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Review

Influence of Processing Parameters on Fibre Properties during Twin-Screw Extrusion of Poplar Wood Chips

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Abstract: For sustainable agriculture, the contentious input of peat in growing media needs to be replaced by a substitute with the best possible water-holding capacity (WHC). Wood from fast growing poplar trees, cultivated in short rotation coppices (SRC), is a suitable alternative if it is processed correctly in a twin-screw extruder. The processing parameters, such as the aperture setting of the extruder, moisture content, and specific energy demand (SED), during twin-screw extrusion, as well as their influence on fibre properties such as WHC and particle size distribution, are investigated. SRC-poplar wood chips from clone Max3 are the raw material used for this research. As a result, the best volume-based WHC (75%) at −1 kPa suction tension was achieved for dry extruded wood chip fibre at an aperture setting of 15 mm and an SED of 340 kWh*t^{-1}. The smallest SED of 140 kWh*t^{-1} was measured at apertures of 35 mm and 40 mm, which resulted in a volume-based WHC of approximately 30% and a dry matter mass flow during processing of 0.289 t*h^{-1} (40 mm). The particle size distribution of semi-dry wood chips has the highest fine fraction as well as the smallest coarse fraction. Conclusively, poplar wood can be processed fresh and dry into fibre at an acceptable SED, which results in an acceptable WHC.

Keywords: twin-screw extrusion; water-holding capacity; poplar wood chips; specific energy demand; particle size distribution; peat substitution; processing parameters; aperture setting

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1. Introduction

The use of peat in horticulture will be greatly reduced in Germany until 2030, at which point peat should be replaced almost entirely [1]. Therefore, a substitute is needed soon. The annual worldwide use of peat is calculated at approximately 40 million m^3 [2]. This shows a high potential for possible substitutes if these can match the qualities of conventional peat-based products for horticulture.

Schmilewski predicted that replacing peat in growing media with wood fibre is likely to become increasingly important. Wood fibre use quadrupled from 2005 to 2013 [3].

Developing fibre from wood chips produced in short rotation coppice (SRC) plantations or agroforestry systems is one possibility to substitute peat. On a small industrial scale with a commercial counter-rotating twin-screw extruder, such wood chips can be transformed into fibre. The physical fibre properties, such as particle size distribution and fibre fineness, highly depend on the processing parameters during extrusion. The particle size distribution of a fibre mixture determines its ability to hold water [4]; therefore, the influence of extruder settings, such as different apertures and moisture contents of fibre properties, need to be investigated in detail. The water-holding capacity (WHC) of potential substitutes is of high interest in horticultural application.

The aim of this study is to determine how the WHC, particle size distribution, and SED of poplar wood fibre are affected by the aperture setting and the moisture content of the wood chips during extrusion. Wood chips were processed at a small industrial scale using a counter-rotating twin-screw extruder.

1.1. State of Research of Peat Substitution with Fibre

Several scientists have investigated the use of wood fibre as a peat substitute for plant cultivation.

Raw material for wood fibre production can range from waste wood such as pallets, to debarked softwoods [5]. Agarwal et al. [6] conducted a literature review of potential peat substitutes from many different raw material sources. In Germany and France, the most frequently used wood species for wood fibre production are virgin wood chips, debarked softwoods such as fir (*Abies* L.), spruce (*Picea* L.), and pine (*Pinus* L.). Poplar (*Populus* L.) can also be used, as well as some hardwood species such as willow (*Salix* L.), beech (*Fagus sylvatica* L.), and ash (*Fraxinus* L.) [6]. Pedersen and Løes [7] also concluded from Scandinavian studies that woody material has promising characteristics for peat replacement in growing media.

Atzori et al. [8] claimed that replacing peat with wood fibre is suitable due to its physical properties. Low bulk density (approximately 70–90 kg m^{-3}), good wettability, high total porosity, and high air capacity are positive properties of wood fibre. However, the WHC (1–10 kPa) is low according to the authors [8]. Due to this deficit (insufficient plant-available water), wood fibre is used in mixtures alongside additional substitutes, rather than as a solitary growing media. It is instead used to enhance the physical properties of different material components [9].

Debode [10] investigated how extruded *Miscanthus* A. can be used to replace 20% of the peat in growing media for strawberry cultivation. Nitrogen immobilization only reduced the yield in one experiment. Grießer [11] extruded eight different plant materials available in Lower Saxony for peat substitution. Common reed (*Phragmites australis* CAV.), giant Chinese silver grass (*Miscanthus* × *giganteus*, J.M. Greef and Deuter ex Hodk. and Renvoize), and cup-plant (*Silphium perfoliatum* L.) were used in mixtures with peat and had positive results in cultivation trials. Gruda [12] found that fibre from spruce (*Picea abies* L.) with a high fine fraction resulted in a good WHC. This fibre could therefore replace peat in vegetable cultivation. Kharazipour [13] investigated the WHC and other physical properties of different thermo-hydrolytic defibrated raw materials. It was found that increasing the fibre content decreased the WHC in all substrates. Kir [14] tested how olive saplings develop in peat-reduced and peat-free substrates. Their interesting results showed that olive saplings can be grown in olive fibre produced using a twin-screw extruder. Koller [15] investigated plant growth in peat-reduced and peat-free substrates, and found that a mixture with only 40% peat performed the best and resulted in good plant quality. Peat-free plant production is more complex and requires specialist knowledge of fertilization. König [16] investigated yields of seedling cultivations in peat-reduced growing media. Approximately 50% of the peat was replaced by poplar fibre. Different lettuces, fennel, and cabbage plants achieved comparable yields in pure peat and peat-reduced growing media. Kunz [17] investigated the cultivation of young vegetable plants in peat-reduced substrates and press pots. As a result, press pots can be produced with only 40% peat. Also, potted herbs can be cultivated in peat-free substrates, yet organic production is more difficult due to the different behaviours of substrates from maize straw and wood fibre. Eymann et al. [18] found that wood fibre and other peat substitutes have a low environmental impact as well as positive social benefits; therefore, wood fibre has the potential to substitute peat directly. Stucki et al. [19] studied the environmental and social impacts of different peat substitutes. They found that wood fibre and all eight other investigated materials are significantly more climate friendly than peat. Substrate components from cultivated, renewable, secondary residues, with little competition from other uses or substrate components from waste products, are particularly environmentally friendly. Makas [20] examined pure extruded wood fibre. Spruce and Douglas fir fibre had acceptable growing characteristics, but Scots pine wood fibre inhibited plant growth due to its wood extracts. Furthermore, the WHC was higher for spruce and Douglas fir than for peat if enough fines were present in the fibre. Dittrich et al. [4] investigated the water holding capacity of extruder-produced wood fibre from different raw materials. Results show that no fibre was able to reach the WHC of peat. However, acceptable WHC is achieved with specific machine settings of narrow aperture at 15 mm or 20 mm. The raw materials also had a great impact on the WHC. Sage in particular outperformed all other raw materials in WHC at identical machine settings. Jackson et al. [21] produced a pine-tree-based substrate with a hammer mill for greenhouse nursery crop production. This study highlighted that with increasing hammer-mill screen size, the container capacity (similar to the WHC) decreased, as did plant growth.

1.2. State of Research on the Extrusion of Biomass

The twin-screw extruder used in this experiment to comminute poplar wood chips into fibre was used in many other scientific investigations. Dietrich et al. [22] extruded hemp shives to produce fibre, and Gusovius et al. [23] and Pecenka et al. [24] extruded wet preserved hemp for fibre board production. Wallot et al. [25] investigated the comminution of hemp, softwood, hemp-shives, and common reed using a twin-screw extruder and subsequently a disc mill. For more details about twin-screw extrusion technology, please see Dittrich et al. [4]. Furthermore, extrusion technology is already used industrially to produce wood fibre for peat substitution. ZM-Technik is one company that produces industrial scale twin-screw extruders, specifically designed to defibre wood chips and produce a peat substitute. The quality label "Gütegemeinschaft Substrate für Pflanzen e.V" stands for a quality assurance association, which examines and assures a specific quality in seven product categories, of which one is a substrate. The company Klasmann-Deilmann produces a wood fibre peat substitute product called GreenFiber® with a reverse extruder system [3].

1.3. Hypotheses

Different parameters are calculated and monitored throughout the experiments conducted for this research. As a result, the following hypotheses are formulated:

1. Dry extruded poplar wood chips have a higher fine fraction due to increased friction in the extrusion process as a result of the absence of lubricant (water).
2. Poplar fibre with a high fine fraction results in high water holding capacity (WHC).
3. A high moisture content during extrusion leads to reduced specific energy demand (SED) because more water decreases friction and therefore comminution.

2. Materials and Methods

2.1. General Information

Investigations on WHC and particle size distribution were conducted on fibre samples produced in the SED trials. For better comparison, every investigation of SED and WHC was executed fourfold. In particular, the same samples from each extrusion fibre production repetition were used for all subsequent investigations. As a result, it is necessary to compare different mean values statistically estimated from raw data than mean values aggregated previously.

2.2. Raw Materials

For these experiments, only wood chips from poplar clone Max 3 (*Populous nigra* L. × *Populus maximowiczii* Henry) cultivated on fields at ATB premises without the use of any pesticides, herbicides, or fertiliser were used.

The wood chip size after harvest and before processing in the twin-screw extruder was P31. P31 is an abbreviation that describes wood chips as follows:

- 60% of the wood chips must be between 3.15 mm and 31.5 mm in size
- fine fraction (<3.15 mm) cannot exceed 10%
- coarse fraction (>45 mm) cannot exceed 6%

- maximum length of the particle cannot exceed 150 mm
- cross-section of oversized particles cannot exceed 4 cm^2

The raw material (Max 3 poplar wood chips) was processed into fibre in the twin-screw extruder at three different moisture contents. Firstly, freshly harvested wood chips with a moisture content of 55% (wet based) and a bulk density of 353 $kg{*}m^{-3}$ were processed immediately after harvesting. Semi-dry wood chips from a cold-air ventilated storage pile, with a moisture content of 45% and a bulk density of 289 $kg{*}m^{-3}$, were processed in a second experimental procedure. In a third experimental trial, dry wood chips from the same cold-air ventilated storage pile, with a moisture content of only 25% and a bulk density of 212 $kg{*}m^{-3}$, were processed into fibre. The moisture content of each raw material and all fibre was determined according to DIN EN ISO18134-2 [26].

2.3. Experimental Setup

The commercial twin-screw extruder (Model MSZK B90e, Lehman Maschinenbau GmbH, Jocketa, Germany) used for defibration in these experiments had a drive power of 90 kW. The experimental setup is shown in Figure 1. The raw material was fed into the extruder via a conveyor belt. Wood chips were defibred between 2 counter-rotating, intermeshing screws. Further details are described in Dittrich et al. 2021 [4]. In this extrusion process, the 2 extruder screws inflict high friction onto the wood chips, which results in temperatures between 95 °C and 120 °C [27]. As a result, the energy consumption for processing lignocellulose biomass, such as poplar wood chips, into fibre in a twin-screw extruder is rather high compared to olive or grapevine [4,28]. Therefore, energy consumption during the extrusion process was monitored. This parameter is called the specific energy demand (SED) and was calculated based on the data collected with a frequency converter and the mass throughput through the extruder per time (see Section 2.4). Apertures (opening at the end of the extruder) from 15 mm to 40 mm were applied in 5 mm steps for the wood chips.

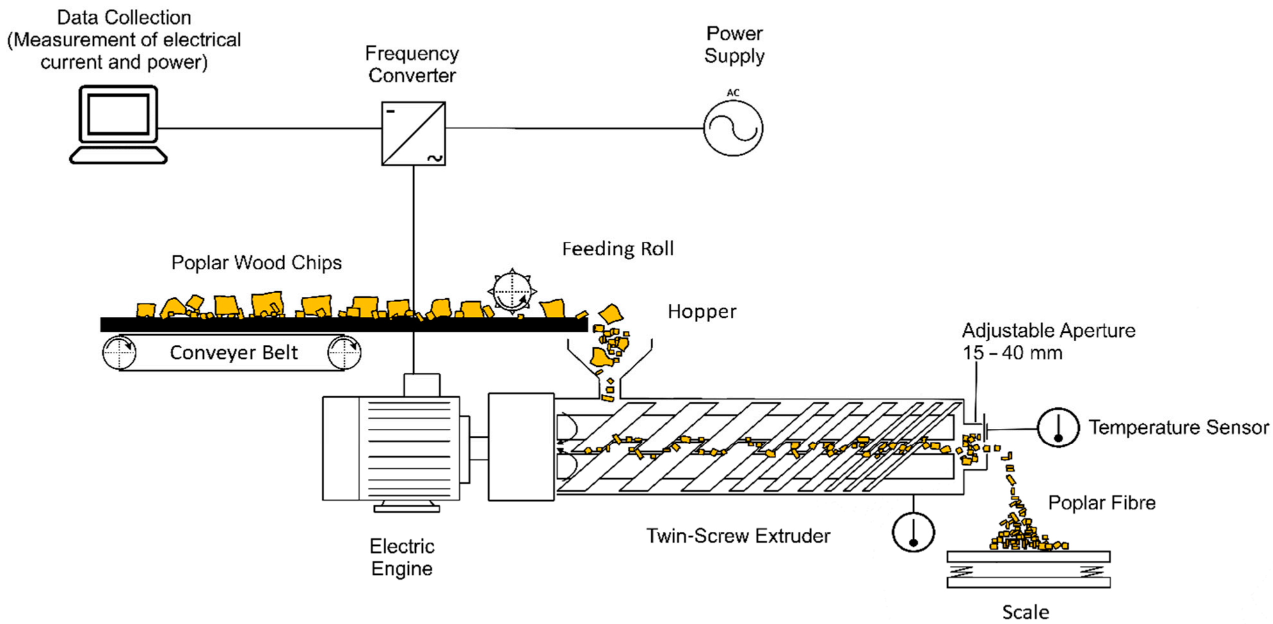


Figure 1. Experimental design of fibre processing in a twin-screw extruder.

Each investigation started with the determination of the (SED) for every single aperture setting. For each measurement of the SED at varying apertures, a fourfold measurement was conducted. Fibre samples were taken according to DIN EN ISO 14780 [29] from every individual processing run (single experiment) and investigated in detail regarding the

WHC and particle size distribution. Consequently, each single repetition from the extruder can be linked to the exact WHC and fibre analysis repetition (see Table 1).

Table 1. Overview of all investigated traits, number of samples, and repetitions.

Measurement/Trait	Unit	Repetitions/Sample Size	Standard/Method
Specific energy demand at:	kWh t^{-1}	n = 4	Calculation with values collected from frequency converter and scale (Equation (1))
➢ Aperture (15–40 mm)	mm		
➢ Moisture content (output material)	%		
Sieving analysis per aperture	%	n = 4	ISO 17827 [31]
Water holding capacity per aperture	%	n = 4	DIN EN 13041 [30]
Moisture content input material	%	n = 10	DIN EN ISO 18134–2 [26]
Sample preparation	-	n = 1	DIN EN ISO 14780 [29]
X-50 (average particle size)	mm		

In each single experiment, between 5 kg and 10 kg of wood chips were processed. This means that for each aperture setting, approximately 30 kg of wood chips were needed and 5 to 6 aperture settings were investigated for each raw material. In total, approximately 550 kg of wood chips were processed into fibre for this research.

The duration of a single SED measurement was 2 to 5 min depending on the width of the aperture and the resulting throughput. The entire fibre content of each single measurement was collected and dried in a large industrial scale blow dryer (Model Luftus-213206, Luftus Zwenkau Anlagenbau GmbH, Zwenkau, Germany) at 160 °C until it reached approximately 10% moisture content (DIN EN ISO 18134-2) [26], which took approximately 10 min. At this moisture content, the fibre was stored for further investigation. Dried fibre was put into sealed plastic bags and stored in the processing hangar, so that the moisture content remained at 10%.

The material supply is always metered in such a way that the extruder runs at 2/3 of its maximum power consumption. Short-term peak loads can be absorbed without the extruder triggering the overvoltage protection and coming to a standstill.

2.4. Specific Energy Demand (SED)

The power consumption (kW) data for calculating the specific energy demand were collected with a computer-controlled frequency converter. For the throughput (mass output per time), the power consumption during extrusion, and the dry matter content, the specific energy demand (kWh $t_{DM}{}^{-1}$) was calculated based on dry matter, according to Equation (1). The idle energy consumption was determined and subtracted from the overall power consumption of the extruder.

Equation (1), calculation of specific energy demand:

$$W_{spec} = \frac{(P_{ex} - P_{Id}) \times t_{ex}}{m_d} \quad (1)$$

W_{spec}, specific energy demand for extruding based on dry matter [kWh t^{-1}];
P_{ex}, average power consumption during extrusion [kW];
P_{Id}, average idle power consumption during extrusion [kW];
t_{ex}, time required for extruding 1 fibre batch [h];
m_d, dry matter of the produced fibre batch [t].

2.5. Water Holding Capacity

The volume-based WHC was measured according to DIN EN 13041 [30] in a water-tension measuring box, as is common for fibre applications in horticulture. Therefore, fully saturated fibre was placed in a double-ring cylinder and dewatered on the sand bed at a suction tension of −1 kPa and −5 kPa. For the calculation of the WHC, only the lower part of the double-ring cylinder was included. The difference in water mass within the fibre (after drainage and drying at 105 °C) divided by the volume of the lower double ring, results in the WHC. Further details about the measurement procedure are described in DIN EN 13041 [30] and Dittrich et al. 2021 [4].

Additionally, the mass-based WHC was calculated for a better comparison of the extrusion effect on the fibre properties. The mass-based WHC relates to the ability to hold water on the dry-matter mass of the sample.

2.6. Sieving Analysis

A sieving analysis was conducted according to ISO 17827 [31] for all individual samples. For each analysis, 100 g of fibre was sieved sequentially with 10 sieves from 5.6 mm down to 0.25 mm. The coarse fraction has been defined as the percentage of fibre which did not pass through a sieve at a mesh width of 3.15 mm. The fine fraction, alternatively, has been defined in this research as every particle that passes through a sieve with a mesh width of 0.5 mm. On the basis of the cumulative particle size distribution curve, the X-50 has been calculated as the sieve width at which exactly 50 mass-% of all particles would pass through due to their shape and size [32].

2.7. Statistical Analysis

The Pearson correlation coefficient was calculated to assess the relationship between various factors and traits, specifically SED, WHC, aperture setting, dry matter, X-50, and fine and coarse fraction. Correlations were calculated separately for the different raw materials.

The influence of aperture nested within raw material, dry matter content, and volume-based WHC at −1 kPa and −5 kPa (10 cm and 50 cm water column) on the specific energy demand was tested with a generalised ANCOVA (analysis of covariance) model with a negative binomial distribution assumption and a log link function. Dry matter content and WHC at −1 kPa and −5 kPa were considered regression factors.

Differences between aperture levels nested within raw material levels were tested in multiple pairwise comparisons within the same raw material or within the same aperture. *p*-values were adjusted for multiple testing with the simulation method provided in the LSMESTIMATE statement of the GLIMMIX procedure in SAS 9.4, at a global significance level of 5%.

In a similar way, the influence of aperture nested within raw material and dry matter content on WHC at −1 kPa and −5 kPa was tested with an ANCOVA model where dry matter content again was included as a regression factor. These models assume normally distributed residuals. Post hoc tests were undertaken in the same way as noted above.

3. Results

3.1. Volume-Based Water Holding Capacity

Figure 2 shows the WHC (volume based) of extruded poplar fibre at −1 kPa (A) and −5 kPa (B) for all aperture settings and moisture contents. At first impression, the WHC decreased with increasing aperture, up to an aperture of 35 mm for dry and semi-dry extruded wood chip fibre at a suction tension of −1 kPa. Table A2 shows that the decrease of −1 kPa WHC with increasing aperture was only significant ($p < 0.05$) for fresh processed fibre at 15 mm in comparison to 25 mm, 30 mm, 35 mm, and 40 mm. Semi-dry wood chip fibre WHC differed significantly from the 20 mm WHC to 35 mm and 40 mm, as well as WHC from 25 mm to 35 mm and 40 mm. WHC (−1 kPa) differences between raw materials were only significant between semi-dry and dry wood chips at apertures of 35 mm and 40 mm. At −5 kPa (Figure 2B), only a slight decrease was visible, with increasing aperture only up to 30 mm for dry and semi-dry extruded wood chip fibre. Table A3 indicates that the only significant difference in WHC appeared between the 20 mm and 35 mm aperture within semi-dry extruded wood chip fibre.

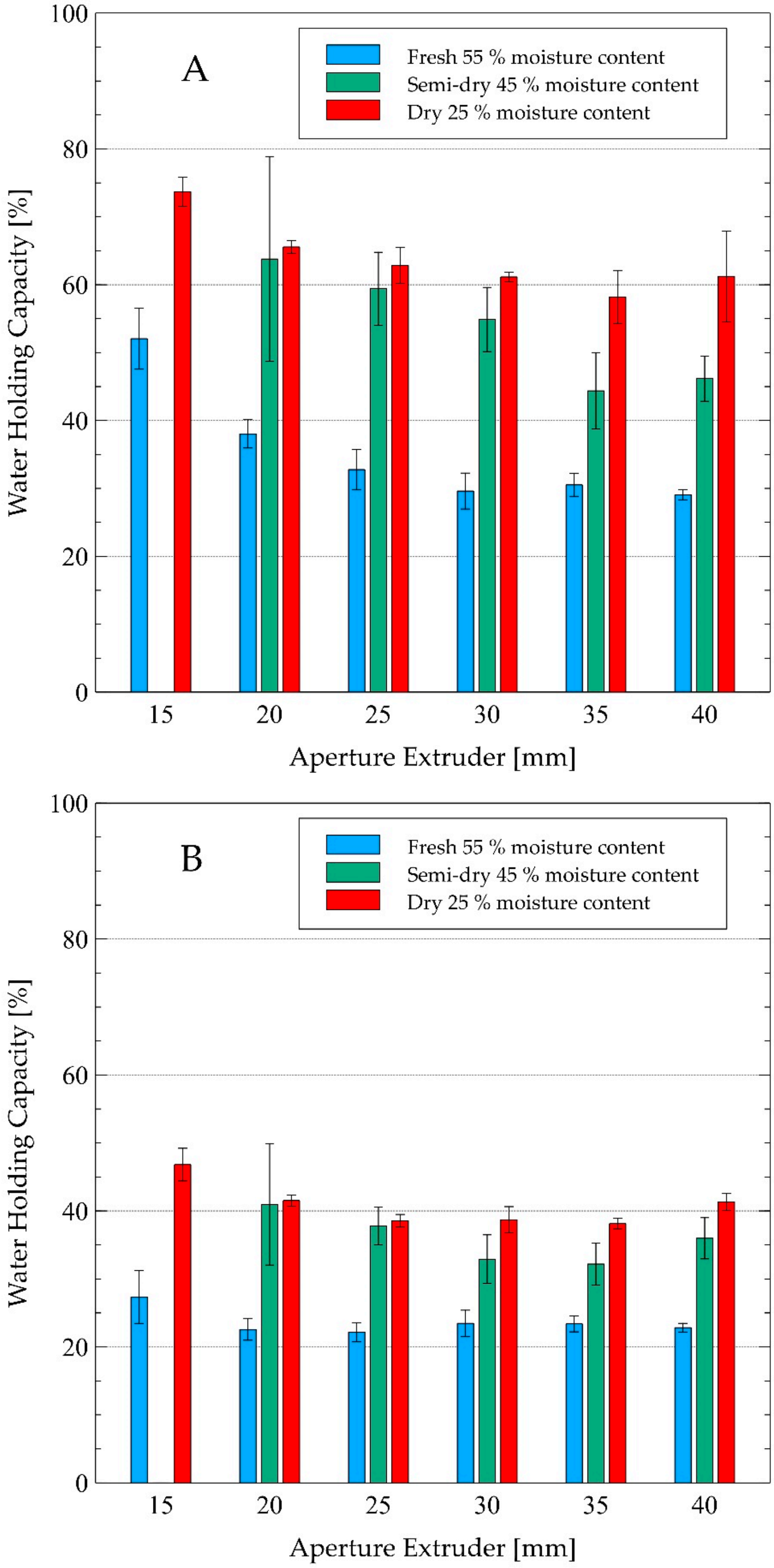


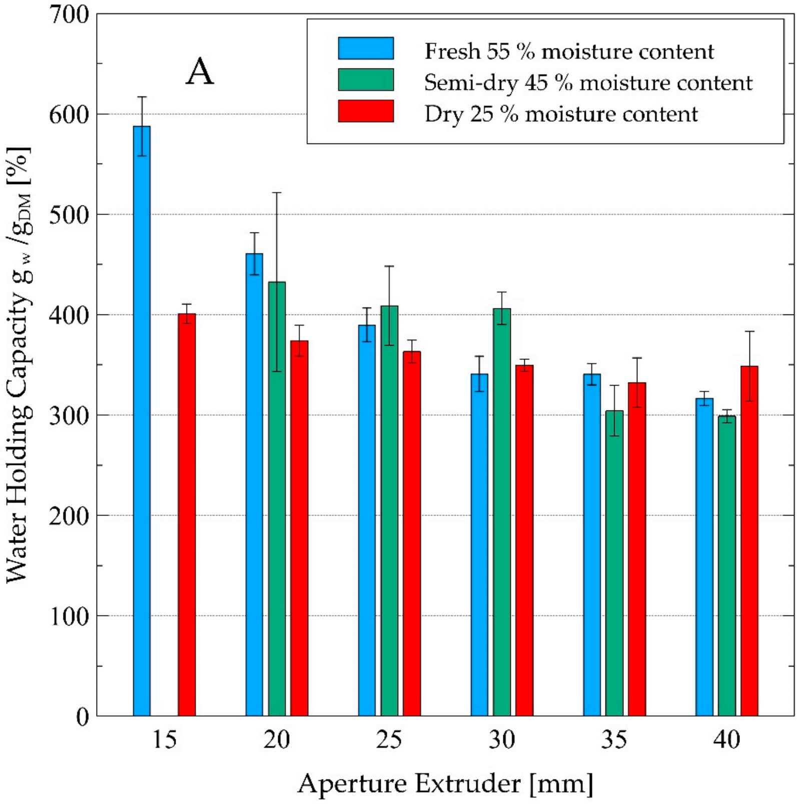
Figure 2. Volume-based WHC (DIN EN 13041) of −1 kPa (**A**) and −5 kPa (**B**). Comparison of fresh, semi-dry, and dry extruded poplar.

According to Figure 2B, the best WHC for all aperture settings was achieved when the poplar wood chips were dry prior to extrusion, yet this is not significant. The difference between the WHC of dry and semi-dry extruded wood chip fibre was a lot smaller compared to the difference between dry and fresh extruded wood chip fibre. The WHC value for the 15 mm aperture is missing for semi-dry wood chip fibre, because the overvoltage protection of the extruder was triggered multiple times. Due to this fact, the 15 mm aperture setting measurements were cancelled for semi-dry wood chips.

The difference in WHC between dry and semi-dry wood chips was marginal, and not significant for −5 kPa suction tension at all apertures (Figure 2B).

3.2. Mass-Based Water Holding Capacity

When the WHC is calculated based on dry matter, the results change notably. The WHC (Figure 3) was significantly ($p < 0.05$) higher for fresh extruded wood chips at suction tensions of −1 kPa and an aperture of 15 mm (Table A4) compared to fibre processed between 20 mm and 40 mm from identical raw material. At this setting, poplar fibre could hold almost six times its dry mass in water. The WHC of fresh extruded wood chip fibre processed at 20 mm was also significantly higher than the WHC of fibre processed between 30 mm and 40 mm. Increasing the aperture did not make a significant difference in the WHC with dry extruded wood chip fibre; however, compared to the WHC of fresh extruded wood chip fibre at 15 mm, the WHC from dry processed wood chip fibre was significantly smaller. With dryer raw material, the bulk density of the fibre increased. This effect applies to all raw materials but is not as substantial as that of volume-based WHC. In addition, the differences between fibre from varying raw material moisture contents were smaller in mass-based WHCs compared to volume-based WHCs. Bulk density was not affected by aperture setting but was affected by moisture content prior to extrusion. Additionally, the WHC of semi-dry extruded wood chip fibre was significantly better than the WHC of dry extruded wood chip fibre, both processed at 20 mm and 25 mm apertures. The WHC within the semi-dry extrusion process differed significantly for 35 mm and 40 mm aperture settings when compared to 20 mm, 25 mm, and 30 mm. This means, with increasing aperture, the WHC significantly decreased for the stated apertures. At −5 kPa suction tension, only the WHC of the semi-dry extruded wood chip fibre processed at 15 mm aperture was significantly smaller than the WHC of dry extruded wood chip fibre processed at 15 mm aperture (Table A5). None of the other results differed significantly with regard to raw material moisture content. Within the semi-dry extrusion wood chip fibre, the WHC at 20 mm aperture was significantly larger than the WHC at 35 mm and 40 mm within the processed wood chip fibre.



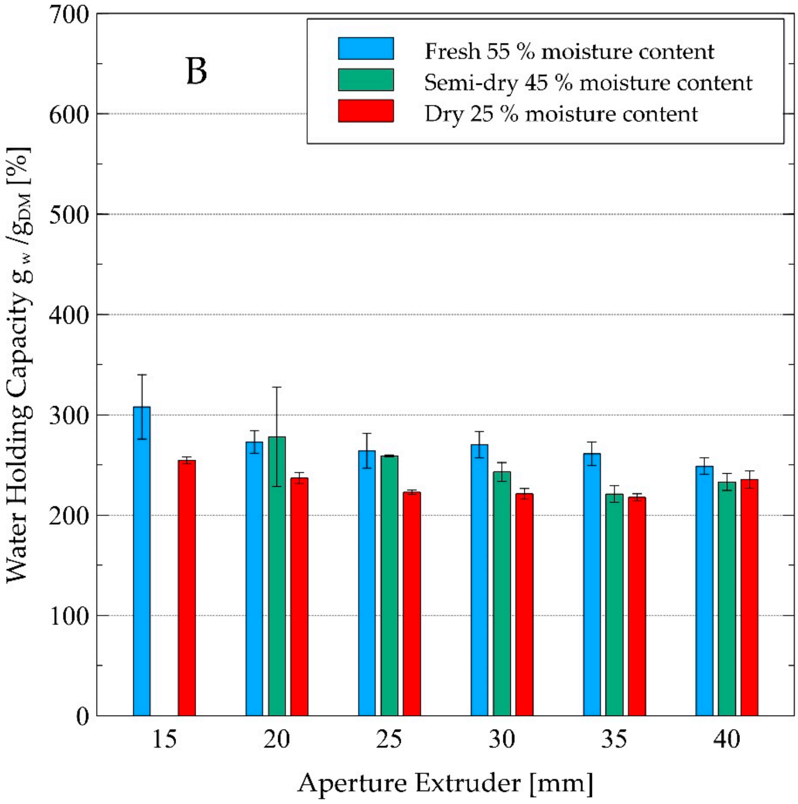


Figure 3. Dry matter-based WHC of −1 kPa (**A**) and −5 kPa (**B**). Comparison of fresh, semi-dry, and dry extruded poplar.

3.3. Specific Energy Demand

The SED (Figure 4) decreased with increasing apertures regardless of the moisture content of the raw material. The reduction in SED with increasing aperture of fresh and semi-dry extrusion processing was significant for most measurements (Table A1). A different result occurs at 40 mm aperture.; where fresh and semi-dry defibration are almost equal in SED, dry defibration in SED was twice as high. Interestingly, within the dry extrusion experiments, the similar SED at 30 mm and 35 mm aperture settings was only significantly different to the SED of a 40 mm aperture. No other SED differed significantly. At a 20 mm aperture, the semi-dry wood chip defibration resulted in the highest SED. Additionally, SED of fresh and semi-dry wood chip processing is not significantly different, even though the means seem to indicate otherwise.

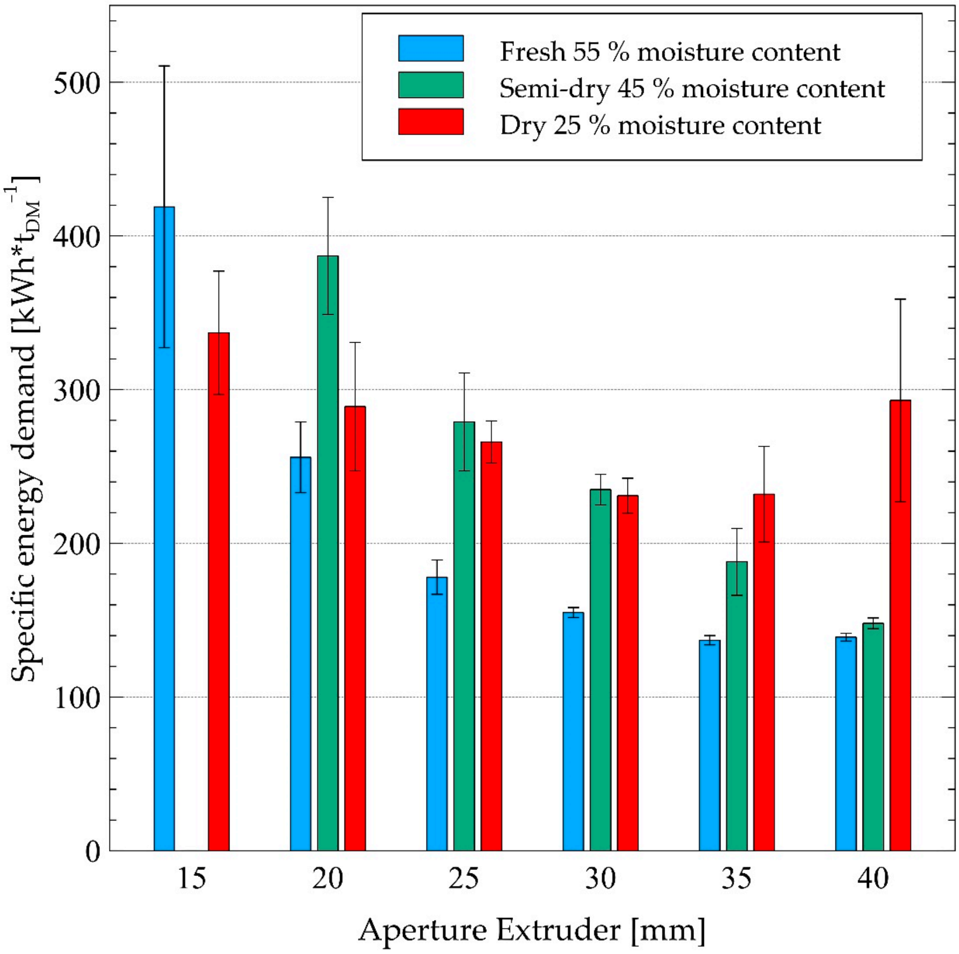


Figure 4. Specific energy demand for all apertures and moisture contents.

According to Figure 4, at a 15 mm aperture the wet wood chip processing resulted in a higher SED than the processing of dry wood chips, yet the difference was not significant (Table A1). Semi-dry wood chips were not able be processed because the overvoltage protection of the extruder was triggered. After several attempts, it was decided to skip this aperture setting for semi-dry wood chip extrusion. Furthermore, during the semi-dry extrusion process, all SED values differed significantly from each other except 25 mm to 30 mm and 30 mm to 35 mm. The strongest linear correlation (0.66575) was found to be between the SED and WHC of −1 kpa (dry matter based). As a result, the WHC −1 kpa (dry matter based) was chosen to be the characterising variable for the analysis of variance of the SED. Significant differences are shown in Table A1 in the Appendix A.

3.4. Mass Flow

Figure 5 shows the dry matter fibre mass flow exiting through the aperture at each trial conducted. With increasing aperture, the dry matter mass flow increased because the feed was accelerated to keep the machine in optimal working parameters with regard to SED. With decreasing moisture content, the dry matter mass flow also decreased. Dry wood chip processing had the smallest dry matter mass flow of all apertures except 20 mm, where it is equal to semi-dry wood chip processing. Fresh wood chip fibre had the highest dry matter mass flow at every aperture setting compared to dry and semi-dry wood chip processing.

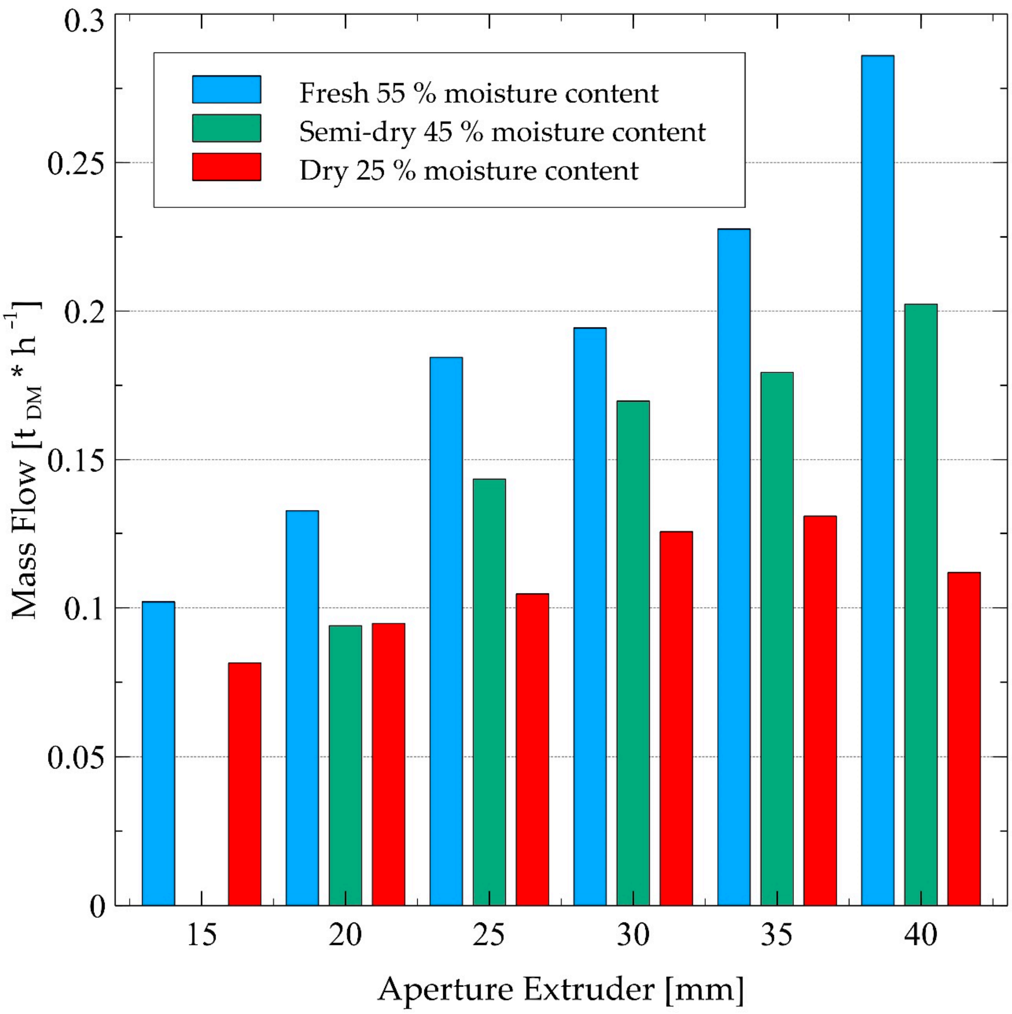


Figure 5. Dry matter mass flow of each raw material at all apertures.

3.5. Sieving Analysis

Figure 6 shows that the particle size distribution of poplar fibre from wood chips processed in the twin-screw extruder in fresh and dry conditions are almost identical. The semi-dry process, on the other hand, resulted in more fines and less coarse material. The X-50 value is also almost identical for fresh and dry processed fibre and smaller for semi-dry processed fibre.

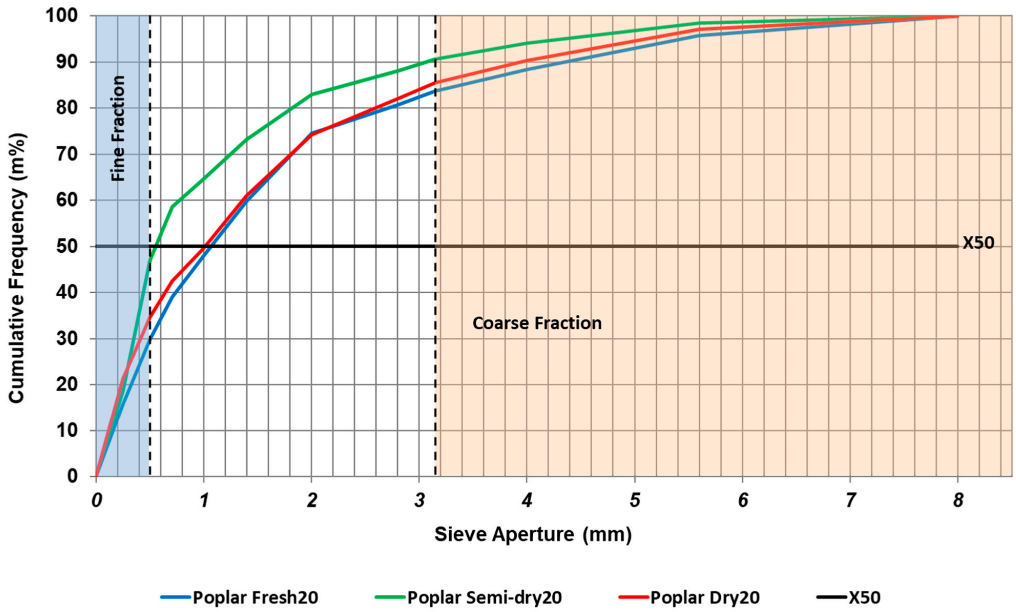


Figure 6. Particle size distribution of fresh, semi-dry, and dry extruded wood chips into fibre extruded at a 20 mm aperture.

3.6. X-50 Value

Figure 7 shows the X-50 value of each sample calculated from the fourfold determination of the sieving analysis. It is clearly visible that the semi-dry fibre had smaller X-50 values compared to fresh and dry extruded wood chip fibre at identical apertures. Dry and fresh wood chip fibre had similar X-50 values. In this series of investigations on poplar fibre, the X-50 value reached between 0.46 and 1.74 for fresh and dry extruded wood chip fibre. Semi-dry approached the X-50 value of 1.23.

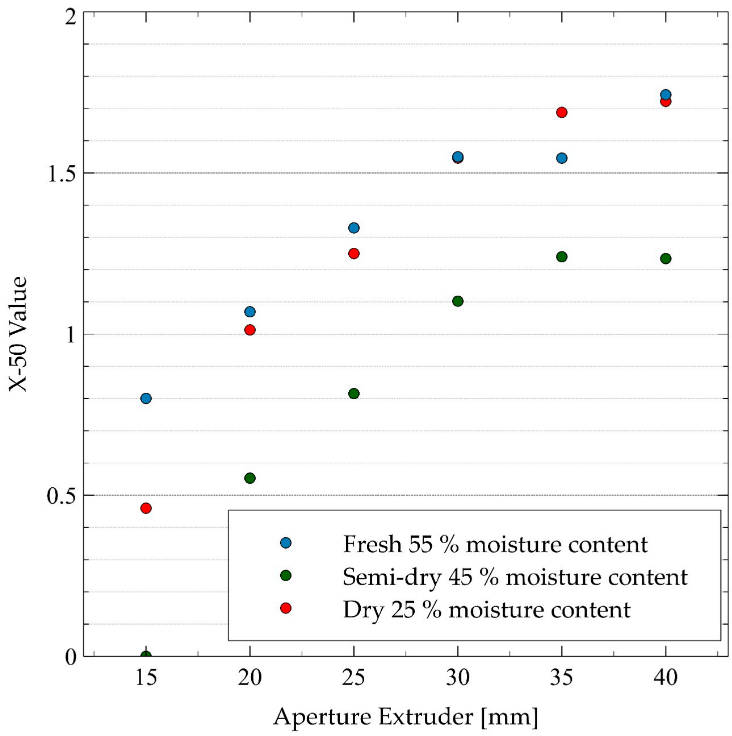


Figure 7. Average particle size (X-50 value) of poplar fibres with dependence on aperture setting during extrusion.

3.7. Decrease in Moisture Content

Figure 8 shows how the moisture content of each fibre developed during the extrusion. In the semi-dry trials, the moisture content decreased by 37% at a 40 mm aperture. Compared to the dry (7%) and fresh (4%) extrusion trials at a 40 mm aperture, this decrease was much stronger. The decrease in moisture content during the dry extrusion trials increased with smaller aperture. No similar development could be seen for fresh and semi-dry trials. The strongest decrease in moisture content at a 20 mm aperture was measured for semi-dry extrusion (36%), compared to fresh (14%) and dry (21%) trials.

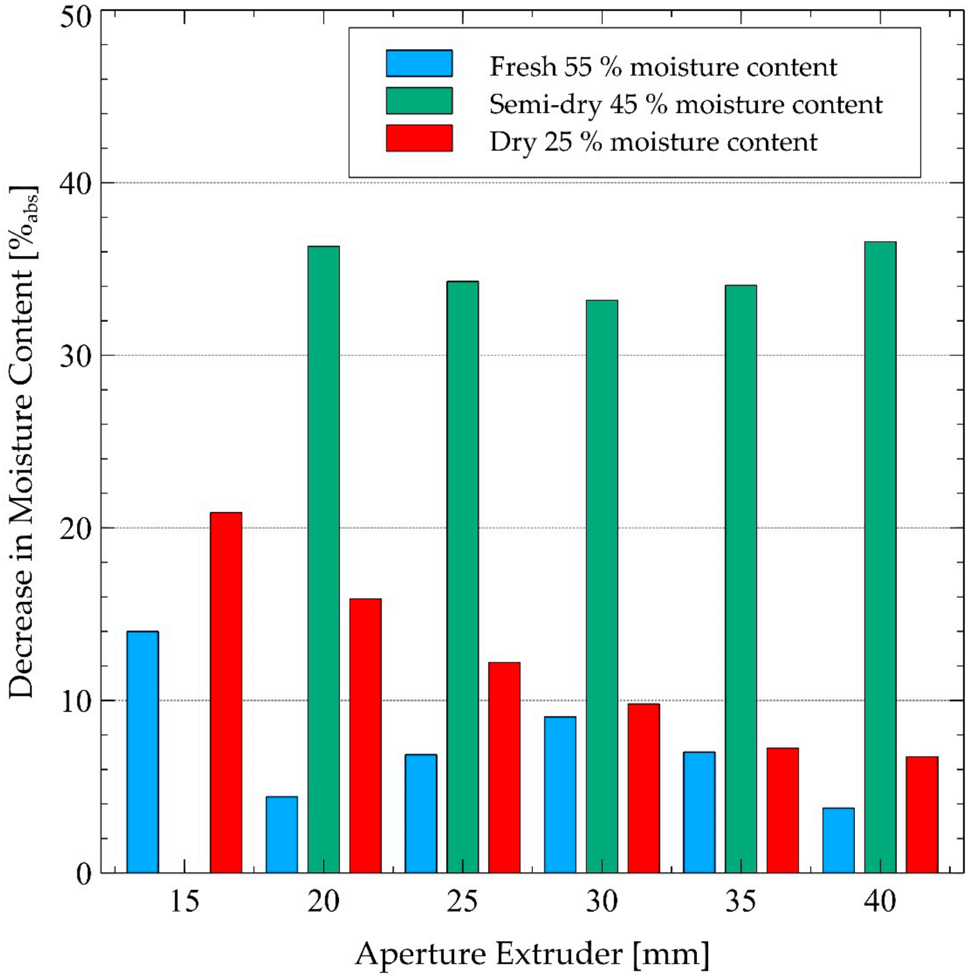


Figure 8. Decrease in moisture content during extrusion [%] in relation to moisture content prior to extrusion.

4. Discussion

4.1. Water Holding Capacity

It is clearly visible in Figure 2 that the WHC at −1 kPa and −5 kPa of dry and semi-dry extruded wood chip fibre was considerably higher than that of fresh extruded wood chip fibre. In general, the dry extruded wood chip fibre achieved the highest WHC in every single investigation, yet it was not significant. Less water during the comminution and defibration process caused higher friction between the wood particles, as well as between the wood particles and the milling tool inside the extruder. Consequently, this should have resulted in a higher fine material proportion as well as in lower average fibre length (represented by the X-50 value) of the produced fibre. The particle size distribution (Figure 6) clearly supports this assumption if semi-dry and fresh extruded wood chip fibre are compared. However, the differences in fine fractions and the X-50 of fresh and dry extruded wood chip fibre were much smaller.

Fibre, as the raw material, was treated with heat several times in the processing chain of these experiments. Firstly, the wood chips and resulting fibre were heated in the extrusion process, followed by drying of the fibre for storage purposes. This might have influenced the fibre on a molecular level, namely the saturation point. The fibre saturation point for untreated poplar wood lies at 33% moisture content (dry matter based) [33]. It is reached when the moisture content of the wood is high enough so that the cell walls are fully saturated with moisture but no free water is present in any part of the visible microscopic capillary structure [34].

Bal [33] showed that the fibre saturation point drops to 24% (dry matter-based) when poplar wood is heated to 200 °C for three hours. A similar result was found in another study for different types of wood. Almeida et al. [35] found that the fibre saturation point of three different eucalyptus species decreases significantly when treated with temperatures higher than 220 °C for five hours. Esteves 2009 [36] discovered that water absorption by cell walls is reduced when wood is treated with heat. The chemical wood structure changes due to a decrease in hydroxyl groups. As a result of intensified crystallinity, water molecules have increasingly limited access to hydroxyl groups. Also, lignin was cross-linked. Furthermore, Sehlstedt-Persson [37] discovered that wood dried at high temperatures has reduced hygroscopicity.

Extruding fresh wood chips led to less friction and therefore lower temperatures, as more water was present in the process which acted as a lubricant. As a result, lower processing temperatures did not decrease the fibre saturation point as strongly as high processing temperatures would have. In these experiments, less water in the extrusion process led to more friction and higher temperatures. This statement is supported by the increased SED according to the recorded data during extrusion. This increase in friction and therefore temperature could have led to a reduced fibre saturation point, which could have resulted in a lower WHC. However, this only applied to the dry matter-based WHC.

In Figure 2, it is clearly visible that the volume-based WHC of fresh wood chips had the lowest values compared to semi-dry and dry wood chips. The dry matter-based WHC (Figure 3), on the other hand, was highest for fresh wood chips, second highest for semi-dry wood chips, and lowest for dry wood chips.

This raises the question: why were the effects of processing parameters on volume based-WHCs in most cases inverted compared to the dry matter-based WHCs? If bulk density is taken into consideration, this question can be answered. In comparison, dry extruded wood chip fibre had the highest bulk density, fresh extruded the lowest. If the WHC is calculated based on volume, the dry matter is not taken into account, as this WHC is based on the volume of the fibre inside the lower part of the double-ring cylinder from the WHC determination (see Section 2.5). A high bulk density results in more dry matter at the same volume. Consequently, a high amount of dry wood can absorb more water.

4.2. Specific Energy Demand

The specific energy demand (SED) decreased with increasing aperture for all raw material moisture contents. A larger aperture led to a shorter processing time per mass unit which resulted in less energy consumption. This explains the decrease in SED with increasing aperture. However, the SED for dry wood chips extrusion did not decrease with larger aperture. It was smallest at an aperture of 30 mm, but increased significantly at 40 mm. An explanation for this increase could be the overfilling of the extruder with wood chips; due to a larger aperture, more raw material could be fed into the machine. As a result, more energy was required for the comminution of wood chips as well as for the transportation of the extruded fibre through the aperture. However, a higher filling level during the process also increased the throughput, which should have resulted in a smaller SED. If the raw material is very coarse, it will also be coarser towards the aperture where more large particles are present in the reverse flow prior to the exit (aperture). This could also have increased the SED.

The moisture content during extrusion also had an effect on the SED. Water acts as a lubricant and reduces friction in the process, and therefore reduces the SED. However, the SED for extrusion of fresh wood chips was higher than for dry extrusion at an aperture of 15 mm. A reason for this could be a higher dry matter mass flow (see Figure 5). Figure 5 does support this statement. Dry matter mass flow of the fresh wood chips was higher compared to dry wood chips. Fresh wood chips contained more water, which reduced friction in the process compared to dry or semi-dry wood chips. Due to reduced friction, increasing the dry matter mass flow and therefore the filling level could have led to an increased SED.

4.3. WHC and X-50 Correlation

Table 2 shows the correlation coefficients of WHC and X-50, as well as their significance. All correlation coefficients of WHC and X-50 were negative and significant. This means that when the X-50 increased, the WHC decreased accordingly. The highest correlation coefficient (0.9633) was found between the X-50 of fresh extruded wood chip fibre and the dry matter-based WHC at a suction tension of −1 kPa. This points to a very strong correlation. The smallest correlation (0.444) occurred for volume-based WHC and X-50 of fresh extruded wood chip fibre. Figures for all WHC–X-50 correlations can be seen in Figures A1–A4 in Appendix A. These correlations indicate that coarser extruded wood chip fibre led to a reduced WHC.

Table 2. Correlation coefficients and their *p*-values of WHC and X-50.

	Fresh X-50	**Semi-Dry X-50**	**Dry X-50**
WHC vol −1 kPa	−0.89853	−0.69404	−0.82398
p-value	<0.0001	0.0007	<0.0001
WHC vol −5 kPa	−0.44422	−0.53415	−0.74877
p-value	0.0297	0.0153	<0.0001
WHC dm −1 kPa	−0.96333	−0.69123	−0.76833
p-value	<0.0001	0.0007	<0.0001
WHC dm −5 kPa	−0.69150	−0.68993	−0.75180
p-value	0.0002	0.0008	<0.0001

5. Conclusions

As a result of these experiments, if scaled up to a large industrial scale, it is not mandatory to moisten dry wood chips before processing them into fibre the regards to the SED. Wood chips can be processed either freshly harvested at moisture contents above 50% or dried to 25% moisture content. The resulting fibres from volume-based WHCs are reduced, with an increasing aperture to an aperture of 30 mm at a −1 kPa suction tension. At −5 kPa suction tension, only the 15 mm aperture had a considerably better volume-based WHC compared to the other apertures.

If the WHC is calculated on a mass basis, the differences are considerably smaller, especially at a −5 kPa suction tension. Additionally, the best volume-based WHC was measured for dry extruded wood chip fibre, but when calculated on a mass basis, fresh extruded wood chip fibre had the best WHC. This result is a matter of calculation. Further research has to be conducted on how this affects the functionality of the different fibres in growing substrates.

In multiple particle size analyses, the semi-dry extruded wood chip fibre had higher fine fractions and less coarse fractions compared to fresh and dry extruded wood chip fibre, with intermediate WHC and mass flow at a high SED. Overall, the SED was highest for semi-dry wood chip fibre production.

In terms of the best dry matter throughput, which is industrially of high interest, fresh wood chips should be processed. Due to reduced friction and grinding as a result of more water being present in the process, fresh wood chips had the highest dry matter mass flow at every aperture. However, fresh extruded wood chip fibre requires additional drying after the extrusion process, which increases energy consumption for this particular process. Interestingly, dry and semi-dry extruded wood chip fibre did not need additional drying after extrusion; the friction inflicted enough heat to dry the fibre during the process and it exited with shelf-stable moisture contents between 10% and 15%. Despite this, the WHC (volume based) of dry and semi-dry extruded wood chip fibre is better than that of fresh extruded wood chip fibre.

Conclusively, hypotheses two and three can be confirmed if only dry and fresh extrusion processing is compared. This also applies to hypotheses two and three presented in the context of physical properties. Hypothesis one, however, is rejected because semi-dry wood chip fibre had more fines compared to dry processed wood chip fibre. Therefore, the absence of water cannot be the sole influencing factor on particle size distribution.

Also, a higher SED for processing and a lower WHC (volume based) was measured for semi-dry wood chip fibre, compared to dry and fresh extruded wood chip fibre. These facts require detailed future research to determine what accounts for these unexpected deviations.

The findings from this research are essential for the application of peat substitute fibre from poplar wood chips in growing media. Not only can fibre with an acceptable WHC be produced all year round from stored dry wood chips, the extrusion process also does not need additional water, while the SED is reasonable and the particle size distribution is acceptable. No additional drying of the produced fibre is required. This shows the high potential of extruded poplar fibre as a substitute for peat in growing media.

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Appendix A

Table A1. SED Significance, plus (+) and green background indicates significant differences, minus (-) indicates statistically insignificant differences.

	F_15	F_20	F_25	F_30	F_35	F_40	SD_20	SD_25	SD_30	SD_35	SD_40	D_15	D_20	D_25	D_30	D_35	D_40
F_15																	
F_20	-																
F_25	+	+															
F_30	+	+	-														
F_35	+	+	+	-													
F_40	+	+	-	-	-												
SD_20		-															
SD_25			-				+										
SD_30				-			+	-									
SD_35					-		+	+	-								
SD_40						-	+	+	+	+							
D_15	-																
D_20		-					+					-					
D_25			-					-				-	-				
D_30				-					-			-	-	-			
D_35					-					+		-	-	-	-		
D_40						-					+	-	-	-	+	+	

Table A2. WHC (volume based) significance −1 kPa, plus (+) and green background indicates significant differences, minus (-) indicates statistically insignificant differences.

	F_15	F_20	F_25	F_30	F_35	F_40	SD_20	SD_25	SD_30	SD_35	SD_40	D_15	D_20	D_25	D_30	D_35	D_40
F_15																	
F_20	-																
F_25	+	-															
F_30	+	-	-														
F_35	+	-	-	-													
F_40	+	-	-	-	-												
SD_20		-															
SD_25			-				-										
SD_30				-			-	-									
SD_35					-		+	+	-								
SD_40						-	+	+	-	-							
D_15	-																
D_20		-					-					-					
D_25			-					-				-	-				
D_30				-					-			-	-	-			
D_35					-					+		-	-	-	-		
D_40						-					+	-	-	-	-	-	

Table A3. WHC (volume based) significance −5 kPa, plus (+) and green background indicates significant differences, minus (-) indicates statistically insignificant differences.

	F_15	F_20	F_25	F_30	F_35	F_40	SD_20	SD_25	SD_30	SD_35	SD_40	D_15	D_20	D_25	D_30	D_35	D_40
F_15																	
F_20	-																
F_25	-	-															
F_30	-	-	-														
F_35	-	-	-	-													
F_40	-	-	-	-	-												
SD_20		-															
SD_25			-				-										
SD_30				-			-	-									
SD_35					-		+	-	-								
SD_40						-	-	-	-	-							
D_15	-																
D_20		-					-					-					
D_25			-					-				-	-				
D_30				-					-			-	-	-			
D_35					-					-		-	-	-	-		
D_40						-					-	-	-	-	-		

Table A4. WHC (mass based) significance −1 kPa, plus (+) and green background indicates significant differences, minus (-) indicates statistically insignificant differences.

	F_15	F_20	F_25	F_30	F_35	F_40	SD_20	SD_25	SD_30	SD_35	SD_40	D_15	D_20	D_25	D_30	D_35	D_40
F_15																	
F_20	+																
F_25	+	-															
F_30	+	+	-														
F_35	+	+	-	-													
F_40	+	+	-	-	-												
SD_20		-															
SD_25			-				-										
SD_30				-			-	-									
SD_35					-		+	+	+								
SD_40						-	+	+	+	-							
D_15	+																
D_20		-					+					-					
D_25			-					+				-	-				
D_30				-					-			-	-	-			
D_35					-					-		-	-	-	-		
D_40						-					-	-	-	-	-	-	

Table A5. WHC (mass based) significance −5 kPa, plus (+) and green background indicates significant differences, minus (-) indicates statistically insignificant differences.

	F_15	F_20	F_25	F_30	F_35	F_40	SD_20	SD_25	SD_30	SD_35	SD_40	D_15	D_20	D_25	D_30	D_35	D_40
F_15																	
F_20	-																
F_25	-	-															
F_30	-	-	-														
F_35	-	-	-	-													
F_40	-	-	-	-	-												
SD_20		-															
SD_25			-				-										
SD_30				-			-	-									
SD_35					-		+	-	-								
SD_40						-	+	-	-	-							
D_15	-																
D_20		-					+					-					
D_25			-					-				-	-				
D_30				-					-			-	-	-			
D_35					-					-		-	-	-	-		
D_40						-					-	-	-	-	-	-	

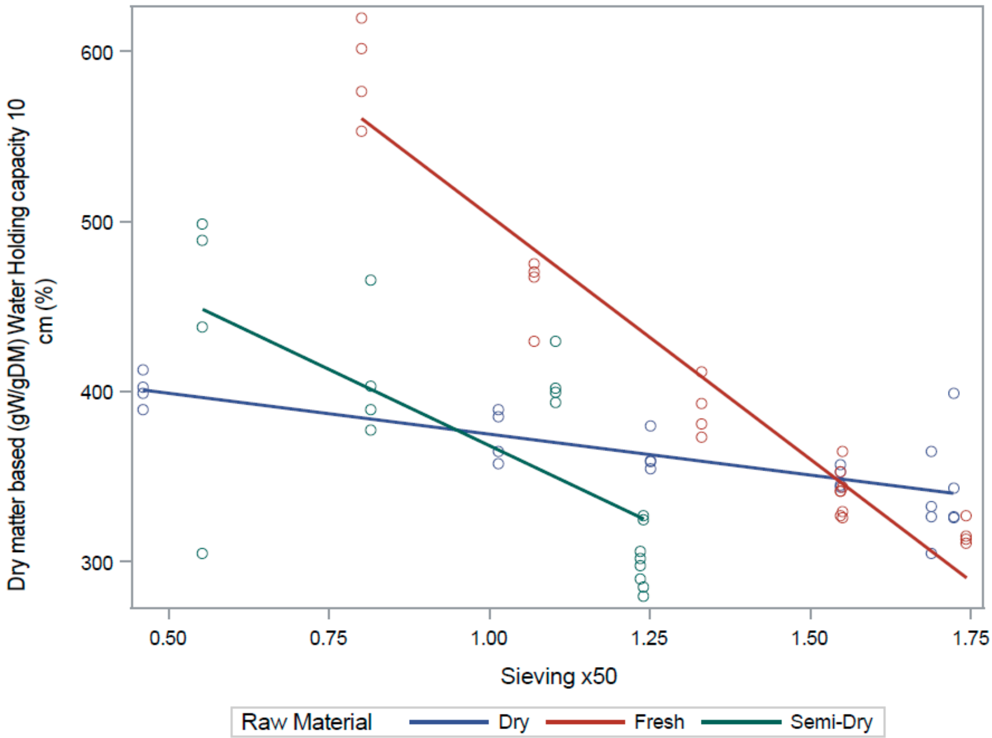

Figure A1. Correlation between WHC −1 kPa (dry matter based) and X-50.

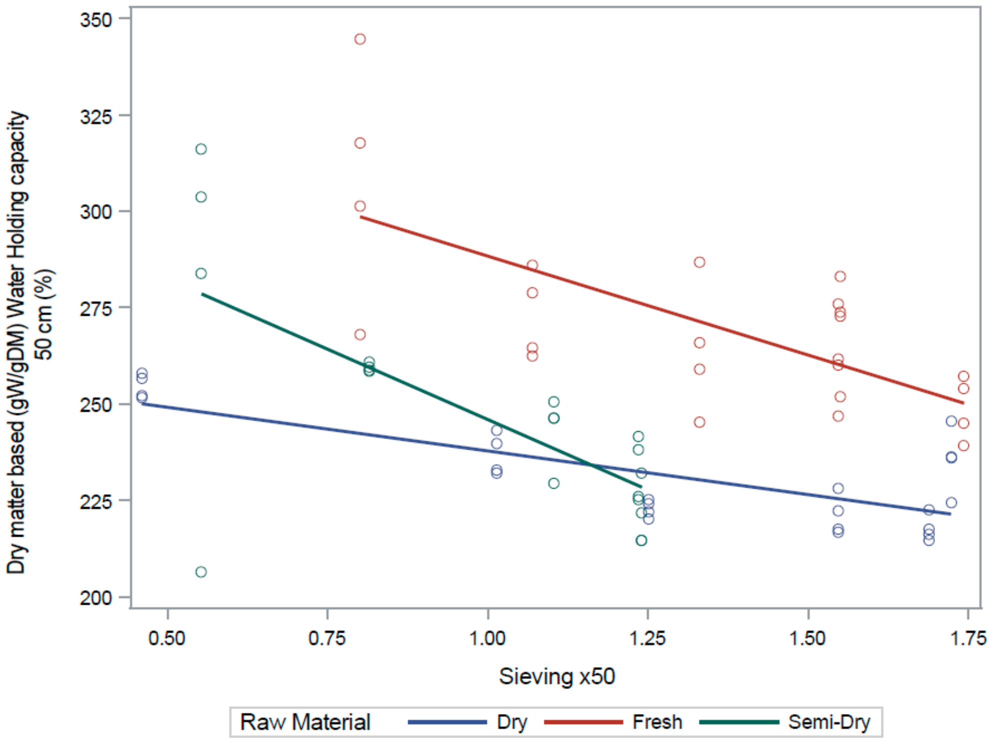

Figure A2. Correlation between WHC −5 kPa (dry matter based) and X-50.

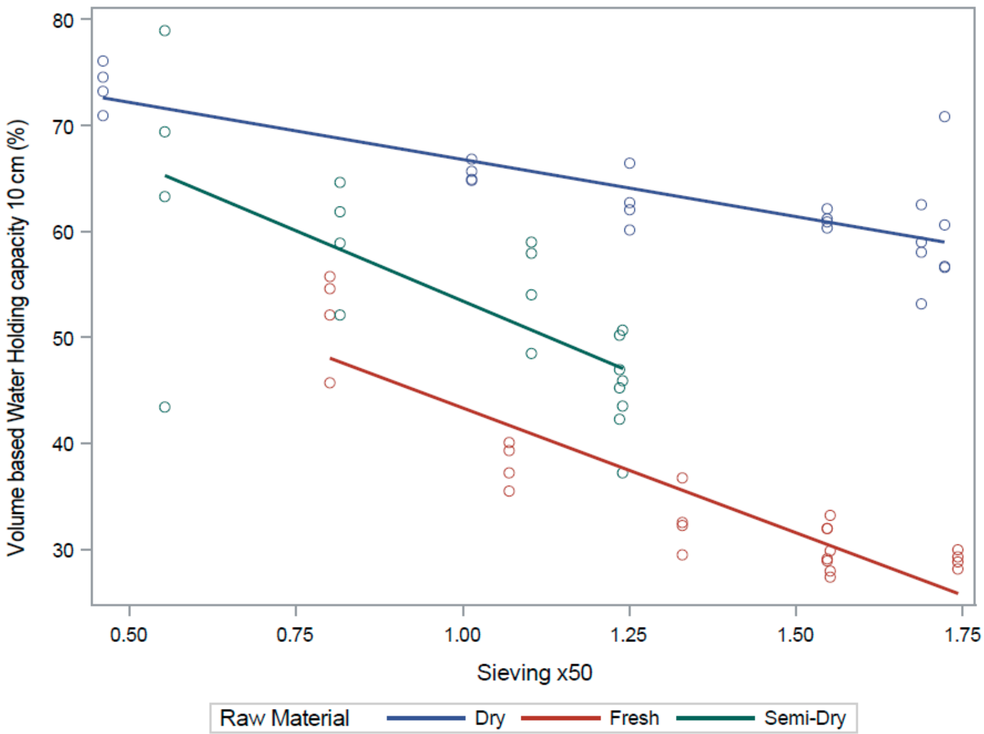

Figure A3. Correlation between WHC −1 kPa (volume based) and X-50.

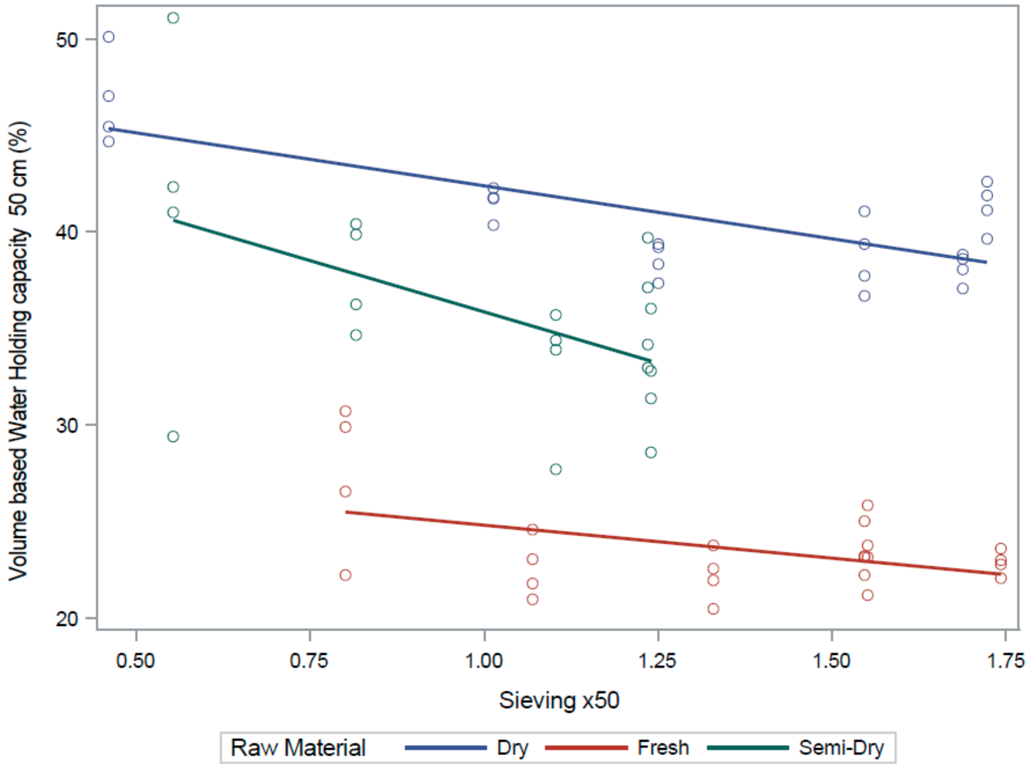

Figure A4. Correlation between WHC −5 kPa (volume based) and X-50.

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