Analyzing rehydration efficiency of hydrophilic (wood fiber) vs potentially hydrophobic (peat) substrates using different irrigation methods

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Abstract

Risks of hydrophobicity are one of the most common issues in most soilless substrates. Their consequences in terms of low ability to rewet and decrease in water retention properties are well known, but have not been studied according to different irrigation methods. To that end, an experimental device has been developed in order to compare the rewetting properties of a hydrophilic (wood fiber) and a potentially hydrophobic (white peat) substrate under two irrigation methods (surface drip irrigation and sub-irrigation). Wood fiber remained hydrophilic and recovered its water retention properties after drying, whatever the intensity of drying and with both irrigation methods. Conversely, peat showed a change from hydrophilic to hydrophobic character and a decrease in the ability to rewet in relation with the intensity of drying. The dynamics in water uptake mainly differed for peat depending on both irrigation methods and initial moisture contents. Interpretation of results demonstrated that rewetting properties depend on the wettability of materials, whereas the dynamics of water uptake are governed by irrigation methods.

Keywords: drip irrigation, sub-irrigation, rewetting, wettability, water uptake

INTRODUCTION

Hydrophobicity is a major potential risk for many organic substrates, especially peat-based substrates (Michel, 2015; Michel et al., 2001, 2017, 2021; Fields et al., 2014; Schulker et al. 2020; Durand et al., 2021), inducing a low ability to rewet and a degradation in their water uptake and water retention properties. This decrease in wettability, with a change from hydrophilic to hydrophobic character, has been shown for a majority of substrates depending on their moisture content. Few organic materials, like some samples of wood fiber and coir products, maintain hydrophilic properties and high ability to rewet after drying. Two main reference methods, i.e. contact angle measurement and hydration efficiency tests, are currently proposed for evaluating wettability in substrates, but they differ in: 1) scale (micro vs macroscopic), 2) volumes of materials tested (5 cm^3 vs 200 cm^3), and 3) their methods of water delivery to the substrate sample. Water is supplied from the bottom for contact angle measurements (i.e., same for sub-irrigation systems), and from the top for hydration efficiency tests (i.e., same as drip irrigation). However, Michel (2015), then Michel et al. (2017) concluded that interpretation of analysis results of both methods is very consistent and thus established a classification of the wettability of substrates, from substrates with no risk to those with high risk of hydrophobicity.

To better understand the physical behavior of substrates during rewetting, and thus improve water management of substrates during crop production, the aim of our work was to analyze and compare the water uptake and rehydration efficiency of hydrophilic (wood fiber) and potentially hydrophobic (white peat) substrates after drying, depending on irrigation methods.

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MATERIALS AND METHODS

Samples

Experiments were carried out on two substrate components supplied by Klasmann-Deilmann company: a white milled peat (0-25 mm, H3-H5 Von Post index, 0.11 g cm^{-3} bulk density) extracted in Lithuania, and a wood fiber marketed under the name GreenFiber (0-4 mm, 0.08 g cm^{-3} bulk density) (Figure 1). This wood fiber results from a process of defibration by passing conifer wood chips through a retruder. No fertilizer or wetting agent were added in order to avoid their potential effects on the rehydration properties.

Figure 1. Wood fiber and white milled peat used as study materials.

Preparation of the materials

Experiments were performed on samples previously equilibrated at three different initial moisture contents (MC) expressed by weight of 40, 50, and 60% w/w. The thresholds for initial MC were defined from results previously obtained by Fields et al. (2014) and Michel et al. (2017, 2021): 40% w/w corresponding to a lower limit where peats become hydrophobic with a very low ability to rewet, and, conversely, 60% w/w representing a MC for which all materials are hydrophilic. The MC was expressed by weight for the preparation of the samples because it allows comparisons among materials and does not depend on the bulk density, which can largely vary depending on the materials and its degree of compaction.

Tests were carried out on 200 cm^3 substrate samples homogeneously packed in 10 cm height cylinders, with the same dry bulk density (Table 1) for a material, regardless of its initial MC.

Table 1. Initial moisture contents expressed by percent weight (MC) and volumetric water content ($WC_{[0]}$) for tested substrates.

Substrates	Dry bulk density (g cm^{-3})	Initial moisture content MC by weight (%)		
		40	50	60
		Initial volumetric water content WC_0 (v/v)		
Wood fiber	0.08	0.07	0.10	0.15
White peat	0.11	0.08	0.12	0.19

Drip irrigation test

Rehydration efficiency by drip irrigation was assessed using the method initially described by Fields et al. (2014) and recently adapted by Durand et al. (2021). This method consisted of measuring the water uptake of substrates during successive drip irrigations. The substrate column was subjected to six successive hydration events which involved passing 200 mL water in approximately 5 min through each sample and to collect effluent as it came out the bottom from which cumulative water content (WC) retained (from WC_1=water content after one hydration event to WC_6=water content after six hydration events, v/v) in the substrate was calculated. After these six hydration events, the substrate column was saturated from the bottom over 15 min, then freely drained for 30 min in order to determine container capacity (CC, v/v) of each material. At least eight replicates per MC and per substrate were carried out.

Sub-irrigation test

As for the drip irrigation test, the method developed for assessing the rehydration efficiency by sub-irrigation consisted of measuring the water uptake of substrates during six successive events, with a same time of 5 min watering per hydration event. The substrate column was placed on a grid in a container filled with water (to allow water flow by capillarity), with an overflow system in order to maintain the same precise 4 cm water level in the substrate column. After each hydration event and 5 min of free drainage, the substrate column was weighted and its volumetric water content was determined. As for the drip irrigation, cumulative water content (WC) retained (from WC_1 to WC_6, v/v) in the substrate was calculated. Again, after these six hydration events, the substrate column was also saturated from the bottom over 15 min, then freely drained for 30 min in order to determine container capacity (CC, v/v) of each material. A minimum of eight replicates per MC and per substrate were also carried out.

Data treatment and analysis

For the analysis of results, the initial MC, expressed in weight (w/w) for the preparation of the materials was converted in volumetric water content (v/v) (Table 1). Curves connecting all points with the same symbol (7 points in total) corresponded to the cumulative water uptake after each successive irrigation event (i.e., a total of six 5-min events). The straight horizontal lines (without symbols) corresponded to container capacity values (CC, v/v) (Figure 2).

From the hydration curves, some notable points were identified:

- The water volumes retained (v/v) by the substrate column after *x* irrigation event(s) « WC_X»; with « WC_1» corresponds to a first event of 5-min irrigation (equivalent to a usual time of watering);
- The container capacity (CC_X), corresponding to the maximum water content (v/v) recovered by the substrate initially equilibrated at initial MC, of 40% (CC_{40}), 50% (CC_{50}), and 60% (CC_{60}) w/w;
- The maximum container capacity (CC_{MAX}), considered as the CC value (v/v) for a substrate prepared at the 60% w/w MC, i.e., when the substrate was fully hydrophilic and quickly rewetted.

The hydration curves were interpreted using calculations of key parameters based on the CC_{MC}, CC_{MAX} and $WC_X(MC)$ (v/v) values obtained for a given material initially equilibrated at a given initial MC, where X corresponded to the number of irrigation events. The $WC_{1(MC)}/CC_{MAX}$ and CC_{MC}/CC_{MAX} ratios, which reflect the ability of a substrate to rewet after a first irrigation event and to recover its initial water retention properties, respectively, were calculated.

Statistical analysis

The statistical analysis of the results was carried out using the R Studio Software. The influence of both irrigation methods and initial MC on the water uptake measurements were tested by one-way analysis of variance (one-way ANOVA, linear models), after checking for normality of data sets by Shapiro-Wilk tests ($p<0.05$). Whenever significant differences were observed ($p<0.05$), Tukey's range tests (Tukey-HSD) were applied to identify where differences occurred.

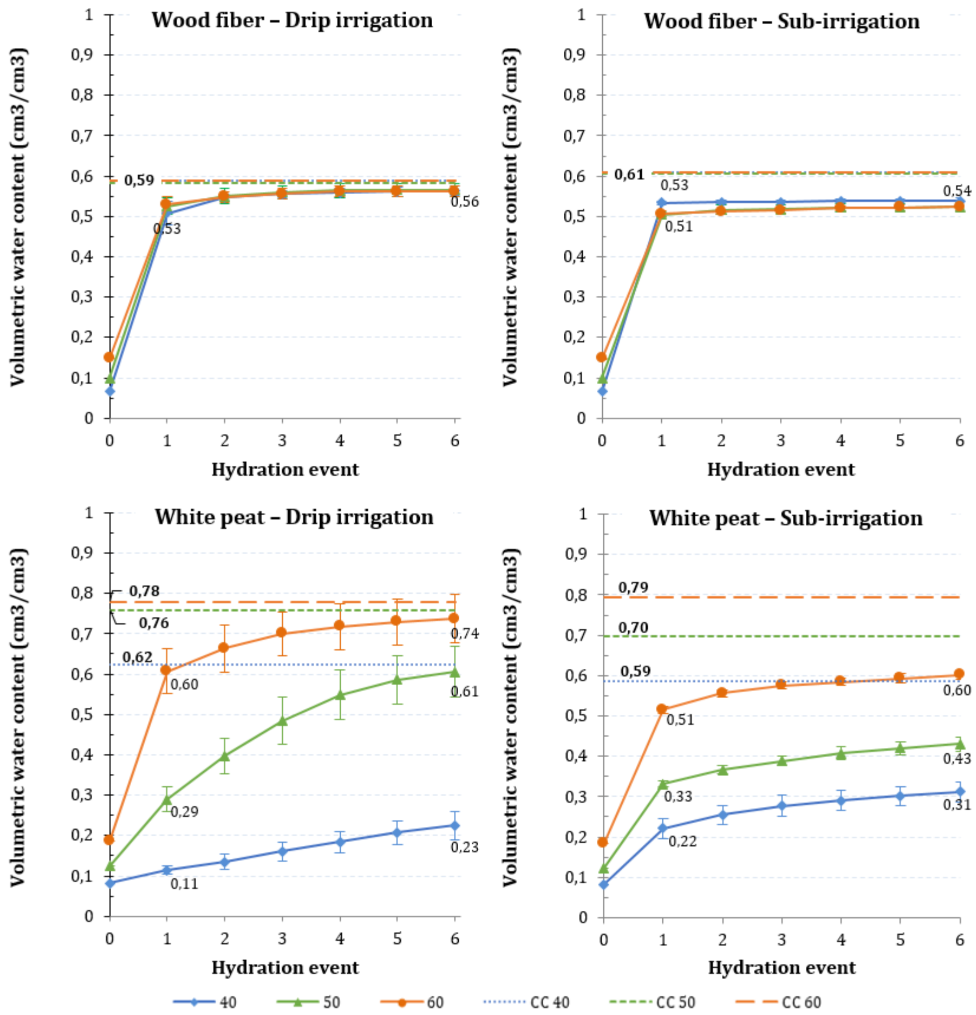

Figure 2. Rewetting curves for milled white peat and wood fiber from drip and sub-irrigation (CC: container capacity).

RESULTS AND DISCUSSION

Wood fiber captured most of the total water retained with a single irrigation event (WC_1=0.51-0.53), and the CC_{MC} values measured at the end of the experiments were also similar (0.59-0.61 v/v), no matter the initial MC or irrigation method (Figure 2). Therefore, the rehydration efficiency (WC_1/CC_{MAX}) reached approximately 80-90% after only one hydration event (Figure 3). These results confirmed that wood fiber remained hydrophilic, no matter the intensity of drying, leading to a high ability for wood fiber to rewet in both irrigation methods (Figure 3).

Slight differences were observed after the first hydration event, where water uptake slowly progressed for drip irrigation to reach values close to the CC_{MAX}, whereas a plateau was reached for sub-irrigation (no water uptake after this first hydration event) (Figure 2), suggesting a slower rewetting by capillary rise, probably due to pore size distribution, rather than wettability issues. That led to slight differences in the rehydration efficiency between both irrigation methods (Figure 3).

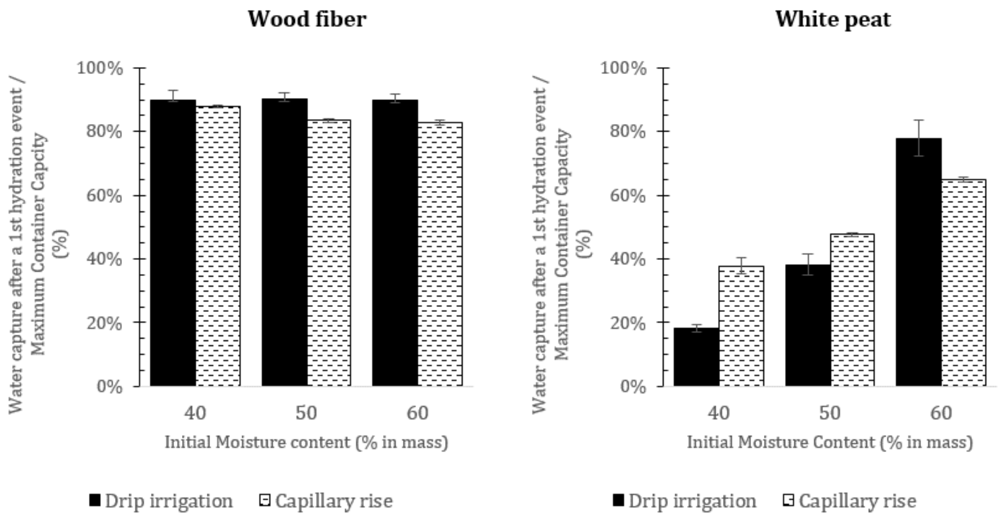

Figure 3. Rehydration efficiency (WC_1/CC_{MAX}) of wood fiber and white peat according to drip irrigation and capillary rise method and their initial moisture contents (w/w).

Conversely, peat demonstrated different rewetting behavior than wood fiber. For both irrigation methods, the water uptake after one hydration event (WC_1) and the CC_{MC} values decreased with the intensity of peat drying (Figure 2). Water retained after a single drip irrigation event (WC_1) varied from 0.60 v/v to 0.11 v/v and the maximum container capacity (CC_{MAX}) also decreased from 0.78 w/w to 0.62 w/w for initial MC of 60 and 40% w/w, respectively. Decreases in WC_1 (from 0.52 v/v to 0.22 v/v) and CC_{MAX} (from 0.79 v/v to 0.59 v/v) were also observed after a first sub-irrigation event for initial MC of 60% w/w and 40% w/w, respectively. These results indicated a reduction in peat wettability according to the intensity of the drying process, with a change from a hydrophilic character for MC=60% w/w to a hydrophobic character for MC=40% w/w.

However, the dynamics of water uptake largely varied depending on irrigation methods. With sub-irrigation, water was mainly captured during the first irrigation event, then water uptake slowly increased for the following five irrigation events. Furthermore, the water uptakes after six irrigation events (WC_6) were much lower than CC_{MC} values. For drip irrigation, water uptake was very slow and progressive for the lowest MC (40% w/w), but conversely was progressively faster and quickly reached a plateau for the highest MC (60% w/w) with a value close to its maximum CC_{60}.

Consequently, WC_1 values (and more largely rewetting behavior) significantly differed between both irrigation methods depending on the intensity of drying (Figure 3): rehydration was more efficient by drip irrigation when peat remained hydrophilic (MC=60% w/w), but conversely was more efficient in case of sub-irrigation when peat became hydrophobic (MC=40% w/w).

When peat became dried and hydrophobic (MC=40 and 50% w/w), preferential flows were observed when drip irrigation was applied (Figure 4a). Water circulated predominantly through these preferential paths, thus describing large non-wetted and hydrophobic zones in the peat column and then drastically limiting its rewetting. With sub-irrigation, water was only retained in the 4 cm lower part of the peat column, corresponding to the 4 cm water level (Figure 4b).

Figure 4. a) Preferential flows and b) rewetting front observed on white peat, from drip and sub-irrigation, respectively.

Water retained after 6 events (WC_6) corresponded to an equivalent CC of the 4 cm peat column, meaning that rehydration only concerned the lower part of the peat column in contact with water, whereas the 6 cm upper part was not rehydrated. No capillary rise was observed beyond the 4 cm water level (Figure 4b) and thus supported this hypothesis.

When peat remained hydrophilic (MC=60% w/w), water uptake was much higher for drip irrigation, reaching values close to the maximum container capacity (0.74 v/v for WC_6 vs 0.79 for CC_{MAX}). In contrast, a large difference between WC_6 (0.60) and CC_{MAX} (0.79) was observed by sub-irrigation, suggesting again, as for wood fiber, difficulties in capillary rise properties partly due to coarse and low-connected pores (Laplace-Jurin's law); peat being hydrophilic for high initial MC.

CONCLUSIONS

Both methods confirmed that the wood fiber remained hydrophilic with a high ability to rewet, whatever the intensity of drying. Conversely, the evolution from a hydrophilic to a hydrophobic character of peat and a decrease in its ability to rewet in relation to the intensity of drying was shown, confirming conclusions previously found in the literature.

Differences in the dynamics of water uptake were also observed depending on both moisture content and irrigation method. Water uptake in drip irrigation is governed by both wettability and gravitational forces allowing the progressive increase of water diffusion in the substrate. In contrast, rehydration by sub-irrigation mainly depend on the wettability of materials. The capillary forces were weaker (for wet and hydrophilic substrate) or negligible (for dry and hydrophobic substrate) due to pore size distribution (and connectivity), as reflected by the rewetting front observed.

The similar maximum container capacity values obtained for a same material for both irrigation methods suggested that rewetting properties mostly depend on the wettability of materials, while dynamics of water uptake are governed by irrigation methods.

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Literature cited

Durand, S., Jackson, B.E., Fonteno, W.C., and Michel, J.-C. (2021). The use of wood fiber for reducing risks of hydrophobicity in peat-based substrates. Agronomy (Basel) *11* (*5*), 907 https://doi.org/10.3390/agronomy11050907.

Fields, J.S., Fonteno, W.C., and Jackson, B.E. (2014). Hydration efficiency of traditional and alternative greenhouse substrate components. HortScience *49* (*3*), 336–342 https://doi.org/10.21273/HORTSCI.49.3.336.

Michel, J.-C. (2015). Wettability of organic growing media used in horticulture: a review. Vadose Zone J. *14* (*6*), vzj2014.09.0124 https://doi.org/10.2136/vzj2014.09.0124.

Michel, J.C., Rivière, L.M., and Bellon-Fontaine, M.N. (2001). Measurement of the wettability of organic materials in relation to water content by the capillary rise method. Eur. J. Soil Sci. *52* (*3*), 459–467 https://doi.org/10.1046/j.1365-2389.2001.00392.x.

Michel, J.-C., Jackson, B.E., and Fonteno, W.C. (2017). Classification of organic substrates' wettability from contact angle measurements and hydration efficiency tests. Acta Hortic. *1168*, 199–206 https://doi.org/10.17660/ActaHortic.2017.1168.26.

Michel, J.-C., Jackson, B.E., and Fonteno, W.C. (2021). The use of coir for reducing risks of peat-based substrate hydrophobicity. Acta Hortic. *1305*, 449–454 https://doi.org/10.17660/ActaHortic.2021.1305.59.

Schulker, B.A., Jackson, B.E., Fonteno, W.C., Heitman, J.L., and Albano, J.P. (2020). Comparison of water capture efficiency through two irrigation techniques of three common greenhouse soilless substrate components. Agronomy (Basel) *10* (*9*), 1389 https://doi.org/10.3390/agronomy10091389.