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The special issue on
Biochar as an Option for Sustainable Resource Management

Review article

SYNERGISTIC USE OF PEAT AND CHARRED MATERIAL IN GROWING MEDIA – AN OPTION TO REDUCE THE PRESSURE ON PEATLANDS?

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Abstract. Peat is used as a high quality substrate for growing media in horticulture. However, unsustainable peat extraction damages peatland ecosystems, which disappeared to a large extent in Central and South Europe. Furthermore, disturbed peatlands are becoming a source of greenhouse gases due to drainage and excavation. This study is the result of a workshop within the EU COST Action TD1107 (*Biochar as option for sustainable resource management)*, held in Tartu (Estonia) in 2015. The view of stakeholders were consulted on new biochar-based growing media and to what extent peat may be replaced in growing media by new compounds like carbonaceous materials from thermochemical conversion. First positive results from laboratory and greenhouse experiments have been reported with biochar content in growing media ranging up to 50%. Various companies have already started to use biochar as an additive in their growing media formulations. Biochar might play a more important role in replacing peat in growing media, when biochar is available, meets the quality requirements, and their use is economically feasible.

Keywords: biochar, greenhouse gases, growing media, horticulture, organic matter, peatland, peat extraction restoration.

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Introduction

Peatlands are wetlands with a thick (>30 cm) water-logged organic layer (peat) made up of dead and decaying plant material. They provide environmental services such as biodiversity, carbon (C) storage, regulation of the local water quality and local hydrology conditions including flood protection. They are also considered important C sinks, but as soon as a peatland is drained, aerated, limed and fertilised or when peat is extracted, the organic matter decomposes quickly and turns into a source of greenhouse gases (GHG). Peat has been used as a source of energy since centuries. Today peat is not considered to be a renewable resource anymore due to its very long regeneration time. However, peat extraction continues, due to the high demand in horticulture (Joosten, Clarke 2002; Renou-Wilson, Farrell 2009).

Worldwide about 4 million km^2 are covered by peatland, equivalent to 3% of the land surface (Table 1). The total volume of peat cannot be determined accurately, since for most countries there is no information about the average thickness of the peat layer available. Taking a mean thickness of 1.5 m as given by Immirzi *et al.* (1992), a peat volume *in situ* can be calculated to nearly 800 billion m^3 within Europe.

In Central Europe, large areas of peatlands have already been extracted. In the European Union, Germany, the Netherlands, Italy, Spain, and other countries depend on the supply of peat from Northern territories such as the Baltic States, in order to maintain or even expand their horticultural production. The Baltic and Scandinavian countries still have large reservoirs of peatlands as shown by Montanarella *et al.* (2006).

Total peat extraction can be estimated at 25 Mm^3 year^{-1} for Finland, 15–20 Mm^3 year^{-1} for Estonia, 9–11 Mm^3 year^{-1} for Ireland and 7 Mm^3 year^{-1} for Germany. In Germany, it is expected that the amount of imported peat from Northern and Eastern Europe will increase from 1–2 Mm^3 up to 7–8 Mm^3 in the next 20 years, as the German peat resources growth has been exhausted (UBA 2016). Also in Spain, comparable to other Southern European areas, the inland peat extraction cannot satisfy the needs of the local horticultural industry and about 142,000 t were imported in 2012 (Marchán-Sanz *et al.* 2014). Thus, the availability of sustainable substrates meeting the quality standards at low cost is of particular interest for European peat-using countries. The current C shift from the Northern to the Central and Southern European countries leads to a loss of C to the atmosphere as a result of both, peatland degradation and unavoidable mineralisation processes during the use of peat in agriculture and horticulture (Fig. 1).

Since peat is rather cheap and has nearly unbeatable beneficial properties for horticultural purposes, it cannot easily be replaced with alternative materials. Hence, it still remains the predominant constituent of growing media, *i.e.* materials other than soil *in situ*, in which plants are grown (CEN Report CR 13456:1999). Other common organic input materials often used to reduce the peat fraction in growing media are compost, treated wood fibres, coir, composted bark, digestates, *Sphagnum* moss and inorganic materials such as perlite, vermiculite, clay granules, pumice and lava rock. Although growers are interested in new compounds for growing media, the alternative materials do not have the same properties, are expensive or not available compared to peat (Schmilewski 2008). However, the demand of hobby gardeners and consumers for peat free growing media and soil conditioners is increasing rapidly. As potential new group of material, chars (biochar, HTC char) derive from the thermal carbonisation of biomass are presently discussed (Tian *et al.* 2012; Busch *et al.* 2013; Steiner, Harttung 2014; Mendez *et al.* 2015; O'Toole *et al.* 2016). Since biochar is characterised by a high porosity and a high water holding capacity, it is not only dedicated to replace peat, but may also be usable as a substitute for constituents, which are already established in the growing media market, but which have a limited supply (Mendez *et al.* 2015). Moreover, a reduction of the peat component in growing media may reduce GHG emissions associated with peat extraction and use, dependencies on peat sources for consumer countries, and the pressure on peatlands.

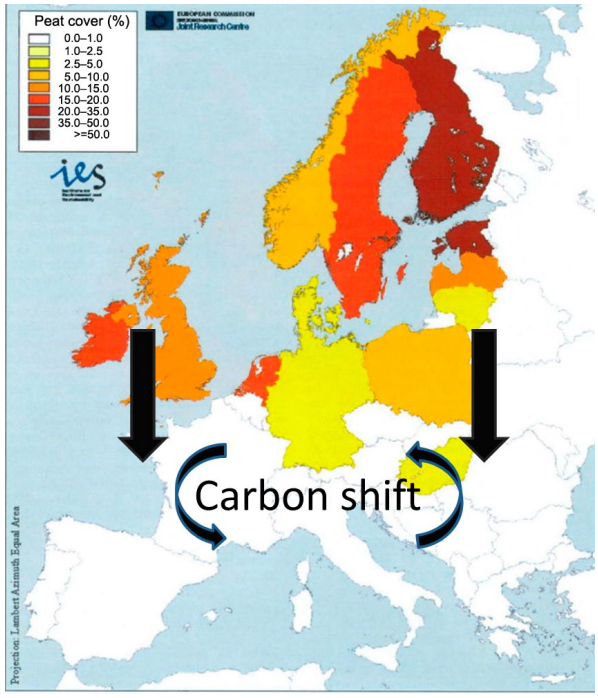


Fig. 1. Relative cover (%) of peat and peat-topped soils (0–30 cm) across Europe according to Montanarella *et al.* (2006). Currently there is a shift of peat from North Europe to Central and South Europe with C loss by mineralisation

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Since peat resources are limited and the supply of new substrates is urgently needed for the production of growing media, a workshop of the EU COST Action TD1107 *Biochar as option for sustainable resource management* was hosted by the Estonian University of Life Sciences in Tartu (Estonia) in May, 4th–6th 2015. This workshop aimed to stimulate discussions on opportunities for using biochar in synergy with peat as constituents of growing media. The key questions were (i) whether char materials can be combined with other non-peat materials; (ii) whether biochars represent a realistic alternative to substitutes such as compost *etc*. and (iii) up to which amount biochar may be added to growing media. Finally, the acceptance of new biochar based growing media by stakeholders such as amateur and professional gardeners was elucidated.

The aim of this paper is to compare characteristics of peat and biochar and evaluate options where there can be synergies to replace peat as growing media.

1. Characteristics of peatlands and its organic matter

In peatlands plant production exceeds the decay, consequently a C surplus is accumulated as peat, resulting in a positive C balance and accumulation of C stocks. They represent unique biological, environmental and economic resources (Clarke, Rieley 2010). Peatlands occur at all continents, from the tropical to boreal and Arctic zones and from sea level to high alpine conditions. The largest known areas are found in Canada and Alaska, Northern Europe and Western Siberia, Southeast Asia, and parts of the Amazon basin, where more than 10% of the land area is covered with peatlands. The total area of peatlands on Earth is about 4 Million km^2. 13% of that area is occurring in Europe (Table 1). In Central Europe, most peat started to be formed after the retreat of the glaciers at the end of the last ice age, around 12,000 years ago (Dudová *et al.* 2013).

Table 1. Global peatland area by region (World Energy Council 2013)

Region	Area (km^2)	(%)
Central and North America	1,762,267	44.4
Asia	1,490,361	37.5
Europe	525,668	13.2
South America	130,800	3.3
Africa	56,165	1.4
Antartica,Oceania	8.048	0.2
Total	3,973,309	100.00

1.1. Peat formation

Peat is a heterogeneous mixture of more or less decomposed plant material, microbial remains and their secondary metabolites that have accumulated in a water-saturated environment due to inhibited decay under acidic and anaerobic conditions. Peat deposits are classified as Histosols according to the World Reference Base of soil resources (IUSS Working Group WRB 2007). Usually peat accumulates slowly at a rate of approximately one mm per year (Keddy 2010), which requires biomass production at a greater rate than its chemical breakdown. Most of the biomass derives from the wetland vegetation such as *Sphagnum* and other mosses, sedges, and shrubs. The overriding physical conditions controlling peat formation is a high water table. Since oxygen moves very slowly in stagnant water, it is used up rapidly by microorganisms (Rydin, Jeglum 2006). In regard of this, peat deposits consist of two layers: an aerobic upper layer, the *acrotelm* and the lower, waterlogged, constantly anoxic and usually more humified layer, the *catotelm* (Moore 1989). In the top 20 cm of the surface, microbial activity is commonly relatively high (Casagrande *et al.* 1985) but with increasing depth it decreases and anaerobic bacterial activity dominates over fungal and aerobic bacterial degradation. Below the level of anaerobic activity, virtually all biological activities cease. The process of disintegration stops before it has been completed and the partially decomposed remains of the peat-forming plants slumber through millennia (Fuchsman 1980). The accumulation of peat usually causes increasingly more acidic and nutrient-poor conditions, both reducing microbial activity and organic matter degradation (Mitsch, Gosselink 2000).

1.2. Role of peat in the ecosystem

Peatlands belong to the most important terrestrial C reservoirs on Earth (Dunn, Freeman 2011). Although they cover only 3% of terrestrial ecosystems, they contain about 550,000 Mt C (Parish *et al.* 2008) accounting for 27% of the global soil C stock (Janzen 2004). Peat deposits are characterised by a high C content of about 50% of the dry organic matter. The accumulation of peat depends on the balance between plant productivity and C losses through the process of decay, leaching and fires. About 5–10% of the biomass produced in peatlands annually ends up as peat (Joosten, Clarke 2002), providing the major global store of terrestrial C besides (non-peat) soil organic C (Bonn *et al.* 2014).

The question arises if the existing peatlands are still net C sinks or sources. Intact peatlands in Europe seem to be in a neutral, alternating state with regard to their C balance. Koehler *et al.* (2011) for example found in a six years C balance study (CO_2-C, CH_4-C and dissolved organic C (DOC)) that the Irish peatland was a net C sink in four of the years However, anthropogenic impact on peatlands can severely affect the overall balance of CO_2 equivalents via the formation or consumption of the greenhouse gases CO_2, N_2O and CH_4. Peatlands become a significant source

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of CH_4 and DOC when the water table drops. Increased emissions of CO_2 and CH_4 can explain the switchover of the peatland from a sink to a source of carbon. The huge C stocks, which built up during the last millennia are being considerably affected by humans today. Drainage and excavation of peatlands augmented by more than 20% from 1,058 Mt in 1990 to 1,298 Mt in 2008 (Joosten 2009). The increase was primarily caused by the demand of new farmland in developing countries and does not include the loss of peat by fires. The EU (27) was with 174 Mt CO_2 yr^{-1} the second largest emitter of drainage-related peatland-CO_2 emission after Indonesia with 500 Mt CO_2 yr^{-1} (Butler 2009). Only 1% of European peatlands can be considered to be intact and still peat-accumulating (Koster, Favier 2005). That means that peatland areas in Western Europe have mostly lost their function as C sinks.

Peatlands contain about 10% of available freshwater resources and many of them are directly connected to rivers, thereby having a significant effect on the water cycles in the catchment (Bullock, Acreman 2003; Holden 2005). Peat can retain large amounts of water (90–95% of its mass), and therefore it has commonly been stated that peatlands reduce floods by "acting as a sponge" (Bullock, Acreman 2003; Holden 2005). This is usually the case, but water saturated headwater peatlands may quickly carry rainfall downstream and thus also increase the flood peaks or volumes (Bullock, Acreman 2003). Peatlands are adapted to the extreme conditions of high water and low oxygen content, and low availability of plant nutrients. As reported by Holden (2005), their water chemistry varies from alkaline (fens or peatlands depending on groundwater) to acidic (bogs or peatlands depending on precipitation). Bogs can retain the majority of the nutrients (*i.e.* P, Ca, K, Na and Mg) that enter the system by rain, acting thus as nutrient traps (Verry, Timmons 1982). In general, peatlands are rather scarce in plant-available nutrients as the bogs receive limited supply of nutrients and the accumulation of peat further immobilises the nutrients. This caused peatland plants to adapt to nutrient shortage (Joosten, Clarke 2002).

Peatlands are unique ecosystems forming distinct units of local, regional, national and global importance for biodiversity maintenance at genetic, species and habitat levels. They contain species that are found only or mainly in peatlands and are home to some of the rarest species of plants and animals. Mires and peatlands are generally characterised by extreme conditions, which call for special adaptations of the species that live there. For instance, leaves of higher plants are sclerophyllic and thicker in response to nutrient limitations, moss genera such as *Sphagnum* can accumulate nutrients by cation exchange mechanisms (Clymo, Hayward 1982) and some specialised plant species feed on parasitism (e.g. Scrophulariaceae; Joosten, Clarke 2002) or carnivory (e.g. Droseraceae; Brewer *et al.* 2011). The high water level and the consequent scarcity of oxygen in the root layer requires adaptations in physiology, anatomy and growth form in order to provide the root system with oxygen and thereby to enable a detoxification of substances, which are produced under anaerobic conditions. Abiotic variables such as pH, aeration and temperature had been reported to be the main factors controlling the microbial activity and community composition in peatlands (Preston, Basiliko 2016). The importance of habitat and biodiversity management and the protection of biological services and ecosystem processes have been recognized internationally more than 20 years ago (CBD 1992). The globally observed loss of biodiversity requires efficient actions such as the restoration of degraded peatlands (Tanneberger, Wichtmann 2011; Ramchunder *et al.* 2012).

2. Peatland management

Peatlands are used and managed for many different purposes. Since 1800, the global peatland area has been reduced by 10–20% through climate change and human activities, particularly by drainage for agriculture and forestry (Clarke, Rieley 2010; Table 2). Undrained peatlands are valuable habitats for a wide range of biodiversity and ecosystem services and many are managed as natural reserves. Besides agriculture and forestry, peatlands are used for instance also for peat extraction to provide energy and for growing media.

Table 2. Global area and proportions of peat(land) use according to Clarke and Rieley (2010)

Use	Area (km^2)	(%)
Undisturbed peatlands	3,500,000	85.91
Temperate agriculture	300,000	7.36
Tropical agriculture	120,000	2.95
Forestry	150,000	3.68
Growing media	2,000	0.05
Energy	2,000	0.05
Total	4,074,000	100.00

In general, peat is considered a non-renewable resource, yet in some regions of northern Europe, the remarkable growth of new peatlands facilitates the use of it as a renewable resource. For instance, in Estonia, the annual peat generation in mires is estimated to equal to 2,600,000 tons, this estimate is the basis for allowing the annual production up to this amount. The fulfilment of the quota is monitored with environmental permits with a new permit being granted if some unused quota is still available. The peat extraction controlled in such a way may be justified today, when the requirements for conservation

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of the vast majority of pristine or semi-natural peatlands are fulfilled. The Foundation Responsible Produced Peat (2014) is certifying peat extraction only from formerly degraded peatland including a restoration after-use.

2.1. Exploitation

While the majority of arctic and subarctic peatlands have been little utilised for agricultural purpose, in other parts of the world, peatlands are intensively used, as for example in Indonesia, where huge areas of peat swamp forests have been deforested and drained for the establishment of palm oil plantations. Up to 20% of peatlands on Earth are used today or considered for agriculture mostly in form of meadows and pastures (Strack 2008). To meet the full requirements of cultivated pasture plants, peatlands have to be drained. One advantage for agricultural use of drained peatland is the initial release of nitrogen by enhanced mineralisation. Ploughing and the physical and chemical alteration of soil properties however, cause a strong increase in CO_2 emissions (Oleszczuk *et al.* 2008). One example is the northern part of Germany, where 75% of former peatlands are being used as intense agricultural grassland or cropland. The drainage of the peat body is causing subsidence of one to two cm per year due to shrinking, sagging and mineralisation. By a change of soil management and groundwater control, nowadays farmers and water authorities strive towards to develop new strategies to mitigate the emission of GHG (Wichtmann, Schäfer 2007).

2.2. Restoration

Restoration is directed to the recovery of degraded peatlands and depends on the definition of a better state and how this is realised (Schumann, Joosten 2008). Restoration of peatland aims to preserve and improve function of the disturbed ecosystem. The development of biodiversity and species protection is traditionally in focus of the measures. Also C storage preservation and development of a C sink is an important goal of recent restoration plans. Various international climate change conventions promote peatland restoration as a key contribution towards reaching both, biodiversity and climate targets (IPCC 2014). Regional C markets have been suggested to fund peatland restoration (Bonn *et al.* 2014).

A recovery of functional peatland ecosystems is strongly dependent on steady water table characteristics even in summer (Menberu *et al.* 2016). In restoration, the first step is to raise the water table of the peatland (fen or bog) by *e.g.* closing ditches, building damns and removing trees. Once the peat layers get wet, the vegetation will gradually change from forest to bog vegetation. The formation of peat will recommence if hammock *Sphagnum* mosses are present in a peat bog. In fens the existence of reed, sedges or *e.g.* alder is necessary for the peat formation.

Instead of peat mining, only the upper living parts of *Sphagnum* moss can be harvested and used as growing media with properties very close to that of peat (Silvan *et al.* 2012). *Sphagnum* farming can serve as a restoration method of disturbed peatlands, and at the same time it supplies a renewable growing media with smaller environmental impact than peat mining. By this approach *Sphagnum* regeneration starts from the remaining fragments with a growth of about 1 cm per year. Thus, after 25 years, about 2–5 Mg dry mass ha^{-1} can be harvested (Silvan *et al.* 2012; Reinikainen *et al.* 2012; Tahvonen *et al.* 2015).

3. Use of peat

The total use of peat in the EU in 2005 was 68 Mm^3 as reported by main producer and consumer countries. 50% was used for energy generation, 42% for growing media production, 5% as soil amendment material and 3% for other uses (CoConcept 2008). This may be construction and insolation materials, animal stable litter, alcoholic drinks, water purification systems, balneology, therapy, medicine and textiles (Joosten, Clarke 2002).

3.1. Energetic use of peat

For a long time, peat has been excavated and used for its energy value, providing an important regional and national source of heat and power. This kind of use is still ongoing with a worldwide consumption of 17.3 Mt per year (World Energy Council 2013). More than 99% of this peat is extracted and burned in Europe. Although the share of peat is only 0.2% of the primary energy consumption in the 27 EU countries, this part is being considered as one source to meet the EU's energy security policy. The most important peat extractors and consumers for energy generation are Finland, Ireland, Belarus and Russia (Fig. 2). The highest annual peat extraction within Europe occurs in Finland with about 25 Mm^3, of which 90% is

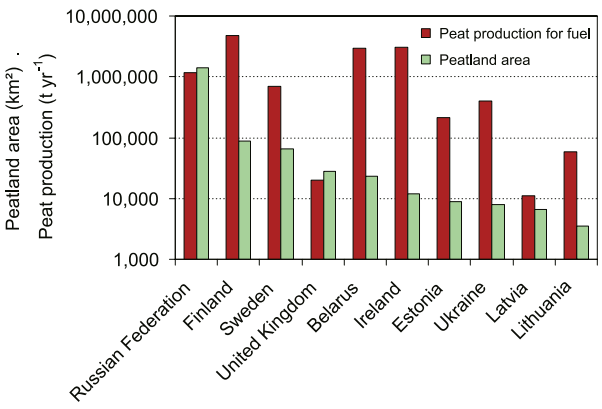


Fig. 2. Country-related pre-disturbance peatland areas compared to their annual peat extraction for energy purpose in Europe and the Russian Federation in 2008 (Data from World Energy Council 2013)

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energetically used and less than 5% is used in growing media. In energy policy, peat is regarded as non-renewable material and treated as fossil fuel. In the national policy, importance of the use of domestic fuels is increasing and peat will thus remain to be an important energy source in Finland (Karhunen *et al.* 2015). Only Latvia, Liechtenstein, Norway, the Russian Federation, Sweden, and Ukraine still have more than half of their original mire area left, whereas in some Central and Southern European countries, the formerly dominant landscape type has been almost completely destroyed (Joosten, Clarke 2002).

3.2. Use of peat in horticulture

Peat was the organic component of the first standardised growing media for plants in containers (Lawrence, Newell 1939). Their mixtures consisted of loam, peat and sand at a ratio of 7:3:2. Further works in Germany, Finland and Ireland showed that peat could be used as a growing medium in its own right both for container plants and for vegetable and cut flower production (Maher *et al.* 2008).

The peat fraction is used to increase the air space of growing media especially for crops that require high aeration and for long-term crops grown in large containers. Peat offers an ideal substrate for horticultural plant production. It forms the basis of growing media that is readily available, easily processed, uniform, high performance and cost-effective. In 1999, nearly 40 Mm^3 of peat were used across the world in horticulture (Joosten, Clarke 2002). In Europe, approximately 90% of all growing media for the professional and private markets are peat-based. The major advantages of *Sphagnum* peat as constituent of growing media include (i) very low salinity, (ii) cellular structure, ensuring a good water holding capacity and air volume, (iii) low pH and nutrient status, allowing easy adjustment by the addition of crop-specific fertilisation and liming, (iv) low number of pathogens, pests and weeds, (v) easy handling, processing, grading and blending, (vi) availability of peat products on a world-wide basis (see Bigelow *et al.* 2004; Desbiens *et al.* 2008).

More than 37 Mm^3 of growing media are produced in the EU every year – by a few large companies (Klasmann-Deilmann and Bord Na Mona with 3.5 Mm^3 and 2.0 Mm^3 per year, respectively) and several hundreds of small businesses – on which a large part of European horticulture industry depends.

Growing media must ensure basic physical and chemical properties. In today's sophisticated nurseries, tailor-made fertilisers and crop-specific growing media are essential. Sorting harvested peat into various size fractions by sieving provides peat fractions with a wide range of physical properties on a predictable basis. Table 3 shows the relationship between particle size and the most important physical properties of fractionated peat (Maher, Prasad 1993). High air space volume in the 6–12 mm and the 10–25 mm fractions were well above those recommended for pot plants grown in flood benches and for nursery stock crops (Kipp *et al.* 2000).

Table 3. Physical properties of fractionated peat according to Maher and Prasad (1993)

Size (mm)	Pore space (%)	Air space (%)	Easily available water (%)
0–3	94.4	13.7	37.3
6–12	92.0	36.3	17.8
10–25	91.5	40.9	14.5

As peat has a low pH and a very low level of fertility, it needs the addition of lime and nutrients in order to support good plant growth. The amount of nutrients needed, depends on the species being grown and the stage of development. Seeding and propagation require only a low level of nutrients in contrast to the growth of more mature plants (Maher *et al.* 2008).

3.3. Components used as additive or for peat replacement

The scrutiny of peat use has led to consideration of various alternatives, some of which have been assessed as 1:1 replacements. When considering new ingredients of growing media whether mixed with peat, or on its own at a technical level there are important physical, chemical and biological factors to be considered. From a physical point of view, bulk density of components of growing media should be low but mechanical stability and total pore space should be high. The particle size distribution affects aeration and water-holding capacity. Especially the fraction <1 mm plays a key role for air capacity and water availability. Standardised tests have been developed for growing media and soil improvers under the auspices of the European Committee for Standardisation during the last two decades (Baumgarten 2013). Among the organic components suitable and already established in growing

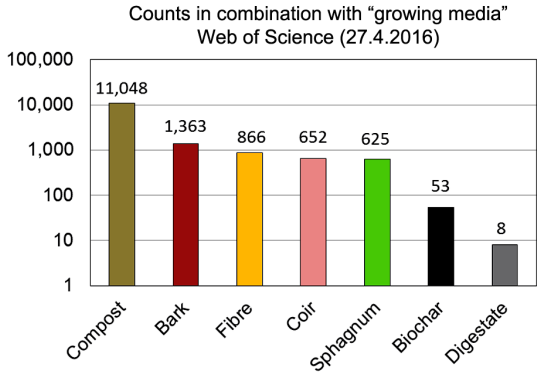


Fig. 3. Overview about the main components in growing media and their corresponding number of related publications listed in the Web of Science in April 2016

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media are composts, bark, wood fibre products and coir (Schmilewski 2008). *Sphagnum* moss, which is the most common constituent of peat itself is also gaining importance. The number of scientific papers about different candidate materials reflects the relevance of each new component in horticulture (Fig. 3).

Today, compost plays the major role as a peat substitute (Prasad *et al.* 2008). Compost made from green waste has a relative high salt content and cannot be considered as an appropriate substrate by itself but can be used as a component for potting mixtures in many peat-based cultivations. Particularly the disease suppressive properties of composts can play an important role in plant cultivation (Van der Gaag *et al.* 2007).

Veeken *et al.* (2005) reported that up to 60 vol % peat replacement by wet-sieved biowaste compost did not affect cucumber growth. However, disease suppressiveness against the plant pathogen *Pythium ultimum* of the potting mixes linearly increased from 31 to 94% when the compost amendment rate was increased from 20 to 60%. Disease suppressiveness significantly correlated with basal respiration and can be explained by the fact that plant pathogens are reduced by soil microorganisms. However, plant yield was significantly lower with compost due to inadequate nutrient supply. The authors concluded that compost from wet-sieved biowaste has high potential to replace peat in growing media for the professional market. *Sphagnum* moss is an excellent growth medium because its chemical and physical properties are quite similar to peat, with the exception of lower content of lignin (<10%) than in peat (20–50%) as reported by Prasad and Maher (2013). The amount of easily available water is similar in peat and *Sphagnum* media (Tahvonen *et al.* 2015).

Other promising options, biochars, are being discussed as additives or substitutes for peat in growing media. Biochars are produced from biomass by heating it in oxygen-depleted environment and are targeted to be used in any way that does not include the quick return of its carbon to the atmosphere. In recent years biochars have been found to be effective tools for waste management, soil remediation, control of GHG emissions and improvers of agricultural soils and soil-less media in horticulture (Lehmann, Joseph 2015; Shackley *et al.* 2016). The typically high porosity and surface area of biochars promote the retention of water and the sorption of nutrients. Further properties of biochars, which may be also a benefit for growing media are their low nutrient content (Gaskin *et al.* 2008), particularly when produced from nutrient-poor feedstock such as wood, their exceptional structural stability (Tian *et al.* 2012) and its extremely recalcitrance against microbial decay (Kuzyakov *et al.* 2014). Compared to peat, a slowed down mineralisation of biochar opens a new way of carbon storage and thus a potential for CO_2 mitigation (see Kammann *et al.*, this issue). Biochars can also be combined with compost and used as a soil amendment with synergetic effects unfolding benefits for water infiltration and retention (Liu *et al.* 2012) as well as for nutrient cycling (Steiner *et al.* 2015; Glaser *et al.* 2015).

Even nutrient-rich feedstocks of biochar such as sewage sludge are being discussed to become in a carbonised form one component in growing media. Recent studies found, that biochars of sewage sludge amendments increased the bioaccumulation of phosphorus in rice plants and also their shoot biomass by up to 92%. However, also the bioaccumulation of Cd and Zn increased (Khan *et al.* 2013). These results are corresponding with the increased availability of Zn, As and Cd for all 19 biochars produced at a process temperature of 750 °C (Buss *et al.* 2016). Although some progress has been made in the development of new growing media, the search for substitutes of peat remains as long as there is no clean and affordable material suitable to substitute peat entirely (Michel 2010).

4. Charred materials as new constituents of growing media

Little is currently known on the properties of individual ingredients and their compatibility and combinability. So, it is not yet possible to define a mix that would be certain to provide the best properties, without extensive case by case testing. Drawing on a range of ingredients also introduces risk in terms of each ingredient's quality as well as its future absolute and economic availability. In the case of biochar, the prospect for a close involvement in the development of pyrolysis facilities recedes if it only provides an "additive" or one of a number of minor constituents. Irrespective of purchase prices, the logistics associated with creating a mix also involves additional cost in terms of labour, equipment and procurement. In terms of reducing peat use, a single ingredient in a mix may not displace enough peat to warrant an intensive investigation of itself, at least not by a single company, organisation or country. It seems that this has presented a significant barrier to biochar adoption in horticulture so far. A further question concerns the parameters for mix optimisation, whether there should be maximum contents, whether peat should be included at all (Sohi *et al.* 2013).

4.1. Functional feasibility

The proportion of char in a growing media will depend on costs and benefits. These benefits may include: i) biological *e.g.* pathogen interaction (Hammer *et al.* 2015; De Tender *et al.* 2016), ii) physical relating to handling and appeal, *e.g.* particle size, integrity, internal porosity and activity of internal surfaces and iii) chemical properties like plant nutrient supply or interactions with agro-chemicals and fertiliser nutrients such as nitrogen, phosphorus and potassium (Prendergast-Miller *et al.* 2014).

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One crucial factor that determines the suitability of a char as component in growing media is the process of biomass carbonisation. Pyrolysis of dry biomass at temperatures around 400–600 °C creates biochars under oxygen-limiting conditions. Hydrothermal carbonisation (HTC) of wet biomass at temperatures between 180 and 250 °C creates a char that is brown in colour and less stable than pyrolysis biochar (Libra *et al.* 2011; Lanza *et al.* 2015). Biochar and HTC char have markedly different physico-chemical properties (Schimmelpfennig, Glaser 2012). The chemical properties playing a key role in the quality of growing media are electrical conductivity (EC) and pH value. They are similarly low in peat and HTC char (Table 4). In terms of toxicity, attention has to be paid to fresh HTC chars, which often contain compounds such as organic acids and phenols, which may affect the seed germination and the growth of seedlings (Bargmann *et al.* 2013; Busch *et al.* 2013). In case of biochars deriving from pyrolysis, polycyclic aromatic hydrocarbons (PAH) and dioxins can be formed due to the kind of biomass source, process temperature and time (Schimmelpfennig, Glaser 2012). Hale *et al.* (2012) reported that PAH disappeared from the biochar with increasing temperature and time of pyrolysis. However, as shown in section 4.3, compounds, which are phytotoxic at high concentrations may also stimulate plant growth at low concentrations (see Frenkel *et al.*, this issue). Besides the chemical properties, which are strongly influenced by feedstock and carbonisation technology, particle size is considered as important for the suitability of the char as a peat substitute or additive (Steiner *et al.* 2015). Functional improvement of peat substitutes could also be achieved by a post-treatment such as washing, composting and activating for particular chemical and biological effects (Schulze *et al.* 2016; Agegnehu *et al.* 2016; Mukherjee, Halder 2016). Modified chars may become a base for a compound ingredient or additive. Slow release of mineral nutrients, provision of active surfaces, volatile disease-suppressant compounds and sites for microbial activity can be provided as reported by Sohi *et al.* (2013). Defining char functional properties linked to feedstock and process conditions can enable a classification of chars to receive standards for chars used in growing media. This could help to introduce this group of compounds into the growing media market.

Table 4. Exemplary comparison of ranges of pH, EC and N content of commercial and experimental biochars and HTC chars with peat substrates (Prasad, unpublished), EC – electrical conductivity, N – nitrogen, HTC – hydrothermal carbonisation

Material	Feedstock Peat origin	pH	EC (μS cm^{-1})	N (% DM)
HTC char (n = 5)	Wheat straw, beer grain, digestate, sewage sludge	5.1–7.5	108–260	1.2–4.9
Biochar (n = 6)	Waste of Wood, oat and food, maize silage, paper fibre	8.0–9.9	300–1,400	0.5–1.6
Peat (n = 3)	non-fertilised Peat substrate from Ireland,	4.0–5.7	50–100	0.6–1.5

4.2. Technological and economic feasibility

For any manufacturer of growing media, the certainty of future supply is pre-requisite in taking peat replacement into consideration. For this purpose, currently two options exist: (i) to purchase charcoal at the world market, or (ii) to produce char materials. The first option is most probable: although the consistency and basic properties of charcoal may be uncertain or sub-optimal, the investment risk is low. However, compared to the price of peat (around 30 € Mg^{-1}), charcoal still remains expensive (ca. 300 € Mg^{-1}), due to the labour intensive nature of the process technology. Charcoal could therefore only function as an additive *i.e.* minor ingredient today – and therefore would need to have significant benefits. Issues of sustainability associated with much of the charcoal imported into Europe, presents a major reservation. Although small suppliers of locally produced charcoal and biochar exist within Europe, they may not compete economically, selling at a premium price of approx. 500–1,000 € Mg^{1} (Shackley *et al.* 2015). Recently, one example of HTC char has been reported, which may become interesting for horticulturists. Fornes *et al.* (2015) analysed the production of forest waste hydrochar at industrial plant scale in Spain (800 t of raw material per year) and estimated a price of 140 € Mg^{-1} (47 € m^{-3}). This price, however, is still higher than peat prices, which range from 39 (*Sphagnum* peat) to 20 € Mg^{-1} (*Phragmites* peat) on the Spanish market. Furthermore, the price of charcoal effectively sets a lucrative floor price that would limit the economic benefit seen by buyers.

The second option then is appealing – it would create the capacity to produce chars from waste streams that are secure and abundant locally, or arising within the growing media operations. If biochar or HTC char could be produced in such situation at a much lower cost than the market price, it could be profitably integrated into a growing medium. A report from the UK compared the costs for biochar in growing media under different production scenarios and found the lowest net costs (around 44 € Mg^{-1} in 2013) for pyrolysis of pre-digested sewage sludge, when sludge treatment was linked to continuous pyrolysis with energy recovery and power generation (Sohi *et al.* 2013). In this case, the stabilisation of toxic metals and the absence of contaminants from pre-cursors in feedstock must be ensured. Additional cost reduction can be expected by

the pyrolytic recycling of growing media into biochar as a sterile ingredient for a new mix in combination with energy generation.

The main barriers are the traditionally low-capital nature of the growing media industry, and the contrasting nature of the expertise required for establishing and operation a carbonisation plant. For this reason, we might envisage a partnership arrangement where it suits waste producers also, to secure a certain disposal route and price. The scale of production could potentially fall below the thresholds required for compliance with Waste Incineration Directive (2000/76/EC). Further, the quality standards of the non-peat constituents need to be clearly defined, and for biochars, the volunteer European Biochar Certificate (European Biochar Foundation 2012) is an important stepping stone on the path for EU-level joint legislation that is currently being developed.

4.3. Experience with char materials in horticultural practice

Among the different components suitable for growing media (Section 3.3), char materials belong to a group, which is relatively new and has not been established in the growing media market yet. The main focus of the growing media industry is on growth-supporting properties such as slightly acid pH, high cation exchange capacity, good aeration and a high water-holding capacity in order to guarantee germination and a good plant growth in the juvenile phase.

In areas where peat is not available, char materials are frequently used with success. For instance Steiner *et al.* (2009) observed the use of rotten tree trunks and biochar in the Brazilian Amazon. This is widespread practice and herbs which are sold in pots are frequently planted in carbonised rice husk as substrate.

To identify the best combination of peat, inorganic compounds such as vermiculite and different doses of chars ranging from 5 to 100% have already been tested (Table 5). Dumroese *et al.* (2011) produced pellets from biochar and saw dust (43% each) with starch and poly-acetic acids as binding agents (7% each). They reported that mixtures of 75% peat substrate and 25% (v/v) biochar pellets gave ideal physico-chemical properties desired in soil-less growing media, *i.e.* biochar pellets improved the hydraulic conductivity and water availability at lower matric potentials while reducing shrinkage. A similar approach was taken by Vaughn *et al.* (2013). In this study, different doses of pelletised biochars from wood and wheat straw ranging between 5 and 15% (v/v) were compared for their effects when replacing peat in growing media. There was an undesirable increase in bulk density, pH and EC, while having variable effects on porosity (Table 5).

Table 5. Physico-chemical properties of soil-less plant growing media with variable peat and biochar amounts. Means within a column followed by different letter(s) are significantly different ($p < 0.05$), EC – electrical conductivity

Biochar (%)	Substrate and Feedstock of biochar	Process conditions	Bulk density (g cm^{-3})	pH	EC (mS cm^{-1})	Total porosity (%)	Biomass yield (% of peat control)	Ref.
0	100% Peat Biochar greenwaste		0.30 b	6.22 c	0.67 c	67.4 a	*Calathea rodundifolia* 100 b	Tian *et al.* (2012)
50	Biochar Greenwaste	160–220 °C 20 min	0.37 ab	7.11 b	0.73 b	57.2 ab	122 a	
100			0.44 a	7.95 a	0.92 a	48.9 b	75 c	
0	50% Vermiculite 50% Peat		0.13	5.1	1.63	91.2	*Tagetes erecta* 100 ab	Vaughn *et al.* (2013)
5	50% Vermiculite	80 min	0.15	5.4	1.69	89.4	88 b	
10	35–45% Peat		0.16	5.5	1.71	87.7	96 ab	
15	5–15% Biochar from Hard wood pellets		0.17	5.6	1.75	87.6	98 ab	
5	50% Vermiculite	180 min	0.14	5.4	1.72	90.4	107 ab	
10	35–45% Peat		0.15	5.6	1.81	92.5	115 a	
15	5–15% Biochar from Wheat straw		0.15	5.8	1.90	89.8	109 ab	
0	100% Peat			4.5	0.63		*Helianthus annuus* 100	Steiner, Harttung (2014)
25	Biochar from wood without bark	600 °C 60 min		4.8	0.47		6	
50				5.0	0.45		81	
75				6.3	0.35		90	
100				9.0	0.61		72	

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The greenhouse experiments with tomato (*Solanum lycopersicum* L.) and marigold (*Tagetes erecta* L.) showed that biochar had no negative effect on yields, but significantly increased plant heights in all treatments. Altland and Locke (2012) focused on the nutrient retention and leaching from a soil-less substrate applied at rates of 1, 5 and 10% (v/v) biochar to a peat-based substrate. They found that biochar might be effective in moderating extreme fluctuations of nitrate levels in container substrates over time. The upper limit of biochar doses in growing media was tested by Tian *et al.* (2012), who used pure peat substrate, pure biochar and a 1:1 mixture of peat/biochar. The highest biomass yield of the ornamental plant *Calathea* was found with the peat/biochar mixture, which was 22% higher compared to peat alone. In another study, large doses of 0%, 25, 50, 75, and 100% (v/v) biochar mixed with peat were tested in trials besides other growing media such as perlite, clay granules, and pure peat regarding the growth of *Helianthus annuus* (Steiner, Harttung 2014). The miniature sunflower was growing well in all substrates and mixtures under study. It was emphasised that acidic peat-based growing media, which are usually limed to adjust the pH for different demands of crops, can work without lime when biochar is used as an additive.

Besides the dose of char in a growing medium, the raw material and the carbonisation technique play key roles in the physico-chemical properties of chars. Comparing biochars and HTC chars from forest waste, for example, resulted in a higher germination index for HTC char for both lettuce and cress (Fornes *et al.* 2015). In biotoxicity testing, Busch *et al.* (2012) used biochar or HTC char in peat at mixture rates of 10, 25 and 50% by volume, without any negative effects on barley germination and early growth found by biochar. In contrast to this, freshly produced, dried-rewetted HTC char often has quite negative effects (Busch *et al.* 2012; Bargmann *et al.* 2013; Jandl *et al.* 2013). It is now well known that fresh HTC char can contain components such as guaiacol, levulinic and glycolic acid (Bargmann *et al.* 2013; Jandl *et al.* 2013) that have germination- and growth-inhibiting properties. However, Busch *et al.* (2013) were able to show that these compounds can be easily degraded *e.g.* by co-composting. Afterwards, the positive properties of HTC char, such as the high cation exchange capacity came into play, and seedling growth was significantly improved. In this regard, HTC char is quite promising, but it likely needs a pre-treatment before using as soil additive, for removing the unstable, potentially phytotoxic, and N-immobilising compounds. A potential pathway may be the inclusion of HTC char, produced from N-poor materials such as bark, *Miscanthus* straw or material from landscape conservation, in the production of composts intended for mixing with peat in growing media production. Composts are often produced at the facilities of peat-substrate producers, to ensure a constant and reproducible quality, and thus ensure the economic viability of the final end products, the peat-reduced or peat-free growing media. At the Austrian company Sonnenerde, Dunst (2015) successfully produces a wide range of biochar-containing compost-based and completely peat-free growing media that are sold to landscape architects, gardener markets and private gardeners.

In a Canadian study the effects of amendments of biochar for different organic soils and peat based substrate up to 50% had been evaluated in greenhouse experiments with tomato, sweet pepper, geranium and ornamental basil (Dorais *et al.* 2016). In accordance with other studies, a high percentage of biochar (≥50 v/v) decreased tomato plant height and total dry mass regardless of the types of soil. However, there was no interaction between biochar amendment and the plant pathogen *Pythium ultimum*. For any of the species studied no positive effect of biochar soil amendment on plant growth was observed. The authors concluded that a proportion of up to 30% of biochar can be used in replacement of peat for organic potted plants without any significant negative effect on plant growth and disease sensitivity. But this finding should be checked for other plant species and well characterised biochars in further studies. A more promising pathway to improve plant growth and health in plant nursery or horticulture seems to be the application of biochar in low doses of less than 1% (Graber *et al.* 2014). Disease severity frequently exhibits a U-shaped response curve, with a minimum at some intermediate biochar dose. It is assumed that compounds found on chars such as n-alkanoic acids, hydroxyl and acetoxy acids, benzoic acids, diols, triols, and phenols, which are phytotoxic at high concentrations, may stimulate plant growth at low doses (hormesis, see Frenkel *et al.*, this issue).

Although horticultural charcoal is on the market in Europe, USA, Japan and Brazil since a long time, there are still economic constraints, which did not enable the establishment of chars in growing media yet. Some commercial activities were reported during the EU COST meeting in Tartu. In Estonia, biochar is already used as absorbing agent in growing media as shown by Matogard company. Besides peat, compost, fertilisers, dolomite, perlite, wetting agent, humic materials, sand, clay, bark and ceramsite, charcoal is used as well to receive an output of about 300,000 m^3 potting soils and compost per year (Matogard *pers. comm.*). A Finnish/Estonian example is the enterprise Biolan (*pers. comm.*), producing 8,000–10,000 tons of biochar annually since 2008. In 2013, Biolan was one of the first companies which introduced garden soil with addition of biochar to the market). In 2014, Biolan launched a new growing media containing wood-based biochar, chicken manure, peat and wood.

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Conclusions

Future horticulture will be increasingly demanding with respect to its requirements for the highest quality of growing media, and peat probably will remain the dominant growing media constituent in the EU for the next years. Constituents other than peat, coming mainly from local or regional sources, will increasingly be used in growing media as the demand and awareness by private customers is steadily rising. However, non-peat constituents will have to be (i) available reliably, (ii) of good quality, (iii) responsibly sourced and manufactured and (iv) they should be affordable.

Horticulturalists have already tested numerous materials, which had been considered as new constituents in growing media. But only few were successful. Wide practical experience as constituents of peat-based growing media already exists with compost, bark and fibre materials, although all of these residual materials are not sufficiently available. Therefore, the search for new alternatives is ongoing and char materials may become a new group with convincing properties in horticulture. In recent years, chars have been proved to enhance the biomass yield at biochar contents of up to 50% in growing media. This means that from a functional perspective, char materials must not necessarily remain on the level of a minor ingredient, but they may have the potential to become major constituents. Largest constraints are the limited amount of feedstocks available for carbonisation and the economic feasibility, even if waste material is being included as feedstock.

Biochar and HTC char may not only play a role as a substitute of peat, but also its synergy with peat and other constituents, which can lead to an added value of growing media. Biochar can be used in synergy with peat for example as a pH-controlling agent in acidic-peat based growing media, or as a disease suppressing component when used in low doses. Probably such combinations of peat with different alternative materials within growing media are the most promising ways forward. Particularly the combination of biochar and compost has shown favorable effects for water infiltration and retention as well as for nutrient cycling, simultaneously providing notable potential for long-term C sequestration.

Practical experience has already shown that chars can be applied as growing media constituents or additives at least in the sector of amateur gardeners. How far char materials can be established in the professional growing market will depend on the product performance that can be achieved with future research and development on the one hand, and on the other hand on the societal consensus to turn every-day C uses from being C source processes to C sinks, and to preserve the still existing peatlands.

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Jürgen KERN. PhD, Senior Scientist of Biogeochemistry, Leibniz Institute for Agricultural Engineering and Bioeconomy, Germany, 1211 citations. H-index 16 (Google Scholar).

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Heike KNICKER. PhD, Profesora de investigación, IRNAS-CSIC, 178 peer-reviewed articles in scientific journals, H-index 48 (WoS).

Claudia KAMMANN. PhD, Professor for Climate Change Research for Special Crops, Institute for Soil Science and Plant Nutrition, Hochschule Geisenheim University, Geisenheim, Germany, 58 peer-reviewed articles in scientific journals, 7 book chapters, 2453 citations, h-index 27 (Google Scholar).

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Synergistic use of peat and charred material in growing media - an option to reduce the pressure on peatlands?

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