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Extrusion of Different Plants into Fibre for Peat Replacement in Growing Media: Adjustment of Parameters to Achieve Satisfactory Physical Fibre-Properties

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Abstract: Peat is a highly contentious input in agriculture. Replacing or reducing peat by substitution with lignocellulosic biomass processed into fibre by twin-screw-extrusion could contribute to more sustainable agriculture with regard to horticultural production. Therefore, plant wastes including pruning from *Olea europaea* L. and *Vitis* spp. L., residues from perennial herbs like *Salvia* spp. L., *Populus* spp. L. and forest biomass were processed to fibre for peat replacement with a biomass extruder. The water-holding-capacity (WHC), particle-size-distribution and other physical fibre characteristics were determined and compared to peat. The specific energy demand during extrusion was measured for aperture settings from 6–40 mm. No fibre reached the 82% WHC of peat. At the setting of 20 mm of all materials investigated, *Salvia* performed best with a WHC of 53% and moderate specific energy demand (167 kWh $t_{DM}{}^{-1}$) followed by *Olea europaea* with a WHC of 43% and a low energy demand (93 kWh $t_{DM}{}^{-1}$). For *Populus*, opening the aperture from 20–40 mm decreased energy demand by 41% and WHC by 27%. The drying of biomass for storage and remoistening during extrusion increased the specific energy demand. Despite a lower WHC than peat, all investigated materials are suitable to replace peat in growing media regarding their physical properties.

Keywords: twin-screw extrusion; fibre; agricultural residues; peat substitution; specific energy demand; water holding capacity

1. Introduction

Using extracted peat from bogs as a growing media is a very contentious input in horticulture. About 26% of all terrestrial carbon which accumulated since the Last Glacial Maximum are being stored in peatlands [1–3] so these are recognised as a vital global carbon reservoir and sink.

The production and use of defibrated lignocellulosic biomass as a substitute can be a solution to reduce the extraction of peat for growing media from peatlands. Worldwide, approximately 40 million m^3 of peat are used annually as raw material for horticultural growing media [4]. Even partly replacing this can have a significant impact on peat extraction, usage and the related greenhouse gas emissions. Therefore, both science and industry are currently involved in the extensive manufacturing of peat reduced products.

Any material to substitute peat in growing media should pose comparable physical properties such as water holding capacity (WHC) and wettability, bulk-density, air capacity, structure and structural stability. Also, the material should have a high WHC while having sufficient volume of air-filled pores; it should not degrade significantly during plant growth. It should not contain weed seeds, phytotoxic compounds or other microbiological contaminants; it should have an adjustable, appropriate pH (4–7), be easy to modify with respect to nutrient content while having a good buffering capacity and low nitrogen-immobilization [5,6].

A small industrial scale counter rotating twin-screw extruder can be one technical solution to process lignified biomass into fibre as a peat substitute [7,8]. With reference to the Latin root, extrusion is understood as the pressing of material through a small opening under the action of force [9]. This fibre substitute may replace some, ideally all, functions of peat in growing media although a combination of composted and extruded wood fibre, or fibre mixed with other composted materials, could be used if necessary.

Different materials are composted and used as a peat substitute already [6], but composting takes significantly more time and space for producing a peat substitute compared to mechanical processing e.g., extrusion. In recent decades, great efforts have been devoted to the use of composts for peat replacement—their main drawbacks are high pH and electrical conductivity [10]. However, this can be minimised by the careful selection of raw materials (wood fibre, coir, compost, bark, etc.) and regulation of the composting process.

Whereas an extruder is fast and does not take much space, the energy requirement for defibring biomass in a twin screw extruder is quite high [11]. The extrusion creates a lot of friction and therefore temperatures are raised up to 95–120 °C [12]. This could have a sanitising effect, e.g., when treating invasive species. At these temperatures, all seeds and potentially reproductive plant parts will be killed, along with other pathogens such as fungi and mould which occur in wood materials [13].

Another controversial alternative for peat-free substrates is vermiculite. It is a non-renewable mined material that consists of hydrated aluminium-iron-magnesium silicate. During production vermiculite is exposed to temperatures as high as 1000 °C, requiring very high energy consumption. It has an accordion-like structure and is already used in peat-free growing substrates based on wood compost. It is used widely due to its low bulk density, high WHC (five times of its weight) and pH-neutrality [14]. Additionally, wood and coco fibre also show drawbacks as peat alternatives. Coir fibre is a high-priced product that is produced from the thick outside layer of the coconut fruit. Coconut palms are mostly cultivated in monoculture in Asia and Latin America which results in long transportation routes and therefore in high import costs for Europe [5]. Using wood fibre to substitute peat results in a business competition between substrate producers and the wood timber industry. Forest areas are limited and an increased demand for wood will lead to higher raw material prices [15]. Also, according to Schmilewski [5] the WHC is very low, and the nitrogen immobilisation is high.

In the present study, researchers from several European countries in the Horizon 2020 project Organic-PLUS (EU funded GA 774340) [16] contributed by shipping different residual materials from perennial plants which are currently poorly utilised to the pilot plant at the Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB) in Potsdam, Germany, where the materials were extruded and further studied. Poplar (*Populus* spp. L.), which has become popular as a bioenergy material and hence highly available with short rotation coppices all over Europe, is very relevant as a potential material for substituting peat. Forest biomass from Spain, which is highly available due to officially mandatory forest fire prevention, was also studied. Residues from medicinal and aromatic plant production in Turkey, including sage (*Salvia* spp. L.), thyme (*Thymus vulgaris* L.), laurel (*Laurus nobilis* L.) and oregano (*Origanum vulgare* L.) were investigated because they are currently commonly incinerated. Other materials of interest are pruning and otherwise left-over materials from growing of hop (*Humulus lupulus* L.), grapes (*Vitis* spp. L.), olives (*Olea europaea* L.) and other fruit, sea buckthorn (*Hippophae rhamnoides* L.), etc., which are also often incinerated or otherwise poorly utilised. Kir et al. showed that it is possible to grow olive saplings in olive pruning material which was chopped, extruded and fertilized [17]. The fibre material for this trial was produced by extrusion at ATB.

1.1. State of Research of Peat Substitution with Fibre

A number of investigations for peat substitution in growing media using short rotation coppices like poplar have been carried out in recent decades, but the results and data have not been published sufficiently. Moreover, processing medicinal plant production residues as well as pruning from vineyards and olive orchards into a peat substitute is a novelty.

Reinhofer reviewed the literature on the state of the art in peat substitution as well as the current availability of raw material to produce such substitute. Machinery to produce peat substitutes such as a twin-screw extruder and future possibilities for increasing the use of peat alternatives to prevent bogs from being overexploited were also investigated [6]. The results show that the applicability of peat-free or at least peat-reduced products is entirely possible and is also used commercially to a limited extent.

More literature on peat substitution was reviewed by Schmilewski who found that wood fibre has a very high air capacity yet very low water holding capacity. The shrinkage value is low, the rewettability is good and the pH value is moderate (4.5–6) [5].

A former German study (Grießer [8]) investigated extruded plant materials as peat substitute for commercial horticulture. From eight in Lower Saxony available raw materials, cup-plant (*Silphium perfoliatum* L.), giant Chinese silver grass (*Miscanthus* x *giganteus*, J.M.Greef & Deuter ex Hodk. & Renvoize) and (common) reed (*Phragmites australis* CAV.) achieved good results in mixtures with peat in cultivation trails. In a study of spruce (*Picea abies* L.) material by Gruda and Schnitzler [7], it was found that fibres with a high proportion of fines had good WHC and were suitable as a peat substitute in growing media for vegetable cultivation. Moreover, press pots for transplants, which are normally made from 100% peat, could be manufactured despite replacing 30 vol% by fibrous material. Additionally, König [18] found that yields of seedling cultivation of different lettuces, fennel and cabbages were comparable for growing media with pure peat and growing media at a mixing rate of 50% extruded wood fibre (poplar and spruce) and 50% peat. These were tested on farm trails by 10 different farmers. It was found that a major problem was the logistics of transporting wood fibre or refined peat substitute to the smaller vegetable growing companies.

Kharazipour [19], on the other hand, examined WHC and other physical properties of different peat substitutes from various raw materials processed by thermo-hydrolytic defibration. The WHC was determined by draining a fully saturated fibre sample on a sand bed. A comparison of the WHC, pore volume and air capacity shows that the air capacity increases and the WHC decreases in all substrates with an increasing fibre content. Makas et al. [20] investigated pure extruded fibres from European spruce (*Picea abies* L.), douglas fir (*Pseudotsuga menziesii* M.) and Scots pine (*Pinus sylvestris* L.). Fibre from spruce and Douglas fir had satisfactory growing characteristics, whereas Scots pine wood fibre was not suitable as a growing media due to wood extracts which seemed to inhibit plant growth. With enough fines in the fibre, WHC was even higher for spruce and Douglas fir than for peat.

1.2. State of Research and Concept about Extrusion of Biomass

A counter-rotating, intermeshing twin-screw extruder like the one used for the experiments presented in this paper, in principle, behaves like a positive displacement pump. This concept is explained in detail by White [21]. Modern counter-rotating, intermeshing twin-screw extruders for the processing of biomass apply pressure on to the input material to force it through an aperture. The milling or defibration degree is a result of the design parameters of the machine (e.g., geometry of the screws), process parameters (e.g., temperature, machine setting like screw speed and aperture) and raw material properties (e.g., moisture content, biomass composition, wood density) [22]. An increase in pressure always pairs with a rise in temperature [23]. The high temperature and high pressure are connected to a higher energy input into the extrusion process compared to other machinery used to crush wood like hammer mills or disc mills [24].

Wood chips are split mainly parallel to the fibre bundle structure during extrusion. The pressure rises to 1500 kPa and temperatures > 150 °C occur inside the extruder. A sudden relaxation (steam explosion) results in tearing of the cell structure. The high temperature in the extruder also causes the lignin to reach its glass transition temperature. This transition is manifested as an abrupt softening of the lignin at a relatively narrow temperature range of 100–170 °C [25,26]. The lignin hardens again after cooling down. Hietala et al. [27] found that using a twin-screw extruder is an efficient process to separate individual fibres from woodchips. Wood chips from spruce (*Picea abies* L.) were extruded in a laboratory scale twin-screw extruder and investigated for physical properties. The fibre length, width and aspect ratios were investigated and statistically analysed. As a result, they found that the fibres have higher aspect ratios when processed in a twin-screw extruder than wood flour which is normally used for wood-polymer composites.

Processing hemp shives into fibre in a small industrial scale twin-screw extruder and a pressure less disc mill was investigated by Dietrich [28]. The fibre was analysed with a focus on the effect of process parameters on different physical properties. It was found that the granulometric (measurement of the size distribution in a collection of grains) and geometric properties (length, width) of the fibres were particularly affected by the setting of the aperture. A large aperture led to a large increase in the share of coarse particles. A small aperture led to increase in the level of dust. It was not possible to determine the dewatering behaviour with the Schopper–Riegler Test [28] (dewatering test for in water suspended fibre). It was also found by Wallot et al. [29] that the quality and aspect ratio of fibre produced by a small industrial scale extruder is mainly determined by the source of raw material. As the raw material, different mixtures of wet preserved hemp and woodchips (softwood) were used.

Figure 1 (product path (a)) shows the processing steps of the raw materials that were studied here (poplar woodchips, hop, forest biomass, etc.) and how they are processed to fibre. The wide field of possible applications for extruder processed fibre is also pictured.

1.3. Hypotheses

The purpose of the present paper was to test, with a broad range of currently poorly utilised residual materials of plant origin, the effect of settings in the extrusion process on physical properties of the resulting fibre, to reveal which types of material are most promising for replacement of peat in growing media. WHC in particular is one of many physical properties which can be measured in growing media. Since all plants need water to grow, the ability to hold water is particularly important and was therefore in focus of this research. On basis of already conducted research and the general need to substitute peat in growing media, the following hypotheses on fibre properties were investigated in detail:

1. A small aperture opening leads to a larger fine-fraction and hereby increases the WHC.
2. Fibre with an even particle size distribution (balanced ratio of fines and coarse particles) have the highest WHC.
3. WHC varies between different raw materials at identical experimental setup, but also between batches of material for the same plant species, due to variation in characteristics such as chemical composition or moisture content during storage.
4. To achieve a higher WHC, higher specific energy demand for extrusion is required.

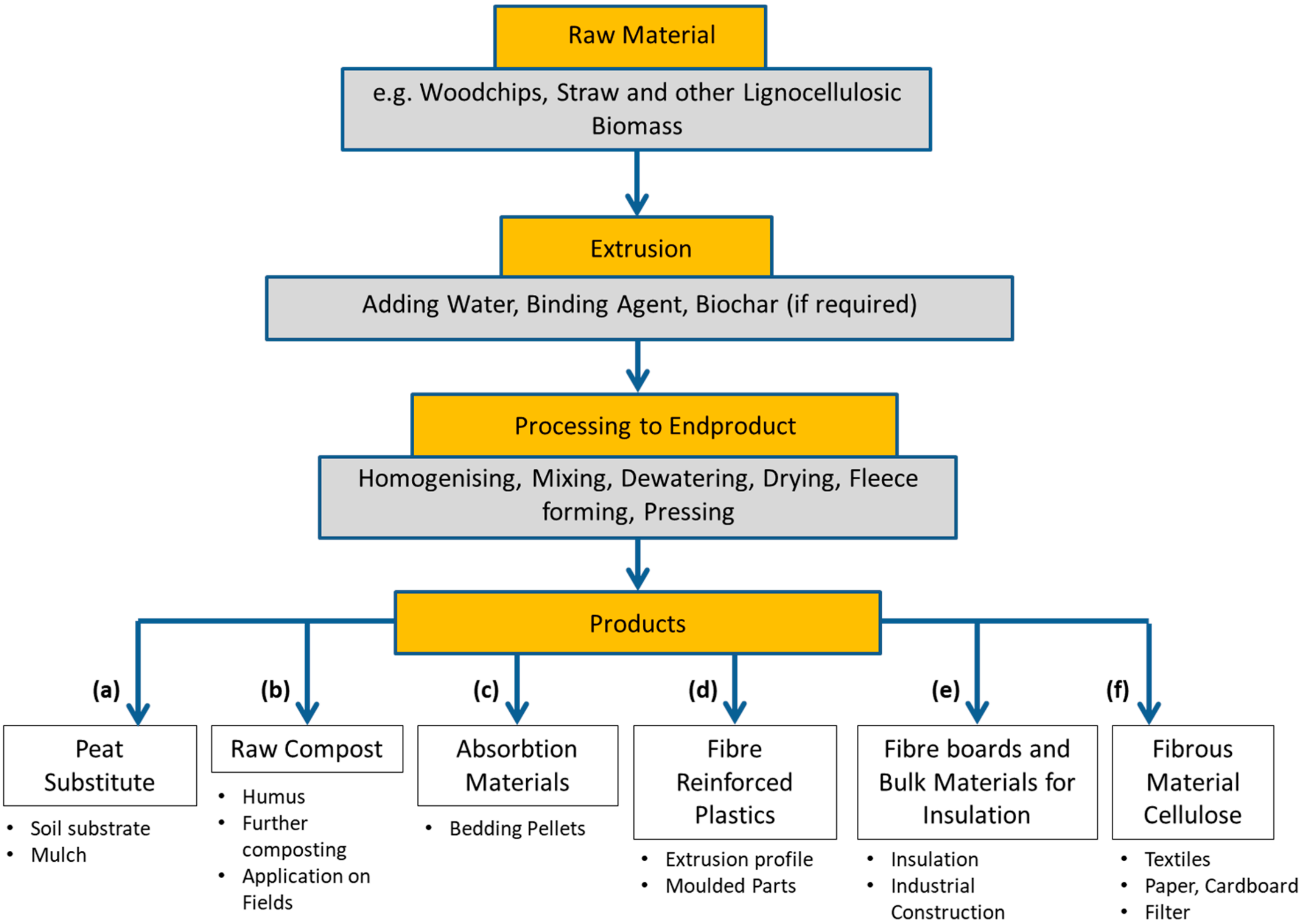


Figure 1. Processing steps and application of extruded wood fibre [22,30].

2. Materials and Methods

For this research project, the objective was to determine the influence of key parameters set in the extrusion process (e.g., aperture size, see Figure 2) on the WHC, bulk density, pore volume, shrinkage, particle size distribution and ash content of the resulting fibre as well as the specific energy demand during extrusion. The specific energy demand during fibre production plays an important role in the sustainability context. An analysis of the particle size distribution of all extruded materials at each aperture setting was also carried out. For the investigation of WHC a sandbox with an adjustable water column for different negative overpressure was constructed by ATB (Figure 3).

Table 1 shows all materials which were collected for this research. Whereas Scots pine and poplar have been subject to several former studies, the other 11 materials were novel with respect to extruded fibre characteristics. In total, 14 different materials including peat were investigated for WHC of which 11 consist of extruded fibre from poorly used lignocellulosic material. The following plants were processed into fibre and investigated: laurel (*Laurus nobilis* L.), olive (*Olea europaea* L.), thyme (*Thymus vulgaris* L.), sage (*Salvia* spp. L.), oregano (*Origanum vulgare* L.), black locust (*Robinia pseudoacacia* L.), poplar (*Populus* spp. L.), sea buckthorn (*Hippophae rhamnoides* L.), hop (*Humulus lupulus* L.), grape (*Vitis* spp. L.) and forest biomass, mainly Scots pine (*Pinus sylvestris* L.) and holly oak (*Quercus ilex* L.). The availability of raw materials like medicinal plant residues as well as olive prunings was limited because they were shipped to Potsdam by our project partners from Turkey. As a result, it was not possible to repeat specific energy demand measurements multiple times at an identical aperture setting for these materials as it was, for e.g., poplar or grapevine. Sand and coco-coir where also investigated for WHC for comparison.

Table 1. Raw material, origin and condition of samples, aperture setting and number of measurements for specific energy demand (dependent on availability).

Sample Code **	Raw Material					Aperture [mm]	Number of Specific Energy Demand Measurements
	Common Name	Scientific Name	Origin	Condition at Delivery	Preparation		
LD10	Laurel	*Laurus nobilis* L.	Turkey	dry leaves and branches 12% MC *	moisten to 50% MC	10	4
LD15						15	3
OLD10	Olive	*Olea europaea* L.	Turkey	dry chipped branches and leaves 11% MC	moisten to 50% MC	10	1
OLD15						15	1
OLD20						20	1
TD10	Thyme	*Thymus vulgaris* L.	Turkey	dry leaves and small sticks 13% MC	moisten to 50% MC	10	1
TD15						15	1
TD20						20	1
TD25						25	1
SD10	Sage	*Salvia* spp. L.	Turkey	dry branches 12% MC	moisten to 50% MC	10	1
SD15						15	1
SD20						20	1
SD25						25	1
ORD6	Oregano	*Origanum vulgare* L.	Turkey	dry leaves 11% MC	moisten to 50% MC	6	1
ORD10						10	1
BLF 20	Black locust	*Robinia pseudoacacia* L.	ATB plantation (SRC)	fresh whole trees 37% MC	chipping	20	4
BLF 25						25	4
BLF 30						30	4
PF15	Poplar	*Populus* spp. L.	ATB plantation (SRC)	chipped fresh trees 50–57% MC	none	15	5
PF20						20	5
PF25						25	6
PF40						40	5
PD30				chipped dry trees 10% MC	moisten to 50% MC	30	1
PD35						35	1
SBTF10	Sea buckthorn	*Hippophae rhamnoides* L.	Germany, harvest residues	fresh sticks, branches, berries 44% MC	chipping	10	1
SBTD15				dry chipped sticks, branches, berries and leaves 11% MC	moisten to 50% MC	15	5
SBTD20						20	5
SBTD25						25	4
HD15	Hop	*Humulus lupulus* L.	Germany, harvest residues	dry vines 10% MC	moisten to 50% MC	15	5
HD20						20	5
HD25						25	6
GVF15	Grape	*Vitis vinifera* L.	Germany, pruning residues	fresh vines 45% MC	chipping	15	5
GVF20						20	5
GVF25						25	5
FBF20	Forest biomass Mainly Scots pine and holly oak	*Pinus sylvestris*, L. *Quercus ilex* L.	Residues from forest cleaning	fresh collected and chipped 42% MC	none	20	5
FBF30						30	5
WP	Floratorf white peat	none	hardware store	appears as substrate pressed and dried in a block	none	not extruded	
C	Neudorf Kokohum Coir						
S	Sand		ATB plantation				

* MC—moisture content, wet based, ** Sample numbering: The first Letter/s stand for the abbreviation of common name for the Raw material followed by an "F" or "D" which describes if the material was extruded as fresh (F) material or arrived in a dried (D) stage and had to be remoistened. The Number at the end gives the aperture setting during extrusion. Examples:

LD 10
GV = grapevine
D = dry at delivery (remoistened prior to extrusion)
10 = aperture setting 10 mm

GVF15
L = laurel
F = fresh at delivery (extruded fresh)
15 = aperture setting 15 mm

Due to the large variation in materials tested, we had to choose an aperture setting which was able to process all materials. After testing apertures from 15–40 mm, a 20 mm aperture setting was shown to be adequate.

Table 2 provides an overview of the parameters investigated and the measurement methods used for this purpose. Further details on the respective methods are presented in the subsequent subchapters.

Table 2. Parameters investigated.

Parameter	Unit	Numbers of Samples per Batch	Methodology Specification
Moisture content (wet based) *	%	3	DIN EN ISO 18134–2 [31]
Sample preparation	-	1	DIN EN ISO 14780 [32]
WHC at all negative overpressures	%	4	DIN EN 13041 [33]
Shrinkage	%	4	DIN EN 13041 [33]
Bulk density (dry)	kg m^{-3}	4	DIN EN 13041 [33]
Particle density	kg m^{-3}	4	DIN EN 13041 [33]
Total Pore Volume	%	4	DIN EN 13041 [33]
Ash content	%	3	DIN EN 13039 [34]
Organic matter	%	3	DIN EN 13039 [34]
Specific energy demand (on dry matter basis, DM)	kWh t^{-1}	Continuous	Calculation with values collected from frequency converter and scale Equation no 2
Particle size distribution	%	3	ISO 17827 [35]
X50 (average particle size)	Mm	3	[36]

* Moisture content (defined as moisture content on wet basis, i.e., moisture mass fraction).

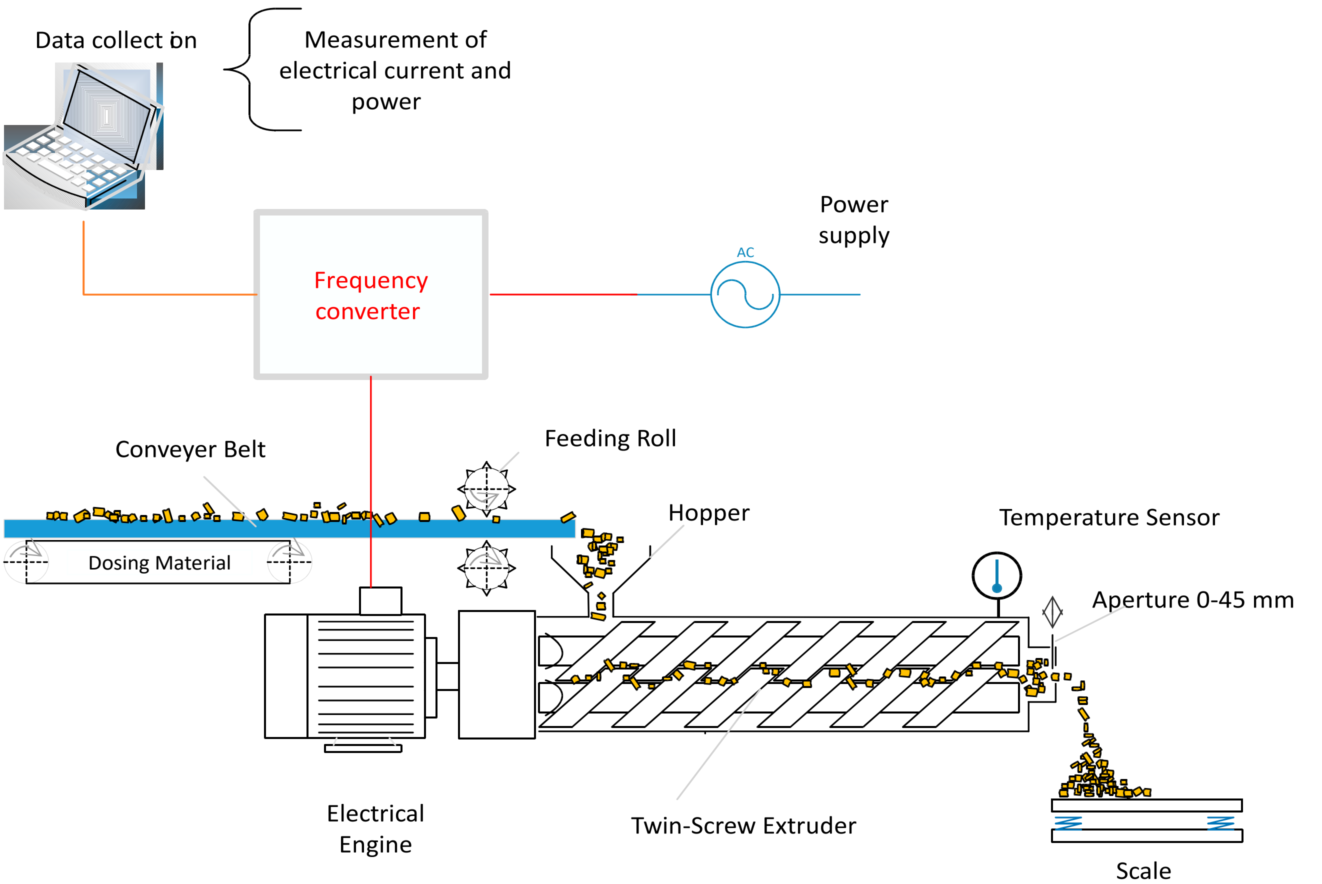


Figure 2. Experimental design of the twin-screw extruder.

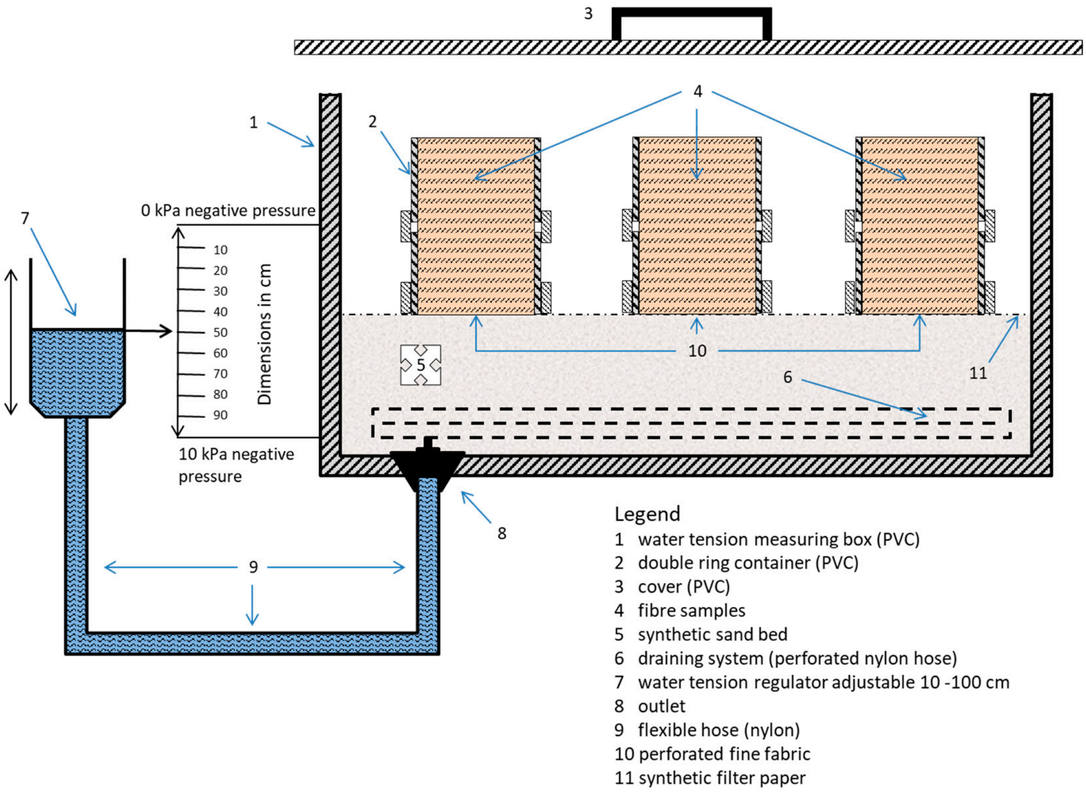


Figure 3. General setup of the water tension measuring box [33].

2.1. Procedure of Producing Fibre from Lignocellulosic Biomass

The plant materials were delivered in different states as shown in Table 1. To be able to process all raw material in the extruder at a constant throughput, a "chip-like" consistency was required. Hence, raw materials not being in the right state/shape were chipped with a stationary Jenz HE100 chipper (Jenz GmbH, Petershagen, Germany) using a 50 mm rectangular sieve [37].

The energy demand for extrusion and quality of the end products depends on the moisture content of the processed biomass. The moisture content of each raw material was determined according to the standard DIN EN ISO 18134-2 [31] and adjusted if required to have 45–55% moisture content (wet based) by adding water to the chipped raw material placed in a barrel for remoistening. This amount was calculated with the following Equation (1):

$$m_{wa} = \frac{m_{wc}}{\left(-1 + \left(\frac{1}{MC_t}\right) * 100\%\right)} - m_{wp} \quad (1)$$

where,

m_{wa}, mass of water to be added [kg]
m_{WC}, dry matter of chips/biomass [kg]
m_{wp}, mass of water present in chips/biomass before watering [kg]
MC_t, target moisture content [%], wet based.

After water was added to the chips the barrels were tumbled for 24 h so the water could be absorbed. The prepared chips were then fed by a conveyer belt via a hopper into the extruder as shown in Figure 2. The extruder ground and crushed the biomass to fibre before passing through the aperture which was set to a specific opening. After the fibre passed through the aperture it was sucked into a blow dryer which was operated at a temperature of 150 °C. The fibre stayed in the blow dryer for approximately 2 s and was then separated from the air by a cyclone. Drying needed to be done for storage reasons, as fibre is only storable at a moisture content below 20% to prevent decay as storage trials at ATB have shown.

2.2. Experimental Design of the Twin-Screw Extruder

For the fibre processing, a commercial twin-screw extruder Model MSZK B90e (Lehman Maschinenbau GmbH, Jocketa, Germany) with an electrical power of 90 kW was used (Figure 2). The aperture can be set to a maximum of 45 mm. Pre-testing showed that narrowing the aperture significantly sometimes triggered the overvoltage protection causing the extruder to turn off. For almost all species extruded, this occurred at an opening smaller than 15 mm, in some cases smaller than 10 mm.

All data for the calculation of the specific energy demand were collected with a computer-controlled frequency converter. The throughput was measured by mass of output per time. The moisture content of output was needed for the calculation of specific energy demand because it is dry matter based. On the basis of this data the specific energy demand was calculated according to Equation (2).

Equation (2), calculation of specific energy demand:

$$W_{spec} = \frac{(P_{ex}) \times t_{ex}}{3600 \times m_d} \times 1000 \quad (2)$$

where

W_{spec}, specific energy demand for extruding on dry matter basis [kWh t^{-1}];
P_{ex}, average power consumption during extrusion [kW];
t_{ex}, time required for extruding of one batch of raw material [h];
m_d, dry matter of the processed raw material batch [t].

The idle energy consumption was not excluded from this calculation because the screws of the extruder must always be floating in biomass. Running the extruder used for this research empty can result in severe machine damage. Additionally, when the extruder had processed most of the biomass fed, biomass always remained in the extruder. As a result, the idle energy consumption cannot be determined. In addition to that, screw geometry, extruder size and rounds per minute also influence the idle energy consumption. Consequently, there are no absolute values to be compared to other extruder plants or units. However, a comparison between the investigated materials in this research is definitely given.

2.3. Sample Preparation for Particle Size Analysis and Water Holding Capacity

The samples for particle size analysis and WHC were prepared according to the standard DIN EN ISO 14780 [32]. First, 1 kg of fibre was piled in cone shape with a small shovel. This was repeated three times. The third cone was than flattened with the shovel and separated into 4 equal sections. Two opposing sections were discarded and the other two were used for investigations.

2.4. Particle Size Analysis

Following the extrusion and drying process a particle size analysis was done for each material processed at various aperture settings according to ISO 17827 in triplicate [35]. For each single sieving analysis 100 g of fibre was used, being sieved sequentially: 5.6; 4; 3.15; 2.8; 2; 1.4; 0.71; 1; 0.5; 0.25 mm.

On the basis of the sieving analysis the particle size distribution and the X50-value were determined. The X50-value describes the sieve mesh width at which precisely 50 mass-% of all particles would pass due to their size and shape [36].

2.5. Analysis of Water Holding Capacity with a Water Tension Measuring Box

The WHC was determined according to DIN EN 13041 [33] by means of a water tension measuring box (see Figure 3). In this investigation, a fourfold investigation was conducted. First, samples of fibre were taken according to the standard EN ISO 14780. Deionised water was used for the operation of the water tension measuring box. To prevent fibre from picking up synthetic sand or getting stuck in the synthetic sand bed and therefore distorting the measurements, the bottom of the lower double ring cylinders was covered with very fine perforated fabric. The synthetic sand bed was also covered with a synthetic filter paper allowing only water to pass through. The fibre was filled in a polyvinylchloride (PVC) cylinder and fully saturated with water. After resting on the sand bed to dewater, the fibre from two preparing cylinders was evenly distributed into 4 smaller double ring cylinders in which the measurement was done. These were again fully saturated and afterwards dewatered on the sand bed. Only the lower part of the double ring container is weighed after dewatering at a desired suction tension in between −1 kPa and −5 kPa. On basis of the measurements for remaining water in the fibre after final drainage and following dry weight of the fibre after drying at 105 °C the WHC was calculated according to the standard DIN EN ISO 13041. The shrinkage, total pore volume and bulk density were calculated as part of determining the WHC.

2.6. Ash Content, Organic Matter and Particle Density

The ash content and organic matter were determined in triplicate according to DIN EN 13039 [34]. The organic matter was calculated as the difference from the dried sample and the ash content and given in percent. The particle density was calculated according to the Standard DIN EN 13041 with the values of ash content and organic matter content [33].

2.7. Statistical Analysis

The statistical analysis was carried out with the software SAS 9.4 (SAS Institute, Cary, NC, USA). A two-factor hierarchical analysis of variance with inequality of variance for the specific energy demand and both WHC's between the raw materials was carried out. Also, multiple pairwise comparisons of specific energy demand and both WHCs for all materials extruded at 20 mm were conducted as well as multiple pairwise comparisons within one raw material for different aperture settings. For the WHC a binomial distribution with logit function was applied, for the specific energy demand a standard distribution without link-function.

3. Results

3.1. Specific Energy Demand

Figure 4 shows the specific energy demand for the processing of raw material into fibres at an aperture setting of 20 mm. Only the best available materials are displayed. Poplar significantly ($p < 0.0001$) showed the highest specific energy demand (261 kWh ${t_{DM}}^{-1}$) followed by forest biomass with a specific energy demand of 215 kWh ${t_{DM}}^{-1}$. The lowest specific energy demand was calculated for olive (93 kWh ${t_{DM}}^{-1}$) which was less than half of poplar. For olive, which is of high interest for southern European countries, only one measurement could be taken at an aperture setting of 20 mm because there was not enough material to do further specific energy demand measurements. According to the conduced statistics the differences in specific energy demand between poplar and all other raw material is significant ($p < 0.0001$). Yet, multiple comparisons showed that the specific energy demand not of all raw materials differed significantly (indicated by different letters in Figure 4) from each other at a 20 mm aperture setting.

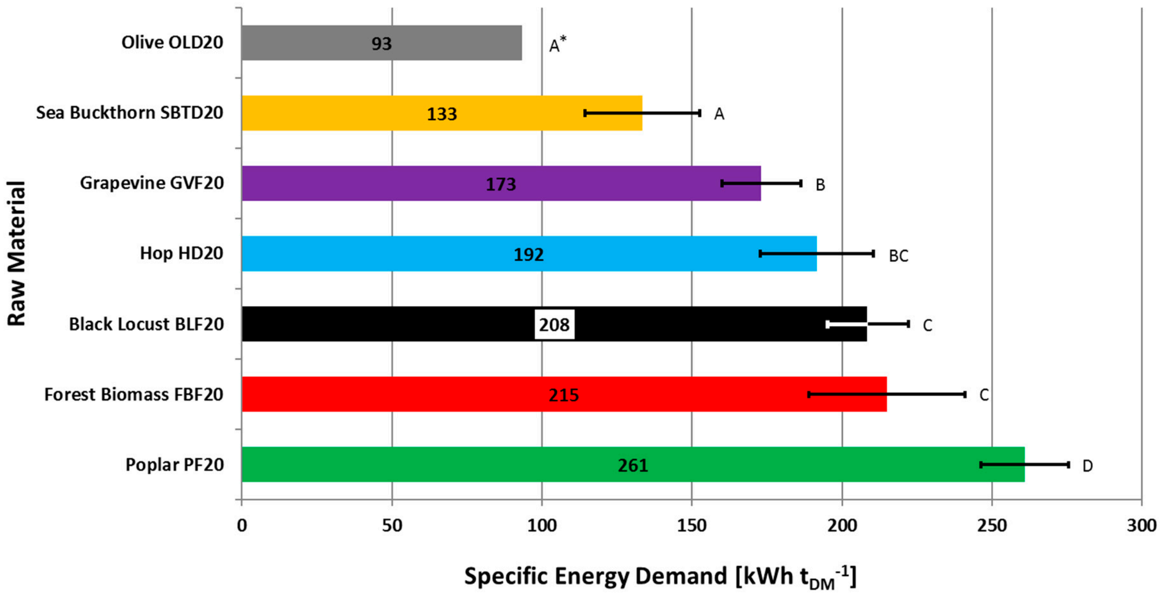


Figure 4. Specific energy demands and standard deviation at 20 mm aperture setting by the extruder at ATB in kWh $t_{DM}{}^{-1}$ at moisture content of approx. 50% for seven different types of raw material. Different letters indicate significant differences between raw materials for $\alpha = 0.05$. * only standard error was available for significance tests, standard deviation could not be calculated with only one measurement.

3.2. Particle Size Distribution

For all sieved fibres shown in Figure 5, the aperture setting during extrusion was set to 20 mm. The fine fraction (defined here as all particles passing a screen aperture of 0.5 mm) and the coarse fraction (everything larger than 3.15 mm) is also displayed in Figure 5, exemplarily for six out of all investigated fibres, as well as the X50-value. As a result, poplar and forest biomass have the highest fine fraction as well as the lowest X50-value. On the other hand, hop and grapevine fibre have the largest coarse fraction and highest X50-value (see also Figure 5).

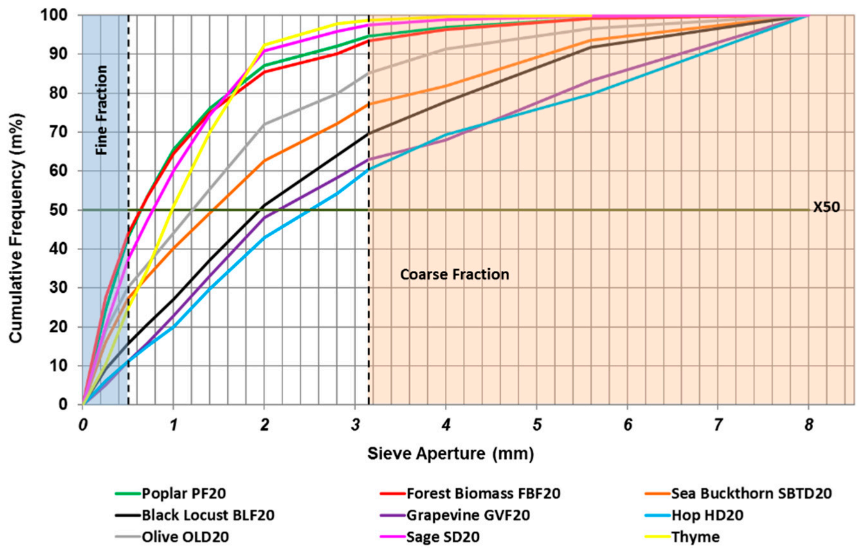


Figure 5. Particle size distribution of fibre produced by the extruder at ATB at identical aperture setting (20 mm).

As a typical example of all raw materials under investigation Figure 6 shows how particle size distribution of extruded poplar fibre varies with different aperture settings. With increasing aperture, the fine fraction is reduced, and the coarse fraction is increased.

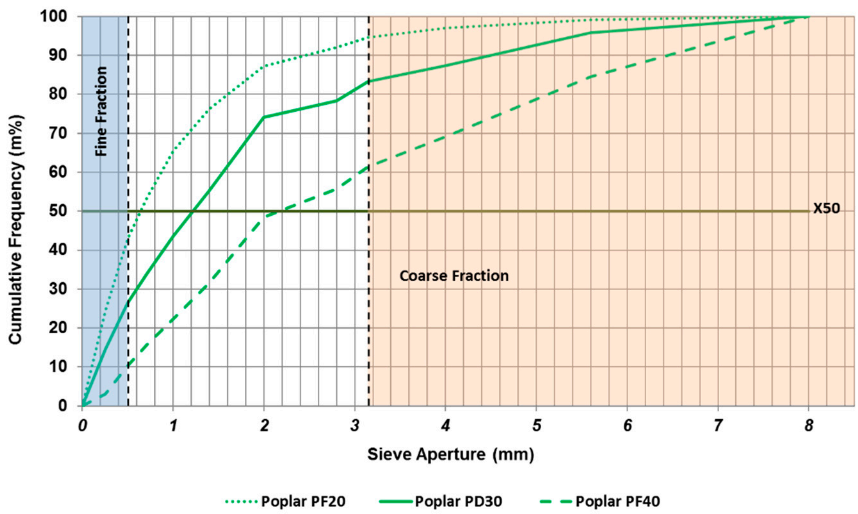


Figure 6. Particle size distribution of poplar fibre produced by the extruder at ATB at 20 mm, 30 mm and 40 mm aperture setting.

In Table 3, all material processed in the twin-screw extruder as well as peat, coir and sand are compared for fine, coarse fraction and X50-values. Besides sand, the largest fine fraction was measured for forest biomass (44 m%). The smallest fine fraction was determined for hop and grapevine, both at 11 m%. They also had by far the largest coarse faction at 30.7 m% and 32 m%. The least coarse material was measured for thyme (0.4 m%), sage (1.2 m%) and coir (1.7 m%). After calculating the X50-value, besides sand, of all at 20 mm extruded material, hop reached the largest X50-value of 2.5 mm followed by grapevine with 2.15 mm. The smallest X50-values besides sand (0.23 mm) was determined for poplar and forest biomass both at 0.64 mm.

Table 3. Comparison of different extruded materials for fine fraction, coarse fraction and X50-value at 20 mm aperture and peat, coir and sand (not extruded).

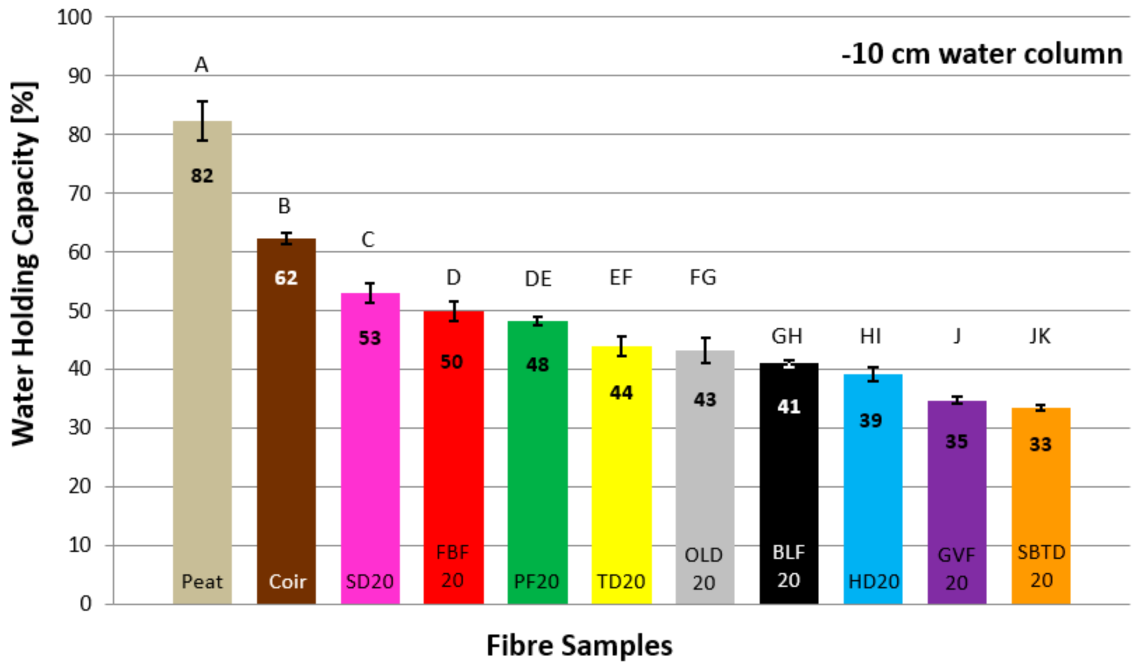
Material Extruded at 20 mm Aperture	Fine Fraction [%] * (<0.5 mm)	X50 [mm]	Coarse Fraction [%] * (>3.15 mm)
Hop	11	2.50	30.7
Grapevine	11	2.15	32.0
Black locust	16	1.95	22.2
Sea buckthorn	27	1.43	18.2
Peat	23	1.30	21.5
Olive	30	1.21	8.7
Thyme	25	0.98	0.4
Sage	37	0.77	1.2
Coir	31	0.76	1.7
Poplar	43	0.64	3.0
Forest biomass	44	0.64	3.7
Sand	82	0.23	1.9

* mass% on dry matter basis.

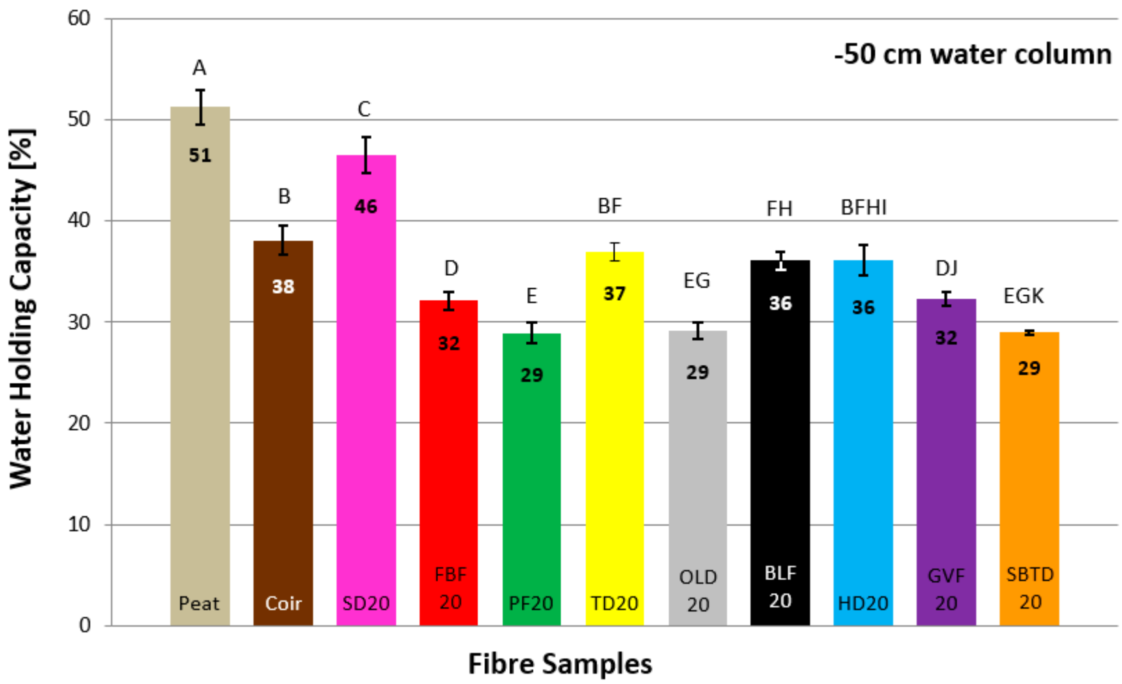
3.3. Influence of Raw Material on Water Holding Capacity

The highest WHC apart from peat and coir was found at 20 mm aperture setting for sage ($p < 0.0001$) with 53% at −10 cm water column (−1 kPa suction tension) (see Figure 7). The lowest measured WHC at −10 cm water column occurred for sea buckthorn.

At −50 cm water column (−5 kPa) sage performed with 46% almost as well as peat (51%) in WHC, it outperformed coir (38%) by far. Coir was only superior in WHC at −10 cm water column. Thyme (37%), black locust (36%) and hop (36%) almost matched the performance of choir at a −50 cm water column (−5 kPa suction tension). Peat WHC significantly ($p < 0.0001$) differed from all other materials. In addition, the capital letters above the columns in Figure 7 show which WHC differ significantly from one another at each suction tension.



(**a**)



(**b**)

Figure 7. (**a**) WHC at −10 cm (−1 kPa suction tension) and (**b**) −50 cm (−5 kPa suction tension) water column and standard deviation as a function of raw material, which was extruded at a 20 mm aperture. Different letters indicate significant differences between raw materials for $\alpha = 0.05$.

3.4. Interconnections of Water Holding Capacity, Aperture, X50-Value and Specific Energy Demand

The influence of different aperture settings in a broader range is shown for poplar (a), sea buckthorn (b), grapevine (c) and hop (d) in Figure 8. Since not all the test materials were available in the quantities required for these extensive measurements, not all settings could be tested for each material. Poplar chips of the same quality could be obtained from a local plantation, which made it possible to investigate aperture settings of 15–40 mm for this material.

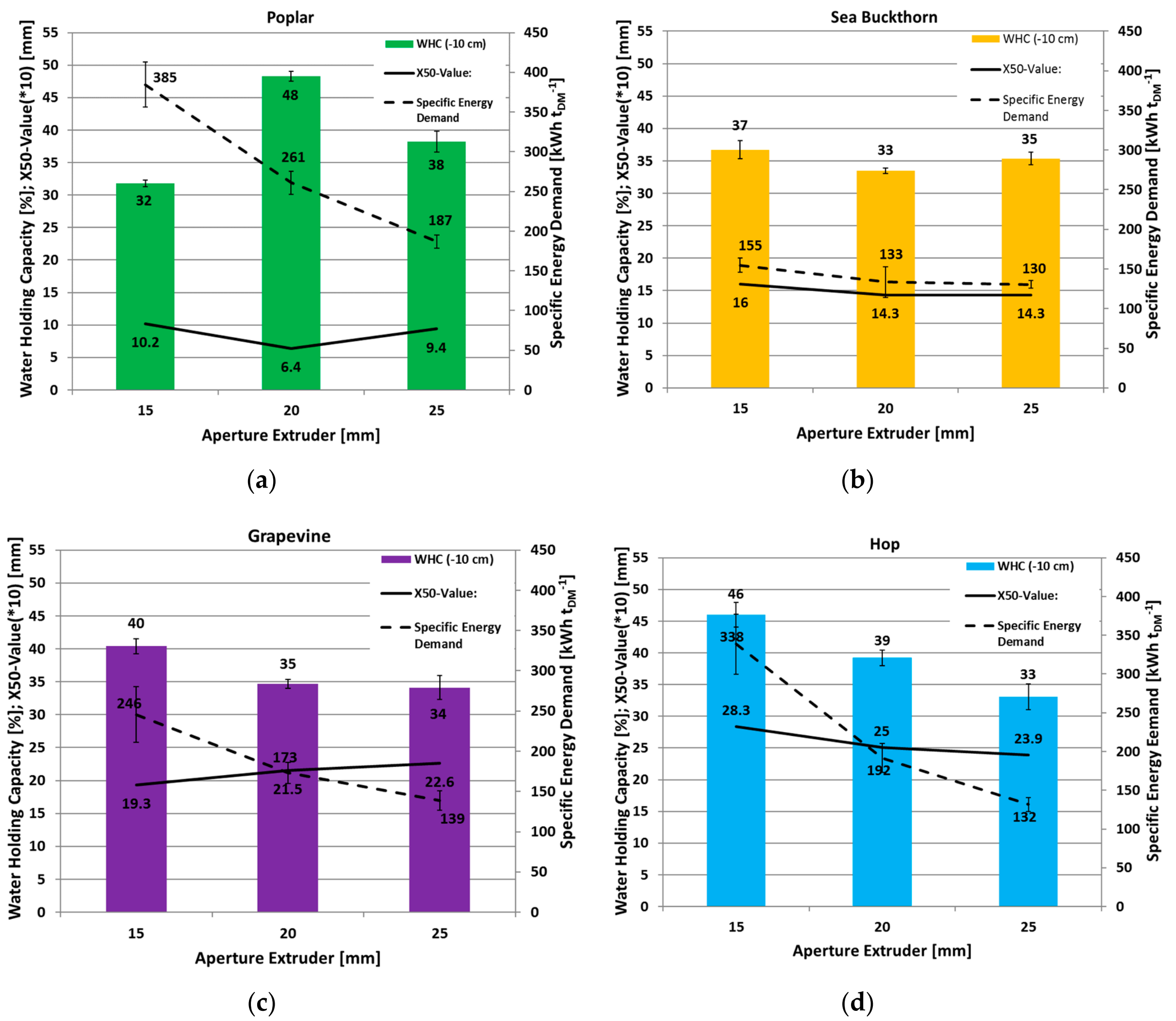


Figure 8. WHC (at −10 cm water column), X50-value (multiplied by 10) and specific energy demand of (**a**) poplar, (**b**) sea buckthorn, (**c**) grapevine and (**d**) hop as a function of aperture.

The specific energy demand significantly decreased with increasing aperture setting from 15 mm to 25 mm for all materials, but sea buckthorn (b) (not significant) presented in Figure 8. The decrease was stronger for poplar (a) (198 kWh $t_{DM}{}^{-1}$) and hop (d) (206 kWh $t_{DM}{}^{-1}$) than for grapevine (c) (107 kWh $t_{DM}{}^{-1}$). Sea buckthorn (b) decreased even less from 155 kWh $t_{DM}{}^{-1}$ at 15 mm to 133 kWh $t_{DM}{}^{-1}$ at 20 mm and 130 kWh $t_{DM}{}^{-1}$ at 25 mm aperture which is 25 kWh $t_{DM}{}^{-1}$.

An aperture setting of 20 mm during extrusion resulted in the best WHC of 48% at −10 cm water column for poplar fibre (a) which significantly (p = 0.0023) differs from the other aperture settings. A 15 mm aperture had a significantly ($p < 0.0001$) smaller WHC (32%) than 20 mm (48%) and 25 mm (38%). Reducing the aperture only had a small but statistically significant ($p < 0.0001$) effect on grapevine (c) for apertures of 15 mm (40%) and

20 mm (35%) but not for 25 mm (34%). For hop (d), reducing the aperture resulted in a statistically significant ($p < 0.0001$) increase in WHC for aperture settings of 15 mm (46%), 20 mm (39%) and 25 mm (33%) compared to one another (see Figure 8). Interestingly the WHC of sea buckthorn (b) was higher at 25 mm aperture (35%) than at 20 mm (33%) but did not differ significantly. Yet, a 15 mm aperture had a significantly ($p = 0.0109$) better WHC (37%) than at 20 mm (33%).

The X50-value (multiplied by 10 for better presentability) decreased slightly for sea buckthorn (b) and hop (d) with increasing aperture. For grapevine (c), it increased with larger aperture. No clear tendency could be determined for poplar (a).

3.5. Specific Energy Demand and Further Material Parameters in Dependence to Raw Material and Aperture Setting

Table A1 (Appendix A) shows the results for specific energy demand for extrusion, bulk density, shrinkage, particle density, total pore volume and ash content for all the extruded material at all aperture settings investigated in this study. The lowest specific energy demand was measured for olive (90 kWh $t_{DM}{}^{-1}$) at an aperture setting of 15 mm and for oregano (10 mm aperture) which required 89 kWh $t_{DM}{}^{-1}$. But oregano could only be extruded successfully to fibre at an aperture of 10 mm or smaller. At these aperture settings, most of the other material had extremely high energy demands (sage 935 kWh $t_{DM}{}^{-1}$) or the overvoltage protection stopped the electrical engine.

The highest bulk density of extruded material was measured for forest biomass extruded at 30 mm aperture, the lowest for poplar extruded at 40 mm. The extruded fibre that shrunk the most was sage with 13% apart from peat which had the highest shrinkage of 20%. Poplar, grapevine and sea buckthorn had the lowest ash contents, and oregano and coir had the highest. The highest WHC of 68% at a −10 cm water column was measured for sage at a 10 mm aperture setting. However, the specific energy demand at that aperture setting was measured at 935 kWh $t_{DM}{}^{-1}$ which was the highest measured of all extruded materials.

4. Discussion

Raw material from different plants, which are living organisms adapting to seasonal changing growth conditions and varying very much in characteristics over their life cycle, will never be entirely reproducible. Hence, the characteristics or energy demand at processing will vary over time between batches, in addition to differences related to plant species. For example, differences in poplar wood chips already occur due to variations in bark content of the sample. Wood chips from branches have a higher bark content than wood chips from the stem [38,39].

4.1. Water Holding Capacity and How It Is Affected

Extruded biomass was not able to reach the WHC of peat (82%) (Figure 7) at an acceptable aperture setting due to high energy consumption (Figure 4). However, reducing the aperture to smaller settings resulted in significantly higher WHCs in most cases for a −10 cm water column (Table A1, Appendix A). Sage for instance extruded at 10 mm aperture performed best (68%) at −10 cm water column (Figure 7) but had a very high energy demand of 935 kWh $t_{DM}{}^{-1}$ (Figure 4). The lowest WHC (25%) was measured for poplar at a 35 mm aperture and 50 cm Water column.

As a comparison, Kharazipour investigated WHC for spruce fibre processed by thermo-hydrolytic defibration. He measured 31% WHC at −4 hPa (−4 cm water coulumn) [19] which compares closest to the −10 cm water column (−1 kPa) WHC in these experiments. All materials investigated at a −10 cm water column performed better than spruce did for Kharazipour at −4 cm Water column. Multiple reasons can be responsible for significantly lower WHC of all investigated materials in comparison to peat. The pore volume of the extruded materials might be too large to be able to hold water as well as peat. But the measured total pore volume of the different fibre does not show large differences. The measured WHC also does not increase or decrease according to the total pore volume.

The aperture setting had a significant influence on the WHC of poplar. It decreased with larger aperture. At a larger aperture setting the raw material remained in the twin-screw extruder for a shorter period of time resulting in less comminution leading to coarser fibre. This clearly affected the particle size distribution (Figure 6). Due to the shorter processing time and therefore larger throughput, the grinding degree was reduced. As a result, the fine fraction was reduced and the pore space within the fibre might be too large to be able to hold water adequately, as compared with a more finely ground fibre or peat. Interestingly the poplar fibre extruded at the smallest aperture setting of 15 mm (PF15) had a lower WHC (32%) than the fibre extruded at 20 mm (PF20) with 48%. At a higher grinding degree, more fine particles were present within the fibre (Figure 6). That could have led to a smaller pore volume and therefore a smaller WHC. Yet, particle size distribution did not affect the total pore volume. Within all poplar aperture settings and resulting WHC measurements the total pore volume was at 94% or 95%. Another possibility for the reduced WHC at 15 mm aperture (PF15) could be the longer processing time which could correspond to a more intensive temperature treatment of the material. Although temperatures have not been measured in detail, higher energy demand can be an indicator for more intensive temperature treatment (energy input → friction → thermal energy). Consequently, the temperature might have been higher compared to the other aperture settings. Esteves (2009) [40] found that after heat treatment of wood, due a chemical change in the wood with a decrease of hydroxyl groups, less water can be absorbed by the cell walls. The cellulose crystallinity increases and as a result enhanced the inaccessibility of celluloses hydroxyl groups to water molecules occurs. Lignin was also cross-linked. Additionally, Sehlstedt-Persson [41] found that hygroscopicity of wood is reduced if dried at high temperatures. This could explain how a fibre with a higher fine fraction produced at small aperture was unable to hold more water than a fibre from the same batch extruded at a larger aperture. However, this aspect needs more research in future. For example, a batch of fibre extruded at, e.g., 30 mm aperture could be treated after extrusion with different high temperatures (100, 150, and 200 °C) at different retention times. These differently heat-treated fibres should then be tested for WHC (very time consuming).

The WHC of extruded forest biomass behaved differently to most other fibres. The fibre produced at an aperture setting of 20 mm (FBF20) had lower WHC at −10 cm (50%) and −50 cm water column (32%) compared to fibre extruded at 30 mm (FBF30) at 32% (−10 cm) and 38% (−50 cm). At a 20 mm aperture setting, the grinding degree was higher than at 30 mm aperture. As a result, more fine particles are present in the fibre extruded at 20 mm aperture. More fines can reduce the pore volume. However, the total pore volume of 20 mm extruded forest biomass fibre was larger than for forest biomass extruded at 30 mm even though the particle size distribution showed a larger fine fraction for 20 mm aperture setting. That larger pore volume could lead to reduced WHC if the pore volume gets too large, meaning the space in between single fibres gets larger, and water tension might not be high enough to hold the same amount of water in the pores. Since the forest biomass fibre consists of several plant species in an unknown ratio, clear connections might not be possible to draw. Therefore, a single origin material would be more suitable for future investigations. More research must be done on the forest biomass fibre to get conclusive results.

4.2. Energy Demand Influence Factors

The lowest specific energy demand was measured for olive OD15 at (90 kWh t_{DM}^{-1}), the highest for sage SD10 at 935 kWh t_{DM}^{-1} (Table A1, Appendix A). An unmistakable result was that WHC of fibre from varying raw material processed at identical experimental setup performed very differently compared to each other (see Figure 8).

The variation of the specific energy demand of different raw material (see Figure 5) at an identical aperture and moisture content can have multiple causes. The presence of essential oils or further chemical compounds (e.g., oils, waxes) in plant parts like bark, leaves and seeds of olive and sea buckthorn which function as an inhibition of bacterial and fungal growth [42,43] can also reduce friction during extrusion. Therefore, sea buckthorn and olive had the lowest specific-energy-demand at an identical aperture setting of all investigated raw materials. Further, the friction depends on the physical properties of the raw material e.g., shear strength, density, hardness etc. The heartwood of black locust for instance has a high resistance to microorganisms, a high raw density of ~0.7 g cm^{-3} and a hardness perpendicular to the fibre of 25 N mm^{-2} [44]. Yet, the specific energy demand was significantly lower than for poplar. An explanation could be that the black locust was chipped and extruded with leaves attached. This reduces friction and therefore specific energy demand. Additionally, the trees used were only about five years old. In young trees, the heart wood percentage is significantly smaller than in mature trees. The sapwood is wetter, not as dense and has fewer substances which are repellent to microorganisms.

It also made an explicit difference if the raw material was processed in fresh state or remoistened before processing after storage. It required more energy to process the same amount of raw material into fibre with remoistened material compared to freshly cut raw material. Even pre-treating with water in a tumbling barrel to reach 50% moisture content for 48 h resulted in higher specific energy demands. This effect has been investigated by Sehlstedt-Persson (2009) and Kießl (1989) and is caused by the sorption isotherm. Wood takes longer to reabsorb water after being dried even at moderate temperatures. With increasing drying temperatures, the hygroscopicity of the wood is decreased [41,45]. Most of the water was only attached to the surface of the woodchips and did not penetrate the cell walls of the wood cells. As a result, a lot of surface water evaporated quickly in the twin-screw extruder before being able to reduce friction in the process. This led to higher temperatures increasing this problem further throughout the extrusion process. Unfortunately, it was not possible to process all raw material in a freshly cut state. Some of it was delivered dried; other samples had to be dried for storage reasons.

4.3. Influences on Particle Size Distribution

Similar to the research conducted by Dietrich [28], the investigations in this research showed that a large aperture led to coarser fibre and a small aperture resulted in more fines as shown in Figure 6.

At an identical aperture setting, the particle size distribution varied significantly between different plant materials (Figure 5). A variation in density of the raw material, raw material specific wood fibre length [44] as well as the presence of additional biomass like leaves, berries and their essential oils influence the distribution. Wallot et al. also found that the raw material source mainly determines the quality of fibre processed in a small-scale industrial extruder [29]. In this research, while a high amount of bark, low wood density and short wood fibres [44] cause more fines within poplar, forest biomass contained needles and leaves and therefore extrusion of this material produced more fines. Sea buckthorn is harder than poplar at a raw density of ~590 kg m^{-3} [46], and remaining berries and leaves add a lot of essential oils to the process which reduce friction and lead to coarser fibre. The chopped materials of grapevine and hop had the least amount of fines and the highest amount of coarse fibre. The residual material of hop plants, after harvesting the hop blossoms, is quite fibrous and originates from the velvet of the annual shoots. A small part of the fibre, mostly fines, could originate from the shives but most fibre should be contained in the outside cell walls of the plant. The highest amount of lignified cellulose can be expected in this part of the hop plant.

For grapevine, the particle size distribution was also not strongly affected by aperture setting. Fibres are strong and durable as compared with fibre from other plant materials (e.g., poplar or olive) in visual appearance. This may be beneficial for various applications of the fibre, e.g., to mix into a growing media from compost to achieve a better structure and air capacity. The extruder was able to separate most of the fibres from the wood structure. However, it was not able to comminute the fibres itself. Small pieces of wood remained in the fibre even after closing the aperture to a very narrow gap. Closing the aperture to a gap smaller than 15 mm triggered the overvoltage protection causing the extruder to turn off. This occurred for almost all species extruded. In some cases, 10 mm was the point when the extruder turned off. Fibre from grapevine, on the other hand, originates entirely from lignified cellulose (wood). There are no shives present in grapevine shoots which are perennial and lignify very quickly. As a result, the fibres after extrusion are quite durable and the appearance of the extruded grapevine is very voluminous (Figure 9).

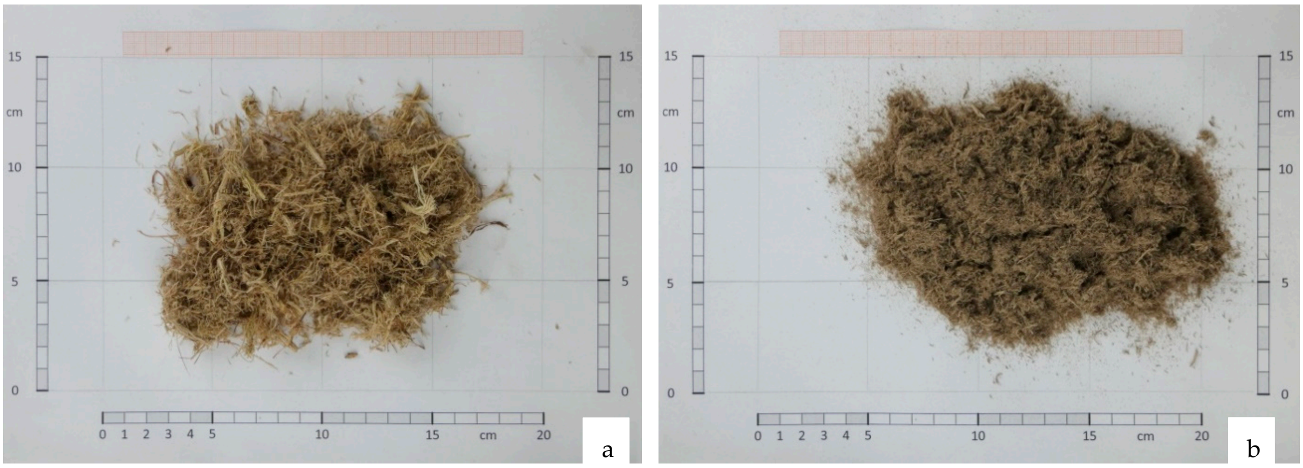


Figure 9. Grapevine fibre (**a**) and poplar fibre (**b**) extruded at 20 mm aperture setting.

4.4. Interactions

At an industrial scale, all material should be extruded fresh because remoistening takes time, space, technology and additional steps. Water can also be added to the process, but the remoistened wood chips always required more energy to be processed in the extruder than fresh material at the same aperture setting as seen in Table A1.

Sage extruded at 10 mm (SD10) was also able to achieve better WHC (68%) than coir fibre (62%) at −10 cm water column, and SD15 (15 mm aperture) was only 2 percentage points lower (60%) (see Table A1, Appendix A). At −50 cm water column, coir (38%) was outperformed by many materials like thyme, oregano and hop at various aperture settings. Besides poplar all other materials were able to achieve a similar WHC like coir at a −50 cm water column. This shows the high potential of extruded biomass as a possible peat substitute since coir is already widely used.

Because olive had the lowest specific energy demand paired with acceptable WHC this has a huge potential for counties where olive is cultivated in large scale. Additionally, Kir et al. 2021 [17] showed that is possible to grow olive saplings in 100% olive fibre if it is fertilized properly. Those results in combination with the results conducted in our research can be of great interest for olive farmers in all of southern Europe. If some of the conventional peat-containing, contentious growing media for sapling cultivation could be replaced with fibre, a significant impact would be achieved. Extrusion does not necessarily need to be done on the farmer's property. A decentralised extrusion plant where treatment of plant waste material can be combined with main local growing media (compost plant, extrusion, landscaping service and horticulture combined) could be a solution. An additional solution could be mobile extrusion. An up to medium industrial scale extruder can be constructed on to a lorry or a trailer as Reinhofer showed in his investigations [6]. This mobile extruder could then travel from site to site and rapidly process freshly harvested wood chips, landscape management residues or invasive species into fibre which can party reduce peat and vermiculite in growing media.

5. Conclusions

The investigation has shown that a large number of agricultural and forest residues can be processed to fibre in a twin-screw extruder with reasonable expenditure of energy.

Depending on the raw material and process parameters these fibres reach WHCs which enable them to be used as a peat substitute in growing media. The WHC of peat could not be achieved with any of the examined materials. However, when compared with other natural fibre like coir, already commonly used as a peat substitute, materials like extruded sage and forest biomass can compete.

For the anticipated substitution of peat in growing media, this research proved that the investigated process can be used to produce fibrous materials which, have a strong potential for replacing peat with focus on the physical properties. However, the extrusion process is very energy-intensive, so that raw material-specific process optimisations should be carried out as part of future investigations for cost-effective productions. Whether extruded material can ultimately be used as a peat substitute does not only depend on the physical properties examined in this paper, but also on its chemical–microbiological suitability. This requires further investigations.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Specific energy demand, WHC, X50-value bulk density, shrinkage, particle density, total pore volume and ash content for all extruded material at all aperture settings with standard deviation.

Sample Number	Specific Energy Demand [kWh t^{-1}] *	WHC−10 cm ** [%]	WHC−50 cm ** [%]	X50-Value [mm]	Bulk Density [kg m^{-3}] *	Shrinkage [%]	Particle Density [kg m^{-3}] *	Total Pore Volume [%]	Ash Content * [%]
LD10	150 ± 17	34 ± 0.83	33 ± 0.62	1.17	124 ± 4.31	7.4 ± 1.80	1575 ± 2.33	92 ± 0.34	3.9 ± 0.35
LD15	123 ± 35	35 ± 0.68	34 ± 0.73	1.54	120 ± 2.12	4.0 ± 0.70	1585 ± 3.03	92 ± 0.08	5.3 ± 0.45
OLD10	156	42 ± 3.77	30 ± 1.31	0.98	165 ± 6.75	5.3 ± 0.84	1582 ± 0.94	90 ± 0.46	4.9 ± 0.14
OLD15	90	43 ± 1.08	30 ± 0.35	1.34	192 ± 1.94	6.0 ± 1.00	1580 ± 1.75	88 ± 0.06	4.5 ± 0.26
OLD20	93	43 ± 2.09	29 ± 0.83	1.21	182 ± 5.65	7.4 ± 0.48	1584 ± 1.05	89 ± 0.36	5.1 ± 0.16
TD10	154	46 ± 1.11	38 ± 0.52	0.68	127 ± 2.39	5.8 ± 1.37	1575 ± 4.14	92 ± 0.14	3.8 ± 0.62
TD15	154	45 ± 0.83	37 ± 0.90	0.76	123 ± 1.79	6.6 ± 0.86	1576 ± 0.88	92 ± 0.13	4.0 ± 0.13
TD20	118	44 ± 1.67	37 ± 0.87	0.98	136 ± 1.81	5.2 ± 0.93	1573 ± 2.51	91 ± 0.09	3.5 ± 0.38
TD25	105	35 ± 1.98	32 ± 1.43	0.73	131 ± 2.40	6.0 ± 0.32	1571 ± 0.81	92 ± 0.17	3.3 ± 0.12
SD10	935	68 ± 1.17	53 ± 1.00	0.97	126 ± 2.61	13.3 ± 2.96	1571 ± 1.01	92 ± 0.18	3.2 ± 0.15
SD15	391	60 ± 0.56	49 ± 0.64	0.77	125 ± 3.79	13.5 ± 2.58	1576 ± 0.74	92 ± 0.24	4.0 ± 0.11
SD20	167	53 ± 1.67	46 ± 1.72	0.77	128 ± 8.08	7.1 ± 1.15	1573 ± 0.18	92 ± 0.63	3.5 ± 0.03
SD25	131	43 ± 0.48	39 ± 0.70	1.04	113 ± 3.46	7.5 ± 1.79	1572 ± 0.67	93 ± 0.27	3.4 ± 0.10
ORD6	100	44 ± 2.70	42 ± 2.15	0.69	170 ± 11.17	8.5 ± 0.24	1595 ± 1.68	89 ± 0.85	6.8 ± 0.25
ORD10	89	43 ± 1.17	41 ± 0.84	0.84	168 ± 2.03	8.0 ± 0.58	1596 ± 1.13	89 ± 0.15	7.0 ± 0.17
BLF 20	208 ± 14	41 ± 0.46	36 ± 0.76	1.95	116 ± 1.77	3.2 ± 0.70	1568 ± 1.14	93 ± 0.01	2.7 ± 0.17
BLF 25	132 ± 3	37 ± 0.35	32 ± 0.39	2.46	120 ± 0.63	2.7 ± 1.80	1562 ± 1.96	92 ± 0.01	1.9 ± 0.30
BLF 30	103 ± 15	37 ± 0.67	33 ± 0.44	2.97	131 ± 1.31	2.7 ± 1.04	1563 ± 2.95	92 ± 0.11	2.0 ± 0.45
PF15	385 ± 28	32 ± 0.51	25 ± 1.19	1.02	74 ± 1.98	2.1 ± 0.64	1563 ± 0.21	95 ± 0.13	2.0 ± 0.03

Table A1. *Cont.*

Sample Number	Specific Energy Demand [kWh t^{-1}] *	WHC−10 cm ** [%]	WHC−50 cm ** [%]	X50-Value [mm]	Bulk Density [kg m^{-3}] *	Shrinkage [%]	Particle Density [kg m^{-3}] *	Total Pore Volume [%]	Ash Content * [%]
PF20	261 ± 15	48 ± 0.75	29 ± 1.04	0.64	93 ± 2.16	6.5 ± 1.87	1565 ± 0.30	94 ± 0.17	2.3 ± 0.05
PF25	187 ± 8	38 ± 1.61	26 ± 0.88	0.94	90 ± 2.33	4.8 ± 1.86	1564 ± 0.34	94 ± 0.07	2.2 ± 0.05
PF40	155 ± 10	35 ± 1.07	27 ± 0.77	2.17	75 ± 3.22	4.6 ± 1.96	1558 ± 0.36	95 ± 0.21	1.2 ± 0.06
PD30	248	34 ± 0.96	24 ± 0.86	1.22	94 ± 2.85	6.2 ± 2.75	1565 ± 0.41	94 ± 0.15	2.3 ± 0.06
PD35	260	25 ± 1.12	21 ± 0.66	1.12	85 ± 2.17	5.9 ± 1.15	1563 ± 0.26	95 ± 0.06	2.0 ± 0.04
SBTF10	172	38 ± 2.36	28 ± 1.48	1.63	106 ± 5.08	7.0 ± 1.06	1557 ± 0.39	93 ± 0.12	1.2 ± 0.06
SBTD15	151 ± 9	37 ± 1.38	31 ± 1.17	1.60	127 ± 4.96	5.6 ± 0.99	1564 ± 0.24	92 ± 0.30	2.1 ± 0.04
SBTD20	133 ± 19	33 ± 0.40	29 ± 0.19	1.43	122 ± 2.87	5.9 ± 0.78	1560 ± 1.92	92 ± 0.08	1.5 ± 0.30
SBTD25	130 ± 5	35 ± 0.99	34 ± 1.04	1.43	131 ± 3.95	6.7 ± 2.99	1560 ± 1.51	92 ± 0.28	1.5 ± 0.23
HD15	338 ± 39	46 ± 1.94	41 ± 0.93	2.83	94 ± 1.28	7.2 ± 1.61	1573 ± 2.88	94 ± 0.06	3.5 ± 0.44
HD20	192 ± 19	39 ± 1.22	36 ± 1.56	2.50	90 ± 2.60	6.8 ± 1.32	1570 ± 2.28	94 ± 0.17	3.0 ± 0.35
HD25	132 ± 9	33 ± 2.06	31 ± 1.83	2.39	83 ± 3.78	8.4 ± 0.68	1582 ± 2.92	95 ± 0.20	4.8 ± 0.44
GVF15	246 ± 35	40 ± 1.15	36 ± 1.18	1.93	89 ± 2.79	5.6 ± 0.65	1566 ± 0.34	94 ± 0.08	2.4 ± 0.05
GVF20	173 ± 13	35 ± 0.65	32 ± 0.65	2.15	92 ± 1.16	2.5 ± 0.84	1563 ± 1.03	94 ± 0.07	2.1 ± 0.16
GVF25	139 ± 12	34 ± 1.82	32 ± 1.66	2.26	91 ± 5.27	3.6 ± 1.28	1565 ± 0.77	94 ± 0.27	2.3 ± 0.12
FBF20	215 ± 26	50 ± 1.63	32 ± 0.91	0.64	153 ± 3.90	9.4 ± 1.60	1578 ± 4.79	90 ± 0.08	4.3 ± 0.72
FBF30	129 ± 13	57 ± 2.17	38 ± 0.60	0.84	212 ± 4.75	6.7 ± 0.75	1576 ± 4.71	87 ± 0.35	4.0 ± 0.71
WP	not extruded	82 ± 3.38	51 ± 1.72	1.30	110 ± 4.22	21.0 ± 1.18	1571 ± 0.96	93 ± 0.32	3.3 ± 0.15
C	not extruded	62 ± 0.94	38 ± 1.42	0.76	82 ± 0.61	6.6 ± 1.40	1662 ± 11.9	95 ± 0.03	16.2 ± 1.60
S	not extruded	42 ± 1.24	36 ± 0.95	0.23	1455 ± 21.0	8.0 ± 0.01	2597 ± 4.77	44 ± 0.89	97.1 ± 0.26

* dry matter based, ** water column.

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