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RESEARCH AND DEVELOPMENT OF ESSENTIALS FOR SILAGE PREPARATION, TRANSPORT AND STORAGE IN FLEXIBLE CONTAINERS OF OPTIMAL VOLUME

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The research purpose was to develop the basics for silage preparation by vacuuming with the use of flexible polymer containers and estimating silage quality. The analysis of modern systems used for silage preparation and storage showed that the main disadvantages include the high storage and preparation costs, and losses of silage weight and nutrients by 3–25% after opening of storage facilities. To eliminate these disadvantages, the basics for preparing the silage by vacuuming in flexible polymer containers that can be transported and stored with optimum volume have been studied and developed. The study pursues its goals by observing the changes in density and degree of silage compaction caused by the vacuum pressure and deadweight. A comparative estimation of silage quality indices was conducted by means of chemical analysis of silage specimens. The results show graphical dependencies of changes in silage volume and density at vacuum pressure up to 60 kPa. Moreover, a comparative assessment of quality indices of silage specimens prepared by vacuuming in soft containers, and traditional method using trenches was conducted. The reliability of results for silage storing quality in a vacuum container was achieved by fivefold test repetition within 2 years. Comparison of silage quality indices obtained using vacuum technology and traditional method showed improvement in favour of the proposed method: dry matter by 2.05%; protein by a factor of 1.47; nitrogenous substances by 1.37; starch by 1.56; calcium by 1.83; phosphorus by 2; digestible protein by 1.24; feed unit by 1.31; exchange energy by 1.16, which was achieved thanks to the elimination of succus leakage.

Keywords: flexible vacuum container; heavy load bags; matrix; degree of compaction

One of the most important types of feed in the diet of farm livestock is silage. It approx. amounts to 40% of the nutritional value (Kalashnikov, 2003; Khokhrin, 2002). Globally, the main crop for silage production is corn (Boyarsky, 2011a). The silage production accounts for approx. 70% of the total cattle forage in Western Europe (Jones, 1998).

Nowadays, various forage storage facilities are used for the preparation and storage of silage, including silo trench (or pit), silo bunker, silo tower, and silo bags. However, all existing technologies utilize mechanical means under stationary conditions using expensive equipment to compact the silage mass (Boyarsky, 2001b; Holmes and Muck, 2000; Revich and Nekrasevich, 2013; McAllister and Hristov, 1995; Karpenko, 1974; Sagyndykova et al., 2019a, 2019b).

Analysis of the feed ensiling using the aforementioned facilities shows a number of significant drawbacks, i.e. high costs of construction of trenches and towers, large losses of silage mass and nutrients (reaching 3–25%), silage mass acidification (Asplund, 1994; Erdman, 1993; Harrison et al., 1994; Keller et al., 1998; Limin Kung et al., 2018; Ferraretto et al., 2018; Kažimírová et al., 2020).

The top priority in silage production is to rapidly reduce oxygen level and increase acidity so that lactic acid bacteria are able to grow in order to stabilize and preserve the forage. In 2–3 days after ensiling, cell juices become available as a food source to silage bacteria. By this time, the oxygen should have been eliminated, and silage pH should have declined to a level at which the lactic acid bacteria can grow (pH = 5.5–5.7). The lactic acid bacteria start to propagate, producing lactic acid (C₃H₆O₃) and certain amount of acetic acid (C₂H₄O₂), which results in increased silage acidity. After approx. six weeks later, silage should reach a final pH value (3.8–4.0 in corn silage) according to Ward and Ondarza (2009), Ralh and Ondarza (2008), and Limin Kung et al. (2018). Furthermore, these researchers reviewed the evaluation of forage fermentation, which produce higher amounts of lactic acid, typically resulting in the lowest dry matter losses.

The construction of expensive structures, such as silo trenches and silo towers, is not effective on a small farm scale due to a long payback period (Orsik and Revyakin, 2008; Yemelyanov et al., 2019). Therefore, the search for efficient

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methods for forage preparation, including silage mass, is relevant.

In addition to this, readily available materials made of polyethylene films used in solar drying equipment (Khazimov et al., 2018a) and in growing vegetables (Khazimov et al., 2018b, 2019) appeared on the market, which were observed to have a wider range of application. Polyethylene films can be also used as wrapping materials in feed preparation (Korotkevich, 1990; Woolford, 1989; Toková et al., 2020).

In the last two decades, the study of vacuum effect on the ensiling process using polymer material has begun (Johnson et al., 2005; Patent RU 2625480; Patent RU 193970). The corn is ground by a forage harvester and the resulting green mass is loaded into soft containers made of airtight polyethylene film, which are installed in transport bags (Big-Bag type). The Big-Bags are placed inside truck-mounted cassettes with rigid solid walls (Patent RK 33415; Sagyndykova et al., 2019a, 2019b; Nekrashevich et al., 2015, 2017; Malarev et al., 2020). The filler of a flexible container with silage is sealed using a heat sealer. Air is pumped out of the flexible container via a flap valve using a vacuum pump. Flexible containers are vacuumed until the juice will flow out. Subsequently, such containers are extracted from a matrix by a manipulator and loaded into transportation unit and delivered to a storage facility.

Feed is stored in flexible containers inside Big-Bags folded on each other under airless conditions. In two to three storage days, the gas produced by a fermentation process inside containers should be pumped out. After 40 days, feed in the flexible containers can be used to feed livestock (Sagyndykova et al., 2019a, 2019b).

The research purpose was to develop the essentials for silage preparation in flexible polymer containers by vacuuming and assess the silage quality (Sagyndykova et al., 2019a, 2019b). The tasks that were solved include theoretical and experimental justification of parameters of flexible containers used for preparation, transport, and storage of silage, as well as comparative study of qualitative composition of silage prepared using proposed and

Fig. 1 Scheme of technological process for silage preparation

1 – generator; 2 – compressor; 3 – tank with compressed air; 4 – vacuum pump; 5 – continuous heat sealers; 6 – tank; 7 – matrix for a flexible container; 8 – forage harvester

existing technological processes under industrial production conditions.

Material and methods

The scheme of the technological process for preparation and storage of silage based on the proposed technology is shown in Fig. 1.

Transport and grinding of silage are performed by a combine. The ground mass is loaded into flexible containers placed on a truck cargo body. A flexible polyethylene container with a load-carrying bag is located inside a metal matrix. Matrix volume depends on the transport body size (Sagyndykova et al., 2019b; Zhukovskyy et al., 2019; Kuzmin and Sharifullina, 2014).

Silage preparation technology includes the following operations: preparation of green mass by cutting, grinding and loading into the vehicle; preparation of containers for filling with green mass, involving also insertion and hanging of intermediate bulk container in the matrix, and insertion of the airtight flexible container into the flexible intermediate bulk container; sealing of the container filler by continuous heat sealers; loading of the prepared containers into the vehicle using manipulator for transportation to storage facilities.

Compaction of silage in a soft container was presented by Nekrashevich et al. (2015, 2017, 2020).

A pycnometer method based on Archimedes Principle was used to determine the dependence of changes in volume of silage mass contained in flexible container on different vacuum pressures. A sealed mini container with silage mass was immersed in a container with water of a known volume and a volume of displaced water was measured before and after the mini container was compacted. The water level in a water-filled graduated cylinder was recorded before vacuuming the container with silage. After that, the air was pumped out of flexible container using a vacuum pump, resulting in an increase in the density of silage in container, and the water level was recorded again. Subsequently, the vacuum pressure inside the flexible mini container was increased. Each increase in vacuum pressure was repeated five times. Changes in the mini container volume were measured with each increase in the vacuum pressure. The differences in water levels in the measuring container were used to determine the silage mass volumes at each observed vacuum pressure (Sagyndykova et al., 2019a).

As a result of measuring the volumes of silage mass, different

density values were obtained at each level of vacuum pressure. The density was defined as the ratio of mass to volume, i.e.:

$$\rho = M \cdot V^{-1} \text{ or } \rho = M_M (V_2 - V_1)^{-1} \quad (1)$$

where:

ρ – density ($\text{kg} \cdot \text{m}^{-3}$)

M – mass (kg)

V – volume of silage mass (m^3)

M_m – mass of silage monolith (kg)

$V_2 - V_1$ – water volume in cylinder before and after putting in the container (m^3)

The silage mass compaction factor was calculated as follows:

$$\lambda_{\gamma} = V_k \cdot V^{-1} = \gamma \cdot \rho^{-1} \quad (2)$$

where:

V and V_k – volume of silage before and after compaction (m^3)

ρ and γ – density of compacted and noncompacted silage ($\text{kg} \cdot \text{m}^{-3}$)

Based on the results of laboratory experiments, graphs of changes in the volume and density of silage depending on the vacuum pressure were obtained.

For the purposes of field experiments, the flexible container was made of flexible polyethylene hoses (PE-115) with a diameter of 1.6 m and a height of 3.8 m. The thickness of polyethylene plastic hoses was 200 microns. The lower side of flexible container was sealed by continuous heat welding. On one side of the flexible container, a check valve was installed for the purposes of pumping the air from a flexible container (Patent RK 33425).

A matrix for placing a Big-Bag and flexible container was made of steel in a shape of square truncated pyramid (lower 1.0×1.0 m, upper 1.2×1.2 m). The matrix height is 1.7 m. The dimensions of Big-Bag were selected from the standard sizes based on the possibility of using mechanized lifting devices (up to 1 ton) at farm facilities. The matrix was mounted on a plain surface. Subsequently, the Big-Bag was inserted inside the matrix until it reached the flat bottom. Lifting loops (in the upper corners) of the Big-Bag were attached to the matrix corners (in the upper part). A flexible container was placed inside the Big-Bag, reaching the flat bottom as well. The container filler was fastened along the perimeter of upper cassette base (Fig. 2).

Ground green mass was loaded into flexible containers up to the top matrix level. The neck surface of soft container was welded after cleaning the impurities. Subsequently, the air was pumped out of a flexible container through the check valve using the vacuum pump. Vacuum pressure was controlled by a vacuum gauge in the vacuum line. External structural dimensions of the container with silage mass were determined using a tape measure. The mass of the container with silage was determined using pre-calibrated dynamometric scales. The determination of parameters of vacuum container was replicated five times.

For the purposes of biochemical analysis, the silage samples (Federal Standard R55986-2014) were taken from a silo trench and from flexible vacuum containers. Thirty flexible vacuum containers have been stored under the same conditions since September 2018 and located near the silo trench. The first flexible vacuum containers were opened in March 2019, the second in July 2019, and the last in September 2019. All silage samples came from the same corn variety and field, were transported during the same period, and had the same physical and mechanical

Fig. 2 Scheme and general view of flexible container "Big-Bag" and flexible plastic container in the matrix for field test

Fig. 3 Changes in density and volume of silage in a flexible plastic container depending on vacuum pressure

Fig. 4 Results of forage chemical analysis in terms of natural moisture (%)

properties. Assessment methods of silage quality were carried out according to the requirements of Federal Standards RF 23638-90 and 53903-2010.

Results and discussion

A graphical dependence of the density and volume of silage mass on the compacting pressure obtained by vacuuming the container is presented in Fig. 3. The density curve in a range

of vacuum pressure of 0 to 60 kPa increases from 460 to 820 kg·m⁻³. Reaching the pressure of 50 kPa, there is a stop to density increasing, which can be explained by the fact that the green mass acquires almost the density of corn stalk (approx. 850 kg·m⁻³). Further compaction causes the succus to flow out. Usually, the silage density in silo trenches does not exceed the value of 650 kg·m⁻³. Therefore, the silage density in flexible plastic containers will be ranging from 650 to 800 kg·m⁻³. Further compaction would result in

increased energy costs and packing time, which is unreasonable.

The change in silage volume due to compaction pressure is presented in a form of curve with decreasing tendency with increasing pressure. The ordinate report starts at 10 kPa, which is due to the fact that, after welding the neck of container with silage, a certain amount of air remains inside the folds. Therefore, for the purposes of experiment reliability, a calculation was performed for range 10–60 kPa of vacuum. Based on the curve obtained, the decrease in silage mass volume at 60 kPa was approx. 37%, which is why the container for field test was taller than the Big-Bag by 30–40%. This approach takes into account the silage mass compaction according to the theoretical calculations and the compaction will occur along the height of the flexible container to a greater extent (due to the self-weight mass of silage). The compaction coefficient λ_y was employed for the purposes of practical control of mass compaction in field. It characterizes the ratio of residual volume to initial volume. A sufficient compaction value λ_y equals to 0.7, which represents a decrease in volume by 30% (Fig. 3). By vacuuming the flexible container with silage in the field, the compacted mass acquired the shape of Big-Bag in the form of a rectangular prism and the dimensions decreased in comparison to original size (Table 1).

The field test showed that dimensions reduced by 9–10% in length and width, and by 40% in height. A significant change in height is related to the fact that there acts the silage weight itself besides the vacuum pressure in the vertical direction. This change was assumed in the theoretical description (Nekrashevich et al., 2020). Furthermore, this test also showed that the average density of silage in containers was 850 kg·m⁻³ (at vacuum

Table 1 Indicators of the geometric dimensions of the container before and after vacuuming

Items (metrics)	Height (m)	Width (m)	Length (m)
Before vacuuming	1.60	1.05	1.05
After vacuuming	0.90	0.85	0.85
After repeated vacuuming after 2 days	0.90	0.85	0.85

Table 2 Statistical analysis of silage quality indicators

Repetitions	Indicators											
	DM	protein	oil	cellulose	NFES	sugar	starch	ash	Ca	P	DP	EE
1	27.5	2.89	1.1	7.47	13.93	1.95	6.08	1.82	0.39	0.15	17.91	2.94
2	29.11	3.2	1.13	7.49	15.32	0.97	5.3	1.97	0.31	0.13	19.82	3.09
3	28.65	2.34	1.08	6.94	16.9	1.82	6.94	1.39	0.28	0.09	17.54	3.13
4	27.13	1.9	1.35	7.79	14.19	2.08	5.3	1.9	0.23	0.09	16.81	2.8
5	29.01	3.41	0.94	6.03	16.29	1.66	5.34	2.31	0.38	0.16	21.12	3.07
Totality	141.4	13.74	5.9	35.72	76.63	8.64	28.96	9.39	1.59	0.62	93.2	15.03
Average readings	28.28	2.748	1.18	7.144	15.326	1.73	5.79	1.878	0.318	0.124	18.64	3.006
Root mean square deviation	0.811	0.556	0.172	0.620	1.152	0.41	0.65	0.295	0.060	0.029	1.59	0.121

pressure of 60 kPa), which is higher by 30% in contrast to the silage density in trench.

The quality indicators of silage obtained by two technologies (vacuum and trench) are shown in Fig. 4, depicting each quality indicator in pairs (the left is for silage from vacuumized container; the right is for silage from trench) for visual comparison.

According to the analysis results, the nutrient and estimated metabolizable energy (ME) composition in each vacuum-packed sample compared to a trench sample exceeded: dry materials (DM) by 2.05%; protein more than by a factor of 1.47; nitrogen-free extractive substances (NFES) more than by 1.37; starch by 1.56; Ca by 1.83%; P more than by 2. Considering the other indicators which were not determined in percentage terms: digestible protein (DP) was increased by a factor of 1.24; feed unit by 1.31; exchange energy (EE) by 1.16. Furthermore, there were indicators that showed decrements: fat was decreased by a factor of 1.16; fibre by 1.21; sugar by 1.18; ash by 0.14%.

The reliability of silage quality study was achieved by conducting five repetitions for each analysis throughout the year. The error deviation was estimated by statistical analysis in order to ensure that the indicators of deviations are in confidence interval (Table 2). Furthermore, these results were supported by analysis of variance of data.

Vacuum-packed silage showed good sensory properties, such as yellow-green colour and the odour showed a clear gentle linear pattern of change like pickled vegetables. Considering the visual comparison (Fig. 4), the silage extracted from the flexible plastic container showed a brighter colour than the silage from trench, which was much darker. The indicators relevant for chemical analysis of the vacuum-packed silage suggest a good quality, which was achieved thanks to good sealing of the container for storage period and storing of the succus (juice) released during the compression process together with the silage mass inside the container. Silage succus in the silo trench flows out, resulting in the loss of valuable nutrients and deterioration of storage environment. The excess of DM by 2.05% in a flexible container is due to the fact that, in case of flexible container, sampling is performed in the middle part and moisture accumulates in the lower part of the

container; in case of trenches, the sampling is conducted in the lower part with high residual moisture. In addition to this, the DM values in the container and trenches are in accordance with the requirements given by the standard. Loss of dry matter in silage depends on quality of grinding; quality of compaction; sugar content, etc. Thanks to the high-quality compaction in the flexible container, the succus does not flow out. In a trench, the silage mass is squeezed and the succus leaks out into the ground, taking numerous components with it. Therefore, the indices of individual substances, such as protein, NFES, starch, Ca and P in a soft container turned out to be underestimated due to the succus preservation. However, DM values in container and trench are in accordance with the standards (Gerlach et al., 2013; Kristensen, 2010). The research results prove the benefits of silage preparation in a soft container with the possibility of transportation and storage (without the necessity of special structures) with a guarantee of its quality preservation. From an environmental point of view, silage storage in a soft container is also a way to avoid the loss of silage (due to decomposition after opening the traditional storage facility) and succus leakage into the ground.

Conclusion

The research results for the technology of preparation and storage of silage in flexible containers using vacuuming showed that its utilization eliminates the majority of disadvantages typical for the classic methods (silage trench, etc.). The construction of special facilities and storage places is not required for its use. Compaction of the silage mass in flexible containers via vacuuming at a pressure of 60 kPa resulted in a density of 800–850 kg·m⁻³. This value is higher by 30% in contrast to the silage density prepared using the traditional method.

Comparative study of the quality indicators of silage obtained by the vacuuming technology and traditional method made it possible to establish an improvement in indicators in favour of the proposed method: dry matter was increased by 2.05%; ash by 0.14%; protein by a factor of 1.47, nitrogenous substances by 1.37; starch by 1.56; calcium by 1.83; phosphorus by 2; digestible protein by 1.24; fodder units by 1.31; exchange energy by 1.16.

After opening the container, its content with an average volume of 1 m³ was fully used as animal feed (no losses from oxidation). After opening the trench, the free space in the silo caused oxidation in the surface, making the silage unusable. The method proposed showed the advantages of storing all silage volumes (30 m³) in separate containers for 2 years during the research.

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