the associated cost. Secondary costs also extend to legislation governing the use of novel materials in commercially available growing media. Materials categorised as wastes are often subject to a complex framework of regulation which can vary at regional, national and international levels. This can make their re-use as innovative growing media prohibitively expensive (McCann, 2016; pers. comm. 26th Feb.). While efforts are being made to clarify and harmonise the regulations governing the re-use of waste stream materials e.g. the revision of the EU Fertilizers Regulations (European Commission, 2015), legislation can still be a significant barrier to the commercial uptake of new materials. Economic considerations are absolutely crucial to a growing media manufacturer’s selection of raw materials. Regardless of its performance, a novel material is unlikely to be considered if its inclusion means an unsustainable increase in the cost of the final product. Despite this, very little published information is available on the relative costs and benefits of different soilless growing media. Useful exceptions include Hernández-Apaolaza et al. (2015) and Barreto and Jagtap (2006); both papers attempt to evaluate the relative economic costs of different growing media alongside comparisons of their relative performance.

2.3. Environmental drivers

The environmental impact of plant cultivation is attracting considerable interest (Youbin et al., 2009). Consumer preferences are changing in favour of sustainable production characteristics such as locally sourced materials (Behe et al., 2013) and biodegradable containers (Hall et al., 2010; Nambuthiri et al., 2015). More importantly, from the perspective of a growing media manufacturer or grower, consumers are apparently willing to pay more for products perceived as being ‘environmentally friendly’ (Khachatryan et al., 2014). This is probably incentivising the implementation of more sustainable production practices (Dennis et al., 2010). While significant progress has been made in the last 10 years to better understand the environmental impacts of different soilless growing media, there are still many knowledge gaps. Measurement of environmental cost: benefit is complicated, and determining the best approach can be challenging (Poveda and Lipsett, 2011; Carlile and Coules, 2013). Life cycle analysis (LCA) has been used by several authors (Verhagen and Boon, 2008; QUANTIS, 2012) to classify different growing media based on their environmental impact. LCA is an extremely comprehensive assessment of all stages of a growing medium's 'life', including extraction of the raw material, processing, manufacture, distribution, use and disposal. This approach is particularly complicated for growing media because the substitution of one material for another will more than likely lead to changes in plant management practices (e.g. fertilization and irrigation). These changes can have a positive or negative impact on the environment and also need to be measured.

A number of organisations with an interest in growing media have produced their own schemes to encourage more environmentally sustainable or 'responsible' practices. For instance, the European peat and growing media association (EPAGMA) have developed a voluntary initiative in which manufacturers are encouraged to source peat resources from areas of degraded peatland, rather than pristine, ecologically rich areas (Foundation for Responsibly produced peat, 2013). The extent to which this approach can mitigate the environmental costs of peat-based growing media are unclear. In the UK, the horticultural industry has been developing a practical, industry focused approach or "responsibility" assessment of the materials commonly included in growing media (Alexander and Bragg, 2014). The scheme has been developed by a group of stakeholders representing growing media manufacturers, growers, retailers, environmental and gardening charities as well as government. It comprises a framework in which different growing media materials can be rated according to various environmental criteria (such as renewability and impacts on habitat and biodiversity).

3. Commonly used materials and drivers for their selection as growing media

Whilst soilless growing media can be constructed from both inorganic (e.g. perlite, rockwool etc.) and organic components (Bragg, 1998; Papadopoulos et al., 2008), the latter have been the focus of the most intensive research effort. This is attributable to their general low cost and widespread availability. Moreover, in relative terms, organic materials are renewable and easier to dispose of (Raviv, 2013), making them a more environmentally sustainable option. At present few organic materials dominate soilless cultivation worldwide, these are primarily peat, coir, wood and composted materials.

3.1. Peat

The term "peat" encompasses many different types of plant material that have been partially decomposed under anaerobic, waterlogged conditions (Bunt, 1988). While not without some problems such as low re-wetting capacity (Michel, 2010), peats generally tend to possess excellent physical, chemical and biological properties for plant growth (Bragg, 1990; Robertson, 1993; Schmilewski, 2008a; Krucker et al., 2010). These properties can vary widely according to conditions under which the peat is produced (Bragg, 1990; Michel, 2010). For instance, younger or less decomposed peats tend to have a higher water holding capacity than older more decomposed deposits (Maher and Prasad, 2004; Schmilewski, 2008a). Crucially, this inherent variability provides a flexible material which can be used across a wide range of horticultural sectors.

In terms of its economic value, demand for peat arises from a number of industries additional to horticulture. For instance, in the EU around 1750 km^2 of peatlands are used annually for the generation of energy (WEC, 2013). Peat is also used within the agricultural industry as a soil improver (Robertson, 1993) and animal feed additive (Trckova et al., 2005). In terms of availability, it is estimated that peatlands cover 4 million km^2 globally (Joosten and Clarke, 2002). Traditionally, this widespread abundance has made it a relatively low cost material for use in growing media. Peat also requires relatively little treatment or few additional inputs to deliver an effective performance; thereby minimising secondary processing costs. These factors, combined with its low bulk density (which makes it light and relatively cost effective to transport), mean that peat is an economically effective component of soilless growing media. Over the last 50 years it has become an extremely well understood, reliable and consistent option for many growers. These benefits, however, present real challenges to finding comparable replacements; few of the more environmentally sustainable materials considered to date perform on a par with peat or are available in such abundance.

3.2. Coir

Coir (also known as coir pith, coir meal, coir dust and coco peat) is a waste product of the coconut (*Cocos nucifera*) industry (Arenas et al., 2002), consisting of the dust and short fibres derived from the mesocarp of the fruit. General physical, chemical and biological properties of coir have been widely reviewed (Bragg, 1998; Prasad, 1997; Schmilewski, 2008a; Nichols, 2013) and, similar to peat, it provides a favourable balance of air and water to plant roots. In contrast to peat, which once dried out can be difficult to re-wet (Michel, 2010), coir has a high re-wetting capacity (Blok and Weaver, 2008). As such, it has been used as a peat replacement across many sectors of the horticultural industry, from soft fruit production to floriculture (Schmilewski, 2008a). As a waste product, not produced specifically for horticultural applications, it may not always be processed and handled in ways that makes it most suitable for use in growing media. As a result its physical, chemical and biological properties can vary widely (Smith, 1995; Evans and Stamps, 1996; Abad et al., 2005; Nichols, 2013). Also, coir that is derived from coconuts grown in coastal areas or washed in saline water (during primary processing) can release phytotoxic levels of sodium and potassium during use (Schmilewski, 2008a; Nichols, 2013). Consequently, in addition to a period of aging to stabilise the material (Carlile et al., 2015), coir requires several washings in fresh water and a 'buffering' treatment (in which calcium nitrate is added to the material to displace harmful concentrations of sodium and potassium) before it is suitable for use as a growing medium. (Nichols, 2013; Poulter, 2014). This secondary processing adds significantly to the economic cost of coir (Schmilewski, 2008a; Poulter, 2014). Another relatively minor cost relates to transportation; commercial coconut production is geographically limited to tropical Africa, America and Asia (90% of material comes from the Philippines, Indonesia, India and Sri Lanka). While dehydration and compression of the material can help to reduce long distance transport costs (Maher et al., 2008), these may still be of significance to the farthest markets in Europe (Schmilewski, 2008a). In its favour economically, coir is at present in plentiful supply for soilless growing media; *c.* 50 million tonnes of coconuts are produced annually in the world and 25% of production ends up as waste coir (Nichols, 2013). As environmental drivers have become increasingly important considerations within the horticultural industry, the relative expense of coir compared with peat has become less of a constraint to its uptake.

3.3. Soft-wood pine bark

In southern Europe, the south eastern USA (Svenson and Witte, 1992; Lu et al., 2006; Bilderback et al., 2013), Australia (Handreck, 2011) and New Zealand (Smith, 2008), pine bark-based growing media dominate container plant cultivation. Factors affecting the performance of pine barks as a growing medium have been widely reviewed (Bragg, 1990; Maher et al., 2008). Generally they have a high air holding capacity and are typically (although not always) mixed with other components such as peat to improve water retention (Bilderback and Lorscheider, 1995).

Pine bark for growing media is obtained from the lumber industry waste stream, and softwoods such as larch and spruce are commonly utilized (Maher et al., 2008). As with coir, pine bark is not produced specifically for use in growing media and tends to have variable physical, chemical and biological properties. In order to meet the performance requirements of growers, growing media manufacturers usually undertake some secondary processing, often aging or composting the material. Aged bark is simply stockpiled and weathered for several months after production, to promote biological stability (Buamscha et al., 2008; Gaches et al., 2011) and drive off phytotoxic volatiles such as terpenes (Naasz et al., 2009). Composted bark refers to materials that have been piled, turned, aerated, and amended with nitrogen (Buamscha et al., 2008). After stabilisation, material is mechanically screened to achieve a desirable particle size distribution and a consistent product (Maher et al., 2008).

In the south eastern USA where the lumber industry is historically very large, pine bark has been an ideal high-volume, low-value, renewable material for soilless growing media (Lu et al., 2006; Boyer et al., 2008). However, in the last 15 years the most recent global economic down-turn has caused the North American lumber industry to diminish, thereby reducing the supply of pine bark. Simultaneously, environmental drivers have caused an increased interest in the production of energy from woody biomass in place of fossil fuels (Lu et al., 2006; Gómez and Robbins, 2011). This has increased competition and hence the cost of pine bark resources (Lu et al., 2006; Bilderback et al., 2013). As a result, pine bark has transitioned from a low-value material to an increasingly high-value one and thus of diminishing relevance for soilless growing media. This change has been an important catalyst for research into novel materials for soilless growing media in North America (Bilderback et al., 2013).

3.4. Wood fibre

The term wood fibre is poorly defined in the literature and applied to a range of materials produced from both primary (e.g. fresh pine chips) and waste wood (e.g. shredded pallets) streams (Maher et al., 2008). The wood fibre materials most widely used in commercial soilless growing media, are those produced using extensive secondary processing methods. Typically, fresh wood chips, usually de-barked softwoods, such as spruce (*Picea* spp.) or pine (*Pinus* spp.), are extruded through a small aperture. The high pressure, high temperature environment created, changes their structure and creates a more stable, sterile and consistent secondary product (Gruda and Schnitzler, 2004; Frangi et al., 2008; Maher et al., 2008; Schmilewski, 2008a; Domeño et al., 2010). In many cases the material is impregnated with nitrogen (Maher et al., 2008) to reduce microbial N immobilization and subsequent instability (Gruda et al., 2000, 2001). The performance of extensively processed wood fibre in growing media has been widely reviewed (Bragg, 1990; Gruda and Schnitzler, 2001; Maher et al., 2008; Schmilewski, 2008a) and is characterized by a high total porosity and air holding capacity (Maher et al., 2008). It is rarely used as a stand-alone growing media component because it retains insufficient plant available water and has a tendency to become compressed (Gruda and Schnitzler, 2004; Domeño et al., 2010). Instead, it is used to optimize the physical properties of other material components (e.g. reducing bulk density, increasing air space and improving re-wetting capacity). In terms of its economic cost, extensively processed wood fibre, requires an initially high level of investment to obtain the machinery required for manufacture. However, subsequent on-going production costs are currently similar to those associated with peat (McCann, 2015; pers. comm, 20th Nov.). Looking to the future, the prospect of wood fibre as a growing media component is uncertain.

The global demand for woody materials in the production of bioenergy and wood-based ethanol is likely to increase competition and therefore the economic cost of forestry wastes. From an environmental perspective, while the raw material for wood fibre production is from a renewable material stream (Maher et al., 2008), its transformation into growing media is an energy intensive process.

3.5. Composted organic wastes

The use of composted organic wastes in soilless growing media has been increasing globally over the last 40 years (e.g. Poole, 1970; Sanderson, 1980; Nappi and Barberis, 1993; Beeson, 1996; Rainbow, 2009; Farrell and Jones, 2010; Raviv, 2013). Composts are an initially attractive prospect because they are high in organic matter and nutrients (Farrell and Jones, 2010). There is also a strong environmental incentive, as composting allows for the re-use of many waste materials that would otherwise end up in landfill or incineration plants (Raviv, 2013). Composts have also been shown to have properties which add to their economic value such as pathogen suppression (Hoitink et al., 1997; Noble and Coventry, 2005; Ros et al., 2005; Van der Gaag et al., 2007). As a result, numerous composted organic materials derived both from plant and animal wastes have been investigated for use in soilless growing media (Table 1). The composting process itself varies widely, but for the purposes of this review we define compost as a general term applied to all organic matter that has undergone a long, thermophilic, aerobic stabilisation process (Raviv, 2013). In Europe, composted green waste (CGW), also commonly referred to as composted green materials or green waste compost, is the most widely utilized compost in commercial soilless growing media. Feedstock materials are primarily derived from gardens and municipal horticultural activities; e.g. grass cuttings, leaves and branches etc. (Carlile, 2008). Interest in CGW has been driven by political pressure to reduce waste to landfill and by recognition of the potential high volumes available (Carlile, 2008; Surrage and Carlile, 2009). The properties of different CGW materials and their impacts on plant performance have been reviewed (Abad et al., 2001; Dimambro et al., 2007; Carlile, 2008; NiChualain et al., 2011). These vary quite widely due to the large number of feedstock materials, different composting methodologies involved, and the many different approaches to identifying mature and stable compost (Forster et al., 1993; Stentiford, 1996; Reinikainen and Herranen, 2001; Raviv, 2013). Some of the most commonly reported challenges with CGW performance as a growing medium include high bulk density and associated transport costs (Benito et al., 2005; Rainbow, 2009), biological instability (Burger et al., 1997; Nichualain and Prasad, 2009), phytotoxicity (Lumis and Johnson, 1982; Hartz et al., 1996), high salinity (Raviv, 2013; Rainbow and Wilson, 1998) and high pH (Prasad and Maher, 2001; Benito et al., 2005). From a commercial perspective, the most important problems are concerned with contamination of the waste stream, principally from herbicides (WRAP, 2010) but also sharps (e.g. glass) and human pathogens (Tognetti et al., 2007; Wever and Scholman, 2011; Blewett et al., 2005). Standards and protocols have been developed independently by many different countries to try and improve control of the composting process and to produce safe, consistent, and better performing material; e.g. the RAL compost standard in Germany (RAL, 2007) and PAS100 standard in the UK (BSI, 2011b). However, CGW is still used primarily for agricultural application and these standards are not developed specifically for growing media. As a result, CGW still exhibits inherent variability among batches, making it generally unsuitable for use as a standalone growing medium (Burger et al., 1997; Carlile, 2008). Consequently, it is incorporated into

Table 1
Summary of reported novel organic materials from primary, waste and transformed waste streams which have investigated for use in soilless growing media. The rationale for material selection is also provided (where reported).

Material	References	Material Category	Published rational for replacement
Almond shells	Urrestarazu et al. (2005), De Lucia et al. (2013), Moral et al. (2013)	Untransformed waste	Economic & environmental
Bluegrass residues	Manning et al. (1995)	Untransformed waste	Environmental
Bracken	Pitman and Webber (2013)	Transformed waste	Environmental
Brewery/Distillery waste	Bustamante et al. (2008), Prasad and Carlile (2009), NiChualain et al. (2011)	Transformed waste	Environmental
Corn/sweetcorn waste	Tzortzakis and Economakis (2005), Altland (2010), Suo et al. (2011), Vaughn et al. (2011)	Untransformed & transformed waste	Economic & environmental
Cotton waste	Cole et al. (2005), Jackson et al. (2005), Warren et al. (2009), Zaller (2007)	Transformed waste	Economic & environmental
Dairy manure/cowpeat	Paul and Metzger (2005), Hidalgo et al. (2006), Lazcano et al. (2009), Krucker et al. (2010), Shober et al. (2010), Li et al. (2009); Shober et al. (2011)	Transformed waste	Economic & environmental
Gorse	Iglesias et al. (2008), Iglesias-Díaz et al. (2009)	Transformed waste	Economic & environmental
Hazelnut Husk	Özenç (2006), Dede et al. (2011)	Untransformed waste	Environmental
Miscanthus	Altland (2010); Altland and Locke (2011)	Primary	Economic
Municipal solid waste	Eklind et al. (2001); Cendón et al. (2008); Herrera et al. (2008); Ostos et al. (2008); Mañas et al. (2009); Wilson et al. (2009); Chrysargyris et al. (2013)	Transformed waste	Economic & environmental
Horse manure	Ball et al. (2000), Hidalgo and Harkess (2002)	Transformed waste	Environmental
Olive mill waste	Papafotiou et al. (2004), Kelepesi and Tzortzakis (2009), Raviv (2009), Sofiadou and Tzortzakis (2012)	Transformed waste	Economic & environmental
Papermill waste	Chong et al. (1998), Campos Mota et al. (2009), Mañas et al. (2009)	Transformed waste	Environmental
Peanut Hulls	Bilderback et al. (1982), Flynn et al. (1995)	Untransformed waste	Economic
Pig Manure	Atiyeh et al. (2000), Atiyeh et al. (2001), Bachman and Metzger (2007), Riberio et al. (2007), Lazcano et al. (2009), Lazcano and Dominguez (2010)	Transformed waste	Economic & environmental
Pine Tree (fresh)[a]	Boyer et al. (2008), Boyer et al. (2012),Wright and Browder (2005); Fain et al. (2008), Wright and Jackson (2008), Wright et al. (2009), Jackson et al. (2010)	Untransformed waste	Economic & environmental
Poultry feather fiber	Evans (2004), Evans and Vance (2007)	Untransformed waste	Economic & environmental
Poultry manure	Flynn et al. (1995), Tyler et al. (1993), Eklind et al. (2001), Marble et al. (2010), Zoes et al. (2001), Zoes et al. (2011)	Transformed waste	Economic & environmental
Rice hulls	Sambo et al. (2008), Barreto and Jagtap (2006), Evans and Gachukia (2004), Evans and Gachukia (2007), Gómez and Robbins (2011), Locke et al. (2013)	Untransformed waste	Economic & environmental
River Waste	Di Benedetto et al. (2004), Di Benedetto and Petracchi (2006)	Untransformed waste	Environmental
Seaweed (*Posidonia*)	Castaldi and Melis (2004), Mininni et al. (2013), Montesano et al. (2014), Parente et al. (2014), Mininni et al. (2015)	Untransformed & transformed waste	Economic & environmental
Sewage Sludge	Mañas et al. (2009), Ostos et al. (2008), Topcuoğlu (2011), López-López and López-Fabal (2013), Vecchietti et al. (2013); Zawadzińska and Salachna (2014), Hernández-Apaolaza et al. (2015)	Transformed waste	Economic & environmental
Spent mushroom compost	Chong et al. (1994), Wever et al. (2005), Medina et al. (2009), Topcuoğlu (2011), Zhang et al. (2012)	Untransformed waste	Economic & environmental
Sugarcane Waste	Stoffella et al. (1996), Jayasinghe et al. (2010), Khomami and Moharam (2013), Webber et al. (2016)	Transformed Waste	Environmental
Switch grass(*Panicum virgatum* L.)	Altland and Krause (2009), Altland (2010)	Primary	Economic & environmental
Willow	Altland (2010)	Primary	Economic

[a] Ground pine chips, *WholeTree* substrate, Clean chip residual and pine tree substrate.

media mixes at between 10 and 50% by volume with other materials (Bragg et al., 1993; De Lucia et al., 2013; Raviv, 2013). While composts may fulfill many of the economic and environmental criteria for an effective soilless growing media, their performance is still not of a generally acceptable standard for commercial plant production.

4. Raw material choice – the options for environmentally sustainable growing media

Table 1 provides a summary of some of the novel materials that have been investigated as soilless growing media components since 1990. The majority of these materials are from industrial, agricultural and municipal waste streams. The re-use of these otherwise environmentally hazardous materials is an attractive prospect for the industries that generate them; moreover, they are of low economic value, and often in abundant supply (Abad et al., 2001; Hernández-Apaolaza et al., 2015; Bustamante et al., 2008; Raviv, 2013). Organic materials can generally be divided into three categories depending on their source and the degree of secondary processing required to render them suitable for use in soilless growing media.

4.1. Untransformed waste stream materials (low secondary processing requirements)

These materials require relatively few inputs or manipulation, and can generally be incorporated untransformed into growing media. Most are from locally or regionally important industries which makes transportation cost-effective. For instance, rice hulls have been utilized in the south eastern USA as a cheaper substitute both for pine bark (Gómez and Robbins, 2011) and perlite (Evans and Gachukia, 2004, 2007; Evans, 2011). Similarly, almond shell waste has been used to reduce peat content, and thus the environmental impact of growing media in Spain (Valverde et al., 2013; Urrestarazu et al., 2005). The main disadvantage of using these materials in commercial soilless media is that they are not produced specifically for horticultural applications and can therefore be highly inconsistent. As such, they are almost always used in conjunction with more traditional materials. Incorporation rates vary widely from study to study even for the same material; this makes it difficult to establish a clear consensus on their influence either on the environmental sustainability or performance of soilless growing media.

In the South Eastern USA, where forestry activity is widespread, researchers have investigated an alternative part of the forestry waste stream. Tree thinning is a widespread practice which leads to smaller and low grade trees being discarded (Boyer et al., 2008). These waste trees are chipped producing ‘clean chips’ (traditionally used for paper making) and ‘clean chip residual’ (wood, bark and needles left over from the chipping process). Researchers have explored both clean chip residual (Boyer et al., 2008, 2012) and chipped whole pine trees (Wright and Browder, 2005; Wright and Jackson, 2008; Wright et al., 2009; Jackson, 2009; Bilderback et al., 2013) as an alternative to traditional pine bark-based growing media. The material from fresh, whole trees is further ground and then screened to a range of particle distributions (Jackson et al., 2010). As such, the same raw material can be used to produce a growing medium with a range of physical properties tailored to meet the specific requirements of different horticultural sectors (Jackson et al., 2010). Other than milling and screening, this material requires minimal secondary processing (Jackson et al., 2010). Most crucially, because the raw material is processed by the manufacturer for sole use in growing media, the resulting medium is of a consistent quality. Pine forests grow locally, in close proximity to growing media manufacturers and growers, thereby minimising transports costs (Jackson et al., 2010). Essentially, this approach could provide a flexible, renewable and cost-effective (Wright and Jackson, 2008; Jackson, 2009) alternative to pine bark or peat in the South Eastern USA, where forestry activity is widespread (Altland, 2010). However, the one important concern in the use of all these industrial waste materials is long-term security of supply. Their availability depends primarily on the productivity of the industry from which they are produced, and this is subject to change. This uncertainty is combined with the potential for increases in competition for waste materials by other markets.

4.2. Transformed waste stream materials (high secondary processing requirements)

Whilst the re-use of organic wastes in soilless growing media is desirable, most industrial, agricultural and municipal waste streams are highly heterogeneous and subjected to varying levels of undesirable contamination. Secondary processing, which leads to the actual transformation of the chemical and/or physical structure of the product, is often necessary before wastes can become useful growing medium components. Transformative processes include composting (Raviv, 2013), vermicomposting (Manh and Wang, 2014), pyrolysis (Rulkens, 2008) and heat/pressure treatments (e.g. wood fibre). When any waste stream material is considered for inclusion in growing media, the cost of secondary processing needs to be assessed against the benefits of its use. Organic wastes such as sewage sludge and animal manures are often considered (Table 1) because they commonly contain useful concentrations of plant macronutrients (e.g. nitrogen or phosphorus). For instance, municipal sewage sludge has been investigated quite extensively as a growing medium component (Table 1). Its disposal represents a major challenge for urban areas (Yachigo and Sato, 2013). In the UK it is estimated that *c.* 1.5 million tonnes are produced annually, with more than 25% of this going to landfill or incineration (DEFRA, 2012a). Thus, it represents a plentiful supply of inexpensive organic matter and also contains an ‘added’ value in the form of high concentrations of micro- and macro nutrients (Waqas et al., 2014). However, sewage sludge also possesses a range of properties that make it unsuitable for use as a growing medium including pathogen presence (Waqas et al., 2014), biological instability (López-López and López-Fabal, 2013) and phytotoxic concentrations of heavy metals (Hossain et al., 2010), soluble salts (Gouin, 1993) and toxic organic contaminants such as polycyclic aromatic hydrocarbons (Stevens and Northcott, 2003). A range of secondary processing methods have been applied to reduce the impact of these detrimental qualities including drying (Kukal and Saha, 2012), composting (Perez-Murcia et al., 2006; López-López and López-Fabal, 2013; Zawadzińska and Salachna, 2014) and co-composting with other materials (Falahi-Ardakani et al., 1987). Researchers have grown plants successfully in growing media containing up to 50% composted sewage sludge (Perez-Murcia et al., 2006) and demonstrated that it can provide advantages such as increased nutrient provision (Perez-Murcia et al., 2006; Ostos et al., 2008; Topcuoğlu, 2011), improved plant water availability (Kukal and Saha, 2012) and disease suppression (Cotxarrera et al., 2002). Despite this, negative consumer perceptions of the safety of the material and inconsistency in its performance, have deterred growing media manufacturers from taking it up commercially.

More recently, sewage sludge has been utilized as a source of biomass for energy generation using pyrolysis (Rulkens, 2008). This is a thermal treatment in which biomass is heated under oxygen deficient conditions, producing bio-oils, biogases and a waste carbonaceous residue frequently referred to as biochar (Zhang et al., 2015). Pyrolysis converts the sewage sludge into a more homogeneous material in which plant available nutrients are concentrated, and the availability of heavy metals and other toxic elements is reduced (Zhang et al., 2015; Waqas et al., 2014). The pyrolysis waste stream, therefore, may have the potential to offer growing media manufacturers a safer, more consistent material that is based on a plentiful waste source. Biochars derived from a range of feedstock materials have been investigated extensively in soil-based cultivation systems (Lehmann et al., 2011; Spokas et al., 2012); but little information is available on how these might perform as, or part of, soilless growing media. A few studies in soilless systems indicate that some biochars can provide nutrients (Ruamrungsri et al., 2011; Altland and Locke, 2013; Locke et al., 2013), reduce nutrient leaching (Beck et al., 2011; Altland and Locke, 2012) and improve both the biological (Graber et al., 2010) and physical properties of growing media as a whole (Dumroese et al., 2011). The use of pyrolysed materials might, therefore, represent a promising development in the search for new soilless growing media components. Perhaps most significantly for the growing media manufacturer, the costs of secondary processing are externalised (borne by the energy producer). Given that increasing levels of competition are likely to arise from the energy market for many untransformed waste stream materials, pyrolysed materials could be of significant interest going forwards.

4.3. Renewable primary materials

A less widely explored approach has been to seek out primary, renewable materials for use in growing media. In the north-eastern and mid-western states where forestry activity is minimal, but arable farmland is abundant, the harvesting of biofuel crops for soilless growing media has been investigated. *Miscanthus x gianteus* (Altland, 2010; Altland and Locke, 2011), switchgrass (*Panicum virgatum* L.) (Altland and Krause, 2009; Altland, 2010) and willow (*Salix* spp.) (Altland, 2010) have all been shown to support container plant growth with minimal secondary processing. Whether the harvest of biofuel crops for primary use in growing media would be economically viable is unclear. It does, however, seem unlikely given the relative size and demand of the emerging biofuel market.

5. Moving forwards

As discussed above, a huge diversity of materials are, or could be, available for use as environmentally sustainable soilless growing media. Some have been investigated quite extensively (such as vermicompost or sewage sludge compost) and can support healthy plant growth within a laboratory or glasshouse setting. Few however, have been adopted on any significant scale; indeed, a survey of growing media constituents carried out in 13 EU countries by Schmilewski (2008b) showed that peat made up by far the highest proportion (77%) of all materials used in growing media manufacture (*c.* 34 million cubic metres). Thus, the question remains – why is the majority of growing media used still peat-based? The rationale for reducing the reliance of large sections of the global horticultural industry on peat are not just environmental. Reliance on just one, non-renewable material is clearly not a resilient model for the longer-term. The dynamic nature of the demand/supply chain for organic material resources, against a background of continued growth of the soilless cultivation industry, necessitates the availability of a wider range of effective, renewable materials. Researchers and growing media manufacturers, need to continue exploring the use of renewable primary materials in conjunction with valuable waste streams. The soilless growing media of the future will most likely rely upon blends of several ingredients, taking advantage of their beneficial properties (Schmilewski, 2012) while minimising their limitations. There are several research areas in which improved focus and clarity would intensify progress in this regard.

5.1. Clearer definition of materials

Organic materials are naturally heterogeneous; physical, chemical and biological properties can vary widely according to source/feedstock, secondary processing and storage factors. For instance, Abad et al. (2005) tested the physical properties of 13 different coir samples from Asia, America and Africa and found that they differed markedly between and within countries of origin. The situation becomes even more complex with transformed waste materials like GWC, where seasonal variation in feedstocks and small changes in the approach to secondary processing methods can create large differences in the properties of material produced, even from the same source (Stentiford, 1996; Prasad and Carlile, 2009). It is crucial, therefore, that researchers clearly describe both the properties and origin of materials investigated. This includes a quantitative assessment of the most important physical, chemical and biological properties which influence the material's performance (such as air and water holding capacity) and a detailed description of the secondary processing, treatments or additives required. This will allow groups of materials to be better defined, benefits to be more clearly aligned with costs, and more consideration afforded to the practical realities of using the material.

5.2. More consistent characterisation of materials

The way in which physical, chemical and biological properties of materials are reported also presents challenges both to research and end-user communities attempting to evaluate the potential of different materials. While much effort has been made to standardise the definition, measurement and reporting of properties (Schmilewski and Günther, 1988; Baumgarten, 2008, 2013; Blok and Wever, 2008), there are still many different methods and terminologies. As highlighted above, the water retention characteristic of a material is an important indicator of its usefulness as a growing medium. While several countries have now developed excellent standard protocols to quantify this property, the methods vary; e.g. the approach used for the Dutch Regeling Handelspotgronden (RHP) quality mark differs from that for the Australian standard (Standards Australia, 2003). The Dutch method is based on water retention curves (http://www.rhp.nl/en/professional) while the Australian standard uses a methodology based on a simplified volumetric method (Handreck and Black, 1994). More recently, Fields et al. (2014), have developed a promising new method which uses a dewpoint potentiometer. As things currently stand, the use of so many different approaches for growing media characterisation poses a significant barrier to the meaningful comparison of published data. While it is reasonable that different countries should develop their own standard methods independently, it is important that researchers attempt to adhere to one and make it clear which this is.

5.3. Approaches to experimental design and plant management

As outlined above, a novel growing medium is usually deemed to perform satisfactorily if it produces plants of equal or better quality than a traditional medium (Bilderback et al., 2013). However, the context in which any plant growth experiment is conducted is almost as important as the outcome. The practical realities of commercial plant production systems mean that growing media must produce an acceptable performance across a range of plant species and under very specific irrigation, fertilization, and pest and disease control regimes. While it is rarely feasible for researchers to recreate the highly mechanised plant husbandry techniques practiced in commercial nurseries, glasshouse and laboratory based studies should give some consideration to how water and nutrients are applied and how this might scale-up to a commercial setting. Using irrigation as an example, statements such as 'watered as required' do not provide much insight into how a growing medium might perform under any irrigation regime. Information about the type, frequency and timing of irrigation, would improve our understanding of which sector the material might be best suited to. A similar approach should be taken with fertilization and pest and disease management. Any modifications required to accommodate new growing media should be clearly described. This should allow other researchers and growing media manufacturers to better identify target horticultural sectors where their inclusion may be appropriate.

5.4. Consideration for economic realities and market forces

While waste materials may cost less to purchase per unit volume than primary materials like peat (Raviv, 2013), the market value of component materials is just one of several factors which determine the relative economic cost of different soilless growing media. From a growing media manufacturer's perspective, secondary processing costs, transport costs and the impacts of material selection on plant management (irrigation and fertilization etc.) all need to be included; this makes accurate cost-benefit analysis extremely complex. While it is unrealistic to expect researchers to undertake such detailed economic analysis, a clearer understanding of the realities and challenges of commercial growing media manufacture might lead to more efficient identification of promising new materials (Schmilewski, 2009). Market value aside, from a commercial perspective a new material should be available in a large volume (50–100,000 m^3 McCann, pers. comm. Jan. 2016). It should also be cost effective to transport (light and/or locally available) and have a relatively consistent composition. Given that an initially large investment would be required to accommodate it into existing growing media production lines, it is important to ensure a secure supply of the material. For many of the novel materials investigated to date, little information has been published on the potential volumes that might be available relative to market demand, and few attempts have been made to evaluate inter-batch consistency, or the long-term security of supply. The results of just a basic investigation into these factors would be extremely useful both to growing media manufacturers and the wider research community. While agricultural and manufacturing industries have historically generated large volumes of organic wastes, the rise of the bioenergy market is, and will continue to, deplete the availability of these materials for horticultural use. It is therefore crucial that, going forwards, economic factors relating to material supply and volume are carefully considered both by the research and commercial community.

5.5. Assessment of environmental costs and benefits

The rationale for using waste stream materials as growing media is often based on the assumption that re-use has less environmental impact than disposal (Table 1). However, with a few exceptions (e.g. Verhagen and Boon, 2008; Boldrin et al., 2010; De Lucia et al., 2013; Vecchietti et al., 2013), detailed quantitative assessments, such as LCA, have not been conducted to support this claim. For example, coir is often used as a peat replacement in Europe because it is perceived to be a more sustainable option. In terms of its impact on climate change, this is probably the case; but when impacts of its production are considered in terms of ecosystem quality and human health, it performs less favourably than peat (DEFRA, 2012b; QUANTIS, 2012). For an accurate understanding of the environmental impact of any growing medium, consideration should to be given to its entire life cycle. For instance, different organic growing media retain and release nutrients in a variety of ways (Ao et al., 2008; Lillywhite, 2014); this impacts both on plant nutrient efficiency and pollution potential during plant production. Consideration should also be given to growing medium effects on irrigation efficiency (Pardossi et al., 2006; Hoekstra et al., 2011) and pest and disease control (Reus and Leendertse, 2000). Determining the comparative environmental costs and benefits of different growing media materials is a complex, costly and time-consuming exercise. Yet without this full understanding there is a danger that new materials selected will prove to be just as environmentally damaging as traditional materials like peat.

6. Conclusions

Over the last 50 years, much excellent work has been carried out to improve the productivity and efficiency of soilless cultivation. The development of effective soilless growing media has been pivotal in this advance. Whilst the principal drivers in the choice of growing media materials have historically been concerned with performance and economic considerations (such as cost and availability), a societal focus on environmental issues has added a new level of complexity to the selection process. Despite the extensive diversity of organic materials investigated over the last 25 years, a relatively small selection has been adopted by the growing media industry. Coir, pine bark, wood fibre (and to a smaller extent green composts) have become the most commonly used materials in place of peat. While physically, chemically and biologically distinct, these materials share some important characteristics. They are from renewable, high-volume waste streams and, through various degrees of secondary processing, can provide growers with consistent, predictable results. Whilst many waste stream materials investigated to date have the potential to offer a multitude of benefits at the experimental level, few are actually able to meet these relatively simple requirements in the commercial sector. Going forwards, therefore, it would seem logical to examine any novel material in a broader commercial context, considering factors like supply, cost and achievable consistency before pursuing time-consuming and expensive experiments to evaluate its performance.

In conclusion, incorporating new, renewable and environmentally sustainable organic materials into growing media is certainly a challenge, but it is also represents an important opportunity. There is enormous potential for soilless cultivation systems to utilize organic waste products from other industries and, at the same time, recycle valuable nutrients and potential environmental pollutants (e.g. nitrogen and phosphorus). In a world of increasing resource scarcity and climatic uncertainty, soilless cultivation has much to offer as a truly green industry; utilizing renewable resources, minimising waste whilst improving the productivity and efficiency of crop production.

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