universität wien

MASTERARBEIT / MASTER'S THESIS

Titel der Masterarbeit / Title of the Master's Thesis

„Physical and Chemical Characterization of *Sphagnum palustre* as a Substitute Material for Peat in Horticultural Substrates"

verfasst von / submitted by

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angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of

Master of Science (MSc)

Wien, 2020 / Vienna 2020

Studienkennzahl lt. Studienblatt / degree programme code as it appears on the student record sheet:	UA 066 855
Studienrichtung lt. Studienblatt / degree programme as it appears on the student record sheet:	Masterstudium Geographie
Betreut von / Supervisor:	Univ.-Prof. Dipl.-Geogr. Dr. Stephan Glatzel

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Abbreviations

BD	bulk density
C	carbon
CH_4	methane
CO_2	carbon dioxide
EC	electric conductivity
EU	European Union
g	gram
GHG	greenhouse gases
Gt	gigaton
hPa	hectopascal
i.e.	that is
kg	kilogram
L	liter
m^3	cubic meter
MJ	megajoule
mL	milliliter
mm	millimeter
t	ton
UK	United Kingdom
Vol.-%	percent by volume
W	watts

Abstract

Peat is still the number one constituent used in the horticultural industry for the production of growing media and more than 25 million cubic meters of peat were used in the European Union in 2013. (SCHMILEWSKI 2017) Negative consequences on greenhouse gas emissions caused by the extraction of peat within drained peatlands, together with the reduction of the availability of peat increases the demand for alternative materials (BLIEVERNICHT et al. 2011; Gaudig et al. 2014). Using harvested *Sphagnum* biomass as a renewable material to substitute peat in growing media might be an innovative alternative, especially when grown on rewetted peatlands (KÄMÄRÄINEN et al. 2018). In this study maximum water holding capacitiy, water retention at pF 2.5 and wettability of processed *Sphagnum palustre* biomass was compared with peat and coir, showing advantageous physical properties of *Sphagnum*. Thermogravimetric and bomb calorimetric measurements, together with elemental analysis indicated that Sphagnum biomass is less stable than peat and coir and that fertilization leads to a decrease of gross heat values and a destabilization of organic matter.

Zusammenfassung

Torf ist der wichtigste Zuschlagstoff für die Produktion von gartenbaulichen Produkten und mehr als 25 Millionen Kubikmeter Torf wurden im Jahr 2013 innerhalb der EU dafür verbraucht. (SCHMILEWSKI 2017) Als negative Folgen der Torfnutzung ist vor allem die Freisetzung von Treibhausgasen von Bedeutung, wobei für die Gartenbauindustrie auch die Verknappung des Rohstoffs von Interesse ist. Daraus resultiert eine größere Nachfrage an alternativen Produkten. (BLIEVERNICHT et al. 2011; Gaudig et al. 2014) Die Verwendung von Torfmoosen könnte als erneuerbarer Ersatzstoff für Torf genutzt werden (KÄMÄRÄINEN et al. 2018). In dieser Arbeit wurde die maximale Wasserhaltekapazität, Wasserretention (pF 2.5) und die Wiedervernässbarkeit von verarbeiteten Torfmoosen (*Sphagnum palustre*) mit Torf und Kokosfasern verglichen und klare Vorteile konnten aufgezeigt werden. Thermogravimetrische, Bombenkalorimetrische und Ergebnisse von Elementaranalysen zeigten, dass vor allem die Verwendung von Dünger negative Folgen für die Stabilität von Torfmoosen hat.

1 Introduction

1.1 Growing media in the European Union (EU)

The total amounts of components used for the production of growing media in 16 countries in the EU in 2013 was 34,609 x 10^3 m^3 of which 43.6 % were used for the non-professional (hobby) sector and 56.4 % were used for the professional market. The biggest producers of growing media in the 16 compared EU countries were Germany with an amount of approximately 8,373 x 10^3 m^3 (4,381 m^3 in the professional sector and 3,993 x 10^3 m^3 in the hobby market) followed by Netherlands with 4,485 x 10^3 m^3 (3,758 x 10^3 m^3 professional and 732 x 10^3 m^3 hobby sector) and Italy with 3.833 x 10^3 m^3 (2,565 x 10^3 m^3 professional and 1,268 x 10^3 m^3 hobby sector). Austria as a small country only plays a minor role ranking to 15th place with an estimated total amount of 312.5 x 10^3 m^3 in 2013. Nevertheless, while other countries reduced their total amount of production from 2005 to 2013 (e.g.: Denmark -57 %, Italy -27 %, Germany -8 %, UK -19 % and Poland -15 %) Austria has increased its production of growing media by 28 %. The decreased production in the mentioned countries in the EU accounts for approximately 3,400 x 10^3 m^3, while the increase in the other countries summed up to only 680,000 m^3. The materials used for the production of growing media can be separated into peat, organic components other than peat (without composts), composted material and mineral components. The main constituent used in growing media is peat in different variations (fen and bog peat) which accounts for more than 75.1 % of all materials used. Other organic materials only account for 10.8 %, composts for 7.9 % and other mineral constituents for only 6.2 %. Especially countries with own peat resources predominantly use them for the production of growing media in high percentages (e.g.: Estonia 99 %, Lithuania 99 %, Latvia 92 %, 87 % Ireland, 88 % Finland, 87 % Sweden, 87 % Denmark and 81 % Germany). Countries without significant peat extraction sites also use peat in high amounts leading to amounts of 83 % in Belgium, 65 % in Italy, 59 % in Austria and 54 % in the UK. (SCHMILEWSKI 2017)

Table 1 shows the amounts of organic constituents used in 16 EU countries in the year 2013 (in m^3 x 10^3) for the professional and the hobby sector. Next to the already mentioned high amounts of peat (25,988 x 10^3 m^3) especially coir (1,314 x 10^3 m^3) and wood (1,396 x 10^3 m^3) are the main organic components used, but still at low rates. The major fraction of coir is used for professional purposes while wood is used mainly in the hobby sector. (SCHMILEWSKI 2017)

Table 1: Amounts of main organic constituents (in m^3 x 10^3) used in 16 countries of the EU for the production of growing media in 2013 separated in professional (Pro) and hobby (Hob) sector; (Source: SCHMILEWSKI 2017, own illustration)

Country	Peat*		Bark		Coir		Wood		Rice		Heather	
	Pro	*Hob*	*Pro*	*Hob*	*Pro*	*Hob*	*Pro*	*Hob*	*Pro*	*Hob*	*Pro*	*Hob*
Germany	*3,900*	*2,900*	*41*	*48*	*60*	*27*	*144*	*206*	*0*	*0*	*0*	*0*
The Netherlands	*2,450*	*542*	*185*	*20*	*316*	*51*	*54*	*14*	*12*	*0*	*0*	*0*
Italy	*1,750*	*693*	*10*	*50*	*300*	*140*	*0*	*0*	*0*	*0*	*0*	*0*
Latvia	*1,464*	*488*	*0*	*0*	*100*	*50*	*1*	*0*	*0*	*0*	*0*	*0*
Lithuania	*1,454*	*508*	*0*	*2*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
France	*976*	*565*	*170*	*268*	*69*	*22*	*114*	*153*	*0*	*0*	*14*	*60*
Poland	*870*	*950*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Estonia	*737*	*401*	*0*	*0*	*3*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Belgium	*500*	*310*	*15*	*5*	*25*	*5*	*5*	*10*	*0*	*0*	*0*	*0*
United Kingdom	*458*	*966*	*32*	*0*	*29*	*30*	*70*	*595*	*0*	*0*	*0*	*0*
Finland	*440*	*360*	*0*	*15*	*0.5*	*0*	*0*	*4*	*0*	*0*	*0*	*0*
Sweden	*250*	*810*	*1*	*3*	*3*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Ireland	*249*	*520*	*0*	*0*	*0*	*77*	*0*	*0*	*0*	*0*	*0*	*0*
Denmark	*90*	*200*	*0*	*0*	*1*	*0*	*1*	*0*	*0*	*0*	*0*	*0*
Austria	*45*	*140*	*0*	*0*	*1*	*1*	*5*	*20*	*0*	*0*	*0*	*0*
Portugal	*2*	*0*	*25*	*25*	*3.5*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Sum	***15,635***	***10,353***	***479***	***436***	***911***	***403***	***394***	***1,002***	***12***	***0***	***14***	***60***
Total	***25,988***		***915***		***1,314***		***1,396***		***12***		***74***	

**bog and fen peat*

1.2 Peat and side effects

Peat can be described as a concentrated accumulation of dead organic matter that consists mainly of carbon, formed in peatlands. Plants take carbon dioxide from the atmosphere and convert it into biomass by doing photosynthesis leading to a fixation of carbon. After dying the dead biomass can be used by other organisms which are decomposing the organic litter back to inorganic carbon dioxide (CHAPIN et al. 2011). In peatlands and other wetlands, conditions are normally wet, and oxygen is limited or absent. Under these anaerobic conditions the decomposition of dead plant material is highly reduced leading to an accumulation of plant litter. Therefore, peatlands have high carbon densities and are the biggest terrestrial carbon storage among all terrestrial ecosystems. Estimations suggest that all peatlands of the world store more than 450 Gt carbon while covering only 3 % of the earth's land area. Drainage of peatlands can turn them from carbon sinks into sources emitting CO_2, CH_4 and other greenhouse gases (GHG) increasing negative consequences of global warming. (JOOSTEN et al. 2016)

Next to the climate and environmental issues of peat extraction also the availability of the raw material, especially of the most valuable white peat, is decreasing. Due to the protection of many bogs under the EU Habitats Directive and long tradition of peat harvesting in many EU countries the resource is almost depleted in western and central Europe. To overcome the lack of peat, it needs to be imported from the Baltic states, Scandinavia and Canada, influencing both, the GHG emissions and the costs of production. (GAUDIG et al. 2014) In the European Union approximately 0.4 % of peatland areas are used for the extraction of peat, providing together with imported peat, material for an industry with an annual turnover of approximately € 1.3 billion and 11,000 jobs. (ALTMANN 2008) Peat-free substrates and alternatives may help to overcome the dependence on peat and to relax the strained situation.

1.3 Research question

As already described, peat is still the most important substance for horticultural purposes but the need for peat-free alternatives is steadily increasing. (GAUDIG et al. 2014) The use of Sphagnum biomass, the raw material of which peat consists, could help to decrease the dependence on peat. So far, research results of physical and chemical properties of Sphagnum biomass are very limited and many questions are still unanswered (KÄMÄRÄINEN et al. 2018). Therefore, the aim of this study is to answer the following research question:

Are the physical and chemical properties of Sphagnum palustre suitable to substitute peat used in horticultural substrates?

To reduce the wide extent of the research question of this study the focus lies on the water holding properties and the water retention of *Shagnum palustre*, compared with peat, coir and several mixtures containing these components. Chemical properties include the thermostability of the materials, the influence of fertilization and elemental analysis of investigated materials. The investigation of differences between these materials and, as well as a characterization of different mixtures, is therefore an important part of this work.

2 Background

2.1 Properties of Peat

Growing media constituents need to combine several factors and characteristics to be valuable for the use in the horticultural industry. Next to adequate physical, chemical and biological properties also price and especially availability are very important aspects. Therefore peat, especially Sphagnum bog peat, combines most wanted characteristics in only one material and after liming and fertilizing the peat is ready to use. Depending on the decomposition state of peat it, offers a very high air capacity while holding big amounts of water. Nutrient contents are normally low, and pH-values are mainly acidic, forming the ideal basis substrate. By adding lime, the pH-value can be modified to crop-specific values and by fertilizing also nutrient contents can be adapted. (SCHMILEWSKI 2008) Other reasons for the high demand of peat for the production of horticultural substrates are the lack of pathogens, pests and unwanted seeds as well as the favorable structure making not only processing of peat easy, but also resistant to decomposition. Peat helps to minimize financial risk for producers of horticultural substrates by having reliable and well-known properties, being cost effective and offering good availability. (KUMAR 2017; ALTMANN 2008)

2.2 Coir – Coconut fiber

Coir or coconut fiber is an organic material produced of the mesocarp and husk of *Cocos nucifera L*. and the use of the material as a substrate for growing media has been known at least since the 1860s. Problems of quality were the main reason for the exclusion of coir as a prominent substrate for many decades but since the 1980s import rates increased. Main countries of coir production include India and Sri Lanka which are exporting the material to the European Union while produced coir from Mexico is delivered to the United States. Other countries like Indonesia, Thailand, Brazil, the Philippines and Costa Rica produce and export coir too. Material gained from coconuts may contain high EC levels deriving from Cl, Na and K and several washing steps are necessary to leach salts. Depending on the steps of processing, age and source, coir may have different physical and chemical characteristics including differences in EC and pH values. For the use as substrate many positive properties are reported including hydrophilic features, ability to retain water and a favorable porosity increasing aeration. (CARLILE et al. 2019)

2.3 *Sphagnum biomass*

Peat moss has already been used for several decades and for different purposes including the use as packaging material, compostable planting pots and even the use as raw material for the production of surgical dressings is reported (GLATZEL and ROCHEFORT 2017; HOTSON 1921). Using *Sphagnum* biomass as a growing medium can be seen as a renewable alternative to peat as cultivation of *Sphagnum* on rewetted bogs or in glasshouses, also known as "Sphagnum farming", showed promising results. Physical and chemical properties are very similar to them of peat at low levels of decomposition and also during plant growth test results showed practical advantages. (CARLILE et al. 2019)

Globally, more than 600 species of fungi have been found in habitats where peat moss is growing (THORMANN and Rice 2007). They play a major role in nutrient cycling and in the process of decomposition of organic material within peatlands, making them an important part of the ecosystem (ANDERSEN et al. 2006). Unfortunately, some fungi species are harmful for the growth of *Sphagnum* and may lead to the death of moss patches. Especially in greenhouses, which offer favorable conditions (warm, wet and closed) for the spread of fungi, unwanted propagation of fungi can be observed. (LANDRY et al. 2011)

2.4 Water retention

The description of the relation between the water content of a substrate and a specific matric potential is called water retention or is sometimes referred as the moisture characteristics of soils and can be described by water retention curves (i.e. pF curves). The matrix within soils consist of pores and surfaces of particles where drawn water is retained. A differentiation between adsorption of water at the surface of particles and the capillary adsorption is not necessary. (MARSHALL et al. 1996) By measuring water contents at different potentials, pores and its distribution can be calculated (HARTGE and HORN 2009). The maximum water holding capacity is the amount of water retained at pF 0.

3 Methods

The following chapter gives additional information about different methodologies used for experiments carried out in this study.

3.1 Preparation of materials

In the following sections the preparation of substrates and mixtures are presented, including processing of *Sphagnum palustre* biomass, peat and coir.

3.1.1 Sphagnum palustre

The fresh, wet *Sphagnum* biomass was harvested by a local reed farmer in the Netherlands (8377 HD Kalenberg) packed into 25 L bags and stored outdoor for several weeks. A cooled flower-transporter delivered the plant material to Vienna where bags were opened and the mosses were placed on a metal grid placed on euro-pallets to guarantee aeration. There the wet biomass was air-dried indoor for 6 weeks including turning of the mosses twice a week. After drying, mosses were packed in plastic bags and stored until further processing. Subsamples from several bags were taken and the species was kindly determined by the expert ao. Univ.-Prof. i.R. Dr. Gert Michael Steiner as *Sphagnum palustre.*

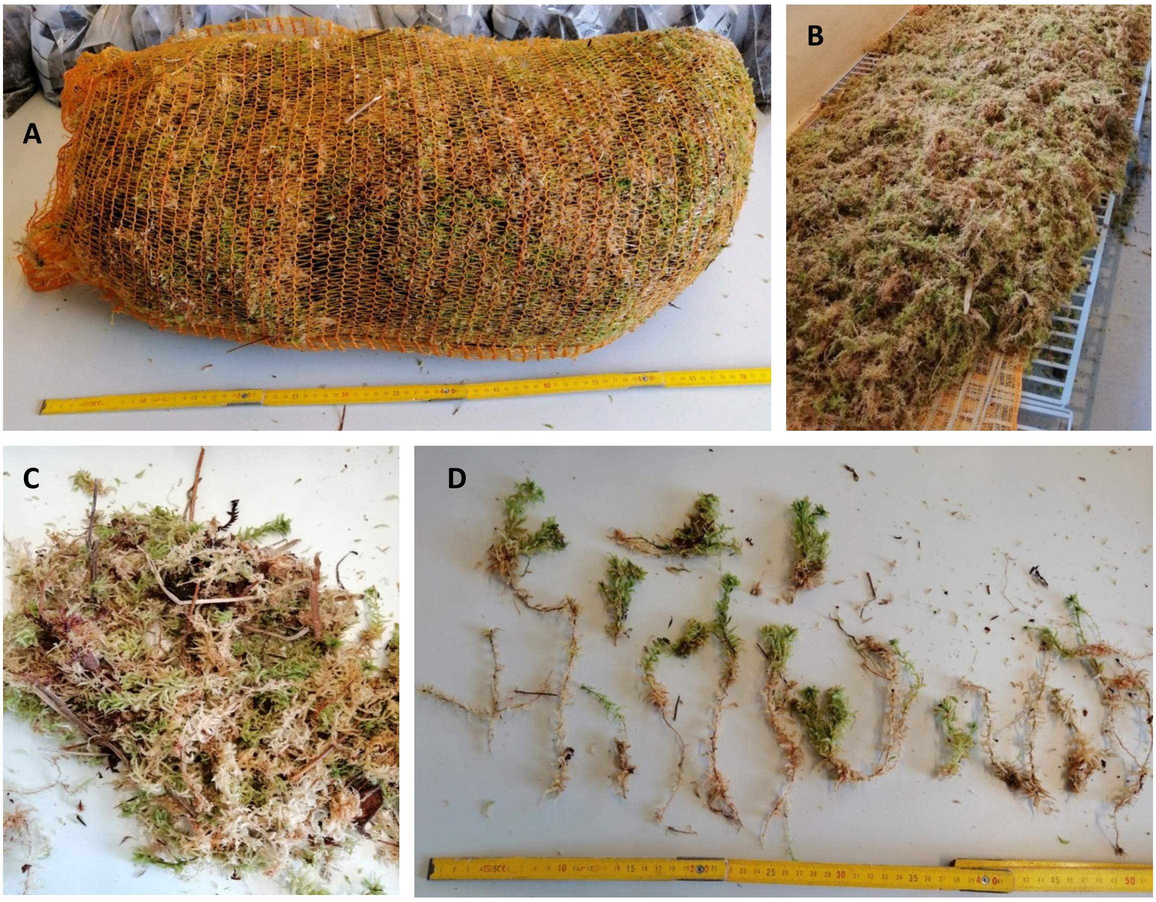

Figure 1: Sphagnum palustre, A: mosses delivered in vegetable nets, B: air-drying of peat moss, C: moss and other materials within delivered nets, D: comparison of fiber lengths

3.1.2 Processing of Sphagnum palustre

For further analysis the air-dried biomass was placed in an oven at 40 °C for at least two weeks. Homogenizing was achieved by rubbing the dry mosses through a 2 mm sieve. During this step also unwanted plant material (e.g. from reeds, leaves, grasses) was removed. To sterilize the material and decrease molding after rewetting the sieved mosses were exposed to microwave radiation at 450 Watt for 4 minutes and 30 seconds. (see YOUSSEF et al. 2001).

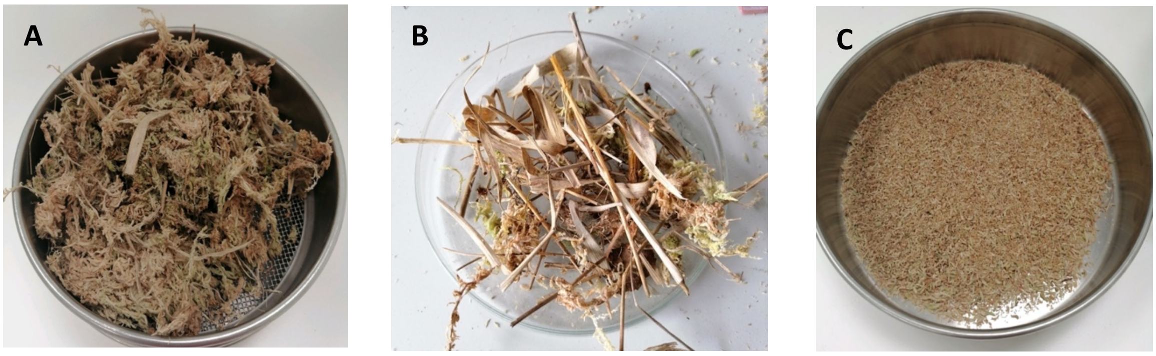

Figure 2: Processing of dry Sphagnum, A: material before sieving (including other plant material), B: plant material, C: sieved peat moss

3.1.3 Peat

Peat material was purchased as Latvian bog-peat bales from “Franz Kranzinger GmbH” (5204 Straßwalchen, Austria) a professional producer of gardening substrates. Decomposition of the peat as stated on the package was weak to medium (H_3-H_5), volume of the bale: 250 L and the pH: between 3-4.

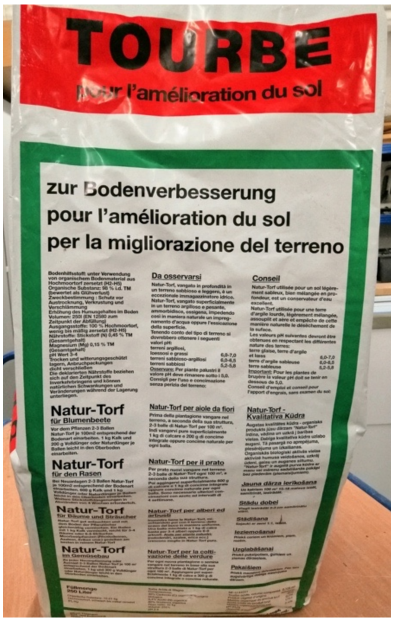

Figure 3: Bog-peat bale 250 L

Peat material was placed in an oven at 40 °C for at least 2 weeks. After the drying procedure, peat was pressed through a 2 mm sieve to separate longer fibers and to homogenize the material. Figure 4 (A) illustrates dry peat before sieving while B shows sieved peat.

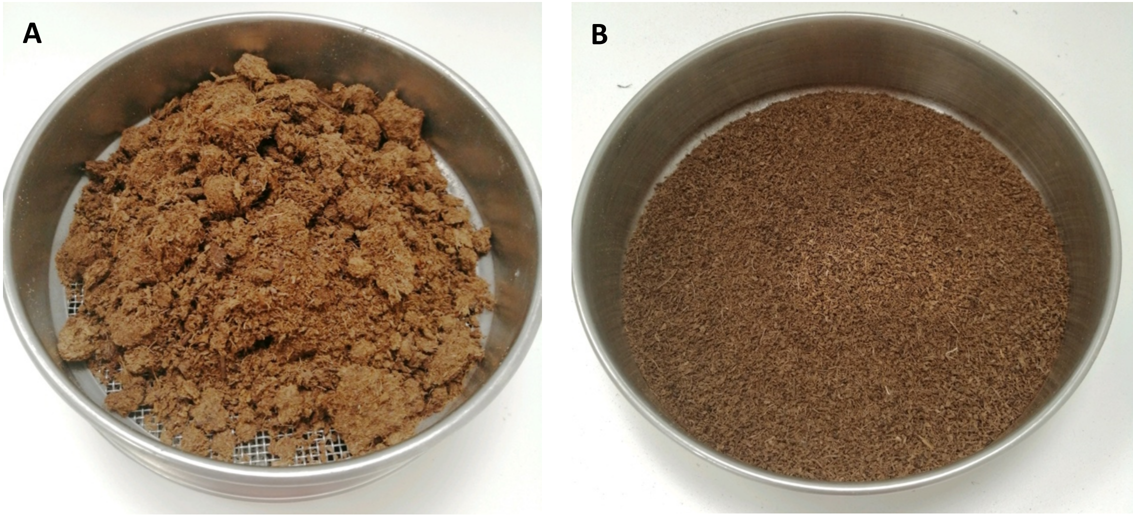

Figure 4: Processing of peat, A: dry peat before sieving, B: sieved peat

3.1.4 Coir fiber

The coir fiber was purchased as washed and pressed bales from “Franz Kranzinger GmbH” (5204 Straßwalchen, Austria) a professional producer of gardening substrates. Fiber lengths of the material ranged between 3-30 mm. Coir fiber was dried in the oven at 40 °C for at least two weeks. After drying, the material was homogenized by cutting coir fibers into smaller fractions using a scissor. Cut fibers were rubbed through a 2 mm sieve to separate remains of coconut shell bigger than 2 mm and other unwanted impurities (e.g. small pebble stones and plastic)

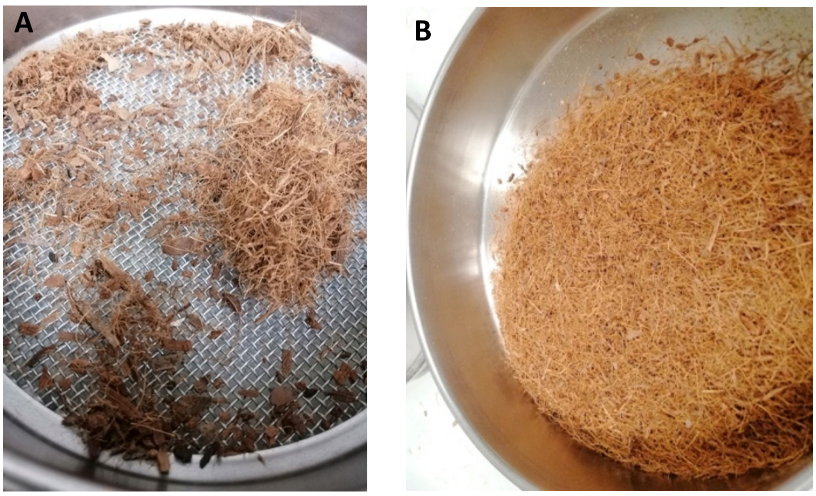

Figure 5: Processing of coir, A: remains after sieving and cutting, B: sieved coir material

The figure below shows the three different base substrates after processing. In the left upper corner: *Sphagnum palustre*, dried and sieved, right upper corner: peat, dried and sieved and upper middle: coir, dried and sieved (including cutting).

Figure 6: Overview of processed substrates: Sphagnum, peat and coir

3.1.5 Preparation of mixtures

All mixtures were prepared on a percentage volume basis (Vol.-%) as this procedure can be seen as common praxis for formulating growing media in the industry. (SCHMILEWSKI 2008) The table below shows the amounts of constituents used for every mixture produced. All amounts were measured for the dried and sieved substrates using a 1 L glass beaker. To produce a 50/50 Vol.-% mixture 500 mL of one substrate was mixed with 500 mL of another material and was blended evenly in a 10 L plastic bucket.

Table 2: Compositions of mixtures

Mixture	***Sphagnum*** **(Vol.-%)**	**Peat (Vol.-%)**	**Coir (Vol.-%)**
Sphagnum (S100)	*100*	*0*	*0*
Peat (P100)	*0*	*100*	*0*
Coir (C100)	*0*	*0*	*100*
Sphagnum/Peat 50 (SP50)	*50*	*50*	*0*
Sphagnum/Coir 50 (SC50)	*50*	*0*	*50*
Coir/Peat 50 (CP50)	*0*	*50*	*50*
Sphagnum/Peat 25 (SP25)	*25*	*75*	*0*
Sphagnum/Coir 25 (SC25)	*25*	*0*	*75*
Coir/Peat 25 (CP25)	*0*	*75*	*25*
Sphagnum/Peat 75 (SP75)	*75*	*25*	*0*
Sphagnum/Coir 75 (SC75)	*75*	*0*	*25*
Coir/Peat 75 (CP75)	*0*	*25*	*75*

**for hydration tests and chemical analysis only 100 Vol.-% and 50 Vol.-% mixtures were used*

3.2 Maximum water holding capacity

To detect the maximum water holding capacity, standardized metal cylinders (100 cm^3) were packed with processed material/mixtures (6 cylinders for each substrate). Masses of cylinders and of dry substrates were noted. One side of the cylinder was covered with a fine mesh fixed with a rubber band and placed in a small round sieve. In the next step the cylinder was placed in a plastic tub and was filled with deionized water up to 1 cm below the upper edge of the cylinder. The tub was covered with a lid to avoid evaporation and the cylinders were stored in the water bath for 3 days until water saturation of the substrates. After 3 days the cylinders were placed in a wet sand box (without round sieves) for 10 minutes to allow draining of excess water. The mesh was removed, and the drained cylinders were weighed and placed on pre-weighed glass petri dishes. Then the cylinder was positioned in an oven at 105 °C and dried until constant weight. To cool the samples down before detection of the dry mass, all cylinders were placed in a desiccator. Gravimetric water content per gram dry weight was calculated by the following equation.

Equation 1: Gravimetric water content (see MARSHALL et al. 1996)

$$\theta_m = \frac{m_w}{m_s}$$

Where θ_m is the water content on a mass basis, m_w the mass of water lost due to drying and m_s the dry mass (MARSHALL et al. 1996). The figure below shows the three main steps of the procedure as described above.

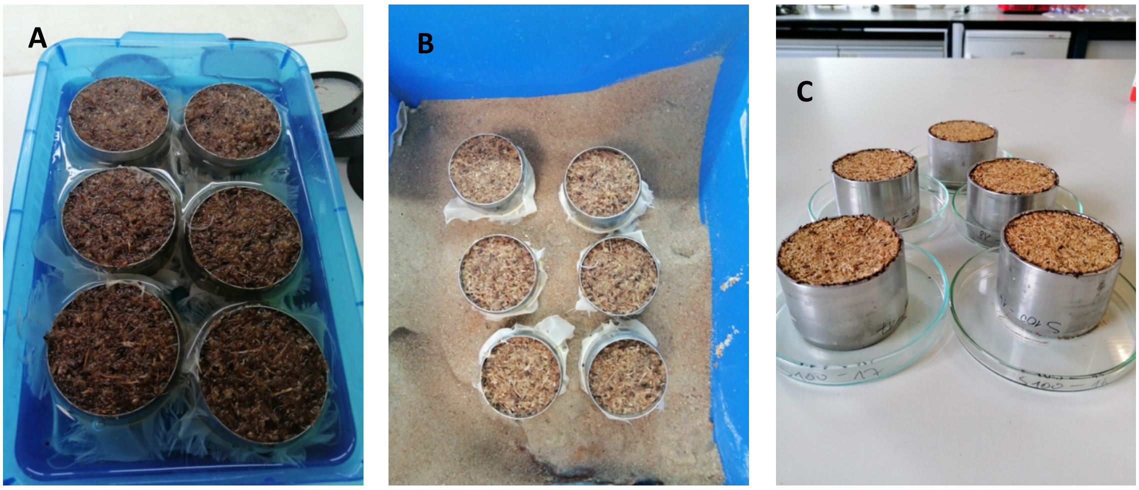

Figure 7: Maximum water holding capacity, A: cylinders in water bath with mesh and round sieves, B: cylinders in wet sand bath, C: dry samples in petri dishes

3.3 Water content at pF 2.5

To detect the water content of mixtures at a matric potential of pF 2.5, all substrates were saturated with water for 24 hours in a glass beaker filled with deionized water. A modified suction method was used for the gravimetric measurement consisting of a metal bowl filled with mainly loess. The structure of the filterpackage consists of benotnite on the edges of the bowl which helps to keep a constant pressure, a sieve within the package which allows drainage of water, and loess (i.e. sieved silt fraction) acting as porous plate. The upper side of the bowl is connected with a water seperator, an expansion tank and a pump. A vacuum pressure gauge helps to adjust the negative pressure produced by the pump. For pF 2.5 a pressure of -300 hPa was used. (HARTGE and HORN 2009)

12 Plastic cylinder (height of 1 cm) were placed on the loess package of which 10 were filled with water saturated samples while the exess two cylinders were filled with water

saturated sand working as controll for the measurement. After placing all samples on the filter package the pressure of -300 hPa was set and checked hourly. After 4 hours, samples were removed and put in pre-weighed glass petri dishes. Followed by weighening, the samples were placed in an oven at 105 °C and dried until constant weight. After cooling, the gravimetric content of water that remained within the sample after the measurement was calculated. To receive the difference of water between water saturation and water content at pF 2.5, the mean amount of water per gram dry weight at pF 2.5 was substracted from the mean water content of the maximum water holding capacity per gram dry weight.

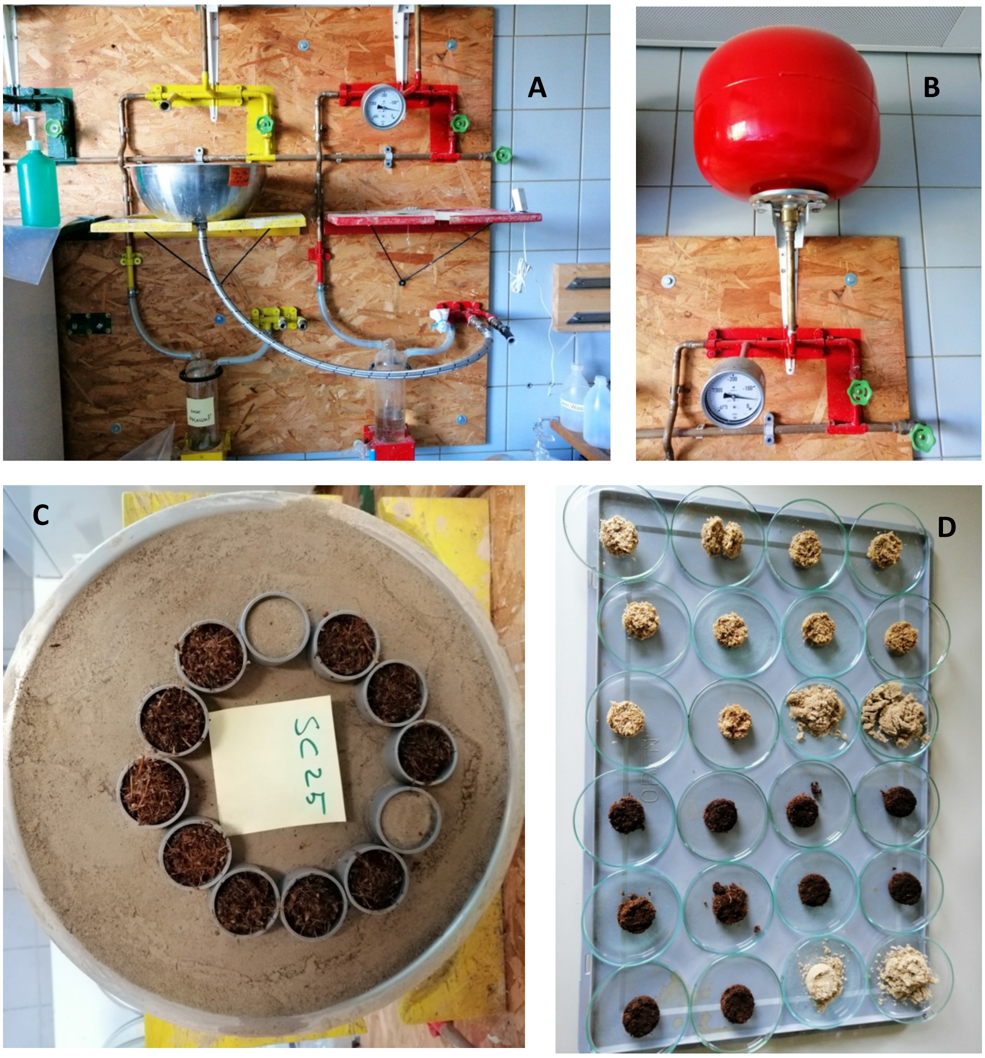

Figure 8: Modified suction method, A: metal bowl filled with filter package, B: expansion tank with vacuum pressure gauge, C: water saturated samples on the filter package, D: dried samples

3.4 Hydration efficiency

Hydration efficiency rates were measured described by FONTENO et al. (2013) and FIELDS et al. (2014) in a modified way. 4 L of substrate (dried at 40 °C) was placed in a PVC-pipe (ø 160 mm) and compacted evenly using a marking line inside the pipe. The bottom end of the PVC-pipe was closed using a polyester mesh which keeps the substrate inside the tube but allows water to flow through. On the upper end, a funnel was placed on which a plastic beaker was attached. The bottom of the beaker was perforated allowing water to diffuse on the substrate.

A plastic bucket with a single hole on the bottom was mounted with an infusion set. One hydration event was performed by adding 4,350 g of deionized water into the plastic bucket. The water entered the funnel through the infusion set and was diffused by the attached plastic beaker. One hydration event took approximately 50-60 minutes resulting in flow rates between 70-90 mL per min. After water flowed through the substrate column, spare water was collected and weighed. pH-values and electric conductivity (EC) were measured in the effluent, each three times and the averages were calculated. The hydrated substrate column was weighed after draining. Remaining water in the plastic bucket was recorded to calculate the actual input of water per hydration. After ten hydration events the whole substrate column was saturated with water for 24 hours using a waterfilled plastic bucket. The mass of the saturated column was recorded after draining it for 30 minutes (i.e. full saturation of the column) followed by drying the substrate for at least 7 days at 105 °C in the oven. The dried and hot material was placed in a desiccator for cooling and the mass of the dry substrate was determined.

The amount of water held by the mixture after each hydration event was calculated by subtracting both, the mass of the PVC-pipe and the mass of the substrate before the first hydration event from the mass of the pipe after the particular hydration. Hydration indices for each hydration event were calculated by dividing the amount of water after a particular hydration event by the maximum water content (full saturation). FONTENO et al. (2013) used the first, third and the tenth hydration index to characterize the wettability efficiency but also other hydration events may be used for further descriptions. Another Index was calculated using the average amount of water retained after the first three hydrations divided by the amount of the last hydration (see NCSU n.y.). The experiments were carried out three times for each pure substrate (i.e. *Sphagnum*, peat and coir) and for all 50/50 Vol.-% mixtures.

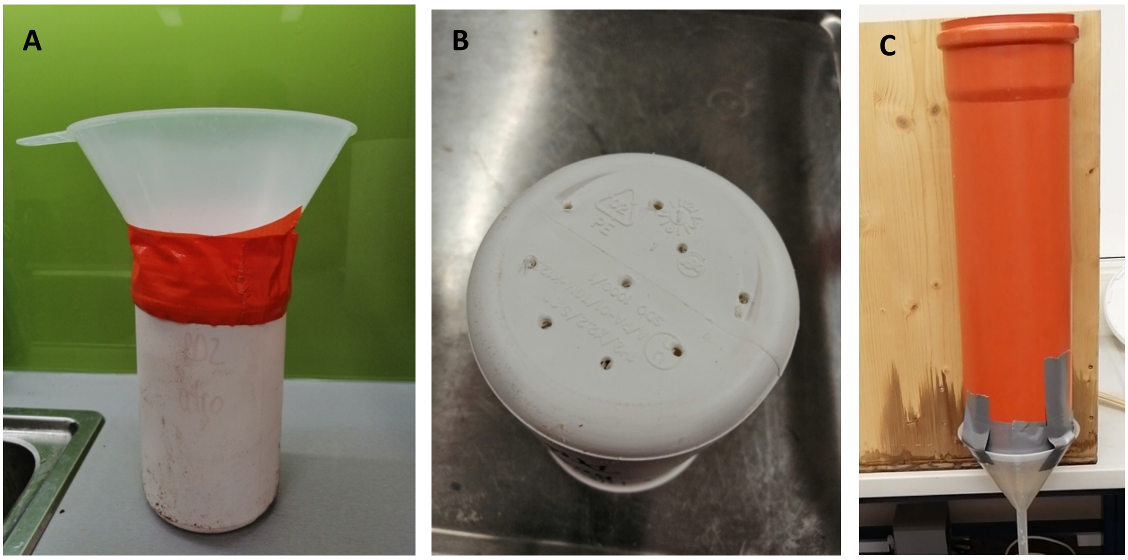

Figure 9: Hydration equipment, A and B: perforated plastic beaker with funnel, C: hydration column with attached funnel at the lower end

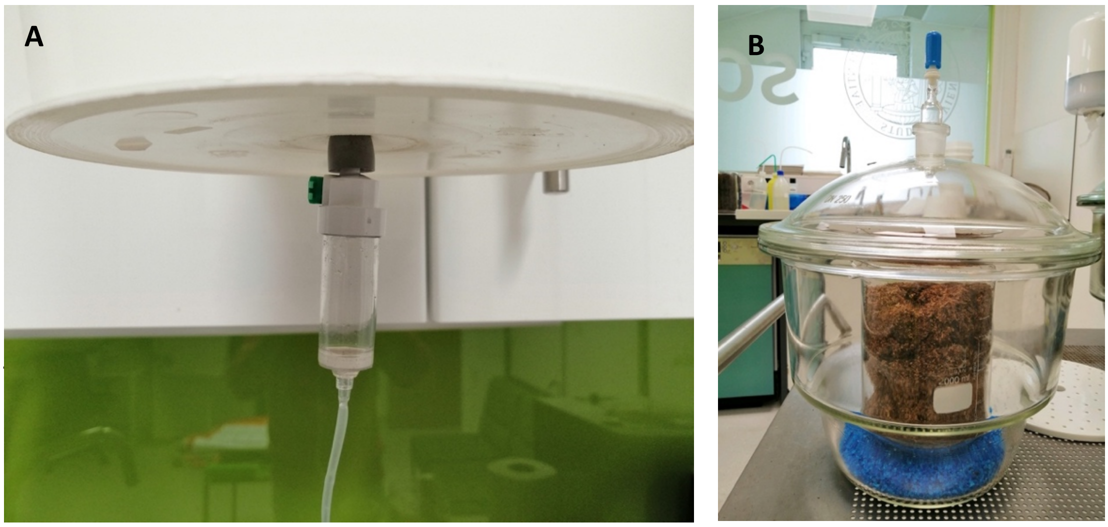

Figure 10: A: plastic bucket with mounted infusion set, B: dried substrate cooled down in desiccator

3.5 Fertilization of mixtures

All mixtures were placed in plastic bags with perforated holes on the lower side to allow draining after fertilization. All samples were fertilized weekly using a foliar fertilizer (Green24 Germany, NPK Professional Trachycarpus, composition: total N: 9.2 %, P (P_2O_5): 5.6 %, K (K_2O): 8.4 %, B: 0.01 %, Cu: 0.004 %, Fe: 0.02 %, Mn: 0.012 %, Mo: 0.001 %, Zn: 0.004 %)) for 4 weeks. The fertilizer solution consisted of 3.9 L of water mixed with 6.5 mL pure fertilizer. Every week all substrates were fertilized using 300 mL of the prepared fertilizer solution, drained and incubated at 40 °C. After 4 weeks material was dried at 60 °C until dry and milled using a mixer mill (Retsch Mixer Mill MM 400). The milled material was stored in plastic tubes. For the elemental analysis the material was dried at 105 °C for 24 hours.

Figure 11: Example of fertilized mixture in a perforated plastic bag

3.6 Thermogravimetric analysis

Thermogravimetric analysis (TGA) were conducted using an SGA TGH 1200 where a minimum of 50 mg of material was places in a sample pan. Samples were heated from ambient temperature to 700 °C using a heat ramp of 10 K min^{-1} within a micro furnace using N_2 as a reaction gas. Measurements were carried out for all basis substrates (100 Vol.-%), 50 Vol.-% mixtures and for the fertilized pairs at least 3 times. Received data was exported as text files and processed with Microsoft Excel for Mac (Version 16.32). Values were adjusted to a common temperature scale and cut to a temperature range between 50 °C and 700 °C. (Worrall et al. 2017) New relative weight loss values were calculated for each run and the derivative thermogravimetry (DTG) was computed giving the rate of mass changes as a function of temperature. All three calculated DTG results where standardized to a common temperature by using the VLOOKUP-function. Mean values of adjusted and trimmed triplicates were calculated and visualized using RStudio (Version 1.2.5019).

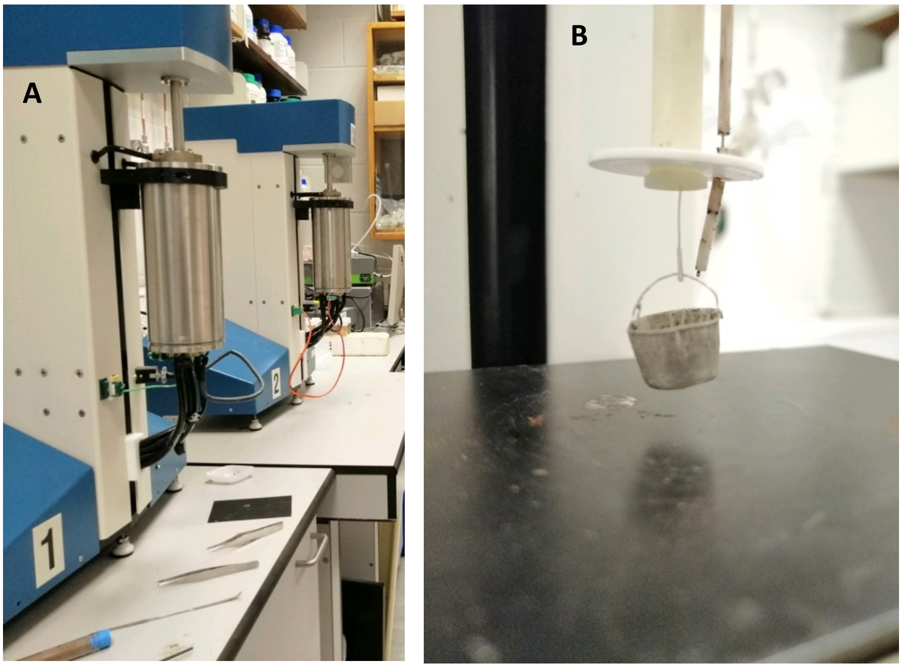

Figure 12: Thermogravimetric analysis, A: TGA device, B: sample pan on fine scale with reaction gas tube

3.7 Bomb calorimetry

Measurements of gross heat values were carried out using a bomb calorimeter (Parr 6200 Isoperibol Calorimeter). Calibration of the machine was done before the measurements using a known amount of benzoic acid standard. Approximately 1 g of milled sample was placed in a combustion pan and a drop of water was added to guarantee total combustion of the sample without sputtering. (Worrall et al. 2018) After connecting the sample with the bomb, using a known length of a standard fuse wire, the bomb was closed and filled with oxygen. After connecting the bomb with the ignition wires, the bomb calorimeter was filled with exactly two liters of deionized and tempered water (measured using a Parr 6510 water handling system) and the bomb was placed within the machine without changing the amount of water using a bomb lifter. Due to limited amounts of sample material measurements were carried out 2 times for each substrate.

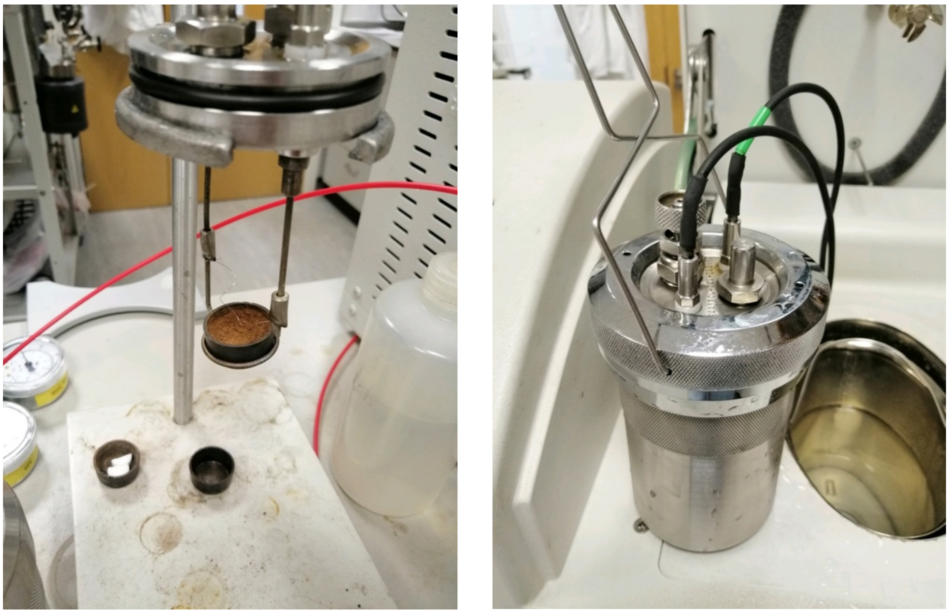

Figure 13: Bomb calorimetry, left: sample connected with fuse wire, right: connected bomb

3.8 Elemental Analysis

Elemental analysis for fertilized and unfertilized mixtures (50 Vol.-% and 100 Vol.-%) were performed using a vario MACRO CHNS elemental analyzer. Dried (at 105 °C), milled, homogenized and powered samples were packed in a tin foil of a known weight, pelletized and placed in the carousel autosampler. Helium was used as carrier gas and after each measurement at least 2 blank measurements were performed to flush detection channels of the machine. The method used for all measurements was a preset program called “biochar” which adjusts the oxygen dosing for the combustion process. Daily factors and calibration were performed following internal standards by laboratory technicians according to the operating instruction of vario MACRO (see VARIO MACRO 2007).

3.9 Software and statistics

Data analysis and visualization was performed with RStudio (version 1.2.5019). For the detection of significant differences between results a Wilcoxon rank sum test (or Man-Whitney test), a non-parametric statistical test for unpaired data, was used. This is especially helpful because acquired data do not meet required assumption for parametric tests. Therefore, the use of a non-parametric test is a likely alternative. (WHITLEY and BALL 2002)

Asterisks used in figures represent different significance levels ("ns": p > 0.05; "*": p < =0.05; "**": p <= 0.01; "***": p <= 0.001). Mean results are presented as "x ± y" where y is the standard deviation.

The following R packages were used for analysis: ggplot2 (WICKHAM 2016), ggpubr (KASSAMBARA 2019) and gridExtra (AUGUIE 2017) for visualization, dplyr (WICKHAM et al. 2019) for data manipulation.

4 Results

In the following section results are described for all experiments carried out during this study.

4.1 Results of maximum water holding capacities

4.1.1 Maximum water holding capacity for different Sphagnum treatments

The figure below shows the maximum amount of water which can be stored in *Sphagnum* biomass with different treatments. To make the numbers comparable among different treatments, relative amounts of water to one gram of dry substrate are used. For the detection of significant differences between treatments and fresh mosses a Wilcoxon rank sum test (unpaired and non-parametric) was performed. The grey dashed line represents the mean values observed for peat.

Substrates show significant differences between specific treatments of *Sphagnum* biomass compared to fresh and unprocessed peat moss (i.e. fresh moss). The mean maximum water holding capacity of fresh mosses is 28.8 ± 1.16 g water per g dry substrate, the median is 28.7 g per g dry mass while the range amounts to 3.8 g per g dry mass. Drying *Sphagnum* biomass at 60 °C (after air-drying) and without further processing (i.e. homogenizing by sieving and sterilizing using microwaves) reduces the maximum water holding capacity of the substrate significantly ($p < 0.01$) to a mean value of 26.4 ± 0.45 g per g dry mass. Differences between drying temperatures of 60 °C and 40 °C are not significant as the mean amount of water amount to 25.82 ± 0.63 g per g dry mass. Compared to fresh mosses the values are significantly lower. For the two sieved groups (40 °C and 60 °C) the amounts of the maximum water holding capacity are even lower than the unsieved groups where no microwaves were used. Group “60 °C, sieved, microwave” has significant lower values then fresh moss resulting in a mean value of 22.6 ± 1.11 g per g dry substrate. The group “40 °C, sieved, microwave” has a mean value of 22.04 ± 0.69 g per g dry substrate indicating that differences between the groups are neglectable. Values of group “burned” are the lowest of all compared treatments with a mean of only 15.93 ± 1.7 g per g dry mass. The material of that group was dried at 40 °C, sieved and sterilized using microwaves but during the last step the material overheated and large parts burned. For the group "standard treatment" the mean amount of water is 28.42 ± 2.23 g and the median is 29.80 g water while the range amounts to 5.4 g. It shows clearly that the standard treatment (drying temperature: 40 °C, microwave: 4:30 minutes with 450 W, sieved < 2mm) has no significant effect on the maximum water holding capacity compared to fresh mosses. Therefore, this specific treatment was chosen as the standard treatment in for *Sphagnum palustre* biomass. Compared to the mean amount of water held by peat (6.38 ± 0.26 g water per g dry mass) all tested treatments of Sphagnum show higher mean values.

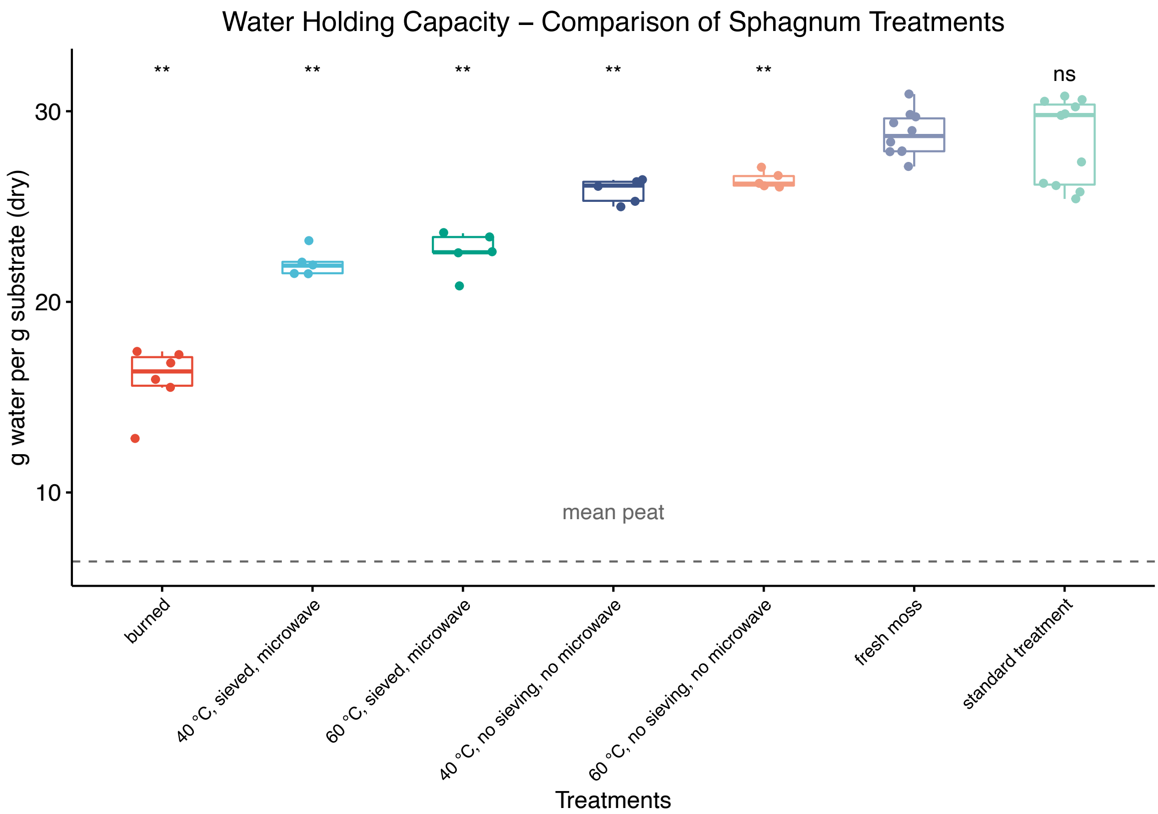

Figure 14: Comparison of Sphagnum treatments - water holding capacity relative to dry mass

4.1.2 Absolute amounts of the maximum water holding capacity for different Sphagnum treatments

The total amount of the maximum water holding capacity is represented in the figure below and it shows high differences compared to the relative amounts presented in the previous section. Cylinders used for the detection of the maximum water holding capacity were filled with the moss biomass with different bulk densities influencing the total amount of water a cylinder can keep. Also, the treatment has an influence on the total amount of water held by the substrate which can be observed especially within the burned group which has a higher bulk density then e.g. "60 °C, no sieving, no microwave" but a much lower absolute amount of water. A comparison between the total amounts of water held by differently treated *Sphagnum* biomass cylinders is therefore not ideal because it includes other factors which are influencing the results and makes interpretation complicated.

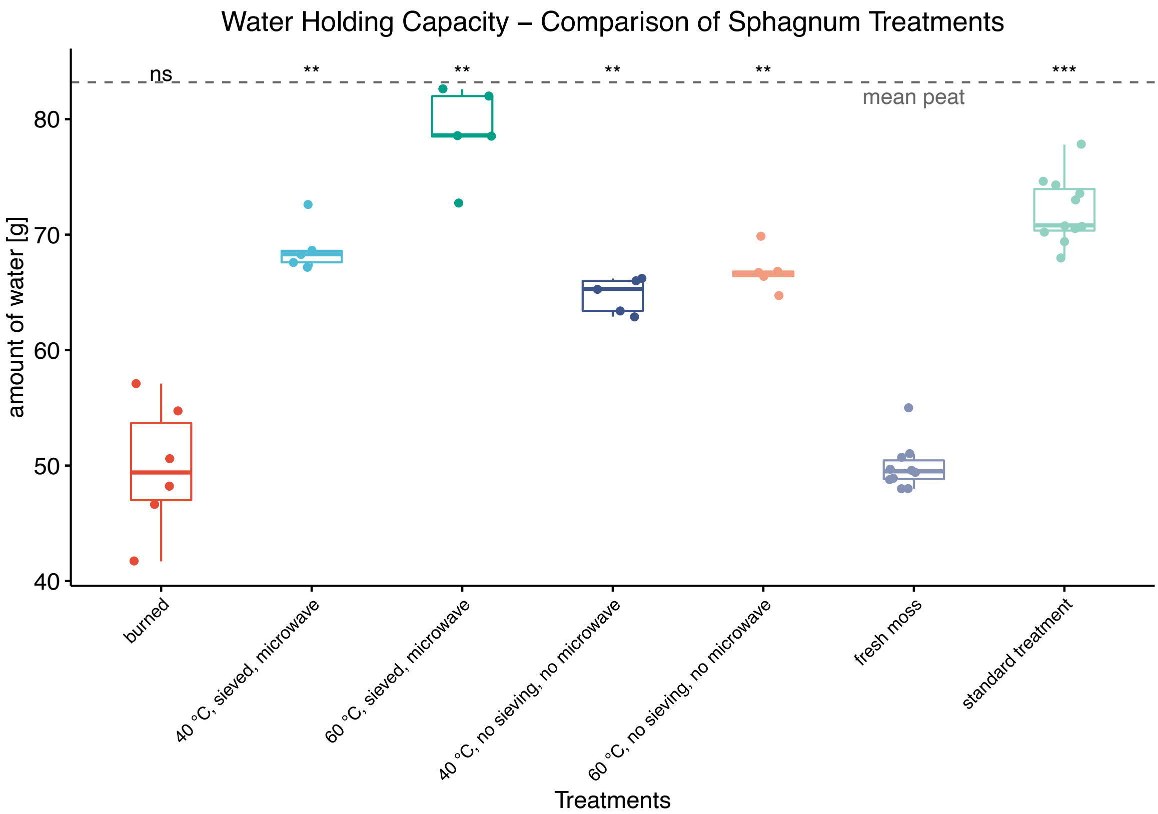

Figure 15: Absolute amounts of maximum water holding capacity for Sphagnum treatments

4.1.3 Starting water contents of different Sphagnum treatments

Relative water contents of treated *Sphagnum* biomass after processing are indicated in the figure below. All values are represented in percent of dry biomass (dried at 105 °C) and statistical significance tests refer to differences between fresh moss and the compared group using Wilcoxon rank sum test.

Mean water content of the group "fresh moss" before wetting summed up to a starting content of 89.63 ± 0.31% (median: 89.6 % range: 1 point). Compared to this group all other treatment groups indicate significant lower values. Group "60 °C, no sieving, no microwave" has a mean of 13.14 ± 1.24 %, a median of 13.0 % and a range of 3.1 points. Mean values for the group "40 °C, no sieving, no microwave" amount to 20.28 ± 0.36 % and median values to 20.4 % with a range of 0.7 points. Drying the peat moss at 60 °C including sieving and microwave treatment results in a mean value of 13.04 ± 0.11 %, a median of 13 % and a range of 0.3 points. Reducing the drying temperature to 40 °C including sieving and microwave treatment results in a mean of 15.86 ± 0.59 % and a median of 15.9 % with a range of 1.5 points. For the burned peat mosses which were dried at 40 °C, sieved and overheated in the microwave, the mean water content of dry material is 9.03 ± 0.49 % and the median 9.1 %, with a range of 1.4 points. For the standard treatment of mosses, dried at 40 °C, sieved and treated with microwaves, the mean water content before wetting them amounts to 16.19 ± 1.09 % and the median to 16.3 % having a range of 1.7 points.

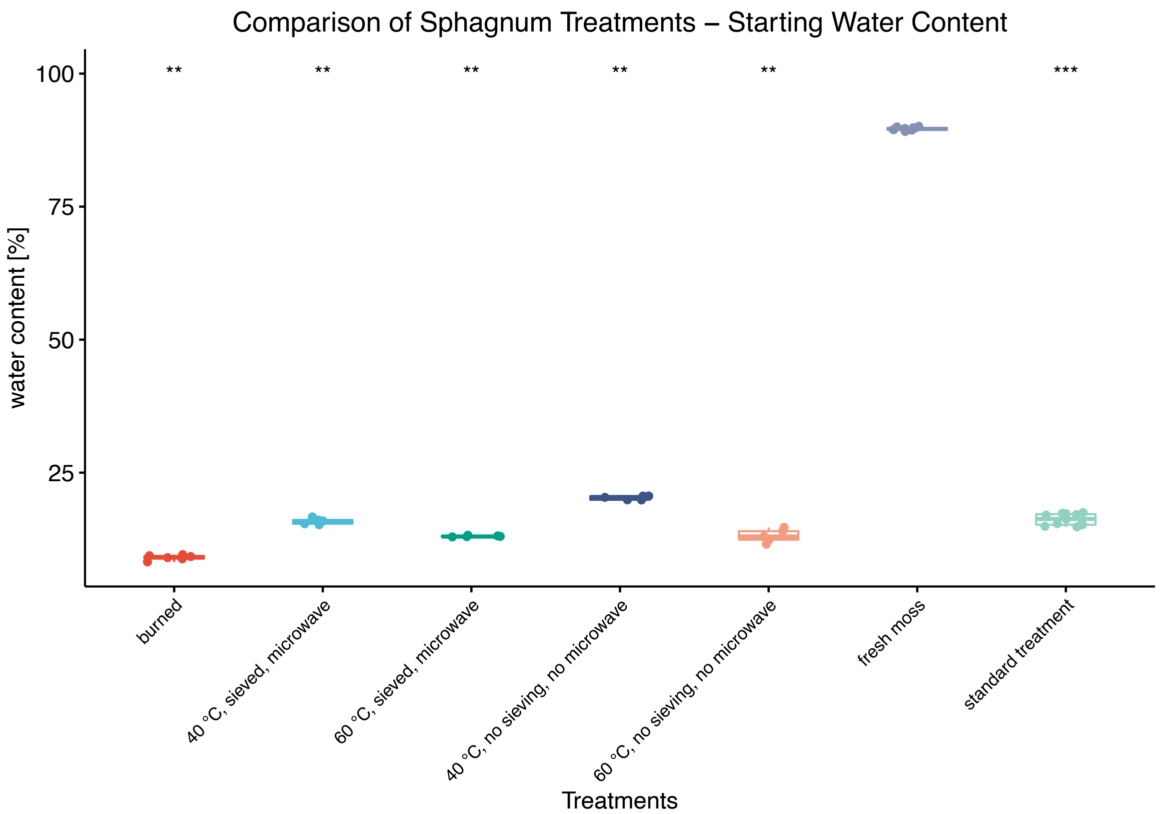

Figure 16: Starting water content for different Sphagnum treatments

4.1.4 *Calculated bulk densities for different Sphagnum treatments*

The figure below visualizes calculated bulk densities in g per dm^3 of packed metal cylinders used for measurements of maximum water holding capacity for all treatments of *Sphagnum* biomass. Evaluation of significant differences was performed using Wilcoxon rank sum test for mean values of fresh moss as comparison basis. Mean bulk density of fresh peat moss is 167.06 ± 0.24 g/dm^3, the median 167.15 g/dm^3 with a range of 0.7 g/dm^3 (min. 166.6 g/dm^3, max. 167.3 g/dm^3). For group "60 °C, no sieving, no microwave" the mean bulk density amounts to 29.16 ± 0.09 g/dm^3 (median: 29.2 g/dm^3, range: 0.2 g/dm^3). The cylinders of group "40 °C, no sieving, no microwave" were packed with a mean bulk density of 31.48 ± 0.24 g/dm^3 (median: 31.6 g/dm^3, range: 0.6 g/dm^3). Mean bulk density for group "60 °C, sieved, microwave" is 40.18 ± 0.18 g/dm^3 (median: 40.2 g/dm^3, range 4.1 g/dm^3), while for the group "40 °C, sieved, microwave" mean values of 37.1 ± 0.12 g/dm^3 (median: 37.1 g/dm^3, range: 0.3 g/dm^3) where measured. "Standard treatment" has a mean BD of 30.45 ± 3.04 g/dm^3 (median: 28.3 g/dm^3 and range 6.5 g/dm^3) and "burned" has a mean of 34.38 ± 1.41 g/dm^3 (median: 34.5 g/dm^3 and range 3.9 g/dm^3)

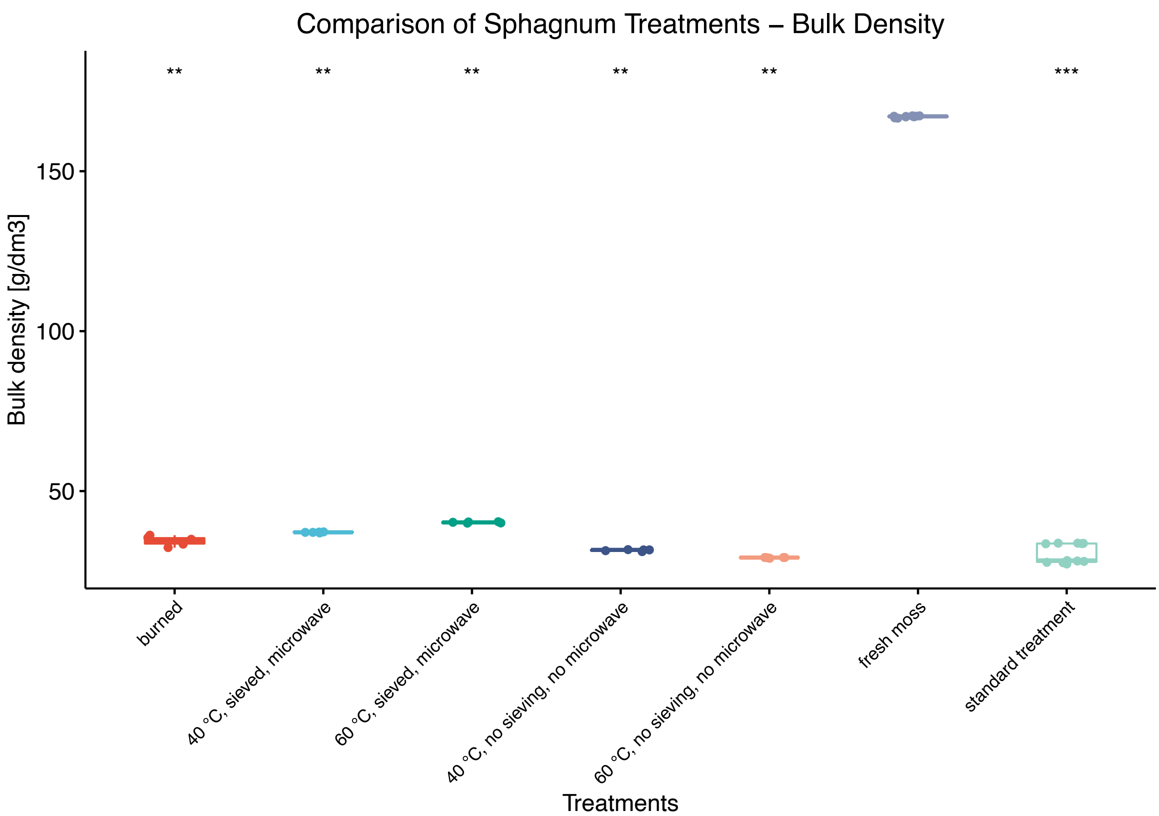

Figure 17: Bulk densities for different Sphagnum treatments

4.1.5 Results maximum water holding capacity of all mixtures

In the boxplot of figure 18 the maximum water holding capacity of all different mixtures are presented in gram water per gram dry substrate indicating relative results. To detect significant differences between all mixtures the results are compared with the outcomes of peat.

The mixture containing only coir (C100) shows a significant less water holding capacity than peat resulting in a mean of 3.31 ± 1.25 g water per g dry substrate, a median of 3.05 g and a range of 3.8 g. A mixture consisting of 25 Vol.-% coir and 75 Vol.-% peat (CP25) has a mean capacity of 4.92 ± 1.33 g water, a median of 5.1 g and a range of 3.6 g. For the mixture containing 75 Vol-% coir and 25 Vol-% peat (CP75) a mean of 5.4 ± 1.1 g, a median of 5.75 g and a range of 2.9 g water per gram dry substrate was measured. The group CP50 which contains of a 50/50 Vol.-% mixture of peat and coir has a mean water holding capacity of 6.3 ± 1.1 g, a median of 6.3 g and a range of 2.9 indicating no significant differences. For peat a mean of 6.38 ± 0.26 g, a median of 6.4 g and a range of 0.7 g water per gram dry substrate was measured. A mixture containing 25 Vol.-% *Sphagnum* and 75 Vol.-% peat (SP25) shows mean values of 8.13 ± 1.69 g, a median of 7.95 g and a range of 4 g, while a mixture of 50 Vol.-% *Sphagnum* and 50 Vol.-% coir has a mean of 9.9 ± 0.3 g and a range of 0.9 g water. Mixtures of 25 Vol-% peat moss and 75 Vol.-% coir shows a mean of 12.25 ± 0.9 g, a median of 12.25 and a range of 2.5 g, SP50 a mean of 15.05 ± 0.82 g, a median of 15.05 and a range of 2.1 g. Mean values for the group SC75 are 17.05 ± 0.62 g with a range of 1.6, for the group SP75, containing of 75 Vol.-% *Sphagnum* and 25 Vol.-% peat the mean is 16.55 ± 0.82 g, the median 17 g and the range 1.7 g water.

In the figure the results for all *Sphagnum* treatments are presented showing a mean of 25.12 ± 4.51 g, a median of 26.1 g and a range of 18.1 g water. The results for the standard treatment are presented in previous sections. Mixtures SC50, SC25, SP50, SC75, SP75 and S100 show significant higher values than peat (P100).

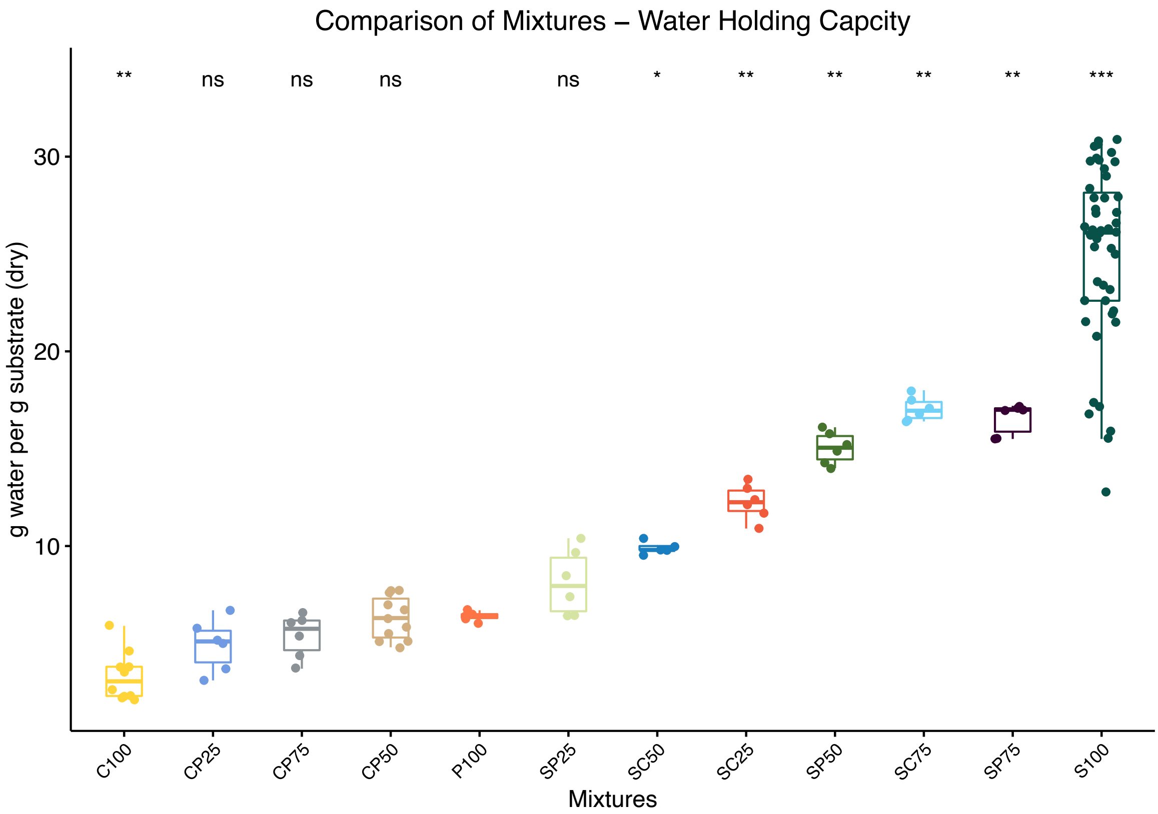

Figure 18: Relative results maximum water holding capacity for all mixtures

4.1.6 Absolute amounts of maximum water holding capacities for mixtures

Absolute amounts of maximum water holding capacities observed for mixtures differ from relative results and show generally higher ranges. Peat shows the highest amounts (mean: 83.2 ± 3.3 g, median: 83.4 g and range: 8.9 g) while *Sphagnum* shows lower mean values 72.08 ± 2.84 g (median: 70.8 g and range: 9.8 g) for the standard treatment. Specific trends do not occur for mixtures with de- or increasing amounts of a certain material. This can be observed especially for coir/peat substrates where high contents of peat in CP25 show lower absolute amounts of water (mean: 38.5 ± 10.7 g, median: 35.75 g and range: 29.7 g) than mixtures with lower peat content i.e. CP50 (mean: 53.55 ± 13.28 g, median: 51.1 g, range: 38.3 g) and CP75 (mean: 40.55 ± 13.19 g, median: 41.1 g, range: 35.5 g) while pure coir has lower amounts (mean: 22.2 ± 9.4 g, median: 20.45 g, range: 27.7 g). Mixtures containing *Sphagnum* are generally higher but show high variabilities. SP25 has a mean amount of 38 ± 15 g (median: 31.2 g and range: 34.9 g), SP50 higher amounts (mean: 69.5 ± 4.9 g, median: 69.8, range: 13.6 g) and SP75 a mean of 78.3 ± 3.9 g, a median of 77.6 g and a range of 10.6 g. Values for *Sphagnum*/coir mixtures show similar values variations, where results for SC25 amount to a mean of 73.1 ± 6.5 g, a median of 75.25 and a range 18.2 g. SC50 has lower amounts (mean: 55.8 ± 1.8 g, median: 55.1, range: 4.4 g) and SC75 a mean of 68.3 ± 3.3 g, a median of 68.45 g and a range of 8.3 g.

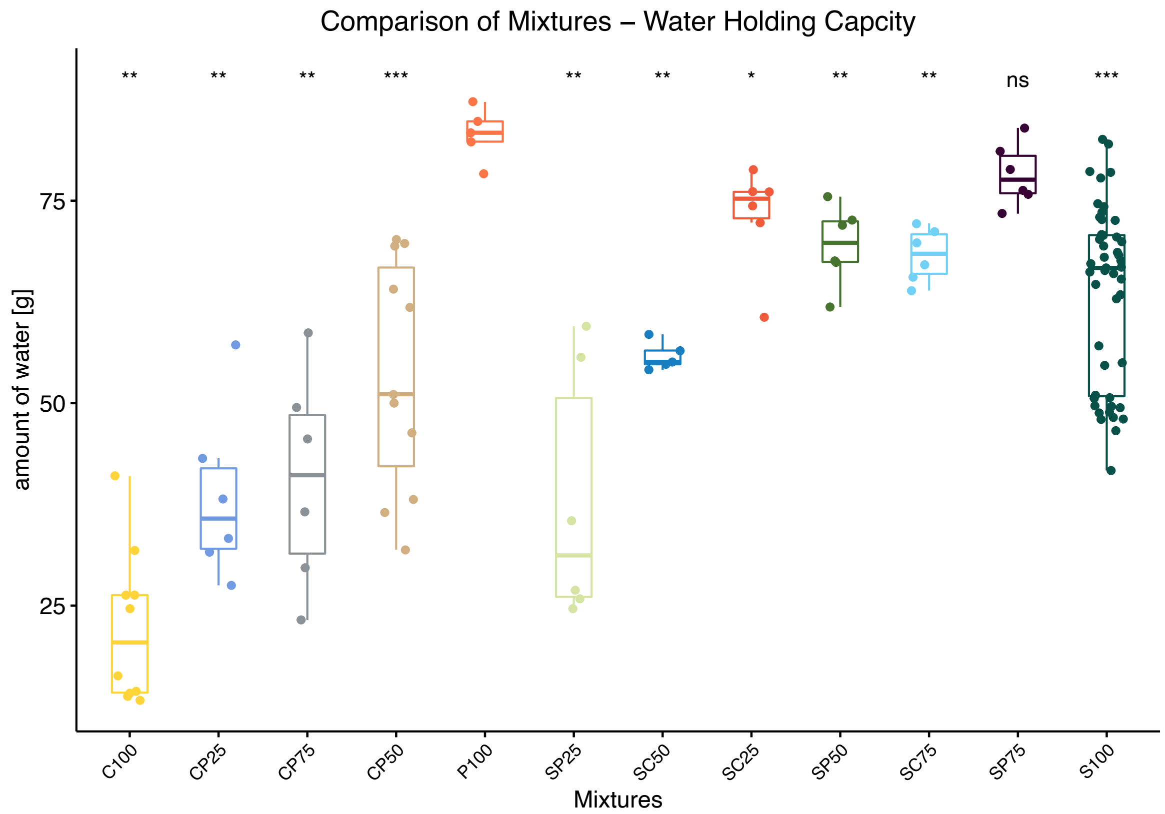

Figure 19: Absolute amounts for maximum water holding capacity for all mixtures

4.1.7 Calculated bulk densities for all mixtures

All calculated bulk densities are presented for all mixtures in g/dm³. For coir the mean bulk density amount to 71.92 ± 3.35 g/dm³, the median 72 g/dm³ and the range 6.7 g/dm³. Cylinders of the group CP25 are filled with a mean bulk density of 97.97 ± 15.48 g/dm³, a median of 91.75 g/dm³ and shows a range of 43.5 g/dm³. CP75 shows a mean of 83.92 ± 11.80 g/dm³, a median of 80.85 g/dm³ and a range of 31.5 g/dm³, while the mean of CP50 amounts to 95.33 ± 8.23 g/dm³, the median 100 g/dm³ and the range 27 g/dm³. For peat (P100), which is also the basis for comparisons of significant differences between mixtures, the mean is 140.24 ± 0.18 g/dm³, the median 140.2 g/dm³ and the range 0.5 g/dm³. Mean bulk density of SP25 is 50.4 ± 11.1 g/dm³, the median 45.55 g/dm³ and the range 24.5 g/dm³. For SC50 a calculated mean of 63.1 ± 0.1 g/dm³, a median of 63.1 g/dm³ and a range of 0.3 g/dm³ can be obtained while the group SC25 shows a mean of 67.58 ± 4.16 g/dm³, a median of 66.4 g/dm³ and a range of 10.8 g/dm³. Means for the group SP50 amounts to 55.45 ± 0.16 g/dm³, the median 55.45 g/dm³ and the range 0.3 g/dm³. SC75 has a median bulk density of 45.03 ± 0.96 g/dm³, a median of 44.7 g/dm³ and a range of 2.7 g/dm³. SP75 has a mean of 54.37 ± 3.23 g/dm³, a median of 53.65 g/dm³ and a range of 8.4 g/dm³. S100 includes also fresh moss and all different treatments leading to a mean of 61.73 ± 55.47 g/dm³, a median of 34.1 g/dm³ and a range of 140.1 g/dm³. Results for standard treatments of *Sphagnum* are presented in previous sections. As stated in the figure below all mixtures have a significant lower bulk density than peat.

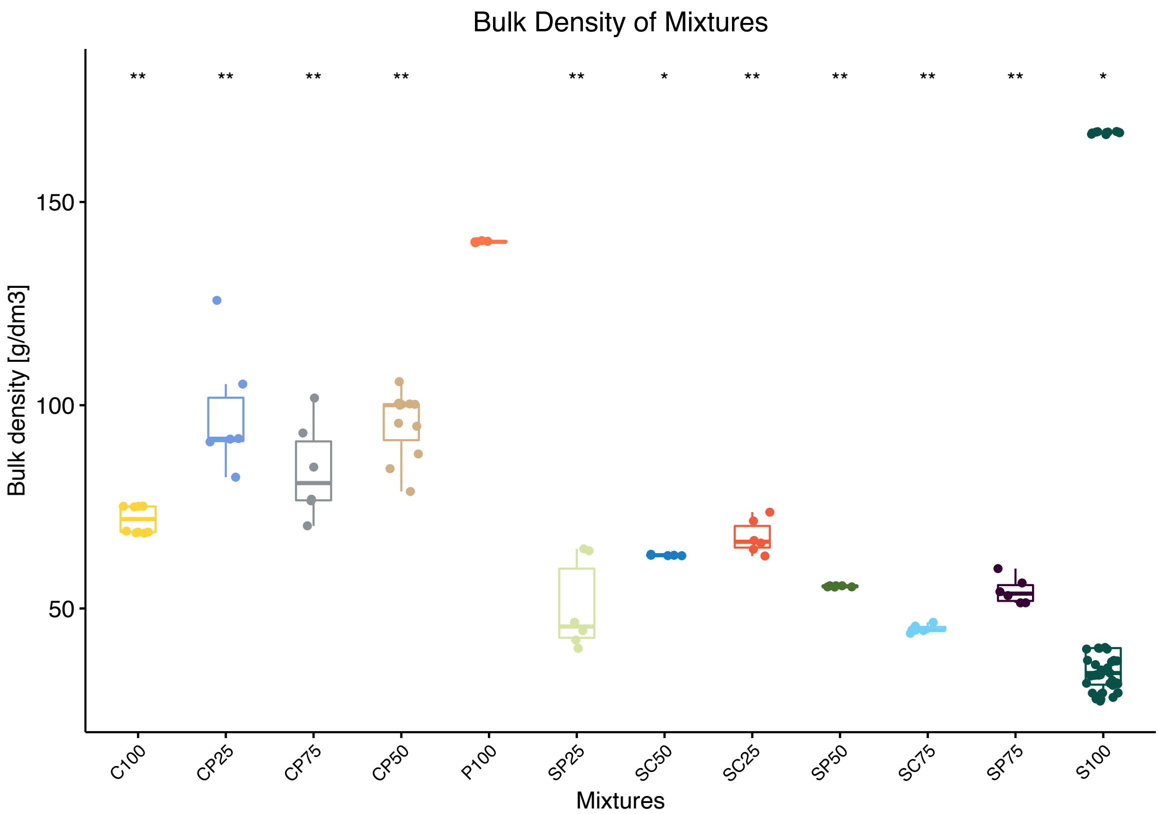

Figure 20: Comparison of all mixtures – bulk densities in g/dm³

4.1.8 Starting water contents of mixtures

Water contents at in all different substrates before wetting (i.e. starting water content) are presented in the figure below in percent of dry weight. Mean content for coir (C100) is 7.92 ± 0.91 %, the median 7.8 % and the range 2.5 percent points. CP25 shows a mean content of 18.78 ± 0.37 %, a median of 18.75 % and ranges from 18.4 % to 19.3 %. CP75 has a mean of 12.5 ± 0.93 %, a median of 12.25 % and a range of 2.2 percent points while the mean of CP50 is 12.39 ± 3.09 %, the median 14.3 % and the range 7.3 percent points. Peat (P100) has a mean starting water content of 7.48 ± 0.16 %, a median of 7.5 % and a narrow range of only 0.4 percent points. Mixtures SP25, SC50, SC25, SC75 and SP75 show very narrow ranges too with mean starting water contents of 10.15 ± 0.58 %, 10.7 ± 0.24 %, 11.76 ± 0.22 %, 11.13 ± 0.49 % and 12.9 ± 0.29 %,medians of 10 %, 10.6 %, 11.85 %, 11.1 % and 13 % and ranges of 1.4, 0.6, 0.5, 1.5 and 0.8 percent points. The group SP50 has a higher range of 9.5 percent points, a mean of 16.68 ± 4.39 % and a median of 14.55 %. Values for pure *Sphagnum* biomass with standard treatment show a mean of 16.19 ± 1.09 %, a median of 16.3 % and a range of 2.7 percent points. Except for C100 (coir) all mixtures show significant higher starting water contents than peat.

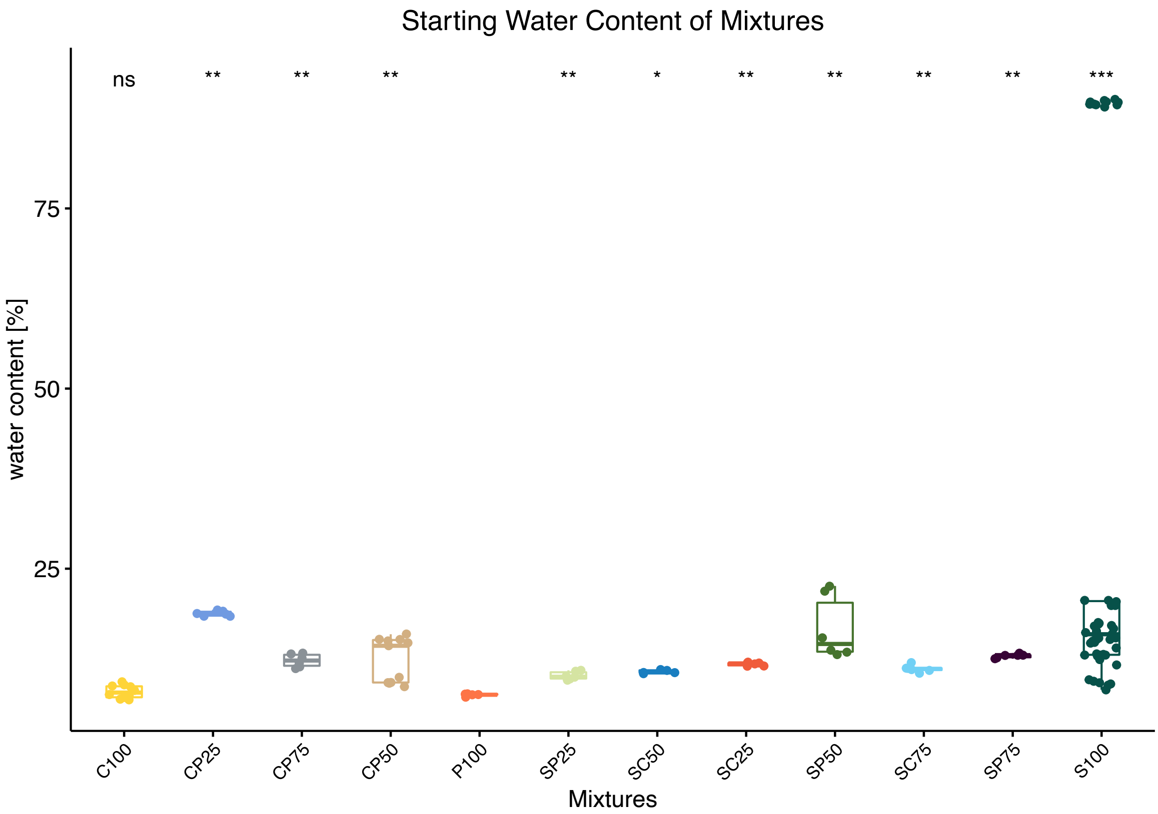

Figure 21: Comparison of mixtures – starting water content in percent of dry weight

4.2 Results wettability and hydration efficiency

In the following section results of wettability and hydration efficiency are presented for peat, *Sphagnum* and coir as well as for several mixtures of these substrates.

4.2.1 Wettability curves of substrates

In the figure below the main results of wettability tests are presented. A) shows the results of the hydration efficiency for the main substrates (*Sphagnum*, coir and peat). Hydration event 0 indicates the amount of water within the substrate before wetting.

Sphagnum shows the highest increases during hydration events and even in later stages of the hydration experiment (hydration events 8-10) no saturation is noticeable, leading to the highest amounts of water within the core gained by hydration only. An average of 1,471.4 ± 87.6 g water is stored in the Sphagnum column after the last hydration.

Peat shows similar trends in the beginning of the hydration (first hydration event). After the first hydration, the amount of water held within the column is increasing very slowly leading to only small changes between hydrations. The average amount of water after the last hydration of peat is about 816.5 ± 197.3 g, a much smaller value compared to the results of *Sphagnum*.

Coir shows a nearly linear increase of water held within the column after each hydration event. Compared to the other substrates the differences after the first hydration are recognizable lower but the overall development of values are similar to them of peat, but at a lower degree. The mean amount of water after the last hydration amounts to 616.8 ± 209.7 g and are therefore the lowest values of compared groups.

4.2.2 Hydration index values for substrates

Section C) gives the hydration indices for the main substrates where the amount of water within the column after a specific hydration event is compared with the maximum amount of water held within the column after total saturation. For the *Sphagnum* substrate the index values are the highest for every hydration (H1 to H10). The mean index value of H10 (i.e. the last hydration event) amount to 0.68 ± 0.05 meaning that hydration alone contributes to more than 68 % of total saturation.

As described before compared to coir, peat can hold higher amounts of water. Relative to the maximum amount of water held by the substrate, peat has higher hydration index values in the beginning than coir, but after the third hydration, the index values stagnate on a lower level, reaching a mean maximum of 0.27 ± 0.03. This indicates that peat is able to store high amounts of water but that it is hard to rewet as after the last hydration only 27 % of the total saturation is reached.

Hydration efficiency values for coir reach slightly higher mean maximum values then peat with a mean index value of 0.38 ± 0.09. Relative to saturation, coir shows therefore a higher hydration efficiency then peat but holds less water within the material after the last hydration then the two other substrates.

Processed *Sphagnum* biomass using the standard treatment described before shows both, higher absolute amounts of water stored within the hydration column and higher hydration efficiencies relative to total saturation of the material, underlining a fast rewetting characteristic of the substrate.

4.2.3 Wettability curves for mixtures

Section B) presents the wettability results for the mixtures (50/50 Vol.-%) of coir/peat, *Sphagnum*/coir and *Sphagnum*/peat. The addition of *Sphagnum* to peat increases the absolute amount of water held by the substrate to a mean amount of 1,329.5 ± 403.2 g water after the last hydration event leading to an intermediate value between pure *Sphagnum* and pure peat substrates.

Mixing *Sphagnum* with coir has a positive influence on the wettability compared with pure coir because higher amounts of water can be stored within the mixture. The mean amount of water after the 10th hydration sums up to 1004.3 ± 259 g and is therefore higher than those of peat and the coir/peat mixture. Wettability curves of coir/peat mixtures display features of both components during hydration events but does not differ remarkably from *Sphagnum*/coir mixtures but the mean amount of water after the last hydration held by the substrate is with 877.5 ± 296.9 g lower.

4.2.4 Hydration index values for mixtures

Comparisons of relative water contents of hydration indices (section C) show that all mixtures have lower index values than pure *Sphagnum* biomass but on the other hand a mixing of materials reduces the differences between water content after the last hydration and completely saturated columns. This highlights especially the positive effect of *Sphagnum* as an amendment in mixtures on wettability.

Differences between coir/peat and *Sphagnum*/coir mixtures get visible by comparing their hydration indices. After the last hydration coir/peat mixtures reach 34 % of full saturation (mean index value 0.34 ± 0.09) while *Sphagnum*/coir has a mean index value of 0.53 ± 0.12. Disparities between *Sphagnum*/peat and *Sphagnum*/coir are notable when looking on absolute amount of water but do not exist for hydration index values. Mean index value for *Sphagnum*/peat of H10 amounts to 0.48 ± 0.11

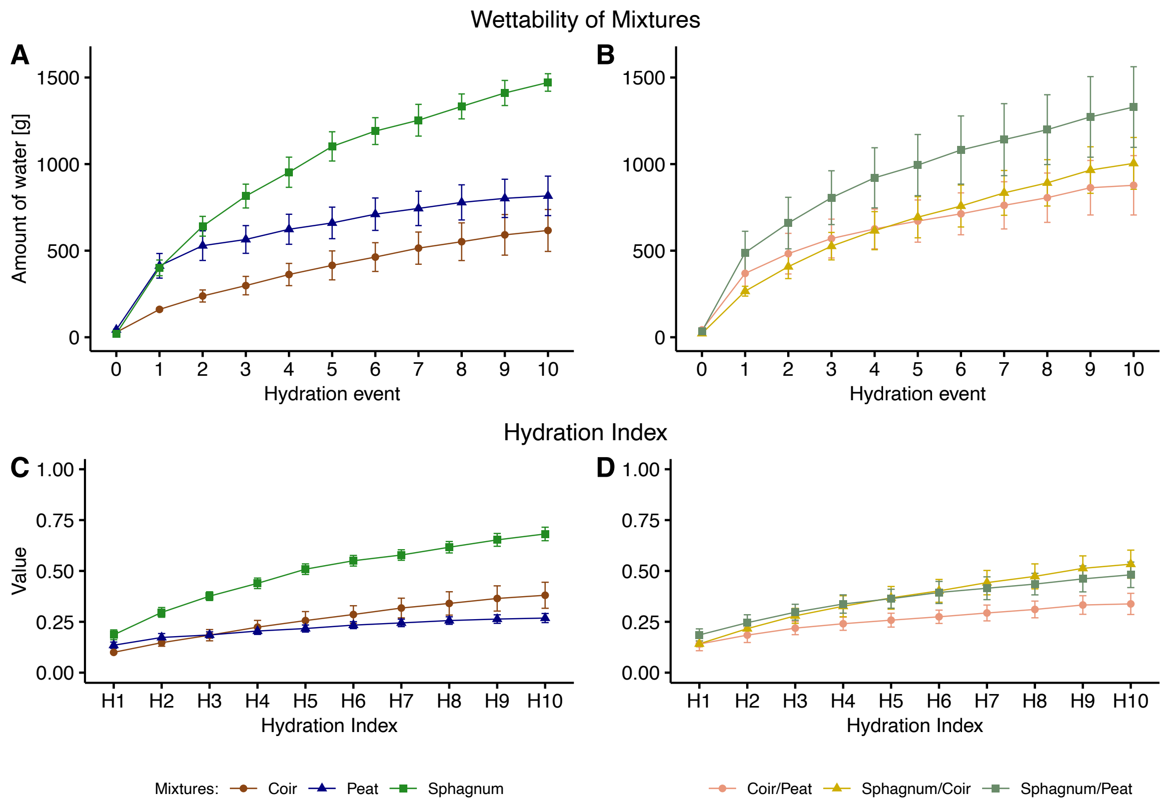

Figure 22: Wettability of mixtures, A: Sphagnum, peat, coir, B: mixtures (50 Vol.-%), C and D: hydration indices from first to tenth hydration (relative to total saturation), error bars indicate standard error, n=3

4.2.5 Additional Results of Hydration Experiments

Factors shown in the table below illustrate additional changes during hydration events. Mean amounts of water in g within each substrate before the first hydration (i.e. starting amount of water) and the mean amounts of total saturation after watering 24 hours are stated below. The mean pH after the first and the last hydration as well as electric conductivity for the same events are presented.

Peat as well as mixtures including peat, show the highest starting amounts of water and also absolute amounts of total saturation are the highest for peat. The results of the saturation for peat demonstrate that it takes long to wet peat (as described in the section of wettability curves) but that the peat filled columns have the highest mass. Starting water contents of *Sphagnum* and coir show lower trends but also lower mean values of total saturated columns than peat. The lowest pH-values after the first hydration (H1) can be observed from the effluent water of peat while after the last hydration (H10) the mean pH increased slightly, however electric conductivity decreased, showing the lowest EC values of compared substrates. Generally, pH-values of all substrates and mixtures increased slightly between the first and the last hydration except for coir where no changes occurred. For values of electric conductivity of the effluents high differences between hydration events are present. Highest EC values arise for *Sphagnum* and *Sphagnum*/peat mixtures which decrease markedly with increasing hydrations while EC values for coir are at lower levels and decrease at slower rates.

Table 3: Additional factors for hydration efficiency measurements (mean values ± SD), pH and EC in effluent water, n=3

Substrate/ Mixture	**Starting amount of water [g]**	**Saturated column [g]**	**pH at H1**	**pH at H10**	**EC at H1 [µS/cm]**	**EC at H10 [µS/cm]**
Peat	43.5 ± 5.7	3,016.7 ± 325.1	4.2 ± 0.2	4.7 ± 0.2	34 ± 17.1	6.0 ± 1.7
Sphagnum	20.2 ±1.2	2,164.1 ± 152.2	4.9 ± 0.3	5.2 ± 0.2	117.3 ± 36.9	27.9 ± 5.7
Coir	28.7 ± 3.7	1,607.3 ± 72.7	5.9 ± 0.5	5.9 ± 0.3	63.7 ± 13.3	37.7 ± 5
Sphagnum/ peat	34.5 ± 4.1	2,833.9 ±144.2	4.3 ± 0.2	4.7 ±0.3	131.4 ± 53	21.7 ± 10.1
Sphagnum/ coir	21.9 ± 4.5	1,874.9 ± 62.2	5.1 ± 0.2	5.4 ± 0.2	74.9 ± 30.2	38.5 ± 11.1
Coir/ peat	42.7 ± 3.8	2,559.4 ± 266.7	4.5 ± 0.2	4.6 ± 0.2	88.8 ± 59.6	21.7 ± 12.2

4.3 Results gravimetric water retention at pF 2.5

Amounts of water remaining in different substrates and mixtures after 4 hours on the suction plate with a negative pressure of -300 hPa are presented in the following figure. CP25 shows the lowest mean of 1.85 ±0.53 g (median 1.85 g, range 0.1 g) while mixtures with lower peat contents (CP50 and CP75) show slightly higher amounts (mean: 1.92 ± 0.04 g and 1.96 ± 0.69 g, median: 1.9 g, range: 0.1 g and 2 g, range 0.2 g). All coir/peat-mixtures show significant less amounts of water than peat. Pure coir has a mean of 2.14 ± 0.15 g, a median of 2.2 g and a range of 0.5. The amount of pure peat is relatively low (mean: 2.07 ± 0.05 g, median: 2.1 g, range: 0.1 g) compared with other mixtures. Highest amounts can be observed for pure *Sphagnum* (mean: 4.32 ± 0.42, median: 4.2, range: 1.4 g) Mixtures with higher *Sphagnum* content (SC75 and SP75) show higher amounts of water per g dry substrate (mean: 3.19 ± 0.18 g, 3.31 ± 0.13 g, median: 3.15 g, range: 0.6 g and 3.3 g, 0.4 g) while mixtures consisting of only 50 Vol.-% *Sphagnum* show lower amounts (SP50, SC50: mean of 2.65 ± 0.7 g, 2.78 ± 0.11 g, median: 2.7 g (range: 0.2 g) and 2.8 g (range: 0.3 g). Substrate mixtures with 25 Vol.-% *Sphagnum* (SC25, SP25) have more water within the substrate then mixtures without peat moss but less than mixtures with higher *Sphagnum* contents (mean: 2.33 ± 0.13 g, 2.42 ± 0.06 g, median: 2.35 g (range: 0.4 g), and 2.4 g (range: 0.2 g).

Summarized, the higher the amount of *Sphagnum* in a mixture the more water stays within the substrate after the measurement. The addition of *Sphagnum* leads to significant higher amounts of water per gram dry substrate compared with pure peat.

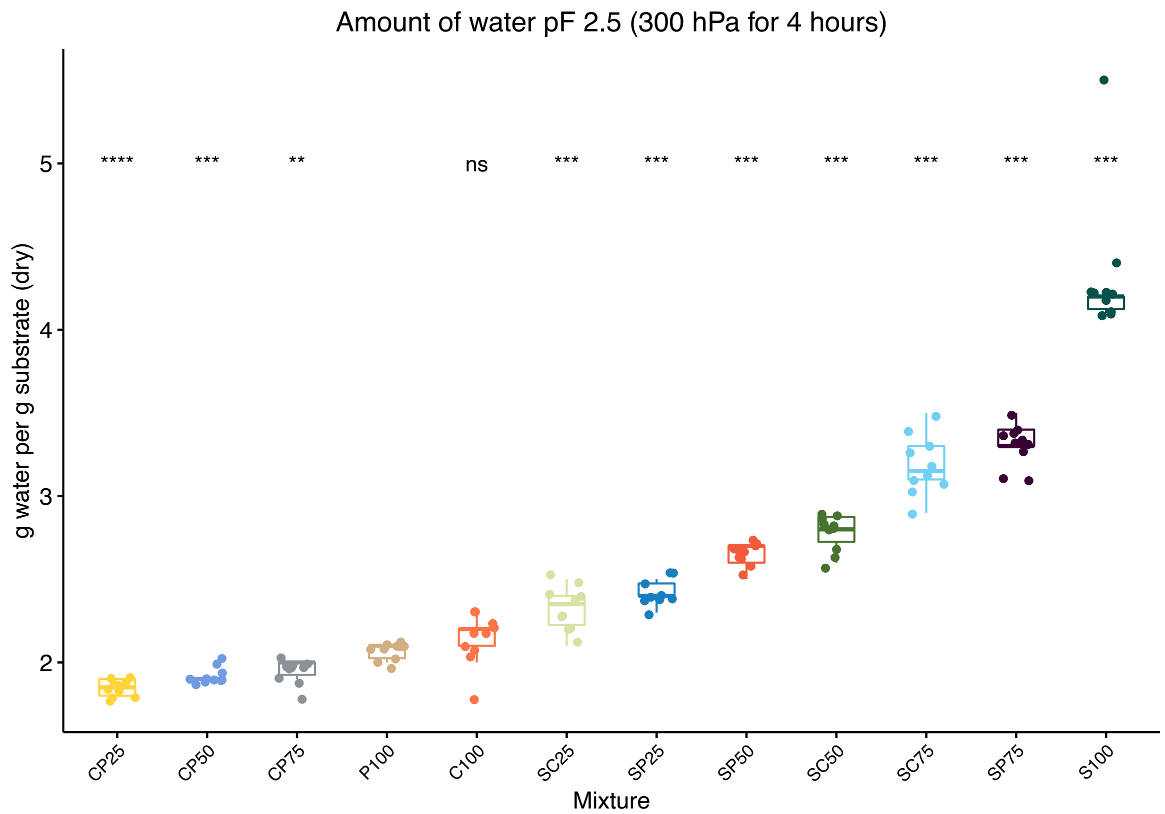

Figure 23: Amount of water in gram per gram dry substrate of all mixtures after 4 hours on suction plate (-300 hPa)

4.3.1 Calculated differences between maximum water holding capacity and water retention at pF 2.5

In the figure below the calculated differences between maximum water holding capacity of samples and amounts of water after pF 2.5 measurements are presented in gram per g dry substrate.

Pure *Sphagnum* shows with 24.1 g water per gram dry substrate the highest amount of water sucked out during the pF-measurement meaning that not only the highest amounts of water remain within the substrate (see section before), but also that the highest amounts of water are held in fine macropores and fast draining pores. For mixtures with 75 Vol.-% *Sphagnum,* differences are already less distinct but still on higher levels. Coir has the lowest differences of 1.2 g and also coir/peat mixtures do not vary greatly. No specific trends can be observed by de- or increasing the quantity of peat.

Pure peat has a difference of 5.4 g water while adding 25 Vol.-*Sphagnum* (SP25) increases the amount to 5.7 g. Mixtures with 50 Vol.-% *Sphagnum* (SP50) have even higher values (12.5 g) and with 75 Vol.-% 13.2 g. Increasing trends can also be observed with increasing the proportion of *Sphagnum* in coir mixtures except for SC50 where lower differences occur.

Summarized, mixtures containing *Sphagnum* show higher differences between maximum water holding capacity and the amount of water in the substrate after pF 2.5 measurements.

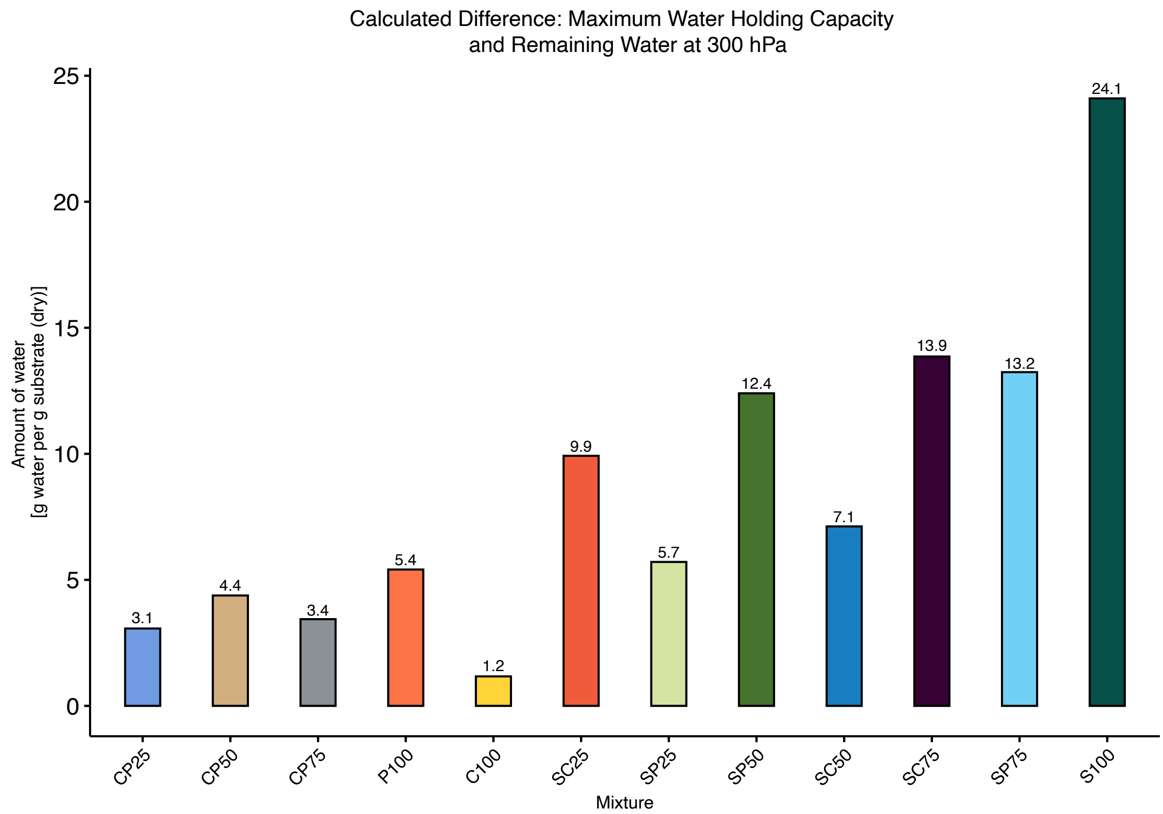

Figure 24: Results of calculated differences between means of maximum water holding capacity and mean values of remaining water after 4 hours on the suction plate in gram water per g dry substrate

4.4 Results Elemental Analysis

Elemental analysis was carried out for unfertilized and fertilized substrates and differences in contents of H, C, N and S are presented below.

4.4.1 Carbon

Unfertilized *Sphagnum* has a measured carbon content of 44.3 % while fertilized and incubated *Sphagnum* has a reduced C-content of 42.6 %. Carbon content of peat is slightly higher (46.4 %) and differences between fertilized peat are negligible (46.2 %). Unfertilized coir amounts to a carbon content of 45.3 % and fertilized 46.9 %. Fertilization of *Sphagnum*/coir mixtures reduces the carbon content from 47.3 % to 46.9 % while for mixtures of *Sphagnum*/peat the differences between unfertilized (46.4 %) and fertilized (46

%) are negligible. Similar results can be observed for *Sphagnum*/coir mixtures (unfertilized: 47.3 %, fertilized: 46.9 %) and coir/peat mixtures (unfertilized: 46.9 %, fertilized: 46.8 %).

4.4.2 Nitrogen

Total nitrogen contents show bigger differences among mixtures and treatments. Unfertilized samples have lower N-contents than fertilized ones but amplitudes of differences show variations among substrates. Nitrogen content of unfertilized *Sphagnum* sums up to 1.03 % while for fertilized 1.36 % were measured. Fertilization of peat leads to an increase of N-content from 0.84 % to 1.15 % while increases observed from coir are lower (unfertilized 0.44 %, fertilized 0.58 %). The amounts of total nitrogen for *Sphagnum*/peat mixtures increased after fertilization from 0.91 % to 1.15 %, for *Sphagnum*/coir mixtures from 0.54 % to 0.75 % and for coir/peat mixtures from 0.66 % to 0.81 %.

4.4.3 Sulfur

Fertilization of *Sphagnum* decreased the amount of sulfur from 0.57 % to 0.41 % while pure coir shows inverse tendencies with an increase from 0.19 % to 0.49 %. Results for pure peat show nearly no differences between treatments (unfertilized: 0.21 % vs. 0.22 % fertilized). In mixtures of *Sphagnum*/peat the trend of pure *Sphagnum* is still notable because fertilization leads to a decrease from 0.35 % to 0.25 % while in coir/peat mixtures the effect of coir is visible in the increase from 0.21 % to 0.27 %. For *Sphagnum*/coir fertilization shows nearly no changes (unfertilized: 0.20 %, fertilized: 0.21%) indicating effects of both decreasing tendencies from *Sphagnum* and increases from coir.

4.4.4 Hydrogen

Results for H-contents of *Sphagnum* show a slight decrease from 6.21 % to 5.69 % after fertilization while for peat results are more constant (unfertilized: 4.91 %, fertilized: 4.93). Fertilization of coir decreases the H-content from 4.11 % to 3.76 %, a trend also visible for *Sphagnum*/coir mixtures (decrease from 4.75 % to 4.48 %). Treatments with fertilizer of *Sphagnum*/peat and coir/peat mixtures show slight increases from 4.38 % to 4.47 and 5.15 % to 5.48 %.

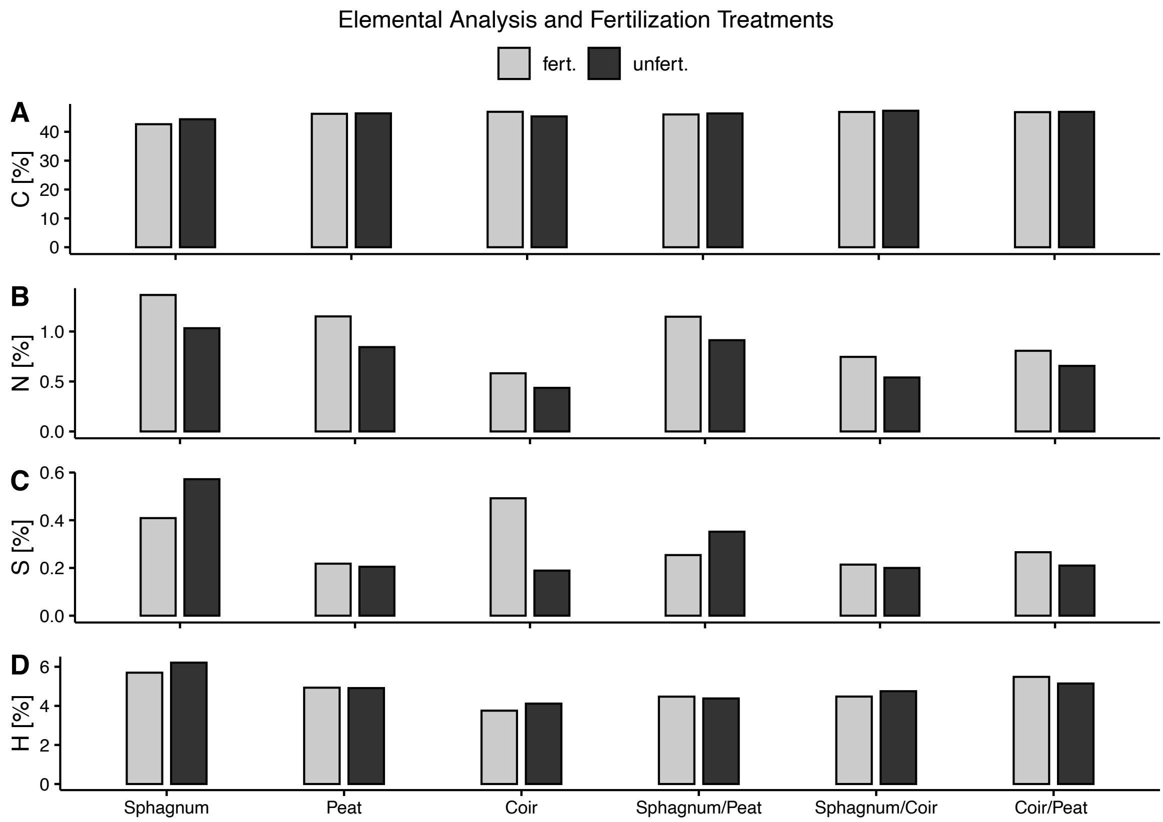

Figure 25: Results of elemental analysis (C, N, S and H) for unfertilized and fertilized mixtures

4.5 Results thermogravimetric analysis (TGA)

Results of thermogravimetric analysis are presented in the figure below for unfertilized and fertilized main substrates (peat, *Sphagnum* and coir). The black lines represent loss of mass during the combustion process relative to the weight at 50 °C while the red line shows the relative change of mass at a certain temperature (i.e. derivative thermogravimetry or DTG) For all substrates, major peaks of DTG curves occur within a temperature range of 100-450 °C but the number of peaks and their specific temperatures vary between substrates and treatments except for the first peak between 100-150 °C.

Unfertilized *Sphagnum* shows two other peaks indicating the highest mass losses around 300 °C and a third peak at 350 °C. A fertilization of *Sphagnum* leads to a loss of the third peak and increases the maximum loss around 300 °C indicating a destabilization of the organic matter. Remaining mass after the combustion sums up to 27.4% for unfertilized and 28.9 % for fertilized *Sphagnum*. For unfertilized peat DTG curves are very similar to curves of *Sphagnum,* but the amplitude of the peak at 300 °C is lower and the third peak occurs at lower a temperature (330 °C). By fertilizing peat, the loss of the third peak can be observed with a shift towards the peak at 330 °C. Relative weight after combustion amounts up to 32.6 % for peat and 33.6 % for fertilized peat. DTG curves for coir show very different peaks compared to the other substrates. Next to the first peak around 150 °C a second peak at 300 °C and a third peak at 380 °C can be observed. The fertilized coir shows a slight increase of the temperature for the third peak (at 390 °C) and a development of a shoulder between the second and third peak (350 °C). Residue amounts to 32.1 % for coir and 31.8 % for fertilized coir.

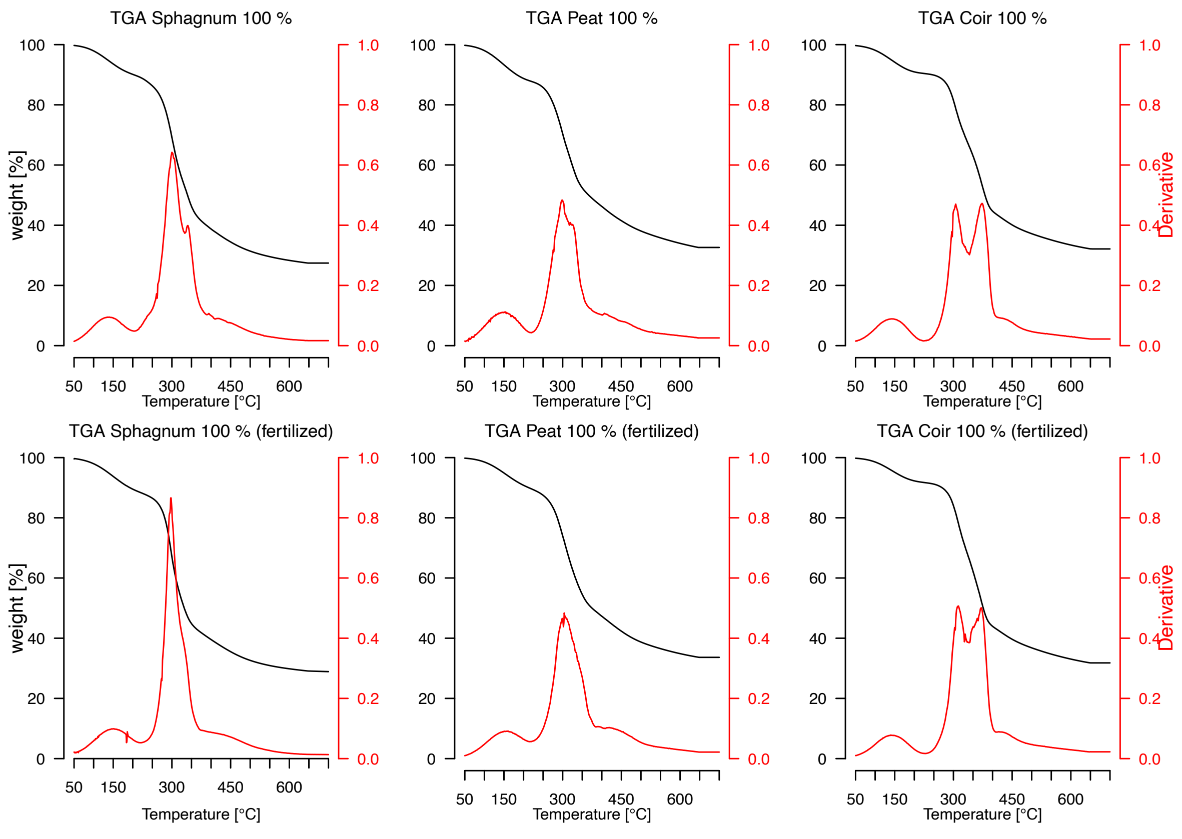

Figure 26: Thermogravimetric measurements for unfertilized and fertilized mixtures

4.6 Results bomb calorimetry

In the figure below the results of calorimetric measurements using bomb calorimetry are presented for fertilized and unfertilized mixtures. Calorimetric values for coir (mean: 16.87 ± 0.22 MJ/kg, median: 16.84 MJ/kg and range: 0.44 MJ/kg) are lower than for fertilized coir (mean: 17.63 ± 0.19 MJ/kg, median: 17.63 MJ/kg and range: 0.27 MJ/kg).

Values of coir/peat (mean: 17.23 ± 0.56 MJ/kg, median: 17.28 MJ/kg and range: 0.08 MJ/kg) show similar increasing trends (mean: 17.43 ± 0.01 MJ/kg, median: 17.43 MJ/kg and range: 0.02 MJ/kg). Also, peat has lower values for unfertilized material (mean: 16.77 ± 0.33 MJ/kg, median: 16.95 MJ/kg and range: 0.57 MJ/kg) and higher amounts for fertilized peat (mean: 17.29 ± 0.05 MJ/kg, median: 17.29 MJ/kg and range: 0.08 MJ/kg). Contrary results can be observed for *Sphagnum* (unfertilized: mean: 17.09 ± 0.01 MJ/kg, median: 17.09 MJ/kg and range: 0.02 MJ/kg and fertilized: mean: 16.44 ± 0.09 MJ/kg, median: 16.47 MJ/kg and range: 0.17 MJ/kg) and *Sphagnum*/coir mixtures (unfertilized: mean: 18.01 ± 0.36 MJ/kg, median: 18.01 MJ/kg and range: 0.51 MJ/kg and fertilized: mean: 17.77 ± 0.04 MJ/kg, median: 17.77 MJ/kg and range: 0.05 MJ/kg) where a decrease of energy can be seen. In *Sphagnum*/peat mixtures only small differences can be detected (unfertilized: mean: 17.02 ± 0.14 MJ/kg, median: 17.02 MJ/kg and range: 0.02 MJ/kg compared to mean: 17.08 ± 0.04 MJ/kg, median: 17.08 MJ/kg and range: 0.05 MJ/kg for fertilized samples)

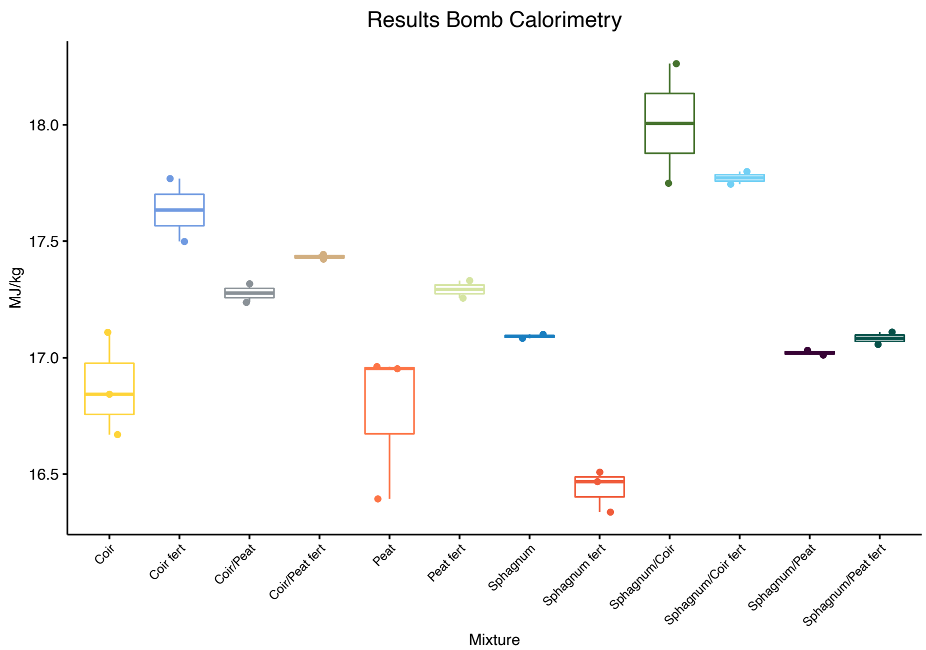

Figure 27: Results of bomb calorimetry for unfertilized and fertilized substrates

5 Discussion

The main aim of this study is the description of physical characteristics, especially the water holding properties and a chemical outline of *Sphagnum palustre* under unfertilized and fertilized conditions. In the following section the already presented results shall be discussed finding answers for described research questions.

5.1 Provision of *Sphagnum* biomass

Provision of fresh *Sphagnum* biomass for this study turned out to be harder than initially expected as the availability in Austria is limited. Therefore, the material needed to be imported from the Netherlands and transported to Vienna increasing not only the carbon footprint, but also the price due to transportation costs. Insufficient availability of *Sphagnum* biomass needs to be considered as a problematic factor when dealing with reliable production of horticultural substrates.

Actually, there were and still are many ongoing projects and studies working especially on this problem. Some examples carried out in Germany by the University of Greifswald are: “PEATMOSS” (2004-2007), “GEORGIA” (2007-2010), “MOOSFARM” (2007-2010), “PROSUGA” (2010-2013) and “MOOSGRÜN” (2010-2014), dealing especially with the propagation of peat moss in glasshouse and in outdoor experiments. (GAUDIG et al. 2014)
Next to the availability of material also costs are still constraining a use on larger scale. In our case, costs of more than € 7,- per 25 L bag incurred without transportation costs, making mixtures including *Sphagnum* expensive. Costs are still an issue especially when a material like *Sphagnum* need to compete with low-cost peat (CARLILE et al. 2019) although examples of economic rentability of *Sphagnum* farming, especially for niche markets, do exist (GAUDIG et al. 2014).

5.2 Processing of *Sphagnum* biomass

Delivered fresh *Sphagnum* biomass had a high mean water content of 89.6 ± 0.31 % relative to dry weight which made air-drying prior oven-drying necessary because storage space and oven capacity was limited. Therefore, a euro-palette construction similar to the one described in AUBÉ et al. (2015) was used. Further steps of processing differ from other publications because in our study very small fractions of *Sphagnum* biomass (< 2 mm) were used while others used *Sphagnum* fibers and bigger fractions (AUBÉ et al. 2015; GAUDIG et al. 2018; KÄMÄRÄINEN et al. 2018)

Fungal pests occur very likely in mires where *Sphagnum* grows. Generally, some associations of fungi may enhance growth of peat moss while others harm plant growth (GAUDIG et al. 2018). During this study, molding of *Sphagnum* also occurred during tests of maximum water holding capacity (see figure above). The experimental design offered optimal growing conditions for fungi, as *Sphagnum* was stored in a wet, water saturated, and warm environment, additionally covered with plastic to avoid evaporation. To decrease colonization of fungi during wetting, different procedures were carried out, including drying moss at higher temperatures (60 °C vs. 40 °C) and the use of microwaves.

Drying material at higher temperatures (60 °C) had no notable effect on the growth of mold on substrates. Microwave radiation has been used for sterilization of small volumes of soil and plant material before but with different effects, depending on microbial communities, time and level of energy used for the procedure. (MCGOVERN and MCSORLEY 1997; YOUSSEF et al. 2001) Using microwave radiation for 4:30 minutes and 450 watts decreased the development of mold on the surface of wet *Sphagnum* samples but did not stop it completely. As described by MCGOVERN and MCSORLEY (1997) the effect of sterilization through microwaves is strongly affected by thermal disinfection as water within the material is heated.
Analysis of the fungal associations colonizing the material were not carried out for this study but for future research, analysis of potential pests and detailed characterizations of microbiological communities are necessary.

Figure 28: Example of molding Sphagnum after wetting

5.3 Maximum water holding capacity of different treatments of *Sphagnum*

Treatments of *Sphagnum* biomass shows significant differences of maximum water holding capacity relative to dry weight compared to fresh peat moss. Especially burned *Sphagnum* substrates demonstrates that the positive characteristics (i.e. high water holding capacity) of natural *Sphagnum* (fresh moss) can be reduced significantly when using unsuitable methods, while other treatments reduced the maximum water holding capacity by lower rates. Groups with lower levels of processing (i.e. no sieving, no microwave) show tendencies to higher relative water holding capacities than groups with higher levels of processing (i.e. groups including sieving and microwave treatment) except for the standard treatment.

Water content of *Sphagnum* after drying and processing is an important factor describing the material because it influences the appearance and its handling properties. KUMAR et al. (2017) described *Sphagnum* material with very low water contents as “brittle” and unfavorable to handle as substrates with water content below 20 % are difficult to rewet. Treatments used in this study resulted in starting water contents between 20-13 % (except for burned *Sphagnum* with approximately 9 % of dry weight). Drying at higher temperatures (60 °C) leads to the lowest water contents while the use of microwaves after drying at 60 °C shows no influence. Samples dried at 40 °C show higher water contents and an influence of microwave radiation is visible, reducing the water content from approximately 20 % to 16 % relative to dry weight. Using microwaves for sterilization heats water within the material and increases evaporation especially in samples with higher starting water amounts (McGovern and Mcsorley 1997).

Gaudig et al. 2018 stated, that there is still no optimal water content for Sphagnum biomass and that further research is needed to quantify the upper and lower limits that are influencing physical properties. In this study the starting water contents of Sphagnum mixtures do not show influences on the maximum water holding capacity nether compared to relative amount per gram dry weight nor to absolute amounts.

5.4 Mixtures

Formulation of different substrate mixtures, using processed peat, coir and *Sphagnum* biomass was carried out on a volume by volume basis. This approach can be seen as a standard for industrial production of horticultural substrates and even other publications and researcher work behalf this method. (Emmel 2008; Blievernicht et al. 2012; Jobin et al. 2014; Gaudig et al. 2018) Materials used in this study have different bulk densities, making mixtures based on mass unhandily. Coir shows a mean bulk density of approximately 72 g/dm^3, *Sphagnum* (standard treatment) of approximately 30 g/dm^3 while peat shows the highest mean bulk density with approximately 140 g/dm^3.

Bulk densities of processed *Sphagnum* are relatively low compared to results of Kämäräinen et al. (2018) where *Sphagnum fuscum* was cut in fiber lengths of 5 mm, 40 mm showing bulk densities above 30 g/dm^2. For further tests, cylinders with target bulk densities between 40 and 80 g/dm^3 were used. Bulk densities of peat were lower (between 90-100 g/dm^2) for light peat while BD for dark peat ranged between 190-200 g/dm^3 and were higher compared to peat used in this study. Bulk densities of coir are similar to values observed from coir pith presented in Abad et al. (2005) where BD between 72-89 g/dm^3 for material from Sri Lanka and 61-72 g/dm^3 for material from Mexico are reported.

Differences between bulk densities of used substrates and the diverse structure of particles or fibers influenced the distribution of components within the mixture. Compared to coir and *Sphagnum*, peat substrate used in this study had a very fine texture leading to a fast separation of peat after mixing with other components. This problem of bad mixing is shown by the high ranges observed from absolute amounts of maximum water holding capacities from coir/peat mixtures.

Presenting results of maximum water holding capacities relative to dry weight seems to be more adequate than using absolute amounts, because the effect of different bulk densities is reduced. Results of maximum water holding capacities for mixtures show that absolute amounts of water are higher in mixtures where bulk densities are higher. BD of peat is high, leading to the highest absolute amount of water held by the substrate. *Sphagnum* (standard treatment) has lower bulk densities but still shows high absolute amounts of water (approximately 72 g). When looking on relative amounts, *Sphagnum* biomass shows even higher water contents than peat (appx. 25 g vs. 6 g water per g dry weight) indicating the suitability of *Sphagnum* to substitute peat in substrates by means of maximum water holding capacity.

Mixtures including *Sphagnum* biomass show higher relative amounts of maximum water holding capacity which means that even partial reduction of peat in mixtures are possible to reduce the use of peat in substrate mixtures while having a positive effect on physical properties. When looking on absolute results, this positive effect is still notable. A replacement of peat with coir shows no significant differences compared to peat alone and therefore a partial substitution of peat using coir has no negative effects on the measured factor. This is not the case for absolute results as all mixtures including coir and peat show significant less amounts of water.

5.5 Water retention at pF 2.5

Observed gravimetric water retention values at pF 2.5 showed significant higher amounts for treated *Sphagnum* biomass than peat. This trend also can be observed for all mixtures that contain *Sphagnum* biomass, meaning that the addition of *Sphagnum* to substrates increases gravimetric water retention. With increasing amount of *Sphagnum* also the water retained within the material increases (from 25 Vol.-% to 75 Vol.-%) without differentiating the second component of the mixture (coir or peat). Findings for higher gravimetric water retention capacities for peat moss (*Sphagnum fuscum*) were also observed by KÄMÄRÄINEN et al. (2018) where different fractions of *Sphagnum* (natural fibers, 5 mm and 40 mm fiber length) were compared with light and dark peat. Values at pF 2.5 for natural *Sphagnum* were higher than for the 40 mm fraction and the 5 mm fraction showed the lowest amounts. Findings described in our study show even lower gravimetric values than described by KÄMÄRÄINEN et al. (2018), maybe due to the smaller fractions used (< 2mm).
Calculated differences between the relative amount of water at maximum saturation and the relative amount of water within the substrates at pF 2.5 showed that mixtures which contain *Sphagnum,* have higher differences than mixtures without. This indicates that the use of *Sphagnum* increases fine and fast draining macropores. KÄMÄRÄINEN et al. (2018) showed that it is possible to use Sphagnum biomass either to alter air capacity or to increase values of water retention by adapting the bulk density.

A methodological problem needs to be discussed when looking on mixtures containing coir and peat because pure peat and pure coir have higher amounts of water at pF 2.5 than mixtures consisting solely of these two substrates. One possible explanation might be that the materials within the mixture distributed unevenly because of the different structures and bulk densities.
Possibly, the results for pure coir are not representative because the coarse structure of fibers reduced the effectivity of suction as the connection between samples and the porous plate can be lost (HARTGE and HORN 2009) leading to higher amounts of water in the sample. By the addition of fine peat particles, the connection between pores might be more stable resulting in lower water amounts for coir/peat mixtures.

5.6 Wettability

Drying of organic matter can decrease the ability of a material to retain water, a phenomenon also known as hydrophobicity or water repellence (Blok et al. 2019). *Sphagnum palustre*, coir and peat are organic materials and drying is an essential part of industrial processing. Wettability is therefore an important factor to evaluate the potential of a substrate additive (Fields et al. 2014).

Wettability curves provided for *Sphagnum* shows that the processed biomass can hold the highest absolute amounts of water while peat and coir cannot store as much water by hydration alone. *Sphagnum* shows the highest increases of water after each hydration event showing that the material is able to rewet quickly. This is not the case for peat which shows low increases of water for each hydration. The mass of the saturated peat shows the highest absolute values indicating that peat needs more time to rewet than *Sphagnum*. Coir has the lowest water holding capacity after 24 hours of saturation and also the lowest increase of water after each hydration. For this reason, its hydration index values for the last hydration surpasses peat, indicating that also coir is able to rewet faster than peat. Fonteno et al. (2013) used a similar method and detected that coir with a moisture content of 30 g per dry weight rewetted faster than peat with the same starting water content. Similar results were presented by Fields et al. (2014) where initial water contents of 25 % were used.

The use of *Sphagnum* in different mixtures has a positive effect on the amounts of water held within the column. *Sphagnum*/peat mixtures show the highest amounts but especially *Sphagnum*/coir mixtures are very promising as a peat-free mixture with higher amounts of water after the last hydration than pure peat. Addition of *Sphagnum* to mixtures increases also the index values at H10 and increases therefore the water content after the last hydration relative to the maximum saturation. These findings underline the efficiency of *Sphagnum* biomass as a compound in substrate mixtures or even as a substitute for peat.

Next to the time-consuming procedure (at least 10 hours per run, meaning 180 hours for 3 replicates and 6 substrates/mixtures) and high amounts of water (approximately 783 L) some methodological problems occurred. Especially during several hydration events of peat, some discrepancies between the weight before and after a hydration event occurred, as sometimes the mass after a hydration was lower than before.
A possible explanation therefore can be the high volume of substrate used (4 L) in which hydrophobic zones or pockets can accrue where several milliliters of water can be stored for a short term without getting absorbed by the substrate. These waterfilled pockets may increase the mass for a short period of time but can be discharged and decrease the mass again. MICHEL et al. (2017) described these pockets and hydrophobic zones as well as the problem of preferential flow, where water drains through hydrophobic channels without infiltration. Other evidence for unequal distribution of water within the hydrated column is provided by the results of electric conductivity. After a hydration event, a steady decrease of EC values can be obtained resulting from leaching, but in some cases the EC values increased after a hydration. Eventually, water stored within a hydrophobic pocket from previous hydrations, where EC values where higher, increases the electric conductivity after drainage of the pocket.

5.7 Thermostability

Our results show that treatments with nutrient solutions have a notable influence on the physicochemical characteristics of tested substrates and mixtures. Elemental analysis showed that the carbon content of *Sphagnum* decreased after fertilization and incubation for 4 weeks while this was not the case for peat. Fertilization of coir even increased the total carbon content.

Also, thermogravimetric measurements show a shift of the second peak of unfertilized *Sphagnum* towards lower temperatures, resulting in a single peak around 300 °C. This is typical for processes of decomposition of organic materials as described by ROVIRA et al. (2008) and also results of fertilized peat show a slight shift towards lower temperatures.

Mass losses around 100 °C are known as loss of water which is often called “hygroscopic moisture” (ALMENDROS et al. 1982) while other researcher expand the temperature range up to 150 °C (MÉNDEZ et al. 2011). Losses within this expanded evaporation range can be observed in all substrates at similar levels.

Sphagnum and peat samples have quite similar DTG curves with main peaks around 250-400 °C but especially fertilized *Sphagnum* shows a very narrow single peak indicating that the substrate consist of higher fractions of labile carbon compounds. Mendez et al. (2011) relates losses within a range of 200-375 °C to losses of carbohydrates including cellulose and lignocellulose, while losses between 400-600 °C account for more condensed organic substances. Coir has a more complex structure with two distinct peaks, one around 300 °C and another at approximately 400 °C. Even fertilization of the material does not influence the stability of the material as no shifts of peaks are present.

Bomb calorimetric results show that gross heat values of *Sphagnum* biomass decreased after fertilization. No other material showed similar effects. Also, the reduction of total carbon was only detected for fertilized *Sphagnum* biomass. These findings suggest, that fertilization of *Sphagnum* biomass may lead to a decomposition of organic matter including the loss of carbon compounds and a decrease of gross heat values. As biological stability of organic materials is also influencing physical properties of substrates (e.g. the structure and pores within substrates) (CARLILE et al 2019) further investigations dealing with the biodegradation of *Sphagnum* are necessary, including the characterization and quantification of microbial activity.

6 Conclusion

For this study fresh *Sphagnum palustre* biomass was used, giving the possibility to set up a whole production procedure for substrates. That included different steps of drying, crushing and sterilization of the biomass, allowing also the evaluation of specific consequences on physical parameters. Our results show that different procedures of *Sphagnum* biomass treatments influence the maximum water holding capacity and may decrease this parameter significantly, compared with fresh biomass. Nevertheless, the so-called standard treatment used here (air-drying followed by drying at 40 °C, sieving into fraction < 2mm and using microwaves (450 W for 4:30 minutes)) showed no significant differences showing that a careful selection of processing steps is a key factor when working with *Sphagnum palustre*.

Compared with other substrates used in this study, namely coir and peat, the handling of Sphagnum was easy. While coir fibers are coarse and hard to crush, making mixing with other substrates difficult, peat was easier to process but especially the high amounts of dust were disadvantageous. Dry Sphagnum substrates showed electrostatic charges but were easier to mix with other substances and was less dusty. As the processing in this study is only hard to compare with an industrial production line, further investigations depending upscaling and the implementation in industrial settings are necessary.

Findings for the maximum water holding capacities presented in this study suggest, that the use of *Sphagnum palustre* is comparable with peat, as the absolute amounts of water held by peat are only slightly higher than amounts of *Sphagnum*. Relative amounts of water held by Sphagnum are significantly higher than values of peat. This is also the case for mixtures including *Sphagnum*, showing that the addition of peat moss has positive effects on the maximum water holding capacity. Adding Sphagnum to different mixtures showed similar effects on the water retention values at pF 2.5, as all mixtures containing Sphagnum showed significantly higher water contents than pure peat.

Substrates used in this study, originating from *Sphagnum palustre,* showed not only positive effects on the maximum water holding capacity, as also wettability and hydration efficiency were advantageous. Pure *Sphagnum* rewetted many times faster than peat and coir alone. The addition of peat moss biomass increased wettability and hydration efficiency of other substrates, making mixtures including coir and *Sphagnum* a promising peat-free alternative.

Summarized, the analyzed physical properties of *Sphagnum palustre* used in this study underline the ability of *Sphagnum* biomass to substitute peat in growing media. Comparison of presented results were sometimes difficult, because methods, definitions and substrates used in other studies vary greatly. This is also the case for technical standards of horticultural norms which differ between countries. This problem was already discussed by others.

> *„[...] we should learn from our colleagues in soil science: start with definitions, develop a framework, then develop procedures that can be used to collect the needed data"* (FONTENO 1993)

While physical properties of *Sphagnum* showed very positive characteristics compared to peat, chemical characterization showed several weak points. The undecomposed biomass of Sphagnum consists of less stable carbon compounds and is therefore less resistant to decomposition than peat. Fertilization of *Sphagnum* showed a destabilization of organic matter observed within thermogravimetric results. The decrease of total carbon due to fertilization underlines the low stability. Compared to peat, Sphagnum biomass was found to be less stable as observed by losses of gross heat value after fertilization treatments.

Summarized, the use of *Sphagnum palustre* as a substitute material for peat shows partial advantages, especially when comparing physical properties, namely the maximum water holding capacity, water retention contents and rewettability. On the other hand, stability of the material, especially when fertilized, shows disadvantages compared to peat and also problems of molding need to be clarified. More research needs to be done on the microbial activities and its impacts on the stability of *Sphagnum palustre* used for horticultural substrates.

7 Acknowledgements

This study was supported by “bellaflora Gartencenter GmbH”, an Austrian company interested in peat-free substrates.

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