SUBSTANTIATION OF EQUIPMENT PARAMETERS FOR COMPACTING PLANT MATERIALS

ОБОСНОВАНИЕ ПАРАМЕТРОВ ОБОРУДОВАНИЯ ДЛЯ УПЛОТНЕНИЯ РАСТИТЕЛЬНЫХ МАТЕРИАЛОВ

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ABSTRACT
The article addresses the development of foundational principles for improving the quality of plant product preservation. The application of the proposed technologies enables a reduction in nutrient losses in raw plant materials during storage. This assertion is supported by the results of both theoretical and experimental studies on the physical and mechanical properties of plant materials, as well as on the energy, operational, and technological performance of the equipment, including its structural design parameters and modes of operation. The use of the proposed technology enhances nutrient preservation by preventing cell structure damage and preserving plant juices, while also minimizing internal voids and reducing the amount of free air within the compacted monolith. Consequently, this leads to a decrease in the cost of dietary components. The implementation of the proposed technological process in haylage production significantly reduces nutrient losses during storage. Furthermore, using plant raw materials stored with this method results in lower milk production costs compared to traditional storage techniques.

АННОТАЦИЯ
Статья посвящена разработке основ повышения качества хранения растительной продукции. Применение предложенных технологий позволит снизить потери питательных веществ в растительном сырье в процессе его хранения. Достоверность такого утверждения подтверждаются результатами теоретических и экспериментальных исследований физико-механических свойств растительного сырья, энергетических, эксплуатационных и технологических показателей агрегата, его схемы, конструктивных параметров и режимов работы. Использование предложенной технологии улучшает сохранность питательных веществ, благодаря отсутствию повреждений клеточной структуры и сохранности внутриклеточного сока, снижением свободного пространства между стеблями, что соответственно уменьшает объем воздушной массы в уплотненном монолите. Предложенная технология обеспечивает снижение стоимости компонентов рациона. Применение предложенной технологической линии при заготовке сенажа обеспечивает снижение потерь питательных веществ в процессе консервирования растительного сырья. При использовании растительного сырья, заложенного по предложенной технологии, себестоимость молока снижается в сравнении с существующими вариантами.

INTRODUCTION
Much attention has been paid to plant raw materials research since ancient times. Compaction of straw materials as an alternative fuel can be considered as the first attempts. The devices for stem materials compaction have been used since the end of the 9th century. Approximately the same time, there were the first attempts to provide a scientific substantiation for this process. Yet more detailed studies of stem materials compaction were started in the early twentieth century.

The first mechanisms for fuel briquettes production were peat briquette presses of the stamp type. But they were not adapted to the pressing of plant raw materials. Therefore, it was necessary to conduct physical and mechanical research as well as technological properties of materials to be pressed. All of the above was necessary for defining the design and technological parameters and modes of operation of the press equipment.

Great contribution to the study of vegetable raw materials compaction problems was made by the scientists *Goryachkin,(1965), Gutyar, (1936), Pustigin, (1948)* and others and no plant materials (*Olaleye et. al., 2020; Vanhoorne et al., 2020; Orisaleye and Ojolo, 2019 and others*).

Special press briquetting machines for stem materials were the results of their work for stem materials. As the result of stem materials compaction research, having been conducted by many authors, various dependences of the material density ρ and the degree of its compression on the applied force P were set. However, despite all the efforts, researchers did not come a single opinion as for the regularities of the process of hay and straw materials pressing.

On the bases of data obtained, many equations have been proposed that relate the pressure to the deformation or density of the pressed material. Some scientists believe that the relationship between the pressing pressure and the density of the material in the chamber can be expressed by a power function, in the form $P = C\rho S$, while other researchers (*Pustigin M., 1948, Osobov V., 1963, Dolgov I., 1971*) consider that the dependence should have an exponential dependence in the form $P = AeB\rho$. Whereas *Dolgov I. (1971)* was certain that the relationship between pressing pressure and density will change its physical meaning when the humidity of the pressing materials changes, namely at humidity up to 15.6%, the dependence will be gradual, while with increasing humidity more than 18% the dependence will already be exponential. We should also not forget about the supporters of Hooke's law, such as *Goryachkin V., (1965)* and *Gutyar* E., *(1936).*

For example, *Goryachkin V., (1965),* proposed the dependence of the axial pressure on the movement of the piston.

$$p = p_{max}(1 - \frac{x^2}{S^2}) \quad (1)$$

where:

p, p_{max} - respectively, the current and maximum pressure on the piston, [Pa];

x, S - respectively, the path and stroke of the piston, [m].

Pustygin M., (1948), noticed that in the presence of nodes availability, leaves and stems with different orientation there is no direct fracture of the stems, and the process takes place along with the flattening. As a result, the compaction process proceeds smoothly and evenly. The materials to be pressed have only physical, mechanical and technological properties that affect the compaction process. That is why many researchers have sought to identify these properties and identify their impact on the process. For example, *Gutyar E., (1936),* in the proposed dependences took into account the modulus of elasticity of the first kind and the Poisson's ratio. Such researchers as *Perezhogin M., (1963),* and *Khrapach E., (1956),* took into account the moisture content of the fodder as well as the rate material of deformation.

THEORETICAL BACKGROUND

At the present stage, it is no longer a secret that the preservation of feed should first avoid contact of the feed mass with the air. It is achieved in a various way, such as filling storage containers with inert gases, compacting the feed mass, compacting near the shelter storage or containers with airtight films or laying in polymer sleeves, and so on. But the most widespread ones are the processes of compaction of the feed mass, where due to the direct compression of freely placed particles there is the displacement of air from the feed mass. *Khvorostyanov, (1980), Semenikhin, (1998),* and others have already dealt with these issues. However, these issues could not be finally resolved. Theories of fodder mass compaction as well as theories of porosity, stacking, etc. were offered. However, the issue remains topical due to excessive nutrient losses (about 15%) during storage. Therefore, the relevance of this topic remains and needs further development. *Khvorostyanov, (1980),* was engaged in the processes of self-compaction of fodder masses in small storages. He most systematically considered the physical and mechanical properties of silage. Academician Muller R., (*Muller, 1963*) put forward some empirical formulas for soils of normal humidity, which, with certain assumptions, can be applied to silage monoliths. According to them, the normal vertical pressure p_z will be equal:

For containers with rectangular cross section:

$$p_z = 9.81\rho_{cp}\frac{1}{2}\sqrt{\frac{\pi si}{2\Psi(i+1)}}\cos\left(\sqrt{\frac{1}{s}}\cdot\frac{2x}{a}\right)\cos\left(\sqrt{\frac{1}{s}}\cdot\frac{2y}{b}\right)\Phi\left[\frac{2z}{a}\sqrt{\frac{\Psi(i+1)}{si}}\right] \quad (2)$$

For containers with round section:

$$p_z = 9.81\rho_{cp}\frac{1}{2}\sqrt{\frac{\pi si}{2\Psi(i+1)}}\cos\left(\sqrt{\frac{2}{s}}\cdot\frac{r}{R}\right)\Phi\left[\frac{2}{R}\sqrt{\frac{2\Psi}{s}}\right] \tag{3}$$

where:

ρ_{cp} - average mass density, [kg/m³];

a, b - length and width of a rectangular container, [m];

i - the ratio b/a;

R - the radius of the round container, [m];

s - the coefficient that characterizes the smoothness of the tank walls;

Ψ - coefficient of lateral pressure;

Φ (a) - is the Laplace function;

$$u = \frac{r}{R}\sqrt{\frac{2\Psi}{s}}$$

x, y, z, r - coordinates of the point for which the pressure is being determined, [m].

The optimal from the positions of providing the highest normal vertical pressure p_z are containers with a round cross section, which are already followed by containers with a square cross section because they have a smaller perimeter with the same cross-sectional area. Moreover, in all cases, containers with large cross-sectional areas have advantages over containers with small cross-sections, and containers with large heights have advantages over smaller ones.

Many authors in making their hypotheses use the provisions of Hooke's law on the deformation of elastic-plastic materials, namely:

$$Hn\frac{d\varepsilon}{dt} + E\varepsilon - \sigma - n\frac{d\sigma}{dt} = 0 \tag{4}$$

where:

E, H - long and instantaneous modulus of elasticity, [Pa];

σ, ε - stress and relative deformation, [Pa];

$n = \mu / E$ - relaxation time, [s];

μ - viscosity, [Pa*s].

Semenikhin A., (1998), studied the compaction processes of forage material by tractors, specifically how the forage mass is compacted in the track or inter-track area of the tractor. He derived the following equation, which expresses the magnitude of the relative deformation in the horizontal plane: (5), where L is the track width or wheelbase of the traction vehicle, and l_0 is a parameter of the laying body.

$$\varepsilon_H = \frac{2l_0}{(L-2l_0)} \tag{5}$$

where:

ε_H is the amount of relative deformation in the horizontal plane;

L is the width or wheelbase of the energy source;

l_0 – is a parameter of the laying body.

In the work of *Semenikhin, (1998)*, it was proposed to continue the above theory through the use of echelon loading of the feed mass when stacked in storage. As a result, they offer optimal conditions for the implementation of the proposed method of compaction, which requires maintaining the required level of the monolith surface, and setting the required geometric size of the deformation. To maintain a zero balance of voids and compaction along the stroke of the rammer, and to ensure that the monolith remains in a position aligned with the path of the support element, it is necessary to implement a combined scheme with geodetic levels placed along the direction of movement. Additionally, several studies have examined the effects of periodic loading in similar contexts.

For example, *Gurinenko, (2007)*, in her work, in addition to examining the impact of heavy mobile equipment, also addresses the problem of particle placement within the feed mass monolith during compaction and proposes three placement schemes.

The process of distributing silage mass within the storage volume is accompanied by periodic loading from caterpillars or wheels over a gradually increasing layer. This layer consists of particles with finite size, geometric shape, and varying orientations. At the points of loading, specifically under the tracks of the rammer, these particles form discrete aggregates that respond differently to the rammer’s deformation. These include both relaxing and non-relaxing deformation centers, which are not structurally connected. In such conditions, the feed mass does not form a unified structure; its mechanical strength is governed by frictional interactions, which are influenced by the height and size of the particles. As the layer's height increases, the number of elementary aggregates also increases, while the distances between them decrease only slightly. This results in the silage mass simulating imperfections of the original discrete particles and gradually integrating the mechanical behavior of these disconnected aggregates. Eventually, the mass transitions to a new boundary condition level, where elementary structures begin to interconnect.

At this stage, the structure becomes dominated by horizontally oriented particles. When the layer height reaches approximately 0.8 m to more than 1 m, its surface begins to exhibit load-bearing capacity, characterized by shear strength (τ) and compressive strength (σ) due to cross-dense packing, while retaining the elastic-viscous behavior of its constituent components. Thus, it can be concluded that before compaction, the feed mass behaves as an elastic-viscous body composed of numerous aggregates distributed throughout its volume.

The particles possess defined dimensions and can migrate toward areas of lower density and between layers. Under the influence of periodic loading, the feed mass undergoes changes in both its physical-mechanical and rheological properties, gradually approaching the upper density limit and minimum porosity characteristic of a compacted monolith. This study is based on the dynamic behavior of multicomponent media, considering variations in their damping properties and their capacity to absorb mechanical energy during compaction.

The mechanics of elastic-viscous media of plant origin are characterized by properties such as stress relaxation, viscosity, and creep, which are not functionally dependent on porosity and density. This distinction highlights the relevance of the present work. Considering all the above, it can be concluded that significant efforts have been made to reduce porosity - an important factor in minimizing feed contact with air. However, there is still a lack of sufficient technological solutions to effectively eliminate voids and prevent the formation of empty layers within the feed mass. Therefore, it is deemed necessary to enhance the theoretical foundations of the feed mass compaction process and to continue research in this critical area.

MATERIALS AND METHODS

Based on the results of laboratory research having been conducted by *Milko, (2020, 2019), Maraldi et al., (2016), Lisowski et al., (2020), Kaliyan et al, (2013), Cabrales et al, (2020), Siyal et al., (2021)*, an experimental and production prototype of equipment for plant material compaction was developed (Fig. 1).

The system consists of a frame *1* equipped with a feeder *2* and a twin-screw compactor *3*, all integrated into a single technological unit. All actuators are powered by adjustable electric drives, which are automatically controlled and can also be manually operated via a centralized control panel. The technological process for compacting vegetable raw materials is as follows: the material is first delivered by the feeder *2* into the twin-screw compactor *3*, where the screws - arranged in layers - separate and structure the incoming particles. The mass is then directed toward the diffuser, where it undergoes a twisting motion. This twisted mass is subsequently fed through the diffuser, where it is compacted (Fig. 2).

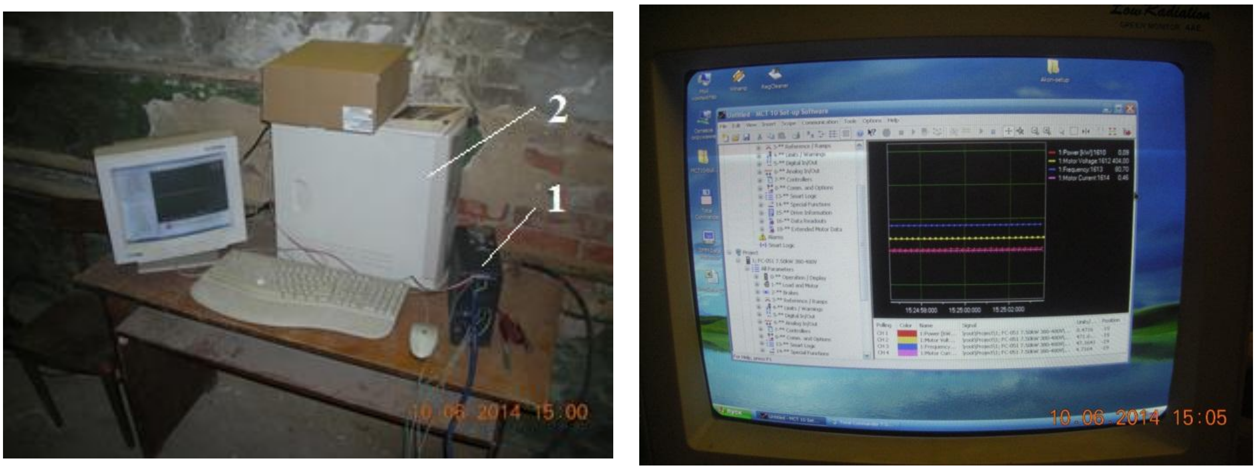
In the present research, the following equipment was used: RN-50SHVP-1 scale, electronic scales, laboratory quadrant scales VLK-500-M, sampling bags, a box for volume determination, caliper, engineering ruler, and a type S 0.2 stopwatch. Scales for measurements up to 500 kg. Additional measuring instruments included: dial scales РН–10Ц13У (TU 25.06.575–70), laboratory technical quadrant scales VLTK-500, pointer tachometer PM-10R (GOST 21339), mechanical stopwatch SOPpr-2a-3-000 "Agate" 4282 (GOST 5072-79), metal ruler 0–500 mm (GOST 427-75), tape measure P2 (GOST 7502-80), vernier caliper ShTs 0–150 (GOST 166-80), camera, metal container ($V = 0.15\ m^3$), and a measured set K-50 (GOST 8711 and GOST 8476).

Fig. 1 - Equipment for plant raw materials compaction

1 – frame; 2 – feeder; 3 - twin-screw compactor.

Fig. 2 - Compaction of the twisted mass as it passes through the diffuser

The measuring stand was equipped with a Danfoss VLT Micro FC51 frequency converter integrated with the MCT-10 software suite (Fig. 3). Using the mathematical theory of experimental design, the dependencies of quantitative, qualitative, and energy performance of the preservative dispenser and the twin-screw compactor on the studied factors were also determined. The corresponding regression equations were based on three factors.



a) b)

Fig. 3 – General view of the measuring stand

a) Danfoss VLT Micro FC51 frequency converter; b) MCT-10 software package;
1 - Danfoss FC-51 frequency converter; 2 - personal computer.

The research on a twin-screw compactor for vegetable raw materials was conducted by analyzing the influence of design parameters, operating conditions, and material properties. Specifically, the study focused on the ratio of the inlet height to the screw diameter, screw rotation speed, and the initial mass density of the material. Both active and passive experimentation methods were employed - active variation of selected factors was combined with passive observation of others. The screw speed and the inlet height-to-screw diameter ratio were varied according to a three-level, three-factor experimental design matrix. The initial mass density was based on values obtained during previous compaction cycles. The variation range for the inlet height-to-screw diameter ratio was 1.27 to 1.95, with an average value of 1.6, representing a 20.6% variation. Screw rotation speeds ranged from 21 to 125 rpm, giving a variation interval of 72 rpm or 71.2%, indicating a wide experimental scope for both parameters. The initial mass density of haylage varied from 150 to 555 kg/m³. To optimize the design and operational parameters of the twin-screw compactor, a full second-order factorial design matrix with three levels and three factors was applied.

RESULTS AND DISCUSSION

During the experiment, screws with the required pitch and diameter were installed on the twin-screw compactor for vegetable raw materials, and the screw rotation speed was adjusted accordingly. The pre-compaction press parameters were then set, including the loading window height coefficient and the piston speed, to achieve the desired density at the entrance of the twin-screw compactor. Next, the hopper of the pre-compaction press was loaded with vegetable raw materials. The electric motor reducers of both the twin-screw compactor and the pre-compaction press were activated, and the compaction cycle was initiated. Throughout the process, energy consumption and the productivity of filling the polymer storage unit were recorded. These values reflect all stages of the material handling process: loading, compaction, and storage. To prevent air infiltration during storage, it is necessary to hermetically seal or tightly pack the polymer storage unit after filling. The variation levels of the independent factors - screw speed n (1/s), window height coefficient k (the ratio of the feed window height to the screw diameter), and the pre-compacted mass density ρ (kg/m³) - along with their combinations, were organized according to a three-level, full-factorial second-order experimental design and are presented in Table 1.

Table 1

Variation levels of factors for investigating the twin-screw compactor for plant raw materials

№	Factor level					
	Coded			Decoded		
	X_1	X_2	X_3	Screw speed	Window height coefficient	Pre-compacted mass density
				[1/s]	-	[kg/m³]
1	-1	-1	-1	25	1.25	320
2	1	-1	-1	125	1.25	320
3	-1	1	-1	25	1.95	320
4	1	1	-1	125	1.95	320
5	-1	-1	1	25	1.25	720
6	1	-1	1	125	1.25	720
7	-1	1	1	25	1.95	720
8	1	1	1	125	1.95	720
9	-1	0	0	25	1.6	520
10	1	0	0	125	1.6	520
11	0	-1	0	75	1.25	520
12	0	1	0	75	1.95	520
13	0	0	-1	75	1.6	320
14	0	0	1	75	1.6	720

Experimental data and studies for performance (Q), power consumption (N), energy consumption (E), and output density (R), based on the factor combinations presented in Table 1, are summarized in Table 2.

Table 2

Results of hay compaction studies

№	Screw speed	Window height ratio	Input density	Productivity	Power	Energy consumption	Output density
	[s^{-1}]	-	[kg/m³]	[kg/h]	[kW]	[kJ/kg]	[kg/m³]
1	25	1.25	320	173	4.17	88.23	803
2	125	1.25	320	526	7.17	54.10	630
3	25	1.95	320	232	4.15	63.69	813
4	125	1.95	320	404	6.15	52.64	676
5	25	1.25	720	198	5.82	113.58	761
6	125	1.25	720	342	8.16	88.84	619
7	25	1.95	720	681	5.38	25.69	851
8	125	1.95	720	589	6.73	33.56	745
9	25	1.6	520	237	4.77	77.53	803
10	125	1.6	520	393	6.95	61.80	664
11	75	1.25	520	136	6.55	149.04	377
12	75	1.95	520	300	5.82	90.60	444
13	75	1.6	320	156	5.77	112.65	416
14	75	1.6	720	253	6.88	111.92	430
15	25	1.25	320	178	4.39	87.39	841
16	125	1.25	320	535	7.60	53.92	666
17	25	1.95	320	236	4.42	63.64	847
18	125	1.95	320	416	6.48	51.92	706
19	25	1.25	720	202	6.17	112.92	802
20	125	1.25	720	351	8.63	88.05	644
21	25	1.95	720	707	5.66	25.11	894
22	125	1.95	720	603	7.03	33.07	780
23	25	1.6	520	242	5.04	76.79	845
24	125	1.6	520	386	6.64	62.32	637
25	75	1.25	520	134	6.24	150.44	364
26	75	1.95	520	294	5.55	91.20	427
27	75	1.6	320	152	5.53	114.27	400
28	75	1.6	720	250	6.52	111.85	413
29	25	1.25	320	169	4.00	89.05	779
30	125	1.25	320	519	6.83	54.28	603
31	25	1.95	320	230	3.96	63.76	785
32	125	1.95	320	395	5.89	53.27	651
33	25	1.25	720	195	5.55	114.14	730
34	125	1.25	720	335	7.79	89.66	598
35	25	1.95	720	663	5.13	26.09	819
36	125	1.95	720	579	6.48	33.98	720
37	25	1.6	520	232	4.55	78.21	770
38	125	1.6	520	403	7.34	61.26	698
39	75	1.25	520	140	6.96	147.63	393
40	75	1.95	520	308	6.18	89.92	467
41	75	1.6	320	161	6.06	111.11	436
42	75	1.6	720	257	7.43	112.19	448

According to the data presented in correlation Table 3, which is based on the experimental results in Table 2, a statistically significant ($p < \alpha$) moderate correlation (as per Chaddock's scale) is observed between productivity, power, and output mass density with the screw rotation speed during the compaction of haylage and heap material. Notably, the correlations for output mass density are negative.

Productivity, energy consumption, and power also show statistically significant correlations with the window height coefficient, but only when considering the input density. Among these, power demonstrates a correlation strength ranging from moderate to relatively high across all analyzed indicators.

Table 3

Correlation table for haylage compaction estimation

Indicator	Productivity	Power	Energy consumption	Output density R
Haylage				
Screw speed	.3780	.8020	-.1982	-.3654
	p=.014	p=.000	p=.208	p=.017
Window height ratio	.4299	-.2706	-.5806	.1763
	p=.004	p=.083	p=.000	p=.264
Input density	.2962	.4118	.0057	.0348
	p=.057	p=.007	p=.971	p=.827

The results of the preliminary evaluation of the experimental data for determining the values of productivity, power, and energy consumption - using Student's *t*-test, the range of the truncated sample, and Cochran's test at a significance level of α = 0.05 - are presented in Table 4.

Table 4

Preliminary evaluation results of experimental data using statistical criteria

Name of the criterion	The value of the criterion	Criterion			
		Productivity	Power	Energy consumption	Output density
Haylage					
Student's *t*-test	Maximum value	1.061	1.061	1.135	1.066
	Critical value	4.303			
Truncated sample range k	Maximum value	0.602	0.602	0.805	0.612
	Critical value	3.157			
Cochran's test G	Estimated value	0.438	0.146	0.298	0.124
	Critical value	0.570			

Table 4 shows the preliminary evaluation of experimental data for productivity, power, energy consumption, and output density. Statistical assessments were carried out using Student's *t*-test, the range of the truncated sample (k), and Cochran's G test at a significance level of α = 0.05 are given in Table 4.

Table 5

Regression equation indicators for the dependent variable – performance of the two-screw compactor

Indicator	Decoded regression coefficient	Standard error of the regression coefficient	Student's actual criterion	Significance Level
Haylage				
Free term	1634.059	171.534	9.526	0.001
Screw speed	0.738	0.688	1.072	0.344
Window height ratio	-1487.907	217.063	-6.855	0.002
Input density	-2.382	0.239	-9.950	0.001
Speed of rotation × Window ratio	-2.984	0.259	-11.533	$3.228 \cdot 10^{-4}$
Speed of rotation × Input density	-0.006	$4.528 \cdot 10^{-4}$	-13.096	$1.963 \cdot 10^{-4}$
Window ratio × Input density	1.420	0.065	21.957	$2.546 \cdot 10^{-5}$
Square of screw speed	0.057	0.003	17.533	$6.214 \cdot 10^{-5}$
Square of window height ratio	378.571	66.640	5.681	0.005
Square of input density	0.001	0.000	3.966	0.017

As a result of processing the extended matrix of experimental data - including pairwise interactions of independent factors and their squared terms, based on Table 1 - Table 5 presents the decoded regression coefficients and their statistical evaluation for haylage compaction. The regression model was established using Statistica software.

CONCLUSIONS

Analyzing the response surface of energy consumption during plant material compaction - based on the screw speed of the two-screw compactor, the window height coefficient, and the input density - it is observed that optimizing compaction parameters for maximum productivity also allows achieving the desired output density. Specifically, when the screw rotational speed is set at 40-45 rpm, the window height coefficient is around 1.8, and the input density is approximately 350–370 kg/m^3, the output density of the compacted heap reaches 600 - 700 kg/m^3 under the same equipment settings.

Based on the conducted research, the following compaction parameters for vegetable raw materials are recommended. For haylage compaction: window height coefficient: k = 1.6; input density ρ = 620 kg/m^3; screw rotation speed n = 100 rpm. For heap compaction: window height coefficient k = 1.8; input density: ρ = 420 kg/m^3; screw rotation speed: n = 100 rpm

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