Sphagnum farming substrate is a competitive alternative to traditional horticultural substrates for achieving desired hydro-physical properties

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SUMMARY

The provision of raw material is an important ecosystem service provided by peatlands. Using materials produced on re-established peatland sites can help to increase the interest of stakeholders in expediting further restoration measures. Promising possibilities include paludiculture and *Sphagnum* farming, which offer new perspectives for exploring renewable alternatives to peat as constituents of growing media. Therefore, gaining knowledge about processing and physical properties of the material becomes increasingly necessary. The hydro-physical properties of harvested and processed *Sphagnum palustre L.* biomass can compete with those of peat and coir, which are materials traditionally used in the horticultural industry. Even a partial substitution of peat with *Sphagnum* biomass increased maximum water-holding capacities and plant available water contents of mixtures while increasing wettability and hydration efficiency.

KEY WORDS: biomass, peat substitute, *Sphagnum palustre*, water-holding capacity, wettability

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INTRODUCTION

According to evaluations provided by Schmilewski (2017), with a proportion of 75.1 %, peat is still the number one constituent used for the production of growing media, while other organic materials (such as wood fibre, coir, bark and composts) amount to 18.7 % of total constituents, in 16 European countries. The importance of peat as a horticultural substrate is due to physical and chemical properties that are favourable for the production of growing media, while guaranteeing constant quality and reducing risks for growers and substrate producers. Fibrous, slightly decomposed peat (H1 to H4 according to the von Post Humification Scale), generally known as white peat (Blievernicht *et al*. 2012a, Carlile *et al.* 2015), provides a high water-holding capacity, good drainability low pH and nutrient contents and is free of pathogens, pests and unwanted seeds (Schmilewski 2008). These properties, together with the low price and the abundance of peat, aggravate the replacement of peat by other materials (Gaudig *et al.* 2014). In most western and central European countries, white peat is a depleted, non-renewable resource (Joosten 2012), increasing the dependence on imports and making the transportation of peat from extraction sites to growing media producers or end users a cost intensive challenge (Alexander *et al.* 2008). Besides depletion of the non-renewable material - and therefore the tightening of profitability for producers - especially environmental concerns question the continuation of peat extraction. Intact peatlands are valuable carbon sinks, storing between 545 Gt and 1,055 Gt of carbon in their soils (Nichols & Peteet 2019). Although peatlands may act as sources of the potent greenhouse gas methane (CH_4) (Matthews 2000), *Sphagnum* mosses may accommodate methanotrophs in water-filled hyaline cells, which oxidise CH_4 before reaching the atmosphere (Larmola *et al.* 2010). Drainage of peatlands, a necessary step before extracting peat (Alexander *et al.* 2008), turns the former carbon sink into a source of greenhouse gases (Joosten *et al.* 2016, Miettinen *et al*. 2017, Leifeld *et al*. 2019). In addition, other ecosystem services such as water regulation, nutrient cycling and preservation of biodiversity, are negatively affected by peatland degradation (Blievernicht *et al.* 2011).

The professional use of *Sphagnum* biomass already comprises a wide field of applications (Glatzel & Rochefort 2018). Using grown and harvested *Sphagnum* biomass may substitute the finite peat resource with a renewable alternative growing media constituent. Therefore, the cultivation of *Sphagnum* biomass in paludiculture on degraded peatlands, i.e. *Sphagnum* farming, offers synergistic effects by providing a useful raw material while tackling environmental challenges such as the degradation of drained post-mining peatlands (see Gaudig *et al.* 2008, Gaudig *et al.* 2014, Gaudig *et al.* 2017, Wichmann *et al*. 2020).

Growing media are used for a variety of purposes such as soilless cultivation of vegetables in greenhouses (Asaduzzaman *et al.* 2015), the production of substrate mixtures for the hobby and professional market (Schmilewski 2008) and substrates for green roof systems (Ampim *et al.* 2010). The broad field of application of growing media is based on the formulation of different mixtures using constituents with diverse physical properties, including both organic and inorganic materials (Carlile *et al.* 2015). Coir, a former waste product of coconut production, is a fibrous material formed in the mesocarp (Carlile *et al.* 2015). It is the most often used material after peat in the horticultural sector and provides many similar and favourable properties, including drainability and water-holding capacities in line with horticultural products, high re-wettability, while being a renewable (Mariotti *et al.* 2020). Coir is a well-known constituent of growing media, an established substitute material for peat, and is used for many purposes such as the cultivation of cut flowers, vegetables, tree saplings and as a rooting substrate (Raviv *et al.* 2002). To ensure optimum growth of plants with different physical and chemical requirements the formulation of mixtures is necessary to mitigate specific limitations of single substrates (Londra *et al.* 2018), such as adding coir to peat to reduce decomposition, increase aeration or alter re-wettability (Meerow 1994).

The quality of growing media is a key issue and is mainly described by physical and chemical properties such as bulk density, degree of humification, water-holding capacity, pH and electrical conductivity (Schmilewski 2008). Among physical properties, high water-holding capacity, water retention and pore size distribution are essential for growing media (Kämäräinen *et al.* 2018), especially for substrates used for planting in pots, as container volume is limited (Michel 2010, Oberpaur *et al.* 2010). Hydrophobicity is a property describing the repellency of materials for water due to contact angles of water greater than 90° on the material's surface (Michel 2010). The fact that many organic growing media constituents have hydrophobic features increases the importance of evaluating the wettability (Michel *et al.* 2017), a property determining the ability of the material to take up water after drying (Michel 2010). It is primarily important for irrigation management in horticulture as it influences physical properties of growing media (Michel 2015), irrigation amount and frequency and therefore potential leaching of nutrients (Blok *et al.* 2019). Biological quality requirements for plant-based growing media include low rates of unwanted seeds and pathogens. Composting, steam treatments, solarisation treatments and drying at high temperatures are commonly used techniques to ensure disease-free and weed-free substrates (Gaudig *et al.* 2018, van Os *et al.* 2019). To fulfil commercial standards, harvested *Sphagnum* biomass needs to be dried prior to further processing, using different approaches including hot-air drying, conveyor dryer and different air-drying methods (Kumar 2017). Drying of organic material changes its physical properties including its volume, pore space/size distribution and aeration, enhances its hydrophobicity and thus reduces the material's ability to rewet quickly (Michel *et al.* 2001, Michel *et al.* 2017).

Studies dealing with the evaluation of physical characteristics such as water-holding capacity, hydraulic conductivity, water retention and bulk density often investigate properties of whole plant parts or fibres and include only air-drying of the biomass (see Aubé *et al.* 2015, Kämäräinen *et al.* 2018, Kämäräinen *et al.* 2020), but these contributions do not examine drying temperature and chopped material, which is common in horticultural practice (milling of organic materials) (Carlile *et al.* 2015, Carlile *et al.* 2019). This study aims to answer the question of how the water-holding capacity, water retention and wettability of processed harvested *Sphagnum palustre L.* biomass, peat and coir, as well as mixtures of these materials, compare with those of white peat.

METHODS

Substrates and raw materials

Living, wet *Sphagnum palustre L.* biomass (shoots 10–15 cm long) was carefully excavated in the Weerribben-Wieden National Park (Netherlands), using an industrial excavator (20 cm depth). This management procedure is carried out regularly to support the survival of rare fen species such as *Liparis loeselii L.* The biomass was placed on a metal grid to guarantee aeration while it was air-dried indoor for 6 weeks and turned twice a week. After air-drying, mosses were packed in plastic bags and stored until further processing. To test the consequences of different processing methods on the water-holding capacities, biomass samples were oven-dried at 40 °C (reflecting usual temperatures observed in nature (Haraguchi *et al.* 2011)) and 60 °C (above usual temperatures). Dry biomass was homogenised by rubbing it through a sieve (< 2 mm), unwanted materials (e.g. residues from reed, leaves and grasses) were removed and subsamples were exposed to microwave radiation for sterilisation (450 W for 4 minutes 30 seconds) to reduce moulding during hydration experiments (see Youssef & Amin 2001). After all processing steps, the

Sphagnum substrate used for further experiments can be described as dry, loose, fractionated and homogeneous material (all constituents < 2 mm due to sieving).

Commercial horticultural peat (250 L bale Latvian bog-peat, decomposition: H3–H5 (von Post humification scale), pH: 3–4) and coir fibre (washed and pressed bales, fibre lengths 3–30 mm) were purchased from “Franz Kranzinger GmbH” (5204 Straßwalchen, Austria) and transferred to Vienna. Both materials were oven-dried at 40 °C prior to cutting and sieving (< 2 mm) for homogenisation. Mixtures of all three substrates (peat moss, peat and coir) were prepared based on a percentage volume (vol.-%) basis using two materials in different proportions for each mixture, resulting in mixtures containing *Sphagnum*/peat, *Sphagnum*/coir and coir/peat (i.e. 25/75, 50/50, 75/25 vol.-% mixtures).

Experimental setup

Maximum water-holding capacity (MWC) of all substrates was measured gravimetrically. Standardised stainless steel cylinders (soil sample rings, diameter 53 mm, height 51 mm, 100 cm^3) were packed with processed substrate. The lower end of the cylinder was covered with a fine mesh to avoid loss of material before placing in round sieves. Packed cylinders (n=5) were placed in a tub filled with deionised water (1 cm below the upper edge of the cylinder) for three days. After total saturation, cylinders were placed in a regular wet sand box for 10 minutes to allow drainage of excess water and the mass of water-saturated cylinders was measured after removing the fine mesh. Dry mass was measured after oven-drying at 105 °C until constant weight and gravimetric water contents of water-saturated substrate mixtures were calculated as follows:

$$\theta_m = \frac{m_w}{m_s} \qquad [1]$$

where θ_m is the water content on dry mass basis (in g), m_w the mass of water lost due to drying (in g) and m_s the dry mass (in g) (see Marshall *et al.* 1996). MWC was calculated as grams of water per gram dry weight.

Wettability of pure substrates and mixtures (50/50 vol.-% mixtures only) was determined as the hydration efficiency according to an adapted version of methods described by Fonteno *et al.* (2013), Fields *et al.* (2014) and Michel *et al.* (2017). 4 L of processed dry substrate were measured using a glass beaker and transferred into a PVC pipe (diameter: 160 mm), covered at one end with a polyester mesh to avoid loss of material while allowing water percolation. To ensure equal packing within the three replicates of the same substrate, the dry material was evenly compacted by hand using a flat tamper after filling the PVC pipe, until reaching the calculated height of a cylindrical 4 L volume (PVC pipe) indicated by a line on the inner side of the PVC pipe. Substrates were hydrated 10 times using 4,333 ± 23 g (mean ± SD) of deionised water. All substrate columns were weighed after each hydration to measure hydration efficiency. Hydration was performed by diffusing water through a perforated beaker placed on the upper end of the PVC pipe. Constant water flow rates of 70–90 mL/min were ensured using an infusion set, while avoiding ponding. After each hydration event, the PCV pipe was drained for 15 minutes before weighing. Flow-through water was collected and weighed. Hydration efficiency is defined as the change in water held by a substrate column (in g) after each hydration event. For the calculation of wettability index values, representing water contents after each hydration event relative to total water-saturation (i.e. MWC), MWC of substrate columns were evaluated. Each substrate column was saturated with water for 24 hours after the last hydration event, drained for 30 minutes to allow drainage of excess water and weighed. After oven-drying the substrates at 105 °C for 7 days, the mass of dry substrate was determined and MWC was calculated.

For the detection of plant available water, water retention at pF 2.5 for all mixtures was detected gravimetrically using a modified suction method. Substrates were saturated with deionised water for 24 hours. Ten plastic cylinders (height: 1 cm, diameter: 4 cm) were filled with saturated substrates and were placed on a filter package for 4 hours under a negative pressure of -300 hPa (pF 2.5) and covered to decrease evaporation. Pressure was revised hourly. Following the suction procedure, samples were weighed, oven-dried at 105 °C until constant weight and water content at pF 2.5 was calculated in grams water per gram dry weight. The filter package consists of a metal bowl, connected to a water separator, an expansion tank and a vacuum pump. It was packed with a water drainage layer, a porous layer (consisting of mainly loess, i.e. sieved silt fraction) and bentonite (to keep constant pressure) (see Hartge & Horn 2009). Plant available water (PAW) was calculated as the difference between mean MWCs of each substrate and corresponding water contents at pF 2.5.

Data analysis

Data analysis and statistical tests were performed using R (R Core Team 2020) and RStudio. Additional packages were used for visualisation (“ggplot2” (Wickham 2016), “ggpubr” (Kassambara 2020), “gridExtra” (Auguie 2017)) and for data manipulation (“dplyr” (Wickham *et al.* 2020)). For the detection of significant differences between materials, a non-parametric Mann-Whitney test (Wilcoxon rank sum test) for unpaired data was used, as assumptions for parametric tests (normal distribution of data) were not met (see Whitley & Ball 2002). Recognition of significant differences of *Sphagnum* processing steps were compared with means of fresh, unprocessed *Sphagnum* biomass, while mixture specific differences were compared with means of peat. Asterisks used in Figures represent different significance levels ($p < 0.05$, *; $p < 0.01$, **; $p < 0.001$, ***; $p > 0.05$, ns).

RESULTS

Maximum water-holding capacities of processed *Sphagnum* biomass

Results of mean MWCs (amount of water held within the substrate after total saturation and drainage) for different treatments of *Sphagnum* biomass showed that nearly all treatments resulted in a significant reduction ($p < 0.05$, see Table 1) of water held by the substrate compared to fresh biomass, except for one treatment. Therefore, processing of *Sphagnum* biomass involving drying at 40 °C, sieving and microwave exposure was set as the standard treatment for the production of mixtures. Initial water contents of substrates after different treatments varied between the two drying temperatures, resulting in higher initial water contents for substrates dried at 40 °C and reduced contents for substrates dried at 60 °C. Exposure to microwave radiation of substrates dried at 40 °C decreased the initial water content additionally while that was not the case for the other group (i.e. 60 °C). Tested correlations between initial water contents and MWC (g/g dry mass) showed strong correlations ($r_s = 0.83$ (Spearman rho), $p = 0.0018$) for treatments using 40 °C, sieving including exposure to microwave radiation and also for treatments using 40 °C without sieving/microwave ($r_s = 0.94$, $p = 0.014$), while for treatments with higher temperatures no significant correlations were observed.

Maximum water-holding capacity of mixtures

MWCs of tested substrates and mixtures show high variations (Figure 1), underlining, together with variations of calculated bulk densities, different structure and physical properties of used materials. Compared with peat, mixtures including processed *Sphagnum* biomass show significantly higher amounts of water held by the substrate (Table 2). Coir and coir/peat (50/50) mixture shows significant lower MWCs than peat and many mixtures including coir (i.e. *Sphagnum*/coir (25/75), coir/peat (25/75) and coir/peat (75/25)) show no significant differences. Calculated initial moisture contents of substrates vary between 7.5 ± 0.2 % (mean ± SD) (for peat) and 18.8 ± 0.4 % (coir/peat 25/50 mixture).

Wettability and hydration efficiency

Mean amounts of water held by substrates before the first hydration events (i.e. initial water contents) were calculated, resulting in 28.7 ± 3.7 g (mean ± SD) for coir, 42.7 ± 3.8 g for coir/peat (50/50), 43.5 ± 5.7 g for peat, 20.2 ± 1.2 g for *Sphagnum*, 21.9 ± 4.5 g for *Sphagnum*/coir (50/50) and 34.5 ± 4.1 g for *Sphagnum*/peat (50/50).

Table 1. Mean values of initial water contents, bulk densities (BD) and maximum water-holding capacities (MWC) for different treatments/processing steps of *Sphagnum* biomass.

Treatment	**Initial water content ± SD (% of dry mass)**	**BD ± SD (g/cm^3)**	**MWC ± SD (g/g dry mass)**	**MWC ± SD (% of dry mass)**
Fresh (n=11)	89.6 ± 0.3	0.17 ± 0.0003	28.8 ± 1.2	2,880 ± 116
40 °C, sieved, microwave (n=10)	16.2 ± 1.1	0.03 ± 0.0031	28.4 ± 2.3^{ns}	2,842 ± 224
40 °C, not sieved (n=5)	20.3 ± 04	0.03 ± 0.0003	25.8 ± 0.7**	2,581 ± 65
60 °C, sieved, microwave (n=5)	13 ± 0.1	0.04 ± 0.0002	22.6 ± 1.2**	2,257 ± 111
60 °C, not sieved (n=5)	13.1 ± 1.2	0.03 ± 0.0001	26.4 ± 0.5**	2,641 ± 44

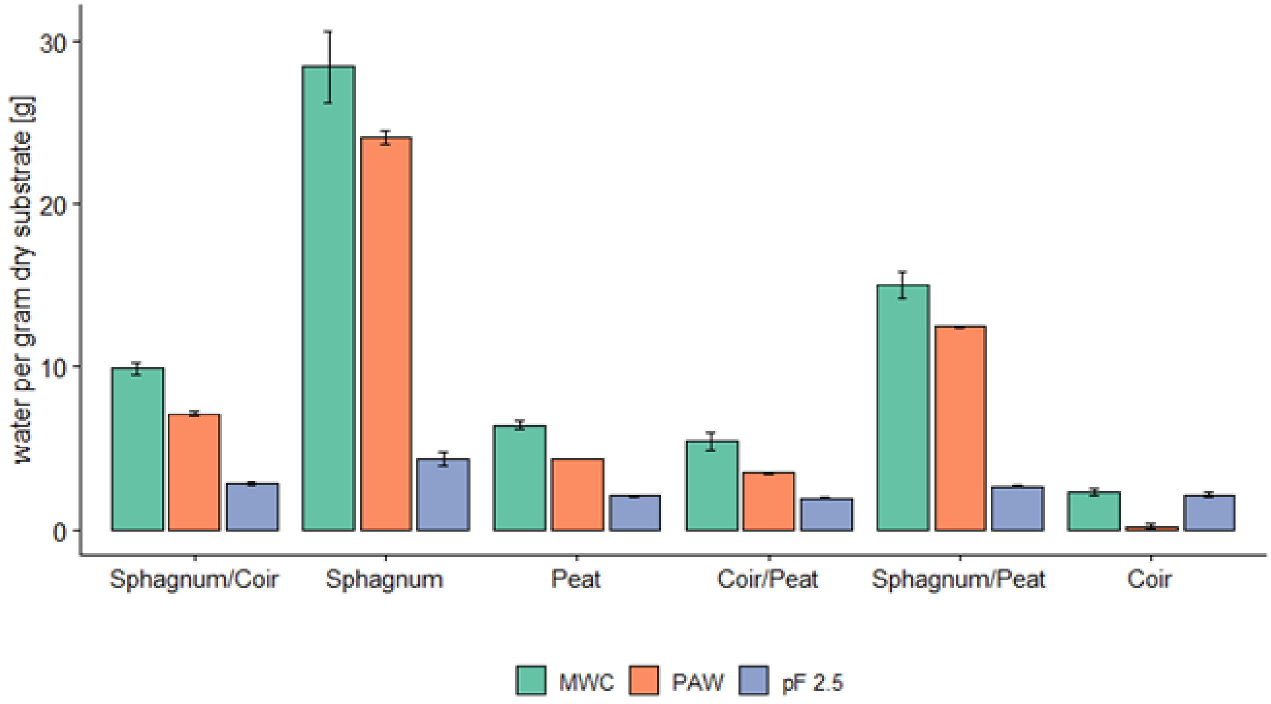

Figure 1. Comparison of gravimetric water retention of water-saturated substrates (MWC) mixtures after suction plate treatments at pF 2.5 (i.e. -300 hPa, four hours) and calculated differences between MWC and pF 2.5 (PAW). Error bars represent standard deviations, pF 2.5: n=10.

Table 2. Mean values of initial moisture contents (IMC), bulk densities (BD) and maximum water holding capacities (MWC) for substrates and different mixtures (n=5).

Substrates	**IMC ± SD (% of dry mass)**	**BD ± SD (g/cm^3)**	**MWC ± SD (g/g dry mass)**	**MWC ± SD (% of dry mass)**
Peat	7.5 ± 0.2	0.14 ± 0.0002	6.4 ± 0.3	641 ± 26
Sphagnum	16.2 ± 1.1	0.03 ± 0.0304	28.4 ± 2.3***	2,842 ± 224
Coir	8.7 ± 0.4	0.07 ± 0.0002	2.3 ± 0.9*	229 ± 18
Sphagnum/Peat (50/50)	16.7 ± 4.4	0.06 ± 0.0002	15.1 ± 0.9**	1,505 ± 83
Sphagnum/Coir (50/50)	10.7 ± 0.3	0.06 ± 0.0001	9.9 ± 0.3*	991 ± 31
Coir/Peat (50/50)	15.1 ± 0.5	0.09 ± 0.0096	5.4 ± 0.6*	542 ± 56
Sphagnum/Peat (25/75)	11.8 ± 0.2	0.07 ± 0.0042	12.3 ± 0.9**	1,226 ± 90
Sphagnum/Coir (25/75)	10.2 ± 0.6	0.05 ± 0.0111	8.1 ± 1.7^{ns}	814 ±167
Coir/Peat (25/75)	18.8 ± 0.4	0.07 ± 0.0155	4.9 ± 1.4^{ns}	491 ± 134
Sphagnum/Peat (75/25)	12.9 ± 0.3	0.05 ± 0.0032	16.6 ± 0.8**	1,655 ± 81
Sphagnum/Coir (75/25)	11.1 ± 0.5	0.05 ± 0.0010	17.1 ± 0.6**	1,706 ± 61
Coir/Peat (75/25)	12.3 ± 0.9	0.08 ± 0.0118	5.4 ± 1.2^{ns}	540 ± 115

Hydration efficiencies (Figure 2A) present the amount of water in g held within the filled substrate column after each hydration event for each substrate and 50/50 vol.-% mixtures. Pure coir showed low increases during hydration events, resulting in a mean of 616.8 ± 209.7 g of water held by the substrate after the last hydration, a mean difference of 456 g between the first and last hydration and a total increase of 588.1 g. Hydration of peat resulted in a mean of 816.5 ± 197.3 g (mean ± SD) (last hydration) and a mean difference of 403.9 g and a total increase of 773 g. Wetting of *Sphagnum* resulted in a mean of 1,471.4 ± 87.6 g after the last hydration, a difference of 1,070.9 g and a total mean increase of 1,451.2 g. Coir/peat mixtures showed slightly higher mean values of 877.5 ± 296.9 g (last hydration) than peat alone, a difference of 508.6 g and a total increase of 834 g during hydration events. *Sphagnum*/coir mixtures resulted in mean values of 1,004.3 ± 259.1 g after the last hydration, differences of 738.3 g and a total increase of 982.4 g, and mixtures of *Sphagnum*/peat respectively 1,368.8 ± 352.1 g (last hydration), 840.9 g (difference between first and last hydration) and 1,334.3 g (total increase).

Wettability index values (Figure 2B), representing water contents relative to total water saturation after each hydration event, show generally higher values for mixtures containing *Sphagnum* and increases started rapidly after the first hydration event, resulting in 71.6 ± 6.1 % (mean ± SD) (*Sphagnum*), 59.8 ± 13.3 % (*Sphagnum*/coir) and 52.6 ± 11.9 % (*Sphagnum*/peat) of total water saturation by hydrations alone. Non-*Sphagnum* containing mixtures and substrates increased constantly at lower rates and pure coir showed the highest index values after the last hydration, reaching 47.9 ± 14.1 % of total water saturation, followed by coir/peat with 39.9 ± 10.5 % and peat alone with 30.9 ± 4.6 %.

Plant available water

Amounts of water remaining in substrates and mixtures after four hours on the suction plate at pF 2.5 (see Figure 1) are highest for pure *Sphagnum*, resulting in a mean amount of 4.32 ± 0.43 (mean ± SD) g water per gram dry substrate, followed by other *Sphagnum*-containing mixtures (*Sphagnum*/coir: 2.78 ± 0.12 g and *Sphagnum*/peat: 2.65 ± 0.07 g). Other mean amounts are: for pure coir 2.14 ± 0.15 g, for pure peat 2.07 ± 0.05 g and for coir/peat mixtures 1.92 ± 0.04 g water per gram dry substrate. Calculated differences between water retained in the substrate after total saturation (i.e. MWC) and water retained after suction plate treatment (pF 2.5) were highest for *Sphagnum* (24.1 ± 2.6 g), followed by *Sphagnum*/peat (12.4 ± 0.9 g), *Sphagnum*/coir (7.12 ± 0.4 g), peat (4.31 ± 0.3 g), coir/peat (3.51 ± 1.3 g) and pure coir (0.16 ± 1.1 g).

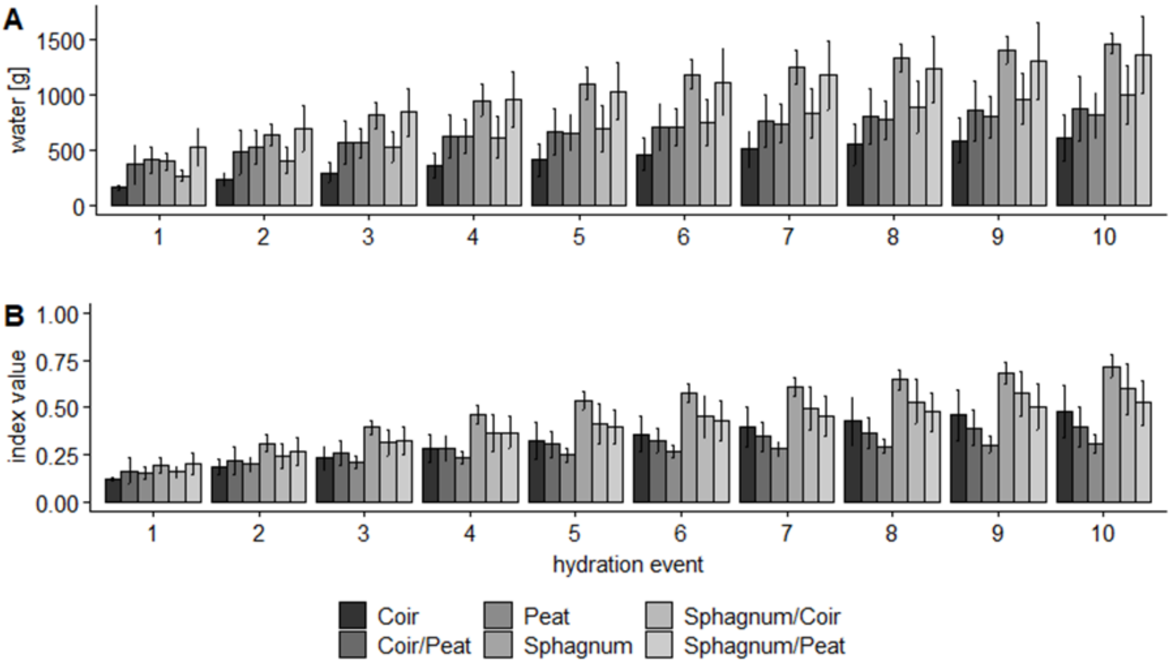

Figure 2. A: hydration efficiencies for different substrates and mixtures, which indicate the amount of water held within the materials after a specific hydration event; B: wettability index values, which show relative increases of water held by the substrate after each hydration to total saturation of the substrate (n=3, error bars represent standard deviations).

DISCUSSION

Maximum water-holding capacities of different *Sphagnum* treatments

The variable MWC depending on drying procedures highlights the importance of choosing an appropriate method for processing fresh *Sphagnum* biomass. Processing steps of horticultural materials often include drying and 'hygienisation' at higher temperatures (Kumar 2017, Gaudig *et al.* 2018), highlighting the relevance of our findings that drying at high temperatures significantly ($p < 0,05$, Table 1) decreased mean MWC of processed *Sphagnum* biomass. Microwave treatment of *Sphagnum* biomass, a direct heating method that can be used for 'hygienisation' in horticulture (Rana & Derr 2018), leads to loss of water vapour and decreases the initial water content (Table 1). Drying often leads to a reduction of the ability of the materials to rehydrate back to their original water contents, by increasing hydrophobicity (Michel *et al.* 2017). In addition to decreased water-holding capacities, hydrophobicity may lead to other undesired effects for horticultural substrates including preferential flow within substrate-filled container columns, additionally impeding water saturation during irrigation (Michel *et al.* 2017). For our measurements of MWC of processed *Sphagnum,* the latter phenomenon played a minor role due to elongated periods (i.e. three days) used for total water saturation.

Observed MWC for different treatments ranged between 22.6 ± 1.1 and 28.8 ± 1.2 g water per g dry weight (Table 1) and are in line with observations that, generally, peat moss can store high amounts of water, ranging between 20 and 30 times its own dry weight (Williams & Flanagan 1998, Maseyk *et al.* 1999, Yoshikawa *et al.* 2004). While in other bryophytes, xylem-like structure similar to vascular plants transport water through the plant (Buck & Goffinet 2012), *Sphagnum* conducts water in the unsaturated zone mainly via capillary rise within the moss matrix (McCarter & Price 2014) while storage of high amounts of water is provided by relatively large (100 × 25 µm) hyaline cells (Thompson & Waddington 2008). Sizes and shapes of hyaline cells vary between *Sphagnum* species (e.g. 50–150 × 15–29 µm in *S. capillifolium*, 70–250 × 27–48 µm in *S. papillosum*, 90–300 × 14–35 µm in *S. cuspidatum* (Hayward & Clymo 1982), as they are adapted to different growth habitats (Watson 1918, Daniels & Eddy 1990). Considering these species-related morphological differences may help to find the appropriate raw material for formulation of substrates, even though knowledge about relations between physical properties of living *Sphagnum* and processed *Sphagnum* biomass needs further investigation. In our study, processing of *Sphagnum* biomass (i.e. drying and sieving) showed distinct differences between treatments, but the function of water storage does not seem to be reduced remarkably by our chosen standard treatment (drying at 40 °C, microwave sterilisation and sieving). Especially warmer drying treatments (60 °C) reduced MWCs significantly compared to fresh unprocessed *Sphagnum* biomass (Table 1). Finding the tipping point between optimal drying temperature and significantly reduced water-holding capacities compared to fresh *Sphagnum* biomass needs further investigation, but considering temperatures lethal to cell tissues killing leaflets of different *Sphagnum* species by overheating (e.g. 49.9 °C (Buchner & Neuner 2010), 56.1–59.1 °C (Balagurova *et al.* 1996)) may help to approximate to that point.

Initial moisture contents of different *Sphagnum* treatments

Moisture content of processed *Sphagnum* biomass is of special importance for practical reasons, as light peat moss tends to become brittle and dusty with decreasing water content (Kumar 2017) making further processing steps, such as the production of horticultural substrate mixtures, difficult to handle. In addition, rehydration of the material can be affected negatively, when initial water contents fall below certain threshold values. While Kumar (2017) stated that moisture contents of *Sphagnum* fibre below 20 % are already causing rewetting problems especially due to elongated rewetting times, Gaudig *et al.* (2018) argued that the determination of a defined threshold for lower moisture contents is still debateable, as further research needs to be done. Results of MWC and initial water contents of different *Sphagnum* treatments presented in this study do not show a specific threshold at a moisture content below 20 %, as mixtures of the standard treatment had lower moisture contents (16.2 ± 1.1 % of dry weight) but highest MWC, while other treatments (40 °C, no sieving) with higher moisture contents (20.3 ± 04 % of dry weight) had slightly lower MWC (Table 1). Nevertheless, the positive correlations between initial water content and MWC for samples dried at lower temperatures indicate the relevance of the initial water content until a certain tipping point, as significant positive correlations were detected for initial water contents above 16.2 % (of dry weight) while no significant correlations were detected for high temperature treatments where initial water contents were below 13.1 % (of dry weight).

Maximum water-holding capacities of different mixtures

When comparing mean results of MWC of different mixtures with peat, all mixtures show higher amounts except for pure coir and all three coir/peat mixtures (Table 2). Total water-holding capacities of coarse coir reported by Abad *et al*. (2005) amounted to 252 mL/L (Costa Rica), 276 mL/L (Ivory Coast) and 137 mL/L (Mexico), compared to 620 mL/L for peat. Dry bulk densities of coir from different sources varied between 0.026 and 0.089 g/cm^3 (Table 2). These results are in line with the findings of the present study (Table 2). The coarse structure of the fibrous coir material increases macropores (> 100 µm), which in turn reduces water retention while increasing air-filled pores (Kumarasinghe *et al.* 2015). In addition, lignin is a principle constituent of coir (Muthurayar & Dhanarajan 2013). Lignin may reduce water absorption of materials (Rozman *et al.* 2000). Bulk densities of growing media used for experiments of physical characteristics described by Kämäräinen *et al.* (2018) varied between 0.18 g/cm^3 and 0.2 g/cm^3 for dark peat and were even lower for light peat (< 0.1 /cm^3), while reported bulk densities for *Sphagnum fuscum* fibres with different lengths (5 mm, 40 mm and natural lengths) were even lower (< 0.05 g/cm^2). Generally, the addition of processed *Sphagnum* biomass increased MWC in all mixtures and with increasing content of added biomass (i.e. 25–75 vol.-%) a steady growth can be observed, increasing MWC of several peat-free mixtures to significantly higher amounts than peat alone (Table 2). Therefore, considering the maximum water-holding capacity of different mixtures, the substitution of peat with a renewable alternative such as *Sphagnum* biomass and even total replacement with other materials such as coir is possible. These findings are in line with results from Jobin *et al.* (2014), who showed that the addition of *Sphagnum* fibres to peat-based substrates had positive effects on the hydro-physical properties and overall quality of brown peat, while not affecting plant growth negatively. Growth trials conducted by Emmel (2008) showed that growing ornamental plants in substrates based on *Sphagnum* biomass had no disadvantageous effects compared to using conventional growing media. In contrast to the observed positive effects of *Sphagnum*, our results suggest that the substitution of peat with coir alone shows disadvantageous effects as mean MWCs of mixtures containing peat and coir are generally lower than those of peat alone.

Hydration efficiency and wettability of mixtures

Results from MWC are based on relatively long soaking periods (three days) and do not reflect requirements for practical use, such as irrigation with shorter exposure to water. However, our results on hydration efficiency and wettability deliver additional insights about the hydro-physical properties of the examined materials. Hydration efficiencies of pure *Sphagnum* show highest total increases during hydration events and highest mean amounts held by the substrate after the last hydration event (Figure 2A). In addition, wettability index values are highest for peat moss substrate meaning that more than 70 % of total saturation can be achieved by hydration alone (Figure 2B). The capacity of *Sphagnum* for repeated rehydration is remarkable: the fifth hydration attained 53.4 ± 4.7 % of total saturation, while coir and peat did not reach such high levels of saturation by hydration alone (i.e. after the tenth hydration). These positive effects can also be observed for mixtures that include *Sphagnum.* Hydration efficiencies of pure peat are lower than those of *Sphagnum*, and increases between hydration events are constantly low resulting also in reduced total increases. Wettability index values of peat are constantly low during any hydration event and do not exceed 30.9 ± 4.6 % of total saturation. That indicates that the peat used in this study had the ability to hold high amounts of water, but that long soaking periods were needed to reach these high levels and that wetting via irrigation alone was insufficient. These effects can be attributed to hydrophobicity induced by drying and sieving of the material. Michel *et al.* (2017) used a comparable wettability approach and showed a similar pattern of wettability for peat with different initial moisture contents (25 %, 37.5 % and 50 %), meaning that drying reduces the ability of peat to retain sufficient amounts of water during hydration procedures and that increased drying of the material decreases wettability. Adding *Sphagnum* to peat increased its hydration efficiency already after the first hydration event, and wettability index values showed higher values than peat alone for all hydration events. These results indicate that even a partial substitution of peat with *Sphagnum* moss has positive effects on hydro-physical properties such as increased total amounts of water by irrigation alone and wettability. In comparisons of white peat and air-dried *Sphagnum* biomass, Blievernicht *et al.* (2012b) discovered similar differences regarding wettability and described peat as difficult to rewet while that was not the case for peat moss. Pure coir showed lowest hydration efficiencies during conducted trials, indicated by lowest total increases and low increases between hydration events. These results are also in line with findings of lowest MWC amounts. Wettability indices in turn surpass means for pure peat after the third hydration event and reach 47.9 ± 14.1 % of total water saturation by hydration alone. The discrepancy between relatively low hydration efficiency and elevated wettability index values points out the generally low water-holding capacity of the material, facilitating saturation by irrigation alone. Michel (2015) describes coco fibre as hydrophilic even under very dry conditions, especially when comparing it with other organic materials such as bark, decomposed peat and wood products, confirming our findings regarding wettability of coir during irrigation. When adding *Sphagnum* biomass to coir, the positive effects already described are clearly visible, increasing hydration efficiency and wettability index values to levels that exceed those of pure peat. A partial substitution of peat by coir slightly increases the ability of peat to rehydrate by irrigation and enhances wettability.

Plant available water

Mean gravimetric water contents of substrates at pF 2.5 show that *Sphagnum* and its mixtures retain the highest amounts of water per gram dry weight after a four-hour suction treatment (Figure 1). Sieved peat showed slightly lower amounts and pure coir as well as peat coir mixtures even lower values. Kämäräinen *et al.* (2018) observed similar trends, as gravimetric water retention by light and dark peat was systematically lower than observed for *Sphagnum* moss with different fibre lengths. Gravimetric water retention of fibres decreased with decreasing length, as approximate values observed were above 7 g/g dry weight for natural *Sphagnum*, above 5 g/g dry weight for 40 mm long fibres and above 4 g/g dry weight for 5 mm long fibres. As the fibre lengths of processed *Sphagnum* were shorter (sieving < 2mm) in the present study, the observed lower mean values of 4.32 ± 0.43 g/g dry weight are comparable with the results provided by Kämäräinen *et al.* (2018). As water contents at pF 2.5 can be considered to be plant available (Heiskanen 1995, Kämäräinen *et al.* 2018), *Sphagnum* and its mixtures have the highest MWC and highest proportions of available water (i.e. calculated differences between MWC and water contents at pF 2.5; Figure 1). A partial replacement of peat with *Sphagnum* enhances the water retention of the peat-*Sphagnum* mixture at pF 2.5. An increase of plant-available water after the addition of *Sphagnum* to light peat was also observed in a recent study by Kämäräinen *et al.* (2020).

Our research demonstrated that evaluated hydro-physical properties of harvested and processed *Sphagnum palustre* biomass can compete with traditional growing media constituents, including peat. Even a partial substitution of peat with processed *Sphagnum* biomass increases the maximum water-holding capacity, plant available water and wettability of mixtures. In addition, processing may have a significant influence on the materials properties, making further research in the field of standardised processing and upscaling necessary. Next to the use of peat moss as a high-quality constituent in growing media, positive feedbacks of cultivation on rewetted peatlands should be highlighted. Current research shows that *Sphagnum* farming has the potential to compete with pretended low-cost peat extraction, delivering a renewable alternative for peat in growing media, while allowing farmers to harvest valuable paludiculture crops (Pouliot *et al.* 2015, Wichmann *et al.* 2017, Wichmann *et al.* 2020).

ACKNOWLEDGEMENTS

Financial support was provided by “bellaflora Gartencenter GmbH (Austria)”. Special thanks to the “Soil Lab” of the working group Geoecology at the University of Vienna.

AUTHOR CONTRIBUTIONS

RM and SG contributed equally to the planning, setup of experimental designs and development of objectives for the study. RM carried out sample preparation, experimental measurements, data analysis and writing of the manuscript. SG supervised the project, critically reviewed the manuscript and contributed to the final version.

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Submitted 10 Feb 2021, final revision 24 Jul 2021
Editor: Jonathan Price

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