Automated pressure regulation for a silage bagging machine

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A B S T R A C T

Ensiling and compaction of silage crops in bags is a well proved method to store fodder anaerobically to feed animals throughout the year. The essential process principle is to compact the silage substrate using a rotor into a press tunnel and the connected plastic bag to generate an oxygen-free environment. The objective of this study was to develop an automatic pressure-controlling system for the compaction process. The automatic system controls elongation of the bag film calculated based on the circumference during ensiling. Due to the different physical composition of pasture grass and maize substrates, only 2% of values in the case of maize silage deviated from the specified tolerance range (9.5 ± 0.5% elongation) while over 50% of the values with grass silage deviated from the tolerance range (8.5 ± 0.5% elongation). To determine the effect on crop density and stability of silage, investigations were made during feed-out. Accordingly, the identified storage density of the maize and grass silage varied between 179.0 and 280.8 kg DM m⁻³, and 89.3 and 197.7 kg DM m⁻³, respectively. Basically, the automated pressure control of silo bagging press machines is possible, and the machine operator can be relieved. However, the homogeneity of the silo bag contours is highly dependent on the stored ensiled material.

1. Introduction

The feed basis of a farm is a very important success factor for professional production. In order to exploit the genetic performance potential of dairy cows, with limited dry matter (DM) intake by the animal, optimal silage quality is the basic prerequisite in order to gain healthy animals with simultaneously high yield. Furthermore, economic milk and meat production is increasingly dependent on silage quality.

Silage is considered an economical alternative to pasture feeding due to the possibility of using it cumulatively throughout the year in the cows’ housing (Wilkinson and Davies, 2012). Silage also ensures the year-round coarse feed requirement of the farm and provides a secure food base in seasons where no growth is available.

Successful ensiling and the duration of aerobic stability after opening the silage depend on several factors. DM content should be > 30–35% during storage, as presented by Spiekers et al. (2009) and von Wachenfelt et al. (2014), to avoid the risk of leachate juice formation. The usage of silage additives, harvesting technology, the type of ensiling (Mahanna and Chase, 2003) and the covering plastic film (Savoie, 1988) also have a considerable influence on ensiling success.

Concerning aerobic stability, particle size as well as compaction to more than 200 kg DM m⁻³ is to be considered (Johnson et al., 2002; Spiekers et al., 2009). Large particle sizes may result in insufficient compaction in the silo (Spiekers et al., 2009; Sun et al., 2015), which can adversely affect the aerobic stability of the silo bunker during the withdrawal phase. Aerobic spoilage is unstoppable once started (Woolford, 1990).

The process principle of filling a plastic bag with ensiled material generally is to compact the substrate using a special machine into the plastic bag as presented by Assirelli and Santangelo (2018) and create an oxygen-free environment, as presented by Sun et al. (2015) for ensiled material.

A certain pressure is generated by the machine operator via a manual control system during the storage process. The operator has to adjust the hydraulic pressure at the brake according to the actual elongation of the strip printed on the bag film (Weber, 2005). Subsequently, the required level of compaction in the plastic bag is achieved. Homogeneous compaction of the substrate over the entire silo bunker depends strongly on the skill of the machine operator and requires full attention and sufficient experience.

The main objective of the presented study was to automate the standard manual pressure control in the commercial silo bagging press machine by optimizing the substrate storage density. To achieve this...
objective, investigations were carried out after intensive preliminary tests on a commercial silo bagging machine with maize and wilted grass silage. Subsequently, density measurements at the silo surface areas provided information about the effects of different compaction intensities on the silage.

2. Material and methods

Adjustment of the pressing is considered as a critical point since incorrect setting can lead to reduced silage compaction whereas extreme pressure cases bursting of the bag. In order to maintain the longest possibility aerobic stability of the silage, a sufficient compaction during ensiling is considered as an important goal. At low compaction, the oxygen may enter through the surface area. The entered oxygen promotes a rapid reactivation of the microbial activity and leads to silage losses. Accordingly, the study was conducted mainly to partially compensate a rapid reactivation of the microbial activity and leads to silage losses. Accordingly, the study was conducted mainly to partially automate silage storage in plastic bags. Also, process regulation should be developed to record and collect all relevant data during filling, to be used later. For achieving this purpose, the study was carried out at laboratory and practical scales.

2.1. Preliminary measurements of the silage bagging press machine

The preliminary experiments aimed to verify the functionality and applicability of the measurement technique at a small scale and check its suitability for the upcoming application. These experiments were conducted based on the system presented previously by Maack (2009) after the measurement technique was modified.

The machine constructed in this study was significantly smaller and easier to handle. The bagging press machine was designed in such a way that allows the necessary measurement technology to be built up in a stationary status without moving forward by pressing. The bag produced is received in a special pallet which can be conveyed via a forklift to another position. This process gave flexibility for selecting the experimental locations (Fig. 1). The gear with the rotor as well as the feeding hopper was positioned stationary with an underlying chassis to receive the pressed bag and to let it move backward. The rope drums with the hydraulic disc brakes and abutment grid were located at the end of the truck. The rolled-up steel cables were fixed in front of the rigid press construction. The bag produced was approximately 4 m in length and 0.9 m in diameter. The machine was connected to a 42-kW drive power tractor via a propeller shaft. The braking system was operated by a linear motor and a brake master cylinder equipped especially for this purpose instead of a hydraulic system.

Bag circumference and elongation were determined continuously using three laser distance sensors (Keyence, model: IL-600, measuring range: 200–1000 mm, repeatability: 30 μm) mounted on a holder frame. One top sensor was used to determine the bag height, and the two other sensors at each side of the bag to determine the diameter.

To calculate the bag volume, the length and circumference of the pressed bag were measured indirectly by detecting unwinding of the cable drum. Steel cables were wrapped in one layer next to each other. This enabled the indirect track to be recorded by a pulser firmly installed on the outer surface of the cable drum. A wheel disc provided by 30 magnets at a distance of 27 mm on its outer edge was positioned on the outwardly extended axis of the cable drum directly in front of the displacement sensor (Fig. 2). The disk equipped with magnets is turned continuously and analogously to the cable handling. Accordingly, the pulses of the magnets were counted by the sensor and thus the distance was calculated. Once the bag vertical and horizontal radiuses were measured by the sensors, an algorithm was used to calculate the circumference (Us) and cross-sectional area (As) of the bag (Eqs. (1) and (2)). As the algorithm is derived from an ellipse formula, a correction factor (kV = 1.1) was used.

\[ U_s = k_V \pi (r_v + r_i) \]  
\[ A_s = k_V \pi (r_v r_i) \]  

where \( r_v \) and \( r_i \) are vertical and horizontal radiiuses.

The filling time was recorded in parallel with determination of the bag length (s) via the displacement sensor and thus the volume (Vs) was specified cumulatively (Eq. (3)).

\[ V_s = A_s U_s \]  

Computer software was developed to process, record and store the data measured by the sensors and other relevant values. These values were displayed in program windows (Fig. 3). Thus, the required pressing of the brake pressure was regulated automatically for the desired bag circumference elongation, with 7.0 ± 1.0% tolerance via the LOCK button. Minimum and maximum pressure in the setup menu could be selected, and within this range, the brake pressure was...
regulated. All values were measured in a one-second interval. The exact structure of the regulation software is described in Fig. 4. If the calculated bag height and diameter exceed the specific tolerance range, it will be recognized by the computer, and accordingly the brake pressure will be lowered to the minimum set pressure. Thereby the track will be moved forward, and the bag will be laid onto it. If the minimum tolerance of the bag elongation is undershot, the brake pressure will be automatically raised again.

2.2. System installation on a commercial silo bagging press machine

According to the preliminary experiments, installation of the measurements and control technology used on a commercial silo bagging press machine was facilitated. The field experiments were carried out in the city of Malchwitz, Saxony, Germany. A 175 hp self-propelled rotor machine (John Deere type M 8000 from BAG Budissa Agroservice, Germany) was equipped with additional sensors and actuators. The rotor length was 2.4 m with 2.7 m tunnel diameter. The machine has a hydraulic circuit system, so the brake control system could be modified and the machine hydraulics used.

2.2.1. Installation of laser distance sensors

The laser distance sensors tested in the preliminary experiments were attached to a modified mounting frame (Fig. 5). The sensors were kept approximately 0.30 m away from the bag in the horizontal direction. Thus, the actual contour was measured about 1 m behind the tunnel end.

2.2.2. Installation of an inductive transmitter for recording elongation

In an analogous way to the preliminary experiments, the length of
the silo bag and the filling rate, in addition to contour properties, were determined using distance sensors. For this purpose, a toothed pulley made of steel (400 mm diameter and 26 mm pulse distance) was firmly installed on the cable drum axis. The attached inductive sensor detected the impulses and transmitted them to the controller.

2.2.3. Construction of the hydraulic circuit system for brake pressure control

The braking system regulates the required brake pressure which was operated previously with an oil hand pump. This construction is not connected to the rest of the machine hydraulic circuit. The applied pressure ensures the braking of the cable drum and drives the material to be ensiled to be well compacted through the machine tunnel and subsequently to reach the bag. With this instrument, the machine operator had the opportunity to regulate bag elongation by a maximum of 10–15%. The procedure for measuring the film extension by the machine operator is illustrated in Fig. 6.

The brake system was developed in order to automate this operation by controlling and regulating it via a process computer. For this purpose, the existing hydraulic circuit was used to provide the oil pressure for the disc brakes of the cable drums. An oil pressure of 14 MPa in pressure load memory was created with active control of brake pressure. A pressure regulation valve connected to the system receives a signal from the computer and the pressure is increased or decreased accordingly. The signal in turn is dependent on the bag elongation and is also influenced by it. The pressure was recorded manually by a pressure gauge and determined also automatically via software by installing a special pressure sensor.

2.3. Experimental procedure on a commercial silo bag press

The distance, displacement and brake pressure were connected to the process computer. The software used was almost identical to that used in the preliminary tests. Preset synchronization enabled recording of all data every second. Chopped maize and pasture grass (203 and 204 tons of fresh mass, respectively) were stored, each of them in two bags. DM content for maize silage ranged between 23 and 68% while DM content for grass silage ranged between 18 and 81%. The brake pressure was not controlled by the machine operator as usual, but for the first time via the sensors and the process computer. After completion of storage, the bags were sealed hermetically and hence the substrates were ensiled.

2.3.1. Determination of DM density

Density distribution measurements of the filled bags were performed. Two cross sections from both sides of the bags with different default settings in the regulation software were investigated.

In the case of maize silage, the first section was located 13 m from one side and pressed with a set value of 7.5 ± 0.5% foil elongation (low density), while the second section was located 17 m from the other side and pressed with 9.5 ± 0.5% elongation (high density). For grass silage, the locations were at 19 and 9 m with 6.0 ± 0.5% (low density) and 8.5 ± 0.5% (high density) bag elongation, respectively (Fig. 7).

Thus it was possible to open the bag from both sides and to examine the densities at the same time, according to their different set-point elongation settings. For more accuracy, 16 samples were collected over the entire cross-sectional area via a drill bit (56 mm inner diameter and 235 mm length) attached to a commercial cordless drill and screwed into the silo bunker to withdraw the material (Fig. 8). The fresh samples were weighed directly, and the fresh matter (FM) densities were calculated from the mass and volume of the samples. The silo’s contour was not continuously homogeneous and varied in both height (between 1.80 and 2.00 m) and width (between 3.20 and 3.35 m). The DM densities were determined according to VDLUFA (2012). Eight repetitions were conducted at intervals of 1 m.

2.4. Statistical analysis

Significant differences in the data were determined using Tukey’s test in conjunction with analysis of variance (ANOVA) using SPSS.
Statistics 22 software. To assess calibration quality, different performance measures were calculated in the quantitative analysis. In order to measure the variation ratio in one of the variables as demonstrated by the variation of another variable, coefficient of determination (R²) was used.

3. Results

3.1. Preliminary experiments

Measuring and controlling technologies were checked in the preliminary experiments for suitability and subsequently were used on a practical scale. The bag contour was recorded using distance sensors and a process computer. Other parameters such as cross-sectional area, circumference and bag elongation were calculated. At the same time, the bag length was determined by setting the brake pressure manually. Circumference and bag elongation were calculated. At the same time, the bag length was determined by setting the brake pressure manually. Consequently, the brake pressure was reduced using the control system from the preset maximum pressure to 2 MPa within only one second associated with increasing the elongation over the preset point; subsequently, the rolling speed was increased in this case up to 0.13 m s⁻¹. Automatically, the brake pressure was increased independently only when elongation was reduced by < 9.0%. In this case, the roll speed ranged from 0.026 to 0.052 m s⁻¹. The cross-section area and maize silage bag volume were calculated. The total volume of the bag at 11 m length was 56.5 m³ while the average density was 235 kg DM m⁻³.

For grass silage, the height and width of the bag with 8.5 ± 0.5% elongation (preset) ranged from 2.12 to 2.34 m and from 2.80 to 3.10 m, respectively. Elongation of the bag clearly exceeded the set tolerance range. Only 55% of the values were within the target range. Also, for the grass silage bag, elongation depends on the brake pressure and feeding rate of the machine. By extending elongation to 9%, the maximum brake pressure was reduced automatically from 5.8 MPa as preset to 2 MPa and thus the rolling speed was increased to 0.234 m s⁻¹ due to the elasticity of grass silage. In the time in which the brake established the maximum pressure, there was no forward movement of the silo bagging press machine. The total bag volume at a length of 11 m was 55.6 m³ and the density was 143 kg DM m⁻³.

3.2. Field experiments

3.2.1. Silo bag contour measurements

Measuring and controlling technology was installed on a commercial silo bagging machine as described previously. Contour measurement over the whole bag length was determined by distance sensors at storage time. Based on the measured data for bag geometry, the brake pressure was independently regulated by a process computer. The values measured by the distance sensors were recorded and displayed every second. The pre-setting for maize silage bag elongation was 9.5 ± 0.5%, and maximum brake pressure was 8 MPa. The bag width measured by sensors located in the side sections ranged from 3.05 to 3.14 m, while the bag height measured by sensors located in the middle section varied between 2.09 and 2.18 m. Bag elongation depends on brake pressure, crop properties and the rolling resistance of the machine. With the pre-setting, three results were illustrated as examples. At these points, elongation was below or above the set point. Consequently, the brake pressure was reduced using the control system from the preset maximum pressure to 2 MPa within only one second associated with increasing the elongation over the preset point; subsequently, the rolling speed was increased in this case up to 0.13 m s⁻¹. Automatically, the brake pressure was increased independently only when elongation was reduced by < 9.0%. In this case, the roll speed ranged from 0.026 to 0.052 m s⁻¹. The cross-section area and maize silage bag volume were calculated. The total volume of the bag at 11 m length was 56.5 m³ while the average density was 235 kg DM m⁻³.

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3.2.2. Density measurements

The comparative density measurements were performed at 16 measurement points over the cross-sectional area of the bags in several repetitions (n = 8). The density distribution in the maize bags is presented in Fig. 9, where the measuring points are shown schematically as black dots. Via the program used (ArcGIS 9.2), the measured values were interpolated, and the density distribution was visualized. Higher densities in the middle zone were coloured blue while lower densities were in the edge and upper zones and coloured red.

Not only high density in the core zone of the silage bag was observed but also low density in the peripheral areas, as presented in Fig. 9a. The red colour at the edges was visually reduced due to the effect of increasing the press pressure by adjusting the bagging press machine.

Visual differences between the variants (7.5 ± 0.5% vs 9.5 ± 0.5% foil elongation) were observed. For the adjustment variant of 7.5 ± 0.5%, a storage density up to 270 kg DM m⁻³ in the middle was achieved. Outwardly, the density decreases continuously. Only values between 180 and 200 kg DM m⁻³ can be found at the edge and in the upper area. The density of variant 9.5 ± 0.5% foil elongation is, as expected, higher overall. The more intense pressing pressure resulted in higher densities in the core zone but also in the peripheral areas of the bag silo. Visually, reduced red coloration on the edges makes the effect of increased pressure setting visible.

The storage density of grass silage bags was lower than that in maize bags where maximum densities were found up to 200 kg DM m⁻³ for both variants (6 ± 0.5% vs 8.5 ± 0.5% foil elongation). Especially in the upper zone, the densities were obviously lower (Fig. 9b).

The statistical analysis provided detailed information about the individual measuring points and allowed direct comparisons. Subsequently, significant differences were observed. Significant differences or homogeneous group divisions between the positions are indicated. Generally, maize silage had higher densities than grass silage. Furthermore, dispersion was significantly lower because of the more
homogeneous substrate texture. According to the locations of the measuring points for both variants, the silo cutting surface was divided into three zones: middle zone (2, 3, 4, 5, 8, 9, 10 and 11), boundary zone (1, 6, 7 and 12) and upper zone (13, 14, 15 and 16). Statistical analysis of maize silage showed that the measuring points in the middle zone varied insignificantly from each other. Also, there were no differences for the measuring points in the upper zone. The boundary values were not divided into separate areas; therefore, the analysis confirmed the visual observation described in Fig. 9. The well-known heterogeneity of grass silage was also confirmed by the statistical analysis.

The boxplots in Fig. 10 illustrate the storage density distribution in the three zones for both types of silo bag. Boxplots consist of a middle box with 50% of the values, and the horizontal line indicates the median. The whiskers which run up and down indicate 25% of the values each, with the endpoints representing the extreme value. Since outliers hardly occurred, they were neglected.

In case of maize silage, the values of the variant 9.5 ± 0.5% foil elongation tend to be slightly higher with only marginally different from the middle zone. Compared with variant 7.5 ± 0.5%, the difference of the density in the boundary area was insignificant. Significant differences between all three zones for maize silo bags were observed (Fig. 10a). The differences are given with their medians and spans. The density values varied in the middle and boundary zones in comparison to the upper zone.

The storage density of grass silage was lower than that of maize, as mentioned previously. The maximum value reached in the middle zone was 255.4 kg DM m⁻³ for 6 ± 0.5% foil elongation. The box with 50% of the values for grass silage was much larger than that for maize silage.

In the case of grass silage, the whiskers indicating a greater scattering of density were more pronounced. The three areas of 6 ± 0.5% foil elongation variant differ significantly from each other while only the middle zone of the bag surface with 8.5 ± 0.5% foil elongation varied from the other two zones (Fig. 10b).

4. Discussion

4.1. Assessment of the measurement methodology used

4.1.1. Suitability of distance laser sensor installation

The distance laser sensors used consistently recorded reliable values through the triangulation method. The accuracies given by the manufacturer of ± 2% were confirmed in the laboratory by distance measurements on silage film. According to the manufacturer, laser sensors measure in high temporal resolution with a scanning rate of around 1000 s⁻¹. The sensors are particularly suitable for outdoor use due to their robust product properties, such as being dustproof and offering splash-water protection (DIN EN 60529 2000).

Deviation of the measuring range from 200 to 1000 mm occurred due to heterogeneous substrate, especially with grass silage, and thus there were measurement inaccuracies. Furthermore, storage of bags on uneven terrain leads to vibrations of the distance laser sensors and thus measurement inaccuracies could also happen. The sensor positions could be changed in horizontal and vertical directions.

The optimum distance between the press tunnel and laser sensor is 1 m in the case of maize storage. This distance ensured homogeneous bag contours. The distance was reduced to 0.4 m for grass silage. This relocation of the sensor technology ensured that irregular bag contours in the formative phase could be detected immediately in the vicinity of the tunnel and influenced by regulation.

4.1.2. Suitability of displacement measurements and modified brake system

The inductive sensor used in the displacement measurements determined values that can be depended upon either in the preliminary or main experiments. The exact bag length was determined via measuring impulses. This allowed exact synchronization of the installed sensors. Accuracy of 27 mm per pulse was found to be especially adequate for these experiments. The principle of displacement measurements by means of inductive sensors has been referred to in previous studies (Howard, 2013; Xu et al., 2007) and was proved here.

The enormously heterogeneous contours of grass silage bags due to the substrate properties led to strong bulges in the bag and also folding.
of the film. The real plastic bag input was greater than the length of silo bag produced, which should be included in harvest planning but did not adversely affect the accuracy of the pulser.

The brake pressure applied in the preliminary experiments was produced by an electrical actuator which operates the main brake cylinder, resulting in a certain time delay in brake pressure control. However, the hydraulic circuit of the commercial silo bagging machine offered the possibility of providing oil for the modified brake control system. A solenoid valve in the circuit regulated the constantly available oil, which caused no time delay for the brake pressure control. The actual brake pressure was displayed and documented directly via an integrated pressure sensor.

4.1.3. Suitability of density measurements

The density measurements were carried out over the cross-sectional area of the silage bag. A cordless sampling drill bit with an internal diameter of 102 mm was developed. Measurement errors by sampling were low compared to the ‘block cutting method’ presented by Kleinmans et al. (2005) (< 5% deviation) because of the relatively large diameter. The inside diameter of the cordless drill bit developed was consistent with the inside diameter used by Latsch and Sauter (2013) for density measurements. However, a sampling drill bit with an inner diameter of 45 mm presented by Kleinmans et al. (2005) showed significant deviations from a silage density of < 200 kg DM m\(^{-3}\), also in comparison to the block cutting method. The internal cutting tooth of the drill bit was suitable for sampling the fibrous silage material.

As expected, grass silage was more heterogeneous than maize silage during storage. Vertical-layer storage of wilted silage was observed during the pressing process. Thereby, hollows were created in both boundary and central regions of the bag cutting surface. These hollows had a negative effect on the accuracy of the density measurements.

Despite the construction of the drill bit, individual fibres occasionally were rotated which made sampling more difficult. To prevent this problem, the drill bit was regularly sharpened and screwed with the highest possible pressure into the silage. Thus, certain inaccuracy of the density measurements was considered, which is based not only on the material properties but also on the sampling technique.

4.2. Evaluation of the regulation software

Brake pressure control is based on the data documentation and the calculation results of the bag circumference. In contrast to the grass silage bags, the contour variations of the maize silage bags were significantly lower. The maize bag height was constantly about 1 m less than the width. The contour measurements of the grass silage showed clear heterogeneity of the bag geometry.

By assuming a close relationship between bag width and elongation values, the third sensor in the middle could be therefore waived. A large variance in the \(R^2\) values between the parameters of width and elongation was observed; \(R^2\) was 0.68 and 0.48 for maize and grass silage, respectively. Accordingly, the relationship obtained between the two investigated silage did not follow the previous assumption. A similar result was obtained for bag height; correlations between bag height and elongation were 0.54 and 0.1 for maize and grass silage, respectively. Subsequently, the bag circumference was calculated with little error only from the values measured by all three distance sensors.

4.2.1. Calculation of the correction factor

The cross-sectional area and circumference of the bag were calculated by algorithm using the distance values measured by the laser sensors and the correction factor. Since the cross-section area and the circumference of the bag did not correspond exactly to an ellipse shape, a correction factor was used. However, it is only possible to determine the correction factor when the silage bags are opened. For this purpose, images of the surface area with the longitudinal scale were processed using the software.

The calculated and applied correction factor was 1.1 for both maize and grass silage. Although Maack (2009) determined the same value,
the correction factor is not a constant, and deviation depends on the substrate property. In particular, the DM content influences the correction factor. The height of the bag is reduced with wet substrates, and the width expanded by silage weight. To specify fixed correction factors, additional studies on silage with different substrate properties are required. In the case of extreme bulges especially with grass silage, deviations may possibly occur which lead to a large measuring error in the calculation of bag elongation.

4.2.2. Evaluation of brake pressure control

The automation of brake pressure control was an essential part of this investigation. During silage storage, bag extension was controlled and compared with a target range, and brake pressure was adjusted accordingly.

This resulted in elongation being calculated from the current circumstance. It was necessary to lower the brake pressure on increasing the elongation, and it again increased on decreasing the elongation. This process, which was checked by the machine operator, was to be automated by means of the regulation software.

The relevant parameters were graphically displayed using the values obtained from the distance sensors. Elongation for the maize silage of 9.5%, with a tolerance range of 0.5%, was chosen over a section of about 3 m. For better comparison, the brake pressure and feed rate values were synchronously presented. Over-expansion was detected directly by the process computer, and the brake pressure control reacted immediately. This result led to homogeneous bag contours due to the regulation. Only 2% of the values deviated from the specified tolerance range over the total bag length, thus proving that the developed brake pressure control is functional in the case of maize silage.

The case of grass silage with a set point of 8.5 ± 0.5% elongation was investigated. Although there was direct reaction of the process control, the elongation exceeded or fell significantly below the tolerance range. So, < 50% of the elongation values were within the prescribed range. This may be due to the elastic substrate property of the grass or to the position of the distance sensors. The sensors should be moved in the tunnel direction in order to detect bulges earlier and to regulate timely brake pressure. Due to the physical properties of the grass, it proved difficult to achieve homogeneous bag contours despite brake pressure control. Therefore, we showed that with the developed brake pressure control system it is quite possible to regulate the brake pressure of a silo bagging press machine automatically. Brake pressure adjustment can be realized in a timely manner at elongation outside the tolerance range.

4.3. Evaluation of the density in the silo bags

Automatic pressure regulation enabled constant compaction over a particular bag surface because of the comparable silage material and the same silo press.

The storage density in the maize silage bags examined was not homogeneous over the cross-sectional area as presented by Assirelli and Santangelo (2018). The density of maize silage located in the middle bag was 0.9% higher, while the density in the boundary zone did not differ. The average density in the upper zone of the bag was determined as 200.0 ± 24.5 kg DM m⁻³, which corresponds to an average density difference of 5%.

It can be concluded that intensification of the bagging machine pressure and the consequent elongation of only 2% led to a significant increase in density in the middle of the bag, by 9%. At the boundary, no effects of adjusting the pressure of the pressing machine on the density were found. This observation may be due to the technical design of the press rotor in conjunction with the tunnel, since the rotor width is less than the tunnel width. Compared to other density tests on maize shells, the data obtained in these studies matched those in the literature (Esau et al., 1990; Muck and Holmes, 2001).

The density distribution in grass silage bags was less homogeneous than in maize silage bags. Within grass silage bags, the middle zone with an average of 173.9 ± 36.2 kg DM m⁻³ density was significantly different from the boundary and upper zones. The average densities for the boundary and upper zones of the grass silage bags were 118.6 ± 39.2 and 101.9 ± 34.1 kg DM m⁻³, respectively. The density values of grass silage in this study were considerably lower than the comparative values presented by Muck and Holmes (2001) and Honig (1987).

Generally, the variation in density distribution was much greater with grass silage than maize silage. This is another indication of the inhomogeneous storage of grass silage. The results of grass silage were significantly lower than the values presented by Muck and Holmes (2001). The density of grass silage with 29% DM content should be < 190 kg DM m⁻³ as reported by Honig (1987). This value was almost reached in the present study, with an average of 173.9 kg DM m⁻³ in the middle zone.

5. Conclusion

The main objective of this study was to automate manual brake pressure control during silo bag ensiling via a process computer, in order to relieve the operator. For this purpose, control software and measurement technology were successfully installed on a commercial silo bagging press machine. The preliminary experiments described proved to be suitable for the fundamental examination of control and measuring technology.

A changed brake pressure setting had an effect on the silo bag. In particular, the storage density of maize silage varied with the intensity of the brake pressure. In grass silage, the effect was not confirmed because of the heterogeneous properties of the substrate. The formation of cavities and bulges was minimized quite well by increasing the brake pressure setting.

The strong bulges created in grass silage bags during storage could not be remedied even by automatic pressing pressure control. Adjustment of the rotor width to the tunnel width has an additional influence on storage density especially at the boundary of the silage bags. Moving the rotor further upwards could also have a positive effect on the density increase in the outer bag areas.

CRediT authorship contribution statement

Ehab Mostafa: Conceptualization, Visualization, Writing - original draft, Writing - review & editing. Maren Roessmann: Methodology, Resources, Investigation, Data curation, Writing - original draft. Christian Maack: Conceptualization, Methodology, Software, Validation. Oliver Schmittmann: Methodology, Software, Validation. Wolfgang Buescher: Funding acquisition, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://

References


