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Presentation of new areas of application for SpreuStroh

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Every year, 10 million tonnes of chaff are available for recovery as residual material in Germany alone. Based on an innovative harvesting process that enables the recovery of the uncleaned grain in a mixture of chaff and chopped straw, the chaff can be put to a value-adding use in the form of the novel biomass mixture SpreuStroh (chaff-straw). In this paper, various processing options and thus possible uses of the chaff-straw mixture are presented. Based on an extensive characterisation of the SpreuStroh, possible applications for the farmer are shown. The system-related removal of weed-seeds and thus the reduction in the use of pesticides represents a particular benefit for the environment. Further processing of the chaff-straw mixture reveals higher-value potential uses, such as use in 3D printing or as an additive in fibre-plastic composites.

Keywords
SpreuStroh, chaff-straw, renewable raw materials, processing, 3D-printing, injection moulding

Every year in Germany, 10 million tonnes of chaff remain on the fields as unused biomass (Rumpler 2016). The chaff yields vary in the range of one to one and a half tonnes per hectare (Berger et al. 2010). A newly developed, innovative harvesting process makes it possible to harvest these quantities of chaff in a mixture with grain and straw. This makes it possible for the first time to reliably provide industrially required quantities (Rudolph 2020).

In the course of the increasingly intensive search for renewable raw materials and the reduction in the use of only slowly renewable resources, such as wood, the use of chaff, as a biological residual material, appears to be an interesting alternative. In recent years, there have been numerous efforts to use the residual material chaff for an application. The main focus was on the use in keeping of animals (Mann et al. 1988) and energy use (Fick-Haas 2015, Khalsa et al. 2016).

In this paper, the possibilities of central processing of the SpreuStroh, recovered with the new harvester, are shown. Various possible applications for SpreuStroh must be considered and application-oriented processing technologies must be made available in a modular process chain. The focus is on the one hand on the comprehensive material and physical characterisation of the raw material and on the other hand on the resulting possibilities for processing the material. Options for special application possibilities are to be made available for the novel product.

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Materials and methods

The SpreuStroh used was harvested in 2019, 2020 and 2021. The mixture consists of wheat straw and wheat chaff in equal mass proportions. SpreuStroh is harvested together with wheat straw. The harvesting method of compact harvesting is described in the literature (Rumpler 2015, Rumpler 2016, Rudolph 2020). In a pre-cleaning process, the grains are separated from the SpreuStroh and the separated SpreuStroh is used for the investigations presented here.

Methods of processing

Various comminution machines were used to crush the material. They differ in their kind of stress. For preparation of fibrous materials comminution by impact and cutting are considered from the five possible kinds of stress (impact, pressure, shear and cutting). An ultra-centrifugal mill from Retsch GmbH (ZM 200) with different sieve inserts from 2 mm to 250 μm was used to realise the cutting stress. For the comminution by impact different mills were used. A pin mill (Gebrüder Jehmlich GmbH, REKORD A, with pin ring) was used for primary crushing. For the fine grinding by impact a small impact mill from Gebrüder Jehmlich GmbH with different sieve inserts from 1 mm to 250 μm were used.

Methods and characterisation

To estimate the possible applications a comprehensive characterisation of the original material and the different products after processing is necessary. In every step of processing the particle size distribution is analysed by an analytical sieving (to 100 μm, plansifter, Haver & Boecker). To analyse the particle size distribution after grinding laser diffraction was used (Analysette, Fa. Fritsch). To compare the different particle size distribution the median value $x_{3.50}$ and the width of the distribution ($s = (x_{3.90} - x_{3.10})/x_{3.50}$) were used.

To assess the flowability of the prepared products, shear tests were carried out according to Jenike (Schubert 2003) at the institute of mechanical process engineering and mineral processing at der TU Bergakademie Freiberg. Therefor the material was loaded and sheared in a defined way in a so called Jenike shear cell and the relevant measured values recorded.

In order to determine the dry matter and mineral content of the individual materials, a thermogravimetric analysis (TGA/DSC 1, Fa. Mettler Toledo) was carried out. The individual stages of mass loss can be assigned to individual stages of decomposition on the basis of the temperature curves. The first loss of mass (stage 1), which is due to the evaporating water, is of importance. In the next loss of mass (stage 2), all carbon-containing substances are decomposed. What remains is a residue (stage 3), which is of a mineral nature and is thus equated with the mineral content of the sample.

The SpreuStroh is mixed with polypropylene in a laboratory extruder (type 20/25 D, Babaender). The state of the mixture is evaluated by thermogravimetric analysis. The extruded composite materials are processed into tensile-test-bars in a laboratory injection moulding machine (Babyplast 6/10-P, Christmann). These are examined with regard to tensile strength and maximum elongation in a tensile testing machine (Z 005 table-top testing machine, ZwickRoell) and examined and compared with regard to the influence of particle size and fibre content in the composite material.

Special properties of SpreuStroh

In order to determine the optimal areas of application for the novel material mixture SpreuStroh, numerous analytical considerations were carried out. The harvested material is obtained as a mixture of grain, straw and chaff in proportion (Figure 1). 25 % of the straw is harvested and 75 % remains on the field for humus formation. On the other hand, 100 % of the grain is harvested and, in addition to conventional harvesting methods, 100 % of the chaff is harvested. This mixture is driven off the field in one pass, followed by pre-cleaning, i. e. separation from the grain. The remaining mixture of chaff and straw is available in a mass ratio of 1 : 1 and can be further processed and prepared.

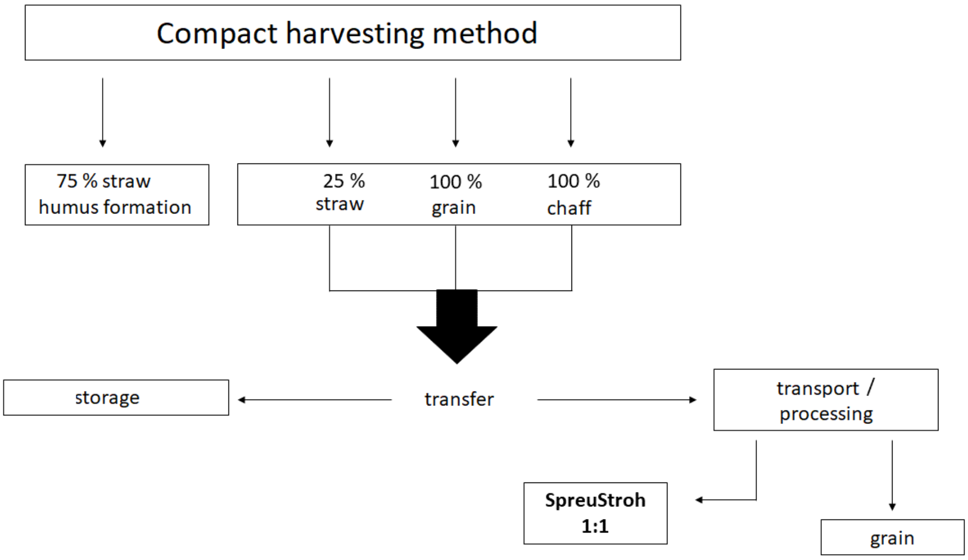

Figure 1: Schema compact harvesting method (Rudolph 2020)

The straw has already been pre-shredded on the harvester by a standard shredder, which guarantees a certain continuity in the starting material. For illustration purposes, Figure 2 shows a particle size distribution of the starting material SpreuStroh from the harvest in 2019.

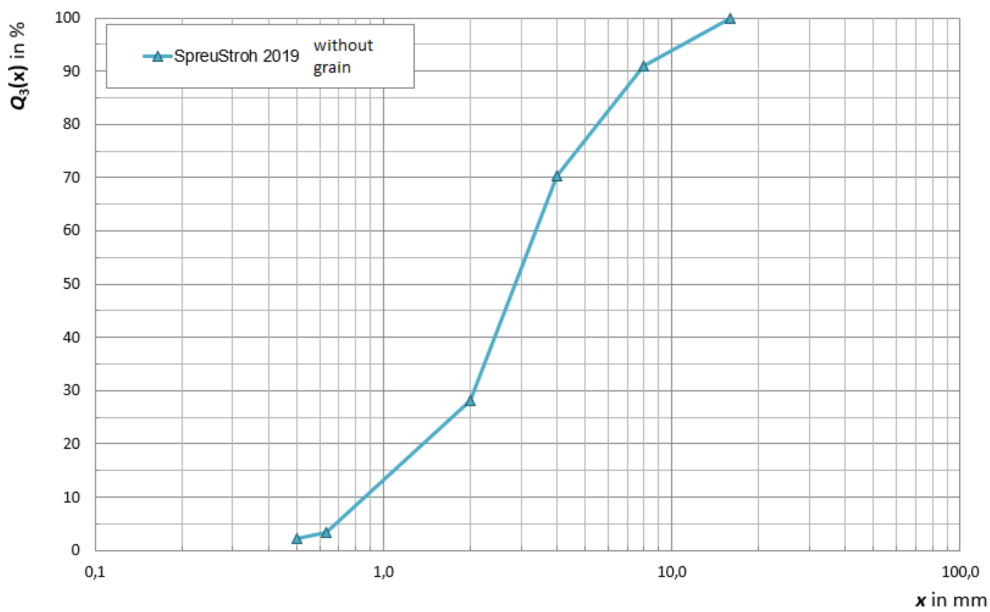

Figure 2: Particle size distribution original material SpreuStroh from the 2019 harvest

Due to the mixture of chaff and straw, there is a rather broad particle size distribution with a range of 2.32 ($x_{3.50}$ = 2.19 mm). In Figure 3, chaff and straw are shown separately. The visual difference between chaff and straw is clearly visible. The mixture of both materials leads to a rather inhomogeneous mixture, which has to be considered when preparing it for different applications. These differences are also reflected in the material composition of the chaff and straw. The main differences are briefly described in the following discussion. The combination of the different properties of chaff and straw leads to numerous advantages in various fields of application.

Figure 3: Individual fractions of SpreuStroh; left chaff, right straw

Thermogravimetric analysis reveals the organic dry matter and mineral content of the material. Samples of pure straw and pure chaff were prepared for analysis. It can be seen that the organic dry matter is lower in chaff (87 %) than in straw (90 %). This is due to the fact that chaff has a 3 percentage points higher mineral content than straw. At 8 %, mineral content of chaff is considered to be high. A mixture of chaff and straw will therefore have a lower organic dry matter and also a higher mineral content compared to pure straw. This has advantages or disadvantages, depending on the later application of the SpreuStroh. The lower amount of organic dry matter, for example, leads to a lower methane yield in a biogas plant. For higher-value applications, such as the use of SpreuStroh in building industry as an insulating material, SpreuStroh has clear advantages due to its higher mineral content than straw, as this improves its fire behaviour.

As already indicated by the differences in mineral content between chaff and straw, the materials also differ in terms of other material properties. The content of cellulose, lignin and hemicellulose is important for various applications of biogenic residues. Wood, as a widespread natural raw material, is always used for comparison. For evaluation, the method according to Weender is applied and the material data of SpreuStroh and wood are shown in Table 1. Compared to wood, chaff and straw have a significantly lower lignin content. For cellulose and hemicellulose, chaff and straw are in a similar range to wood.

Table 1: Content of cellulose, lignin and hemicellulose in chaff, straw and wood determined according to Weender (Gelamin 2020)

Material	**Lignin** %	**Cellulose** %	**Hemicellulose** %
Wood (Pastusiak 2003)	18–30	43–50	22–36
Chaff	6.0	36.8	40.4
Straw	6.5	41.9	30.7

In order to investigate the influence of the chaff content in the SpreuStroh on the fire behaviour, two defined mixtures of SpreuStroh were prepared. In the first sample, the chaff content is only 40 %, in the second sample 66 %. The fire behaviour was carried out for both mixtures according to EN ISO 11925-2:2020. As a result, both samples were classified in fire class E. In terms of flammability when exposed to direct flame, the chaff content therefore has no direct influence and is in the same order of magnitude as pure straw. In addition, the thermal conductivity of SpreuStroh, similar to straw, was also determined with regard to its use as a thermal insulation material. These tests were carried out in accordance to the EN 1602:2013 and EN 12667:2001 test standards for the assessment of building materials. From the results, it can be deduced that a higher chaff content means that the material in a thermal insulation board is more difficult to compact. This is due to the shape of the chaff. During compaction, the chaff particles do not necessarily lie on top of each other in flat layers, as is known from straw. If the proportion of chaff in the SpreuStroh mixture increases, the thermal conductivity also decreases slightly. This is also due to the fact that the shape of the chaff leads to low compression and thus more heat-insulating air can be trapped. The coefficient of thermal conductivity was 0.043 W/(m · K) on average during the measurements.

Results and discussion

Use of SpreuStroh for the farmer's own needs

The simplest form of use for the SpreuStroh is as bedding for animals. Short straw/chaff is easier to spread in the stable and moreover it is easier to remove from the stable after use. The SpreuStroh harvested with the compact harvesting method already has the necessary fibre length and does not need to be additionally shredded. However, in order to have an even easier handling of the SpreuStroh as bedding, the material can be chopped and pelletised before use (Gerighausen and Höner 2008, Schoebel 2010, Khalsa et al. 2016). Another advantage for use as bedding is the high water absorption capacity of chaff. This strongly varying with the different types of grain, but is at least 500% of the net weight. (Berger et al. 2010). It is thus higher than when pure straw is used as bedding, which, at approx. 300 % of its own weight, can bind a relatively small amount of water (Häussermann et al. 2002).

Straw can also be fermented in a biogas plant. The highest possible dry contents matter, as these lead to a higher methane yield (Reuters 2013). Another important aspect with regard to utilisation in the biogas plant is the pulping of the fibres. The lignin in the fibres has to be broken either mechanically or chemically. (Kerkering 2019). Investigations with chaff have shown that one kilogram of chaff can provide approx. 0.33 m^3 of methane in the biogas plant (Marti et al. 2013). Straw, however, has an average methane yield of only approx. 0.16 m^3 kg^{-1}. (Chandra et al. 2012, Kerkering 2019). Straw is currently being pre-treated for use in a biogas plant, thereby significantly increasing the methane yield (Chandra et al. 2012).

The compact harvesting method enables the farmer to save on herbicides. By collecting chaff, a large proportion of weed seeds are also included in the chaff fraction and are not spread back into the field, resulting in a reduction of weeds on the field. These are predominantly weeds whose mature at the same time as the grain. This realisation is not new in itself, but has been forgotten in recent years with the development of ever more powerful combine harvesters (Griepentrog and Brandt 1985, Shirtliffe and Entz 2005). In most cases, the weed seeds can be separated from the SpreuStroh by simple sieving at the farm. Laboratory tests have shown that common poppy and cornflower seeds, for example, can be easily separated from the SpreuStroh using a 1-2 mm sieve (Figure 4).

During the sieving at 1mm not only weed seeds will be separated but also approx.. 10-15% of the SpreuStroh. This fraction could be separated from weed seeds by an air classifier. The laboratory experiments with an air classifier (laboratory air classifier Mini 40-ST, Fa. Samatec GmbH) have shown that the weed seeds are specifically heavier than the SpreuStroh fraction smaller than 1 mm. The SpreuStroh is carried along with the air flow and the weed seeds fall against the air flow following the earth's gravitational field.

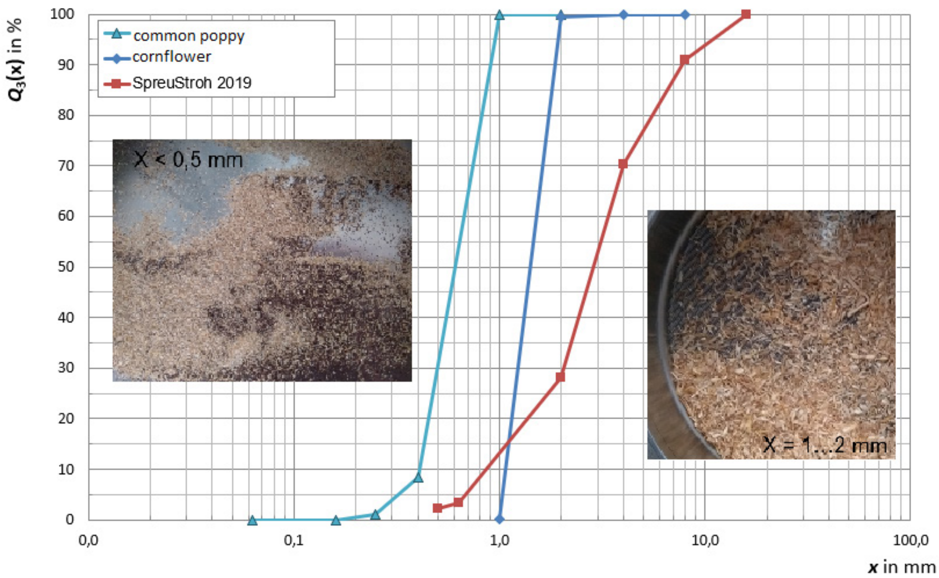

Figure 4: Sieve analysis SpreuStroh as well as common poppy and cornflower

Higher-value uses for SpreuStroh

In addition to the use of SpreuStroh on one's own farm, SpreuStroh can also be used for higher-value applications, for example as an additive in plastic parts produced by extrusion or injection moulding. This requires some preparation steps, which are presented and compared in the following. The application possibilities result primarily from the material properties resulting from the processing. First the material was crushed. This is done in several stages with different shredders, which differ in the type of stress. Figure 5 shows the particle size distributions of shredded SpreuStroh to a particle size below 1 mm. Cutting stress in an ultra-centrifugal mill (ZM200, Fa Retsch GmbH) and the impact stress in a small impact mill (Gebrüder Jehmlich GmbH) was compared.

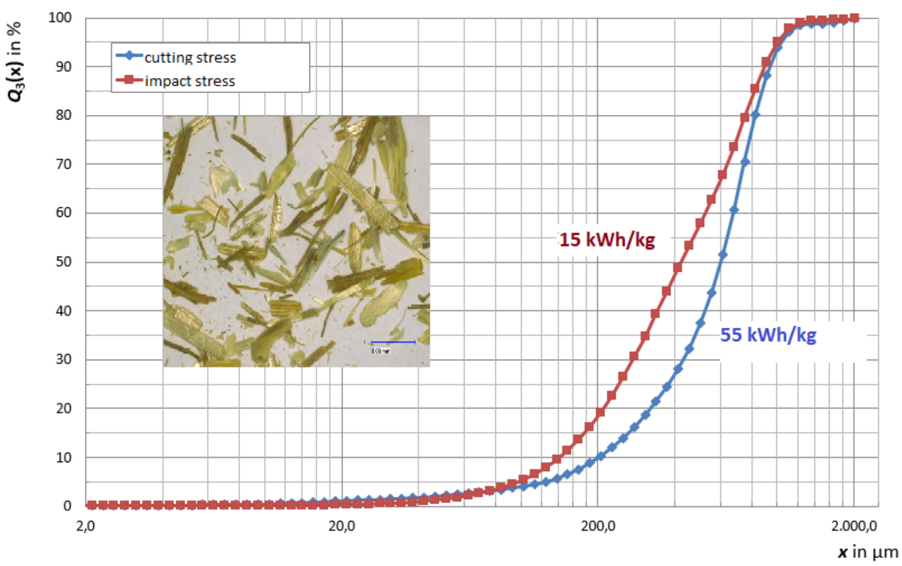

Figure 5: Comparison of particle size distribution of differently crushed SpreuStroh (x < 1 mm), microscopic picture of SpreuStroh (x < 1mm impact stress)

Figure 5 shows a slightly finer product can be achieved with x < 1mm with pure impact stress. That's because chaff, due to its higher mineral content, is somewhat harder and cannot be optimally crushed by the cutting stress. In the worst case, the grinding of SpreuStroh would result in greater abrasion of the cutting tools in the mill. Chaff is more compact than straw and less fibrous. Straw alone is known to crush very well with a cutting stress. It should also be noted that the energy required to break up the SpreuStroh is significantly lower with impact stress.

The particle size distributions in Figure 6 show that there is only a slight difference whether chaff straw is reduced to the final fineness with a pure cutting stress or whether impact and cutting stress are combined. The decisive factors here should be the required comminution energy and the possible abrasion of the grinding tools. This shows that a combination of the stress types is preferable, as significantly less energy is required for a similar final fineness. The combination of stress types also has an influence on the further processing of the crushed material. The flowability of the material is of great importance for the storage and conveying of the crushed SpreuStroh. Investigations of the flowability of the crushed SpreuStroh according to Jenike have shown that a combination of impact and cutting stress is quite reasonable, also with regard to the flowability of the material.

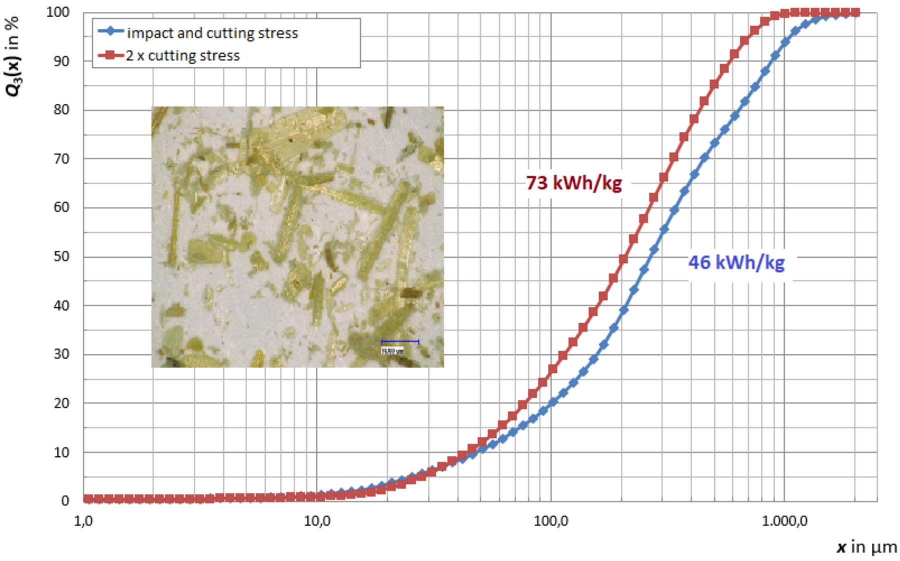

Figure 6: Comparison of the particle size distribution by combination of stress types with the pure cutting stress, microscopic picture of crushed SpreuStroh

Table 2 shows the flow characteristics from the analysis of flowability according to Jenike for two differently comminute SpreuStroh samples. For sample 1, pre-crushing was carried out by means of impact loading and then the final fineness was achieved by means of cutting stress. Sample 2 was produced in a two-step process via a cutting stress. The particle size distributions of both samples are shown in Figure 6.

Table 2: Flow characteristics from the analysis of the flowability of crushed chaff straw according to Jenike

Material	Yield locus	σ_1 kPa	σ_c kPa	ff_c	ϕ_i °	ϕ_e °	τ_c kPa	ρ_b kg/m³
SpreuStroh impact + cutting stress	0	3.7	0.1	38.5	44.8	45.4	0.02	191.0
	1	6.1	0.2	28.0	40.7	41.6	0.05	200.1
	2	12.1	0.1	132.9	42.6	42.7	0.02	211.1
SpreuStroh cutting stress	0	3.0	0.4	7.9	61.0	39.1	0.09	195.1
	1	5.6	0.1	41.1	55.2	42.5	0.03	209.1
	2	12.0	0.6	21.4	34.6	40.3	0.13	203.5

Explanation of the physical quantities:
σ_1 called major principal stress decisive for the strength properties.
Bulk density ρ_b depends on the magnitude of the consolidation stress acting on the bulk solid.
Cohesion τ_c describes the shear strength of the bulk solid.
angle of internal friction at steady-state flow ϕ_i describes the "incipient flow" of the bulk solid.
unconfined yield strength σc describes the strength of the bulk solid under uniaxial loading.
effective angle of internal friction ϕ_e describes the internal friction of the bulk solid during steady-state flow.

Both analysed materials are very loose bulk, which can be compacted by light mechanical stress. Both samples are classified as easy-flowing or free-flowing. This is shown by the high flowability characteristics ($ff_c = \sigma_1/\sigma_c$)in Table 2 across different stress states. This proves to be particularly favourable for later silo dimensioning and transportation of the material. Cohesion also does not increase with increasing solidification and is to be classified as very low. Due to the fibrous structure of the material, this was not necessarily to be expected. During steady-state flow, the fibres nevertheless appear to hook together, as the effective angle of friction is unusually high even at low stresses, indicating high internal friction in the bulk material. Comparatively, it can be concluded for the two samples that the combination of impact and cutting stress is advantageous for comminution. Thus, a combination of different stress types makes not only from an energy point of view sense for crushing of SpreuStroh.

The SpreuStroh, which is crushed in various stages, can be used in different areas and replace other natural materials, such as wood, or reduce the consumption of wood. Some possible applications are presented in the following passage.

A common application of wood fibres is the production of wood plastic composites, short WPC. In this process, the plastic is substituted to a certain percentage by the wood fibre. The proportion depends on the required properties of the product and is adjusted individually. Fibre contents of up to 70% are common. The price of wood has risen significantly in recent years (Markmann 2022) and it makes sense to think about replacing some of the wood fibres used with other biogenic residual materials that grow more quickly. In doing so, certain requirements have to be fulfilled. On the one hand, it should be possible to grind the material to the desired fineness. As described in the previous chapter, it is possible. The average particle size of the material should be between 400 µm and 800 µm. Furthermore, the bulk should be free-flowing so that it can be stored and conveyed well in the corresponding production facilities. The investigations into the flowability of SpreuStroh have shown that the new material SpreuStroh has very good properties in this respect. Another indication of good processing in extrusion processes is the bulk density of the crushed material. Tests on SpreuStroh have shown that the bulk density increases significantly as a result of the comminution (raw material: 25 kg/m³) and is in the required range at approx. 130 kg/m³.

The use of SpreuStroh in injection moulding is also possible. The investigations have shown that a fibre content of up to 50 % is possible without additives to modify the SpreuStroh fibre (Figure 7). For better mixing of plastic and SpreuStroh, both components should be mixed before injection moulding. To further increase the proportion of fibres in the component, the surface of the fibre should be chemically modified and so-called adhesion promoters, such as silanes, should be used. The tensile strength and elongation of the plastic-SpreuStroh composites (Figure 7, right) decrease significantly with increasing fibre content. In the investigations carried out, no dependence on the type of comminution of the chaff straw could be determined.

material	tensil strength in N/mm²	max. elongation in %
100% PP	35,5	6,2
straw (cut) x < 1 mm fibre content 15%	33,5	4,3
straw (impact) x < 1mm fibre content 15%	32,5	4,5
SpreuStroh (cut) x < 1 mm fibre content 15%	33,1	4,3
SpreuStroh (impact + cut) x < 0,5 mm fibre content 33 %	26,8	1,9
SpreuStroh (impact + cut) x < 1 mm fibre content 50 %	26,3	2,4

Figure 7: Injection-moulded tensile test rods made of chaff straw and PP with different fibre content (left); material properties from the tensile test (right)

In summary, the use of SpreuStroh in extrusion and injection moulding processes can replace wood and other fibres (e. g. glass and carbon) in many areas. However, there are areas where application does not seem to make sense. This is, for example, the use as reinforcement in fibre-reinforced plastics for heavily loaded components. SpreuStroh can be used in natural fibre-reinforced plastics wherever it is a question of substituting the plastic and thus reducing the proportion of plastic in a component. As soon as it is a question of reinforcing a plastic and improving the mechanical properties of the plastic, the use of chaff straw will not be possible due to the naturally relatively short fibres.

A very fine material with a particle size of less than 250 µm is required for use in the 3D printing process. It is possible to crush SpreuStroh into this size range. For this purpose, it is recommended to crush the material in at least a three-stage process. This process is quite energy-intensive. A more favourable variant is the use of dusts from dedusting plants of other processes for the treatment of SpreuStroh. Whether this is the dedusting of chaff straw as animal feed, or the material from a processing plant of chaff straw for extrusion or injection moulding, is negligible. The SpreuStroh particles separated in the cyclone of a dedusting system usually have the fineness required for 3D printing.

Research has shown that SpreuStroh can be used in the 3D printing process just as well as shredded miscanthus or even shredded coffee husks. This makes it possible to produce special packaging that is completely biodegradable. For this purpose, it is necessary to use biodegradable plastics such as polylactic acid (PLA) or natural sugar as binders in 3D printing (Zeidler et al. 2018). Initial tests on 3D-printed samples showed that the yield strength for SpreuStroh are in the same order of magnitude as miscanthus.

Conclusions

The special properties of SpreuStroh were analysed and a wide variety of applications in different stages of processing were demonstrated. The direct use of the chaff straw for the farmer's own needs as bedding or in the biogas plant is particularly desirable. However, the material SpreuStroh also has a number of advantages in higher-value applications. It was shown that SpreuStroh is suitable as a filler in plastic composites and that SpreuStroh also leads to good results in the field of 3D printing of natural fibres.

Next, individual application possibilities will be examined in more detail and, above all, more focus will be placed on the energy and economic aspects. The question arises whether the use of SpreuStroh for higher-value applications can be an alternative to wood fibres and other renewable raw materials such as miscanthus, flax or hemp.

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