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The influence of moisture on the sieving performance of lignocellulosic biomass

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Abstract: Sieving is an important operation for sorting solid particles both in industry and the laboratory. Although sorting is necessary for almost every process or energy conversion applied to biomass materials, sieving has not received enough scientific attention. The aim of this study was to obtain experimental data on the sieving performance of biomass materials. Three different biomasses – two wood pellets from the same species but each one obtained from a different process, plus a poplar sawdust residue – were sieved using a laboratory sieve shaker before milling with a hammer mill. Samples with three different levels of moisture were also studied: non-dried, dried for 1.5 h at 75 °C, and dried for 3 h at 75 °C. The results were unexpected because the three samples showed quite different behaviors. A slight drying before sieving significantly enhanced the sieving performance of one of the wood pellets but its effect on the poplar sawdust was just the opposite; in the case of the other type of wood pellets, the effect was intermediate, because it improved the sieving performance but only for a short time and for the finest fraction. These results suggest the importance of conducting a preliminary study of the material to be sieved to save energy, time, and effort. Further research in this area is still necessary to understand the influence of variables in order to reduce blinding during biomass sieving. © 2023 The Authors. Biofuels, Bioproducts and Biorefining published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: biomass; wood pellets; poplar sawdust; sieve blinding; screening; moisture content

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Introduction

Biomass is defined as the biodegradable fraction of materials with a biological origin, i.e. animal and vegetal products and residues from agriculture, forestry, aquaculture, industry or municipal waste.[1] Among the vegetal biomasses, lignocellulosic biomass is mainly composed of cellulose, hemicellulose, and lignin. These three components are macromolecular organic polymers: cellulose and hemicellulose are polysaccharides, whereas lignin is a stronger polymer derived from lignols, which contains aromatic rings.[2]

Wood represents the most common lignocellulosic biomass. It can be defined as a complex composite made of cells, whose walls are formed of layers of the above three polymers. Cells are arranged regularly in two systems, the axial system and the radial system, both named after their orientation with respect to the axis of the trunk. In general, wood cells are elongated, being 100 to 200 times longer than they are wide in the case of the axial cells.[3] This fibrous nature leads to elongated wood-dust particles. For example, Igathinathane *et al.* reported length/width ratios in the range of 2.5 to 3.8 for airborne dusts from pelleting operations of soft pine sawdust and ground bark of pine tree.[4] However, not only fibrous particles can be found in biomass samples but also other different shapes. Gil *et al.* applied four shape factors through image processing to classify biomass dust particles into six different classes: circle, square, rectangle, rectangle fibrous, hook, and hook fibrous.[5]

Almost every energy conversion or bioproduct production process requires milling and/or sorting the biomass material.[6] For example, the production of syngas by entrained-flow biomass gasification is improved when particle size is reduced; the optimum fuel feeding is in the form of submillimetric powder.[7] Biomass comminution to below 1000 µm is also desirable for pulverized fuel burners either in co-firing installations or in biomass power plants.[8] Removing fine particulates by sieving can also improve the quality of solid biofuels, as demonstrated for olive stones[9] and for corn stover briquettes.[10] Particle size specifications are often important for many other industrial applications of biomass.[11]

Milling (or grinding) is a size-reduction procedure that can be performed with a large variety of equipment, such as ball mills, rotary cutters, hammer mills, and roll mills.[12] Sieving or screening is one of the most important techniques applied both in the process industries for large-scale separation of solids and in laboratories for size analysis.[13] It consists of separating a particulate material sample into two or more portions by means of a screening surface; several types of sieving machines exist.[12] Often the term 'screening' is used to refer to a continuous sizing operation, while sieving refers to a batch process.[13]

Although sieving is a common procedure for particle-size analysis of particulate materials, the lack of sphericity in the majority of biomass particles produces a significant degree of uncertainty. Particles that are much longer than the aperture size can go through the sieve because the dimension that is actually measured is the width.[5] However, some particles that are narrower than the aperture size will not pass through, and also some particles that are wider than the aperture size will pass through. As reported by Gil *et al.*, this sieving inefficiency seems to be associated with the shape of the particle: the former case occurs with long, regular particles or with irregular particles that entangle easily, and the latter case occurs with flat particles or with filamentous and flexible hooked particles.[5] Due to these uncertainties, several studies have applied image-processing methodologies for the determination of the particle size of biomass powders.[4,5,14–16]

Apart from size analyses, sieving is also involved in procedures to assess the ignition sensitivity (or flammability) and explosion severity of biomass powders.[17] Biomass dusts are known to be the cause of major fires and explosions.[18] Such experimental tests are conducted by many laboratories all around the world, both in academia and industry, to determine the safety measures to be implemented in industrial facilities. Although some materials are tested without any modification, most samples need prior preparation, particularly if received as non-powdered samples (pellets, chips, grains, etc.). In this sense, 500 µm is the size criterion considered by standard NFPA 652 to define combustible dusts.[19] Standard ISO/IEC 80079-20-2 also proposes 500 µm as the upper limit for combustible dust particles that may form explosive mixtures with air.[20] Thus, material preparation usually involves milling and sieving to obtain a fraction of dust particles with a minimum dimension lower than 500 µm. The modification of samples received in the form of dust is also necessary if it is decided to test only the finest fraction, which usually produces the most easily ignitable and most violently explosible mixtures with air; this is common in some laboratories[21] and may involve sieving or milling plus sieving. Dust samples can also be prepared to determine other characteristics, such as their mechanical and flow properties.[16] However, these sample-conditioning operations are surprisingly demanding both in terms of time and labor, and can impose a severe bottleneck as the lab-scale mills and sieves usually have a limited capacity in terms of either volume per time, or in terms of batch volume.

During sieving, particles can become stuck in the screen openings, reducing efficiency (degree of sharpness of particle

separation) and performance (rate or capacity of the sieving process); this sieve blinding is one of the most important factors that control the sieving process.[13] Some vertical tapping action is usually included in the motion of sieves to reduce blinding. Anti-blinding devices, such as rubber balls and brushes, can be used. However, blinding can reduce productivity and lead to a dramatically increase in the use of time and energy. Sieve blinding reduction has been an active research area for decades,[22,23] due to the importance of sieving to a broad range of engineering applications, from fuels like coal and biomass to pharmaceutical and food products. Experimental studies,[13,24,25] numerical investigations,[26,27] and theoretical approaches[28] have recently been carried out on this subject.

A number of factors have been identified as affecting the sieving operation,[13,29] including particle-related properties, equipment-related properties, and procedural-related parameters, but the complex interactions between variables hinder full understanding of the principles that govern the sieving process.

Some aspects of the sieving of biomass materials have already been investigated. Amponsem *et al.* reported variations in the quantity of fines depending on the rotational frequency selected when sieving mixed sawdust with a sieve shaker (30, 50 or 80 rpm).[30] Falk *et al.* sieved four different biomasses to determine their particle size distributions and concluded that hammer milling produced a finer powder than cutting milling[31]; Paulrud *et al.* had previously reported a similar result.[14] Judá *et al.* studied the fine dust particles generated during woodworking and the influence of thermal treatments applied to several materials (birch, beech, and alder woods) in a pressure autoclave under the action of saturated water vapor for 10.5 h (at 105, 125 and 135 °C); no conclusive results were obtained to indicate whether thermal treatment affected the fine fractions.[32] Wang *et al.* measured energy consumption during the grinding of untreated and torrefied biomasses and determined the particle size and shape of the resulting powder samples.[33] The effect of torrefaction on the pulverization of biomass was also assessed by Bridgeman *et al.*, who used sieving to compare the particle size distributions of two biomasses under several different treatments.[34] On the other hand, a sieving pre-treatment has been proved to enhance the static bending strength of reed-based particleboards.[35]

This study was prompted by an observation during sieving of wood dusts at the authors' laboratory: the fine particles not only became clogged in the sieve holes but also blocked the screen surface by covering it with a layer that adhered to the screen surface. This phenomenon has been also observed in coal particles; the moist fine material can form a covering film that affects the normal operation of the screening process severely.[36] Although the moisture level has also been reported to affect the sieving procedure of flour,[13] its role in the case of woody biomasses is not known. Careless consideration of sieving factors and procedure can lead both to inefficient operation of sieving equipment in industry and to erroneous results of laboratory sieve analysis.

Moreover, it is foreseeable that lignocellulosic biomass could play an important role in the transformation of the energy system and the transition to renewables.[37] Although the bioenergy sector faces several challenges,[38,39] handling of large volumes of solid biomass for energy or chemical use is expected to increase in the near future, as biomass could contribute to a sustainable future through a variety of different strategies and technologies.[40,41]

For all the reasons explained above, it is of great interest to assess the sieving process of biomass materials. In this study, variations in sieving performance depending on time and moisture content were determined for three different biomasses. The final aim of this study was to provide indications that could serve to optimize sieving operations of lignocellulosic biomasses.

Materials and methods

Preparation of samples

Three biomass materials were used for the experiments reported in this study: two different pine-wood pellets (samples S1 and S2) and poplar sawdust (sample S3). The latter was a residue from a timber and fiberboard processing facility owned by Garnica (Logroño, Spain), had no additives, and was received as collected in the industry. The wood pellets were high-quality standardized fuels (class A1 according to ISO 17225-2) made of *Pinus sylvestris* wood.[42] These two types of pellets were selected because they differed in the way in which they were manufactured. Pellets in sample S1 (Coterram Generación, León, Spain) were produced directly from trunks following bark stripping, chopping, drying, milling, and compressing. On the other hand, pellets in sample S2 (Ebinor, Sotés, Spain) were made from sawdust residues received from wood processing plants, which were later dried, further milled, and finally compressed in a pellets factory. Figure 1 shows the visual aspect of the three biomass samples as received in the laboratory.

Wood pellets were ground by means of a GME-1100C hammer mill (Garhé, Amorebieta, Spain), which had an internal sieve with a pore size of 2 mm, a power of 1.8 kW, and a rotational speed of 2850 rpm. The poplar sawdust sample was not milled, as it was already in the form of small particles. Later, the

Figure 1. Biomass materials as received.

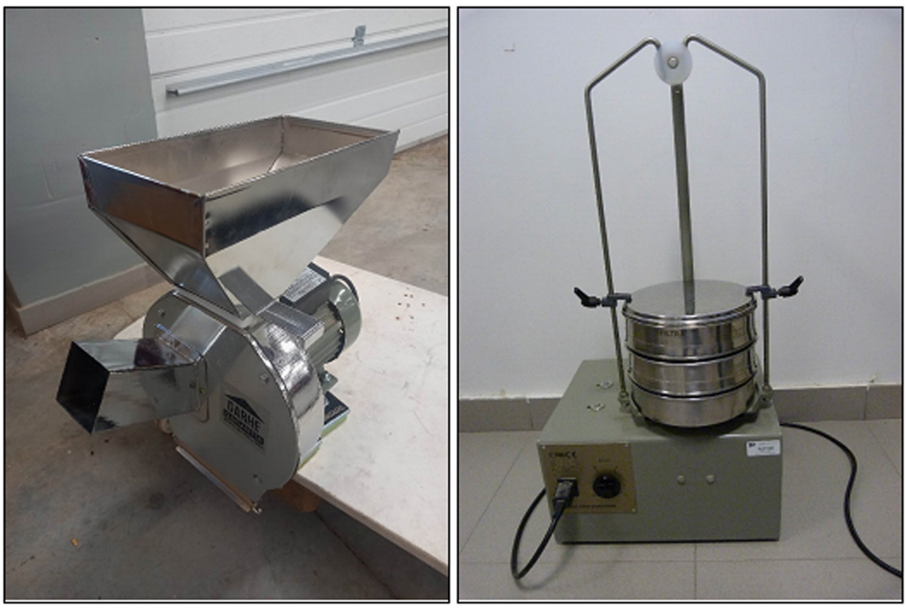

Figure 2. Equipment used in this study: on the left, hammer mill; on the right, shaker with stack of sieves.

three materials were sieved using an electro-mechanical shaker (Controls, Milan, Italy). Circular 400, 250, and 80 µm sieves made of woven-wire cloth with 200 mm in diameter were used.[43] Figure 2 shows the hammer mill and the sieving equipment.

The three biomasses – poplar sawdust as received and the ground wood pellets – were sieved using the 400 µm screen to discard the coarse particles and obtain dust samples. These three fractions (< 400 µm) were the samples used in this study.

Characterization of samples

The three samples were characterized. Proximate analyses were conducted in a UM400 Memmert oven (Schawabach, Germany) and a Selecta 367 PE muffle furnace (Barcelona, Spain) to determine the ash, volatile, and fixed carbon content. Ultimate analyses were also carried out using a CHNS Micro TruSpec analyzer (LECO, St Joseph, MI, USA).

Conventional analytical techniques for fuel characterization were followed in these tests:[44–49] ASTM 5373 for the CHN analysis, ASTM 4239 for S, ASTM 2361 for Cl, UNE 32019 for volatiles, UNE 32004 for ashes, and ASTM 3302 for moisture; oxygen content and fixed carbon content were calculated by difference.

From the above analytical data, the lignin and cellulose content was later estimated by applying the correlations described by Sheng and Azevedo.[50] The hemicellulose fraction was calculated through $X_{hem} = VM - X_{cel} - X_{lig}$, where VM is the volatile matter fraction and X_{hem}, X_{cel} and X_{lig} are the mass fractions of hemicellulose, cellulose, and lignin, respectively.[51]

The particle size distribution (PSD) of three fractions less than 400 µm were obtained by laser diffraction (LS 13320 analyzer, Beckman Coulter, Brea, CA, USA). Optical microscopy was also used to obtain some information on the shape of the particles in the <400 µm fractions, and also in the <80 µm fractions after the sieving experiments. The images were obtained using a Motic BA310 microscope equipped with a HD1080 camera (Motic, Xiamen, China).

The skeletal and bulk densities of the fractions below 400 µm were measured. A Coesfeld apparent density tester (Dortmund, Germany) was used to determine the bulk density (ρ_B) by pouring the dust from a funnel of specified design into a 100 mL cylindrical vessel according to the ISO 60 procedure.[52] On the other hand, the skeletal density or true density (ρ_S), which is derived from the volume occupied by the solid part of the particles plus their closed pores, was estimated by gas pycnometry with nitrogen in an AccuPyc II tester (Micromeritics, Norcross, GA, USA).

Finally, the angle of repose (AoR) was studied by using the Coesfeld apparent density tester mentioned above. In this case, instead of pouring the material into a vessel (see Fig. 3), it fell onto the plate to form a small pile. Then, the pile's slope was measured using a protractor. These experiments were replicated three times and results were averaged.

Sieving experiments

The three dust samples obtained following the procedure described above were sieved using the 250 and 80 µm sieves to determine the sieving performance and the influence of moisture. The samples were sieved for 15 min in intervals of varying length (from 30 s at the beginning up to 120 s at the end). The three fractions of material (x) were weighed in each time interval: $x > 250$ µm, 250 µm $> x >$ 80 µm and $x <$ 80 µm.

This sieving process was carried out for three different levels of moisture: dust without conditioning, dust dried for 1.5 h at 75 °C, and dust dried for 3 h at 75 °C. In addition,

Figure 3. Apparent density tester used to determine the angle of repose. The picture shows the pile of sample S-3 (< 400 µm) on the base plate after discharge. On the left, the 100 mL container used for the bulk density measurements.

the moisture content was determined just before the sieving experiments by drying it in a UM400 Memmert oven (Schawabach, Germany).[53] Four repetitions of the sieving experiment were carried out for each material and for each moisture level. Approximately 100 g of sample was placed on the top sieve of the stack in each repetition. Table 1 summarizes the set of experiments and the average moisture value determined in each case.

Finally, results were studied to assess the sieving performance of each material and to identify variations between moisture levels. An analysis of variance using SPSS Statistics 28.0.0 software (IBM Corporation, Armonk, NY, USA) were carried out for the results obtained from samples with different moisture content. Differences and confidential levels were determined by calculating the least significant difference with Tukey's test, and significant differences were defined at $P \leq 0.05$.

Results and discussion

Properties of the samples

Table 2 presents the results of the proximate and ultimate analyses. Estimates of the lignin, cellulose and hemicellulose fractions according to the empirical correlations by Sheng and Azevedo are also included.[50,51] As can be seen, samples S-1 and S-2 (pine) had a higher C content and much lower N, S, and Cl content than sample S-3 (poplar). On the other hand, differences in lignin, cellulose and hemicellulose composition were not significant. However, the method

Table 1. Moisture content (wt%, wet basis) of the three materials for three different drying levels. Average value for the four repetitions.

Sample no.	Description	Not dried, $t = 0$ h	Dried, $t = 1.5$ h	Dried, $t = 3$ h
S-1	Wood pellets (from trunks)	6.4	5.7	5.3
S-2	Wood pellets (from sawdust)	7.4	6.8	6.2
S-3	Poplar sawdust	6.3	5.0	4.2

Table 2. Proximate (wt.%, dry basis) and ultimate (wt.%, dry ash-free basis) parameters. Estimates of lignocellulosic mass fractions are also indicated.

Sample	Volatiles	Ash	Fixed carbon	C	H	N	O	S	Cl	X_{lig}	X_{cel}	X_{hem}
S-1	82.2	0.34	17.5	50.67	6.13	0.09	43.07	0.02	0.02	24.7	40.8	17.0
S-2	84.0	0.43	15.6	50.52	6.01	0.05	43.38	0.03	0.01	24.4	40.4	19.5
S-3	83.6	0.96	15.4	49.47	5.89	1.40	43.11	0.05	0.07	24.4	40.8	19.2

Table 3. Particle size, densities and angle of repose of the three samples (<400 μm fraction).

Sample	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)	ρ_S (g/cm^3)	ρ_B (g/cm^3)	AoR
S-1	117.7	394.5	838.9	1.4557	0.309	31.7°
S-2	118.6	352.0	704.4	1.4713	0.304	31.0°
S-3	20.23	123.7	445.9	1.7160	0.152	43.3°

applied has limitations, as the correlation coefficient for cellulose is 90%, while for lignin is 81%.[50]

Table 3 shows the main results of the particle size analyses, and Fig. 4 illustrates the complete PSD curves. As can be seen, sample S-3 was significantly finer than the other two materials. Moreover, the particle size distribution of S-3 was skewed and presented a long tail on the left side of the curve. Samples S-1 and S-2 – both produced by milling of pellets – were very similar, though some differences were detected. Considering the D_{50} values, sample S-1 was coarser than S-2. The same could be said about D_{90}. On the contrary, the D_{10} percentile was almost identical for these two samples.

The spans of the PSD curves, i.e. the width ($D_{90} - D_{10}$) divided by the median diameter D_{50},[54] were 1.83, 1.66 and 3.44 for S-1, S-2 and S-3, respectively. Therefore, S-1 presented a wider range of particle sizes than sample S-2, particularly in the coarse size. On the other hand, the span of S-3 was much larger.

Table 3 also gives the skeletal (ρ_S) and bulk (ρ_B) density values. Regarding the skeletal density, sample S-3 gave the highest value. Considering the insignificant differences in chemical composition (see Table 2), these results could suggest a higher number of closed pores or hollow particles in samples S-1 and S-2. On the other hand, large differences were detected in the bulk density; sample S-3 was characterized as a much looser material since its bulk density was half of the others.

The angle of repose (AoR) is also indicated in Table 3. As can be seen, the AoR of S-3 was much greater than those of S-1 and S-2, which were almost identical.

Figure 5 illustrates some pictures obtained with an optical microscope with the aid of a ×4 lens. The images for the <400 μm fractions (on the left) outline the great variety of particle shapes encountered in the samples. However, some differences between samples were evident. Sample S-3 showed a finer granulometry than the others, and its particles presented a great quantity of small lateral branches and a tendency to be entangled; these structures could partly explain its low bulk density. The <80 μm images (on the right) show that the S-1 and S-2 samples had a larger number of long fibrous particles and a lower number of the smallest particles.

Differences in sieving between biomass materials

The sieving process along time is illustrated by Fig. 6, which shows the three size fractions obtained from sample S1 with no drying (S-$1_{t=0}$). As can be seen, each fraction followed a different pattern. The <80 μm fraction showed a quasi-linear relationship with the sieving time. On the other hand, the >250 μm and 250–80 μm fractions followed a polynomial trend. The 250–80 μm curve reached its maximum value at 9.5 min and then started to decline slightly, whereas

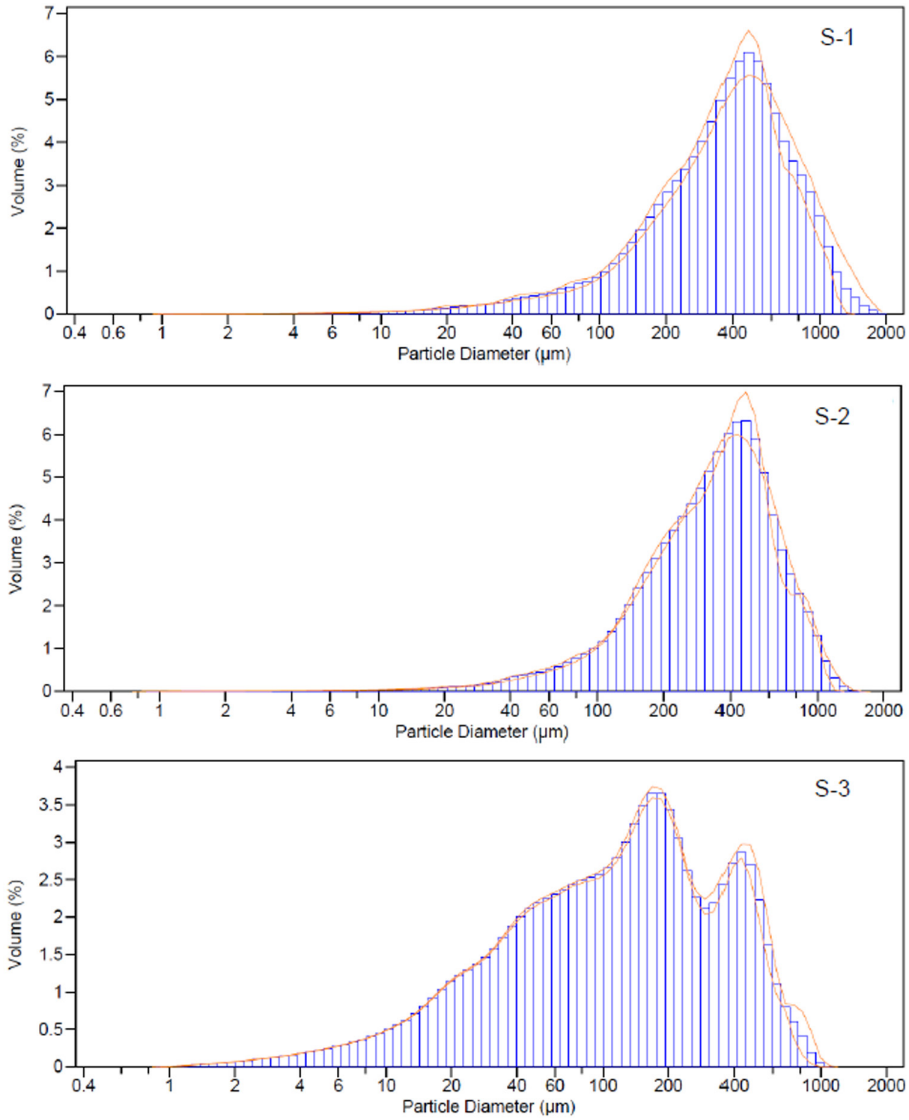

Figure 4. Particle size distribution of the samples (fraction <400 µm).

the >250 µm curve seemed to tend to an asymptote. This latter behavior – variation of mass frequency with time approaching a plateau – has been previously described for other materials when all particles much less than the mesh size have been eliminated from the sample.[55] The gentle slope of the <80 µm curve, which differed from the deep 250–80 µm curve during the first minutes, could be explained by a much lower number of particles smaller than the sieve aperture and by a fast blinding of the 80 µm sieve, as blinding increases sharply for mesh apertures below 100 µm.[22]

The results indicated that 92.7% of the total weight of 250–80 µm particles was obtained in the first 4 min. In the case of the <250 µm particles (the sum of the 250–80 µm and <80 µm fractions), 90.7% of the total amount was obtained in only 6.5 min, and 95.9% in 9.5 min. The percentages obtained at the end of the sieving process (at 15 min point) were 40.7% for >250 µm, 47.3% for 250–80 µm and 11.8% for <80 µm. The two smallest size fractions (<250 µm) summed to 59.2%. Thus, it was deduced that the average amount of material lost during the sieving procedure was 0.1% of the initial sample fed in the stack of sieves.

The curves obtained for S-$2_{t=0}$ were analogous to those shown in Fig. 6 and followed the same trends. In this case, the final results of the sieving operation were the following: 50.6% in weight of particles >250 µm and 49.1% of <250 µm, with 40.0% of 250–80 µm and 9.1% of <80 µm; the lost material was 0.3%. Although both types of pellets were made of *Pinus sylvestris* wood, it is clear that the differences in the technologies applied during the processing of the wood led to different milling and sieving behaviors: S-$2_{t=0}$ showed a

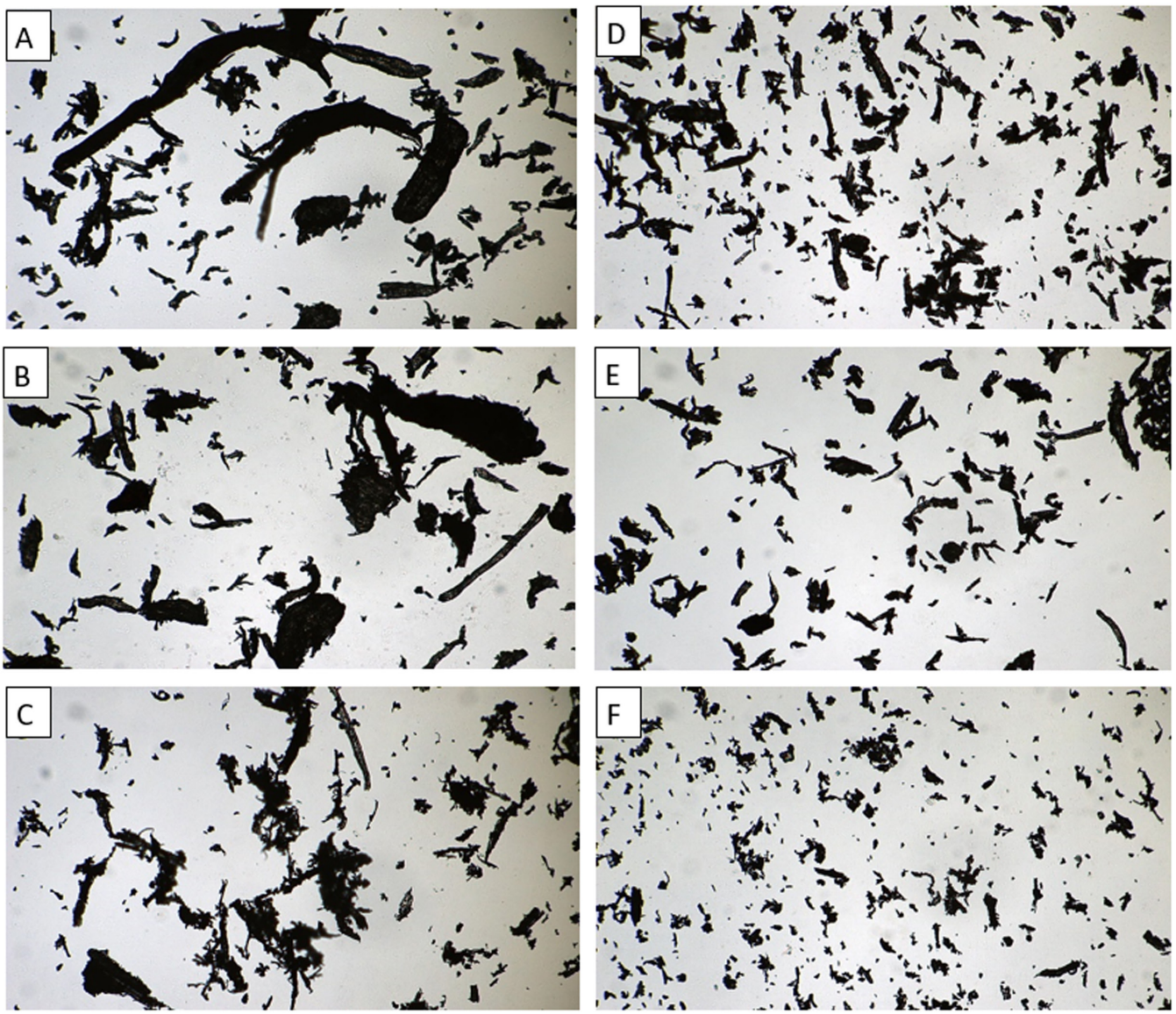

Figure 5. Images obtained by optical microscopy. Sample S-1 (A: <400 µm, D: <80 µm), sample S-2 (B: <400 µm, E: <80 µm), and sample S-3 (C: <400 µm, F: <80 µm).

lower sieving performance than S-$1_{t=0}$. It was also found that sieving of S-$2_{t=0}$ was a slower process than for S-$1_{t=0}$, because, in the first 4 min, only 84.5% of the 250–80 µm fraction was obtained, and only 86.2% of <250 µm in the first 6.5 min. These results suggest that S-2 tended to blind the screen more easily than S-1. A possible explanation is the presence of larger particles in S-1 (higher D_{90}) along with a wider PSD (larger span), as large particles could have helped the sieving process by tapping the screen.

The sample of poplar sawdust with no drying (S-$3_{t=0}$) had a different behavior from the wood pellets. Figure 7 demonstrates that the sieving process of S-$3_{t=0}$ was more gradual. The results after 15 min of sieving were 33.8% of the >250 µm fraction, 60.6% of 250–80 µm, and only 5.0% of <80 µm, with 0.6% of lost material. None of the three curves was found to present an asymptote or a stationary point of inflection. Furthermore, the sieving process was much slower because more than 11 min was necessary to reach ≥90% of total amount produced after 15 min, both for 250–80 µm and <250 µm fractions. Due to this behavior, sample S-$3_{t=0}$ was subsequently sieved for a much longer period (three repetitions were carried out). As can be seen in Fig. 8, the longer sieving procedure led to an analogous behavior with respect to those of wood pellets: the <80 µm fraction showed a quasi-linear relationship with time, the >250 µm and 250–80 µm fractions followed a polynomial trend, and the 250–80 µm curve reached

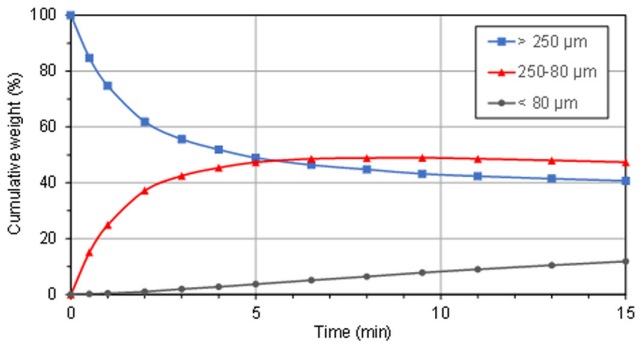

Figure 6. Weight percentage of three size fractions obtained during the sieving process of sample S-$1_{t=0}$.

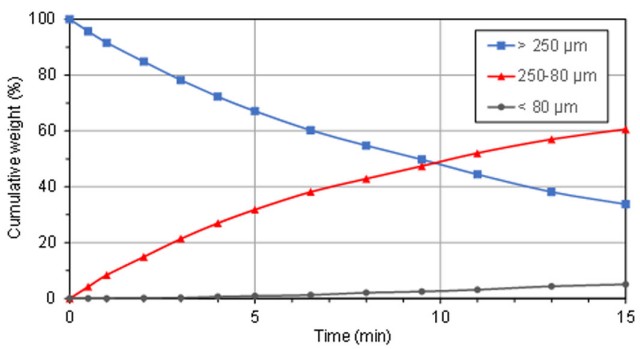

Figure 7. Weight percentage of three size fractions obtained during the sieving process of sample S-$3_{t=0}$.

its maximum value at 40 min, whereas the >250 µm curve seemed to tend to an asymptote.

The differences between materials could be explained by their physical properties. As described above, sample S-3 presented a lower bulk density and a higher angle of repose. The combination of these two factors could cause the dissimilar behavior of S-3. Actually, the friction between particles is linked with a low apparent bulk density.[56] The low bulk density of S-3 seems to be related to the shape of the particles and their tendency to entangle, because the skeletal density was very similar in the three cases. This low ρ_B probably complicated the sieving process by reducing the contact of the individual particles with the screening surface of the sieves. Furthermore, it is known that low bulk density powders are associated with reduced flowability and the presence of bridging phenomena.[31] On the other hand, the AoR is related to the flowability of powders: < 30° is assumed to produce very free flowing, whereas >45° means a poor flowability due to cohesion forces between particles.[15] This means that materials S-1 and S-2 (AoR of 31.7° and 31.0°) could flow much better than poplar sawdust (S-3), which presented an AoR of 43.3°; this could also influence the

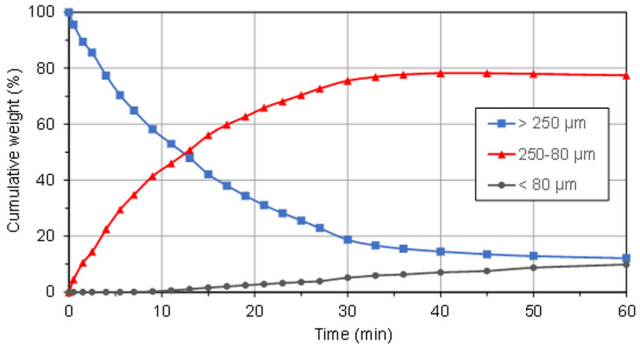

Figure 8. Weight percentages obtained during 1 h sieving of sample S-$3_{t=0}$.

movement of particles during the sieving procedure and the blocking of sieve holes by a layer of powder.

It is also commonly assumed that fine particles stick together more easily.[56] Interparticle forces lead to cohesion between particles and include capillary forces, van der Waals forces, and electrostatic forces.[57] This cohesion can form agglomerates by the adhesion of fine particles to the larger ones, resulting in an underestimation of fine fractions during size analysis by sieving.[5] These forces are particularly important when the particle mean diameter is below 30 µm;[15] a significant part of the PSD in the case of S-3 was below that size, whereas the <30 µm fraction was much smaller for S-1 and S-2. On the other hand, the internal PSD in the wood pellets can affect their milling behavior and the subsequent sieving analysis.[58] Pellets with finer internal particles lead to a finer ground material. This could explain the differences between samples S-1 and S-2.

Influence of moisture

Figures 9–11 show the influence of moisture on the sieving process for each of the three biomasses. The behavior of samples S1 and S2 – wood pellets – was quite the opposite from that registered for poplar sawdust (S3). In the case of wood pellets, the influence of moisture was notable when weighing the <80 µm fraction, but small in the case of 250–80 µm and <250 µm fractions.

For the <80 µm fraction of S1, drying the material for 1.5 h led to an increase in the cumulative weight greater than 100% in the time interval 1–4 min (with a maximum of 135.1% at the 2 min point), i.e. drying the wood pellets doubled the quantity of particles that passed through the 80 µm sieve in the initial phase of sieving. This difference later reduced, and dried and non-dried material only differed by 16.2% at the final 15 min point. However, further drying (t = 3 h) did not produce a substantial increase of the sieving performance for particles <80 µm: in the first 2 min the weighed quantity was

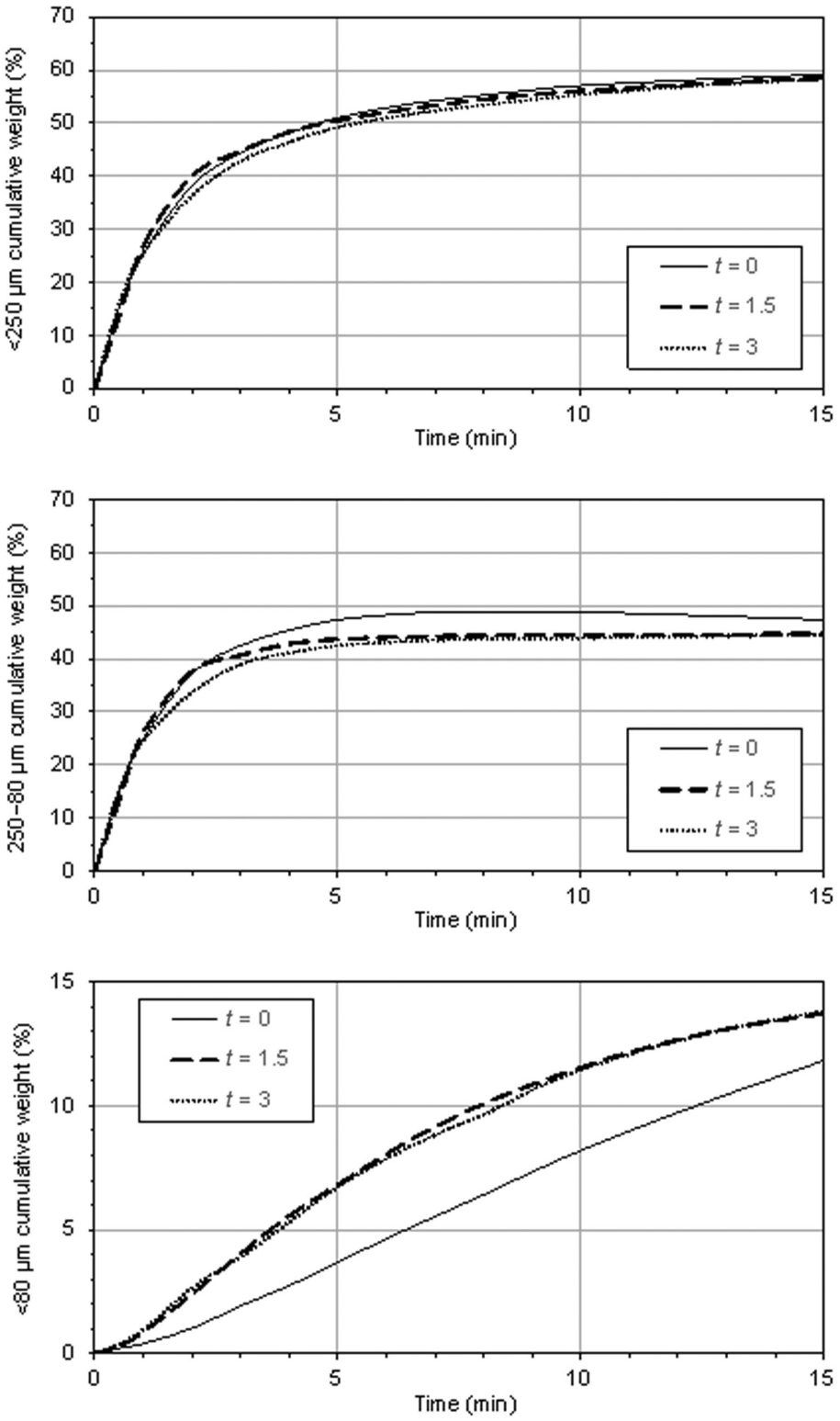

Figure 9. Weight percentage obtained during sieving of sample S-1 for three levels of drying (0, 1.5 and 3 h).

greater, with a maximum increment of 159.4% in comparison with the $t = 0$ sample, but later this difference dropped steeply to achieve a final value of 16.9%.

The results obtained for the <80 µm fraction of sample S2 were analogous to those of S1, but the role played by the moisture content was less important: the maximum

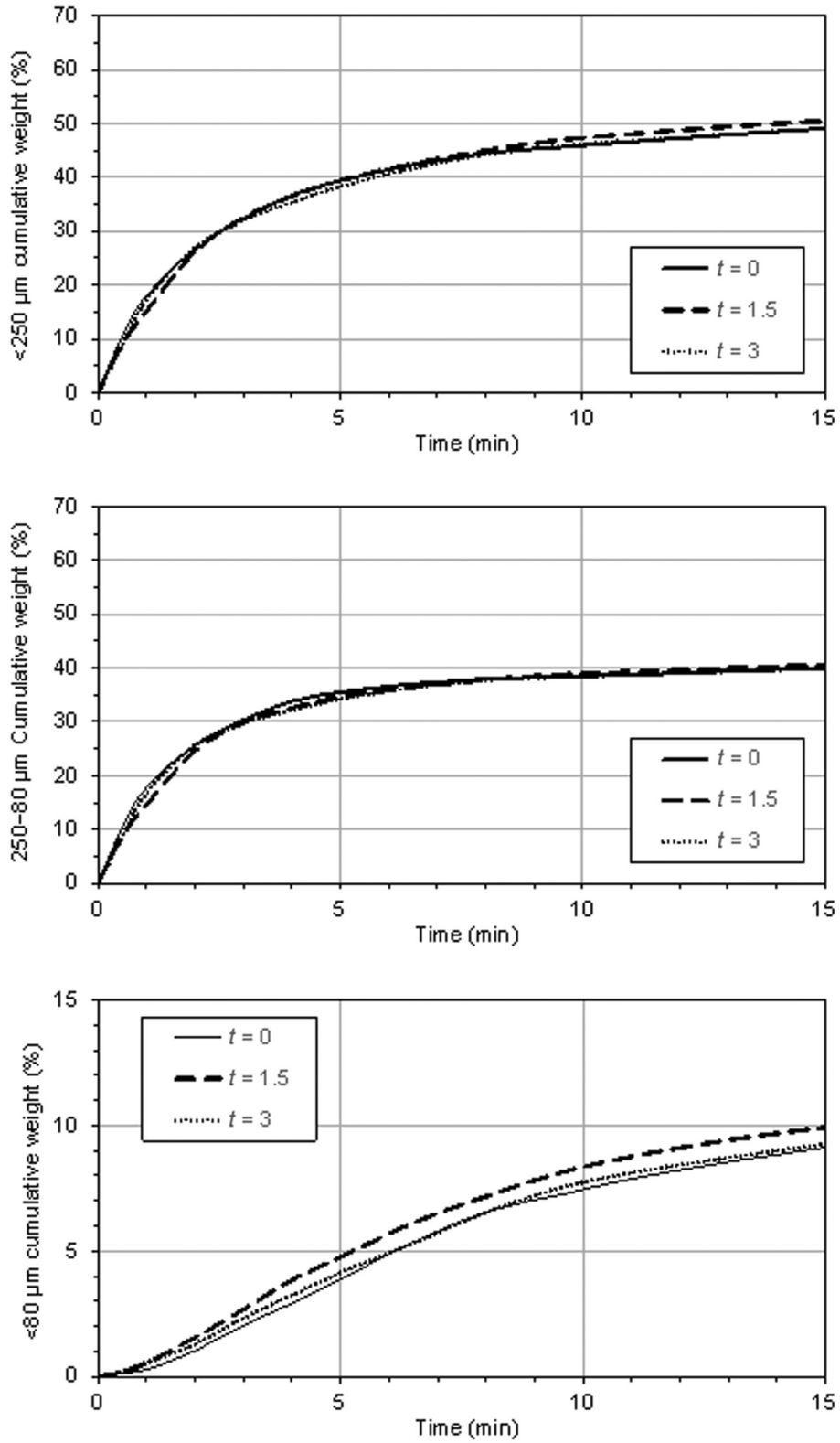

Figure 10. Weight percentage obtained during sieving of sample S-2 for three levels of drying (0, 1.5 and 3 h).

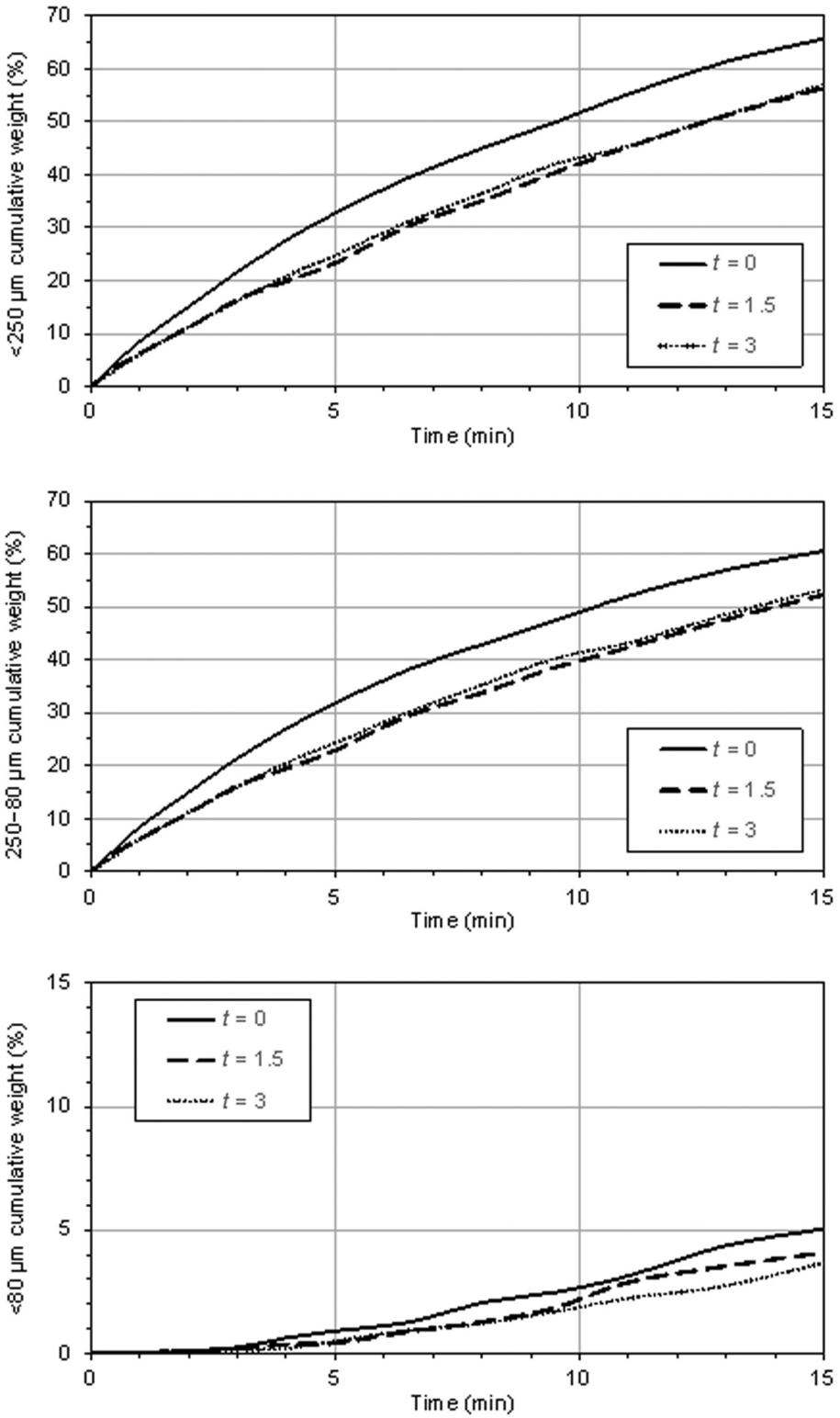

Figure 11. Weight percentage obtained during sieving of sample S-3 for three levels of drying (0, 1.5 and 3 h).

increment of sieving performance was achieved for $t = 3$ at 1.0 min (+94.9%) followed by $t = 1.5$ at 1.0 min (+85.1%), and the final increment after sieving for 15 min was 8.8% for $t = 1.5$ and only 1.4% for $t = 3$. In fact, Fig. 10 illustrates that the $t = 0$ and $t = 3$ curves were quite similar. It can therefore be deduced from these results that a slight drying for 1.5 h

improved the sieving performance for the smallest fraction, which is the most difficult to obtain in large quantities, whereas a longer drying period of 3 h hardly produced any improvement on the sieving performance. It is important to note that sample S-2 presented higher moisture contents than sample S1 for all of the three levels of drying (see Table 1). From the results obtained for S1 and S2, which corresponded to the same wood species, it can be deduced that the particle size and shape of the ground samples (fraction <400 µm), which in turn depended both on the properties of the original particles that were used in the pellets manufacturing process and on the process itself, was more important than the moisture content.

In contrast, Fig. 11 illustrates that drying did not produce any positive effect in terms of sieving performance for <80 µm particles in sample S-3. In fact, quite the opposite was true. Drying decreased the sieving performance of the <80 µm fraction by 18.9% (for $t = 1.5$) or by 27.0% (for $t = 3$) at the final 15 min point in comparison with the non-dried sample ($t = 0$).

In relation to the 250–80 µm fraction, S1 showed an opposite trend to that registered for <80 µm, whereas drying hardly had any effect on the <250 µm fraction. This means that drying did not increase the total weight of <250 µm particles, but modified the share of the two fractions that composed the total weight passing through the 250 µm sieve; if the <80 µm weight increased, the 250–80 µm weight decreased. Actually, drying the sample for 1.5 h produced a small reduction in the 250–80 µm weight for sieving time > 2 min, with a final value of approximately −5.5% at the final 15 min point; this reduction was higher for $t = 3$, with a maximum of −10.8% for 6.5 min. Sample S2 showed a slightly different behavior, and in this case the differences between the three drying levels were much smaller. As can be seen in Fig. 10, the three curves for the 250–80 µm and < 250 µm fractions almost overlapped, with a small 2.9% increase of <250 µm fraction for S-$2_{t=1.5}$ in comparison with S-$2_{t=0}$ at the 15 min point, and a null improvement for S-$2_{t=3}$. On the other hand, tests for sample S3 gave the opposite results. As shown in Fig. 11, drying the biomass significantly reduced the sieving performance, though the degree of drying did not seem to have a relevant influence; this reduction in the sieving performance ranged from −14.1% for the <250 µm fraction of S-$3_{t=1.5}$ to −12.0% for the 250–80 µm fraction of S-$3_{t=3}$.

The analysis of variance performed with SPSS Statistics supported the above discussion of Figs 9–11. In the case of sample S-1, significant differences were found in the sieving performance between the material without prior drying and the dried material (both for 1.5 and 3 h). These differences were observed in the amount of <80 µm powder from 1 min of sieving, being significantly higher ($P \leq 0.05$) in samples S-$1_{t=1.5}$ and S-$1_{t=3}$ in comparison with S-$1_{t=0}$. These differences appeared along the whole sieving time, from 1 min to 15 min. However, this effect was not observed in the <250 µm dust fraction, where the percentage of dust obtained was almost equal for all treatments. The effect of drying on the other two materials was quite different, as described above. For S-2, significant differences were found only for very short sieving times, below 5 min, producing a significantly higher amount in S-$2_{t=1.5}$ than in S-$2_{t=0}$ and S-$2_{t=3}$, which behaved similarly to each other. For the <250 µm fraction, significant differences were not detected in any sieving time. Finally, S-3 presented the opposite behavior with respect to S-1 and S-2, as significantly higher amounts of <250 µm particles were found in S-$3_{t=0}$ (without prior drying) compared to treatments $t = 1.5$ and $t = 3$ (with previous drying); these differences appeared at 2 min point and continued until 11 min of sieving. However, in the case of powder <80 µm, no consistent significant differences were found throughout the sieving time for S-3, although more dust was obtained in the case of S-$3_{t=0}$.

The varying influence of moisture on the sieving behavior could be due to several reasons. The first explanation could be wood shrinkage. As wood changes from completely dry to the fiber saturation point, its dimensions change.[3] Thus, drying can reduce the dimensions of the particles and then improve the sieving performance. However, shrinkage and swelling occur mostly in the tangential and radial directions but are irrelevant in the longitudinal direction of wood pieces. This anisotropy, along with the probable differences in the orientation of the fibers in the dust particles generated by milling or by the technological processes previously applied to the pine and poplar woods, could explain the behaviors of the samples in this study. Dimensional changes depend on the density and growth characteristics of the piece of wood.[3] Lignin content could also play a role because lignin is substantially less hygroscopic than cellulose and hemicellulose,[3] i.e. lignin can constrain the reaction of wood to moisture changes. Although lignin content seemed to be similar in the three samples of this study, such content was estimated from the proximate and ultimate parameters, but not determined by analysis.

Second, there could have been differences in particle shape and structure, including the possible accumulation of certain parts of the trunk section in the finest fractions of the sieved samples. Shape irregularities, the presence of lateral branches (see Fig. 5) and the orientation of the cells, which are elongated and present different shrinkage behavior depending on the direction considered,[3] could have influenced the results.

Finally, there could have been differences in the skeletal density. If these differences are due, even in part, to the presence of closed pores in the particles with lower ρ_S (S-1 and S-2), it is conceivable to think that the shrinkage process could differ. All the above factors deserve further investigation to discover their effects on sieving and verify whether they could explain the dissimilarities reported here.

Drying the biomass material may enhance the yield of fine particles in some cases, such as for the wood pellets in S-1, or may complicate the sieving process, as in the case of the poplar sawdust in S-3. Intermediate situations – enhancement for a short time or enhancement for some fractions but not for others – may also happen, as demonstrated by results from sample S-2. Contradictory responses to moisture were also detected by Elskamp and Kruggel-Emden, who reported that an addition of water to polyoxymethylene or to glass spheres slightly reduced the particle passage in most configurations, whereas blinding can be reduced in some cases.[26] Wet screening of coal has also shown lower efficiency in comparison with dry screening.[59] Biazzi *et al.* also observed that moisture reduces the sieving efficiency of ground maize and proposed pre-drying,[60] and the same was detected by Siliveru and Ambrose using flour samples with 10% and 14% of moisture from both hard and soft winter wheat.[27] On the other hand, Liu found that when the moisture of soft wheat flour increased from 7% to 11%, more fine particles were sifted through the sieve.[13] It seems quite plausible that, as Liu suggested, for a given sieving condition and given particulate material, there will be a moisture level that optimizes the sieving procedure.[13]

With respect to the optimum duration of sieving, the results indicate that a preliminary study of the behavior of the material to be sieved could be beneficial when large quantities of fine particles are to be obtained. Depending on the restrictive factor – time or quantity of original sample – the approach could differ. It is easily deduced from Figs. 7–11 that short times could be enough to obtain large quantities of the coarse fractions (< 250 µm and 250–80 µm), thus saving time and effort, whereas much longer sieving times would be required to obtain a large enough quantity of the finest fraction (< 80 µm). In case of sieving for size analysis, time has an influence on the efficiency and accuracy. Times lower than 10 min can produce significant errors.[61] Moreover, fibrous particles are not adequately characterized by sieving; image analysis techniques are required to determine accurately the particle geometry of most biomass feedstocks.[38]

The results presented here provide some hints that could enhance the sieving tasks in laboratories and industry. However, this study has proved that there is no universal behavior for the effects of moisture on the sieving performance of biomass materials. It is clear that more work is required to know the sieving performance of biomasses, including other materials and levels of moisture content, and different milling and sieving equipment and procedures.

Conclusions

The experiments conducted in the present study investigated the sieving performance of three biomass materials and the influence of the moisture content by applying different levels of prior drying. Several conclusions can be drawn from the results:

- The sieving performance of each biomass is different. Even biomass materials obtained from the same species can behave differently.
- The influence of moisture depends on the type of biomass. In some cases, slight drying before the sieving process significantly enhances the sieving performance, but in others cases this effect is irrelevant, or there could even be the opposite effect.
- Where drying presents a favorable effect, its influence seems stronger for the finest fractions.
- The results suggest the importance of conducting a preliminary study of the behavior of new materials to be sieved in large quantities to optimize time and/or the quantity of raw material.
- The desired fraction size to be obtained by sieving will determine the approach to be adopted. Coarse fractions of dust can be achieved with short sieving durations if enough material is available. On the other hand, fine particles require much longer durations. The optimum duration can depend heavily on the properties of the material to be sieved.
- Further research in this area is still necessary in order to know the sieving behavior of biomass materials, the influence of the different variables involved, and the interactions between them and with the underlying physical principles.

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