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Penetration Resistance and Water-Holding Capacity of Differently Conditioned Straw for Deep Litter Housing Systems

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Recently, litter systems in animal husbandry are gaining attention again due to aspects of animal welfare, environmental issues and low investment costs. In most of these animal housing systems, straw is being used as bedding material. The best storage form and conditioning for this straw is examined critically by determining both the stability of manure mattresses comprising differently treated straw litter and the water-holding capacity of the straw litter. The behaviour of straw bedding in housing systems was tested in a field experiment with 39 heifers in a deep straw system. The use of chopped straw did not reduce significantly the litter consumption, but led to lower manure mattresses. The stability of the manure mattresses in the pens was determined by using a newly developed measuring device. The mattress firmness decreased with time, while both chopping and intensive conditioning also reduced the mattress stability. While chopping or grinding of straw had no positive effect on the water absorption, the conditioning effect of modern baling techniques increased the water absorption significantly.

From the results of these tests, the use of chopped straw as litter in housing systems with deep manure mattresses or sloping floors cannot be recommended. Attention also has to be paid to the conditioning effect of the modern threshing and baling techniques.

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1. Introduction

For many years, straw litter has played a central role in housing systems for all kind of animals and has many advantages. Litter can bind moisture to a high extent, and the manure mattress offers the animals a warm, elastic and deformable base during winter. In addition, straw litter is edible and can be used by the animals, especially by pigs, to satisfy their instincts for activity and occupation.

Furthermore, litter can serve as a source of crude fibre in the animal ration and it has a positive influence on the climatic conditions in animal houses, possibly reducing also ammonia emissions (Cielejewski & Ratschow, 1997; Gronauer *et al.*, 1995). Despite these advantages, a drastic decrease in the use of litter in animal housing has taken place in the last 30 years in Germany, especially in pig houses. This is primarily attributed to the high labour requirements of litter-based animal housing systems compared to liquid manure systems. However, these liquid manure systems are linked with high investment costs, and due to the critical economic situation in agricultural production, more and more farmers are unwilling or unable to defray these high costs. An alternative is to return to littered systems. Existing buildings could easily be redesigned or litter systems could be incorporated with planned new buildings. For these reasons and because of the availability of vastly improved mechanization techniques for the handling of straw litter and the produced solid manure, littered animal housing systems are coming back into favour. In such systems, litter is an essential and precious production factor. Until recently, only little attempt has been made to analyse the complete cycle from harvesting techniques through to storage

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methods, application and recycling, including demand for labour and labour cost and also environmental effects. The main goal of this investigation is to minimize the amount of litter required. For many farmers it is important to control the straw demand because they may only have limited litter resources due to their specialization. Furthermore, harvesting and storing litter is always labour and cost intensive. The main objective was to investigate the stability of differently conditioned straw in animal houses using parameters such as firmness and density of the manure mattress and to determine whether mechanical conditioning of straw would enhance its water-holding capacity.

2. Materials and methods

In order to evaluate the suitability of litter materials for animal bedding at least five or six physical properties of the material should be investigated such as water- (or urine-) holding capacity, penetration resistance, heat transfer behaviour, ammonia-binding capacity, ease of handling and bulk density. There is no doubt that mechanical treatment may change any one of these properties, thereby improving some and deteriorating others. Also, availability, cost and nutritional value are other criteria. The following research is focused on penetration resistance and water-holding capacity since a deeper knowledge regarding these parameters could possibly lead to savings in straw litter consumption.

2.1. *Experimental procedure*

The database was obtained through a field trial performed at one of the cattle houses at the Federal Agricultural Research Centre, Braunschweig. A field trial was mandatory since several other parameters were observed (e.g. litter demand, rotting characteristics and properties of the produced manure), which were affected by a number of factors present only in real housing systems. Furthermore, taking all the gained parameters into consideration, it could be assessed how well the litter system behaves in general.

Figure 1 gives an overview of the heifer house used for the trials. The stable was designed as a deep litter system with a separate outside exercise and feeding area. The littered lying area inside the barn was divided into three pens of which each had the size of 40 m^2. In each pen, a group of 13 heifers, all about 1-year old, was being housed. The animals had an average weight of about 300 kg, the available lying area was 5·11 m^2 per 500 kg body weight. The straw litter for all three pens was harvested from one single field of winter wheat. However,

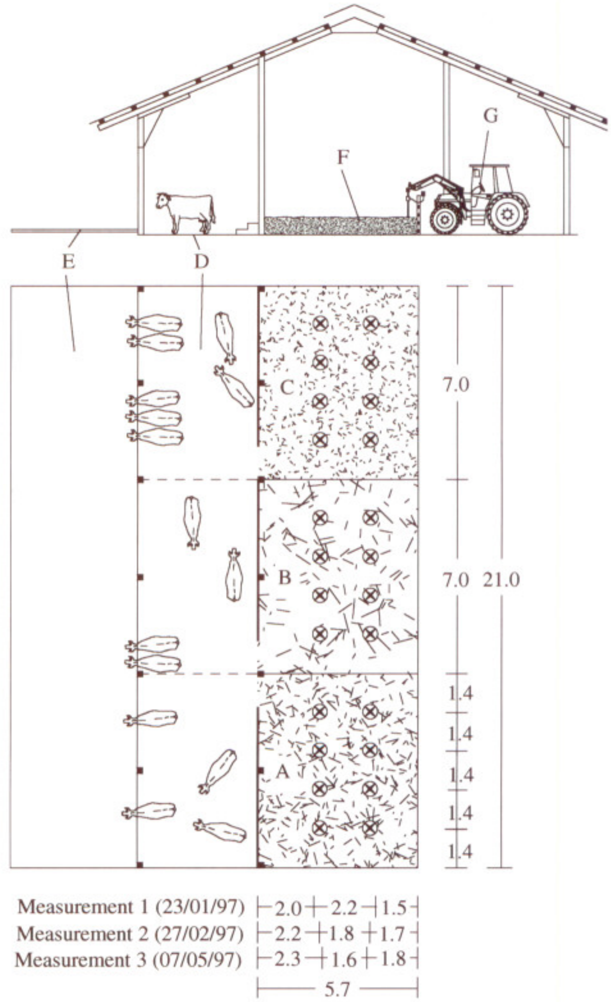

Fig. 1. Design of the barn for the field test at the Federal Agricultural Research Centre in Braunschweig-Völkenrode. A, B, C, pens, size: 40 m^2, 13 heifers per pen; circles with a cross inside indicate measuring points inside the pen (8 points per pen); conditioning of litter straw: pen A, rectangular bales, cut; pen B, round bales, chopped; pen C, round bales, uncut. D, exercise area; E, feeding area; F, deep straw system with manure mattress; G, tractor with measuring device for mattress firmness; all dimensions in m

the straw litter was differently harvested and some straw was cut while other loads remained uncut, so that three differently conditioned sorts of straw litter were obtained for use in each pen. In pen A, long, uncut straw, stored in round bales produced by a round baler without a cutting unit was used. In pen B, straw from the same round bales, ground with a chopper–blower, was spread. In pen C, straw collected by a baler that produced high-density rectangular big bales was applied as litter. The baler was equipped with a cutting unit, the theoretical length of the straw stems being 4·5 cm. In order to prevent differences in the results caused by different activities between the heifer groups, each group rotated around the pens every 4 weeks. The heifers were kept inside the barn from November 1996 until April 1997.

2.2. *Measurements of litter requirement and depth of manure mattress*

Three times per week, straw was given into the pens to maintain a dry mattress surface and to prevent the animals from getting dirty. The straw litter was thrown into the pens by hand. The amount of straw was determined due to the dirtiness of the lying area and the animals, using a method describe by Faye and Barnouin (1987).

Additionally, every week, the total height of the manure mattress in the three different pens was determined. Therefore, a steel pole was driven into the manure mattress until it reached the ground. The exact height of the mattress was determined by a round steel plate which was vertically shifted down the pole until it rested on the surface of the mattress.

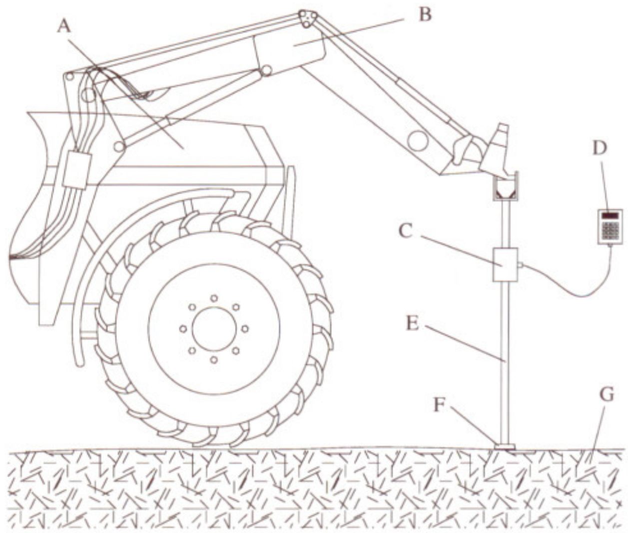

Fig. 2. Device for measuring resistance while penetrating into manure mattresses: A, tractor; B, front loader; C, device for pressure measurement; D, display; E, steel pole; F, steel plate (58 cm^2); G, manure mattress

2.3. *Method for measuring the penetration resistance in littered housing systems*

There are a number of parameters which are important for judging the quality of bedding materials. For most of these parameters, such as demand of litter per day or cleanliness of the animals, a lot of research work has been done (Haidn *et al.*, 1997b, 1998; Kramer *et al.*, 1998). Until recently, little attention has been given to the firmness of the manure mattress in littered systems. This is astonishing because, besides its function as a lying area for the animals, the bedding in housing systems with deep straw or sloping floors also serves as an exercise area. In its function as lying area, the bedding for the animals has to be warm, elastic and deformable underneath, whereas in its function as an exercise area, the bedding must have a firm, stable base, so the hooves of the animals do not penetrate the surface of the bedding and sink into the litter. No procedures or methods to determine the firmness of manure mattresses and no recommendations about the minimum firmness of manure mattresses could be found in the literature. Consequently, a method to determine the stability of manure mattresses in littered systems had to be developed. First of all, efforts were made to determine the firmness of straw mattresses at the laboratory scale. These trials failed because many of the factors present in a stable (e.g. decomposition processes) could not be adequately simulated in the laboratory. Consequently, a new measuring device for the use in animal houses had to be designed. With that device, it was intended to simulate the tread of a single hoof of a cow. A pole of steel with a round steel plate attached at its lower end was used as the penetrating instrument. The area of the disc (58 cm^2) was the same as the area of the cloven hoof of a cow. As high forces were necessary to break through the mattress, a tractor with a front loader had to be used to press the pole with the disc into the manure mattress. *Figure 2* shows the measuring device. Attached to the steel pole was a measuring instrument to register the forces needed to penetrate and to break through the mattress, the maximum values on a hand-held digital display being recorded manually.

In each pen, the mattress firmness was being determined at eight measuring points located in a square grid, altogether there being 24 measuring points (*Fig. 1*). In order to determine the changes in the firmness of the mattress during the entire housing period (November 1996–April 1997), measurements were taken at three different dates: at the 23 January, the 27 February and the 7 May 1997.

2.4. *Method for measuring the water-holding capacity of litter materials*

Surely, the most important quality of bedding materials is their capability to retain moisture. The more moisture they hold, the greater their suitability as litter, and the less litter is needed. The holding capacity for water seems to be a good parameter to judge the quality of bedding materials. It allows an assessment of the quality

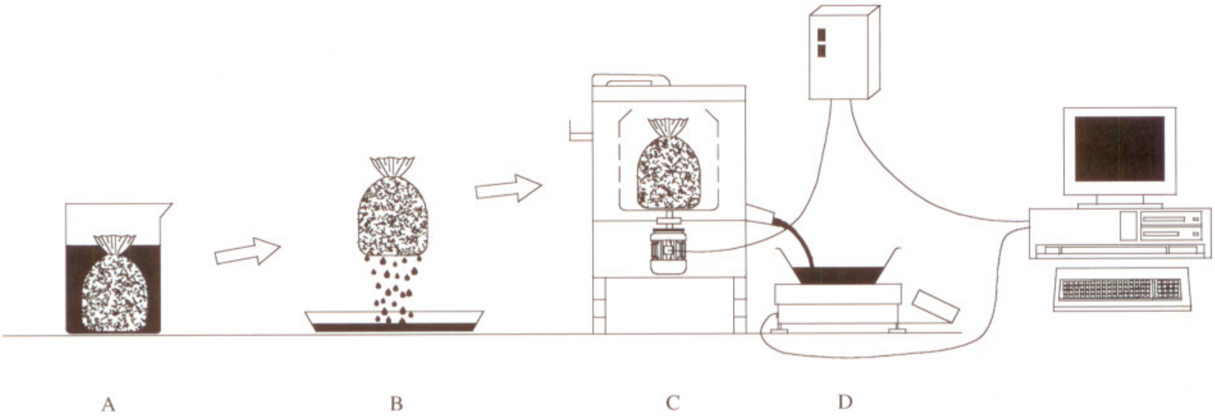

Fig. 3. Measurement procedure for determining the water-holding capacity from different litter materials. A, soaking of the litter sample (sample size: 300 g, soaking time: 24 h); B, dripping off (time: 15 s); C, removal of absorbed water by means of a centrifuge (treatment in three levels. 0, 200 and 1000 min^{-1} = 0, 5, 128 g*); D, weighing the effluent with electronic scale connected to a personal computer*

of single bedding materials as well as the influence of different conditioning on the material used.

In order to determine the water-holding capacity of bedding materials, a new method was developed. *Figure 3* gives an overview over the method which includes three steps.

(a) *Soaking of the litter sample:* A mass of 300 g of dry litter (water content about 10%), contained within a textile bag was immersed in water for 24 h.
(b) *Drainage*: The sample was removed from the water and allowed to drain for 15 s to remove the excess water, which is not really bound within the litter.
(c) *Centrifuging*: After drainage, water extraction by centrifuge was recorded every 10 s. From these data, the water release from the litter over time could be characterized. The sample in the centrifuge was subjected to three different treatments. In the first stage, the centrifuge was static and regarded as a continuation of the process of free drainage. When less than 5 g of water were discharged from the sample in a period of 10 s, the centrifuge was spun at 200 min^{-1} (5 *g*). This speed was maintained until again less than 5 g of water were discharged from the sample in a period of 10 s. Then the speed was increased to 1000 min^{-1} (128 *g*). The centrifugation process was continued until the effluent was less than 5 g water per 10 s, the total weight of water extracted by the centrifuge being recorded. Then the centrifuge was switched off and the centrifuged sample was weighed back. The method described above, which aims at simulating the force applied to the mattress by the hooves of the animals, was repeatedly used to determine the water storage and discharge from different straw litter and other litter materials (Lehmann *et al.*, 1995) and was kept for reasons of compatibility and better comparison of the results.

3. Results

3.1. *Litter requirement and depth of manure mattress*

The average litter consumption per livestock unit (LU = 500 kg) and per day was 3·04 kg using long straw, 3·17 kg using cut straw from rectangular bales and 3·21 kg using chopped straw. While differences in these values were not statistically significant, the differences from the average litter amount of all three pens per week were significantly lower with long straw (− 99 g per LU and day) than using cut or chopped straw (+ 26 g and + 72 g per LU and day, respectively). In total, 700·1 kg long straw, 724·8 kg cut straw and 736·9 kg chopped straw were needed for the individual pen during the 24 week housing period.

The differences from the average height of the manure mattress of all three pens per week were significantly higher with long straw (+ 0·73 cm) than using cut or chopped straw (− 0·60 and − 0·13 cm, respectively). This indicates that long straw cannot be as easily compacted as cut or chopped straw.

3.2. *Penetration resistance of the manure mattress in deep litter systems*

Figure 4 shows the penetration resistance of the manure mattresses. As shown in the right bar group, there were significant differences between the firmness of mattresses depending on straw conditioning. While the

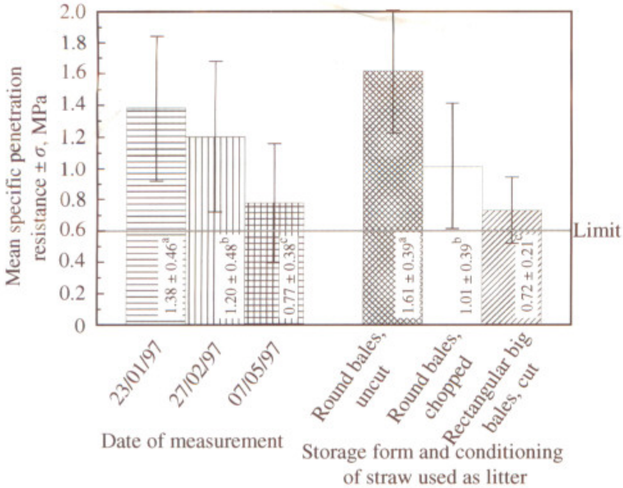

Fig. 4. Resistance when penetrating into manure mattresses. Limit value, minimum mattress stability to prevent animals from sinking into the mattress (0·6 MPa). Left bar group: numbers from different dates of measurement (average from the three straw variants). Right bar group: numbers from mattresses of different conditioned litter (average from three measurements); n = 8 measurements per variant, respectively; numbers give mean values ± SD; letters a, b and c indicate significant differences of the mean values; probability of error, 5%

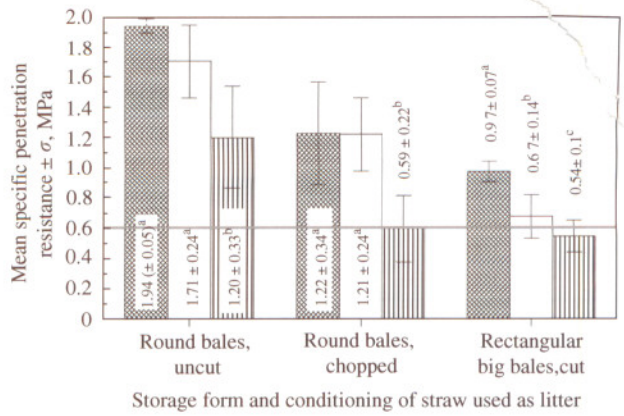

Fig. 5. Resistance when penetrating into mattresses from different conditioned litter. Limit value, minimum mattress stability to prevent animals from sinking into the mattress (0·6 MPa). Left/middle/right bar: measurement 1, 2 and 3; n = 8 measurements per pen; numbers give mean values ± SD; letters a, b and c indicate significant differences of the mean values; probability of error, 5%

mattresses comprising uncut straw were the most solid, relatively little force was needed to penetrate mattresses comprising straw from rectangular high-density bales. Both variants differed significantly from the mattresses incorporating chopped straw, that had a moderate firmness.

As shown in the left bar group, the date of the measurement had an enormous influence on the mattress firmness. Regardless of the type of conditioning, the firmness was decreasing significantly from measurement to measurement.

Figure 5 shows the results when testing the stability of mattresses built from different conditioned straw. As derived below, the mattress should be able to withstand pressures up to 0·6 MPa in order to prevent the animals from breaking through the mattress. With long straw, the limit value was always exceeded, whereas with conditioned straw both from round and rectangular big bales, the mattress firmness dropped slightly below the limit value at the last of the three measurements. In all three measurements, the long straw manure mattress was always the firmest one, the cut straw (4·5 cm) had a medium firmness, and the chopped variant was the least stable one. In all three variants, the mattress stability was significantly higher in the first two measurements than the stability found in the last measurement 3. The stability of the mattress formed from cut straw from rectangular bales decreases continuously and therefore all three measurements differed significantly from the other two variants.

3.3. *Water-holding capacity of the tested litter straw*

Figure 6 shows the results of the measurements concerning the discharge of water while centrifuging. The three sections of the graphs with the three different X-axes show the behaviour of the samples when treated in the centrifuge with 0, 5 and 128 *g*. The water removed in stage I (0 g) is considered as a continuation of the

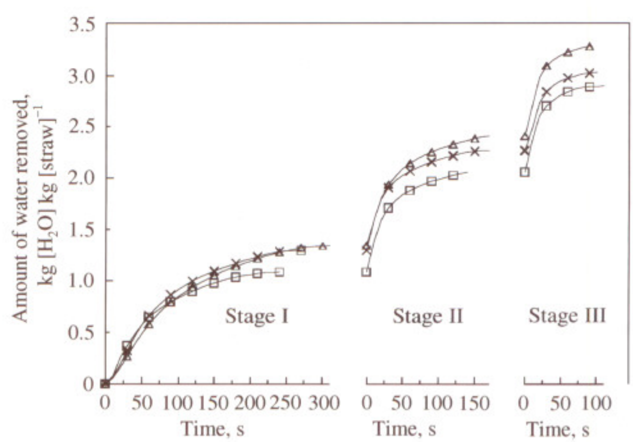

Fig. 6. Release of water from differently conditioned winter wheat straw when cenrtrifuged at different revolutions. State I, 0 min^{-1} (0 g); stage II, 200 min^{-1} (5 g); stage III, 1000 min^{-1} (128 g); □, round bales, uncut; ×, round bales, chopped; Δ, rectangular big bales, cut

Table 1

Water-holding capacity of differently harvested and conditioned winter wheat straw; Results of the soaking and centrifuging experiments with litter materials from five observations; numbers give mean values ± SD; letters a, b and c indicate significant differences of the mean values; probability of error, 5%

	Water absorption, kg [H_2O] kg [litter]$^{-1}$	*Water removed from soaked litter by centrifying, kg [H_2O] kg [litter]$^{-1}$*			*Firmly bound water absorption, (non-removable from litter by centrifuging)*	
	Total	*Stage II*	*Stage III*	*Total*	*kg [H_2O] kg [litter]$^{-1}$*	*%*
Round bales, uncut	3·69a ± 0·12	0·97 ± 0·07	0·83ab ± 0·08	1·81ab ± 0·09	1·88a ± 0·10	51·1 ± 1·9
Round bales, chopped	3·48a ± 0·17	0·97 ± 0·09	0·76a ± 0·06	1·73a ± 0·27	1·75b ± 0·07	50·4 ± 2·0
Rectangular bales, cut	4·15b ± 0·12	1·07 ± 0·09	0·88b ± 0·03	1·95b ± 0·11	2·20c ± 0·01	53·1 ± 1·2

dripping-off process. Consequently, the amount of effluent occurring in this stage is regarded as loose water, not as water bound from the litter. Therefore, the water removed from the soaked litter by centrifuging was calculated as the sum of the effluent in stages II and III.

Table 1 shows the numbers for the water-holding capacity of the tested straw. The total water absorption of the litter is the sum of two components: the firmly bound water in the straw that cannot be removed by centrifuging, and the water that can be removed by centrifuging, but does not drip off without the stress in the centrifuge. One kilogram of uncut straw could bind 3·69 kg water, from which 1·81 kg (or 48·9%) could be removed by centrifuging again. No significant differences were found between the water absorption of uncut and chopped straw, both stored in round bales. However, there were significant differences between the relatively undamaged straw from round bales and the highly pinched straw from rectangular big bales. Whereas the straw from rectangular bales could bind more than 4 kg of water, the straw from the round bales, both chopped and uncut, was only able to bind 3·48 and 3·69 kg, respectively. The smallest amount of water could be centrifuged from the chopped straw (1·73 kg), the greatest amount from the cut straw from the rectangular bales (1·95 kg). Neither the type of conditioning nor the cutting of the material could change the ability of the straw to bind the absorbed water significantly, and nearly 50% of the absorbed water could be removed by centrifuging again.

4. Discussion

4.1. *Straw litter stability in litter-based systems*

The results of our test showed that, regardless of the conditioning, the stability of the mattress was decreasing significantly with time. This fact can be explained by decomposition and rotting processes in the lower layers of the mattress. The higher the mattress is, the better are the conditions for the decomposing processes (temperature, bacteria) and the longer the straw–manure mixture in the lower layers was being exposed to these processes. Until decomposing processes are set in motion, the stability can be almost maintained, afterwards it decreases rapidly. By using the highly compressed straw from the rectangular big bales, these processes started early, firmness decreased constantly, and consequently all three measurements differed significantly. In the other two variants, the mattress stability in the first two measurements was significantly higher than the stability found in the last measurement 3, indicating that the decomposing processes did not come into action before measurement 2. Generally, it has to be considered that these decomposing processes are linked with the decay of the stems which leads to destruction of the internal structure of the mattress, especially in the lower layers. At a low height of the mattress, the whole mattress is more or less homogenous, and the firmness of all layers is rather equal. With increasing height, only the upper layers are responsible for the firmness of the mattress. This fact can be easily proved by observing the process of measurement carefully. Initially, when the steel disc began to penetrate into the mattress surface, there was an elastic deformation of the upper litter layer. While this layer was deformed and compacted, the penetrating forces increased and reached its maximum immediately before breaking through the mattress. In the already decomposed lower layers there was only little resistance, so after the breakthrough, it was very easy to penetrate further into the mattress. Since no information or limit values for the required mattress firmness could be found in literature, a lower limit for the penetration resistance of manure mattresses was calculated. Firstly, it was necessary to know how much pressure can be exerted to the mattress by the tread of a single hoof of a cow. Since deep litter systems can also be used for dairy cows, a weight of 650 kg for the animal standing on the mattress was assumed. The ratio of the weight upon the foreleg compared to the hind leg is 55:45 (Hubert & Distl, 1994). Taking into account that during the movement of the cow, the forces on the hoof can double briefly (Schlichting, 1970), the maximum load on the single hoof can be up to 358 kg. Assuming an average area from the cow hoof of 60 cm^2 (Hubert & Distl, 1994; Pfadler, 1981), pressures up to 0·58 MPa can be applied to the mattress by the tread of a cow hoof. In order to prevent breakthrough, the mattress should be able to withstand pressures up to 0·6 MPa.

With two exceptions, this limit value was always exceeded in our trials. In all cases, the long straw manure mattress was always the firmest one, the cut straw (4·5 cm) had a medium firmness, and the chopped variant was the least firm one. This can be explained by the fact that with decreasing length, the particles become too small to be interlocked and to create a solid interlaced mattress. Generally, chopping (or grinding) the straw to very small particles (< 5 cm) reduces the firmness considerably. However, the effect of cutting the straw to longer pieces (< 10 cm) seems to be ambiguous. In our case, the firmness of this straw was decreased as well. However, as shown in previous trials (Tamm *et al.*, 1997), mattresses from cut straw (14 cm) can be more firm than mattresses from uncut straw from the same batch. Besides the length of the particles the structure and conditioning of the stems also has an enormous influence on mattress firmness. It is likely, that the intensive conditioning through the enormous pressure of the rectangular big baler—and not the reduced particle size of the cut straw—accelerated the rotting processes in all layers of the straw–manure heap in the pen and consequently decreased the mattress firmness. Therefore, these results suggest that, whereas every kind of conditioning seems to reduce the stability, there might exist an optimum length for the stems of the straw used as litter. They also indicate that the modern baling technology had a far higher influence on the behaviour of the straw in littered systems than chopping the straw. Finally, these results also suggest that particularly the influence of modern threshing methods of present combine harvesters on the straw quality has not yet been investigated satisfactorily.

4.2. *Increasing the water-holding capacity of bedding materials in littered animal houses*

Using straw as litter material, both a high water absorption and a high water retention are desirable. High water absorption indicates a good ability to hold moisture, and a high retention results in little effluent from the manure mattress.

In these tests, no significant differences could be found in the water absorption of straw stored in round bales (long and chopped), but there were significant differences between the straw from round bales and rectangular bales. Obviously, the process of baling itself has more influence on the water-holding capacity than the chopping or non-chopping of the straw. While round bales are rotating in the bale chamber of round balers, rectangular balers continuously add layers of straw to the big bale during the baling process. In the compression chamber of a rectangular big baler an enormous pressure occurs. This pressure flattens the round stems of the straw and destroys partially the structure of the stems, so that they get tears and rents. This increases the absorptive capacity of the tissue, furthermore water can more easily invade the inner part of the stem. So the conditioning effect of the baler is much more effective than that of cutting or chopping the straw.

Several sources recommend the chopping of straw as a method to reduce the demand for litter in animal housing systems because of its increased water-holding capacity (Bartussek, 1988; Hessisches Landesamt, 1992). Although these tests could not confirm this, an explanation for the alleged superiority of chopped straw compared to long straw can be given. While chopping does not influence the water-holding capacity, it significantly increases the volume of a certain amount of straw (Haidn *et al.*, 1997a), so one is able to spread more (volume of) straw across the pen. Since chopping the straw does not substantially change absorption characteristic, however, it also does not alter the holding capacity per weight unit (kg H_2O per kg straw). On the contrary, chopping even decreases the holding capacity of straw per unit volume (kg H_2O per m^3 straw).

Other objections raised against the use of chopped straw are the high dust production while chopping straw inside the barn and the additional labour and energy demand for chopping and distributing the straw.

5. Conclusions

The results of this research work show, that while chopping does not improve the water-holding capacity of straw as litter, it has a highly negative influence on the firmness of manure mattresses in deep littered animal housing. Therefore, chopping of straw cannot be recommended. Especially if the deep manure mattress is retained for longer periods, the firmness can be greatly reduced due to composting processes in the lower layers. In this case, there is an increased risk of the animals breaking through and sinking into the moister, weaker manure below the surface.

Further, these results revealed that modern harvesting technologies have far more influence on the water-holding capacity of the straw and also on the stability of manure mattresses than chopping the straw. It was determined that rectangular big balers have an enormous conditioning effect on the straw due to the high pressures that occur in these machines. Until now, little attention has been given to other factors such as the impact of threshing implements of modern combine harvesters on straw quality.

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