Development of technology and means for machine harvesting of head cabbage in the non-damaging mode

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Abstract. During the traditional mechanized harvesting of cabbage the heads are severely injured. In this regard, the purpose of research is to provide scientific justification for the new technology and devices for machine harvesting cabbage in a sparing mode. Using mathematical modeling, new methods of cabbage harvesting are justified, which provide for a gentle mode of shipment of heads by a combine harvester using a special device, first on a flexible flooring, and then carefully transferring them manually into containers. Thus, the methods of reducing the damage to cabbage heads during machine cleaning are formulated, and the nature of the influence of the main parameters of the proposed devices on the quality of the working process is analytically revealed. As a result, the rational parameters of the devices were determined: the departure of the loading zone of the tray Δ=0.100-0.150 m with its flexural stiffness $E I=16-20 \, \text{Nm}^2$, the height difference of the edges of the flexible flooring $h=0.25 \, \text{m}$. The production test established the consistency of the proposed new technology of machine harvesting of cabbage and the possibility of reducing the damage to the heads to a level not exceeding 5-7% of the total mass of products.

1. Introduction

Head cabbage is the main vegetable crop cultivated in Russia [1] and abroad [2-4]. Its harvesting is accompanied by significant labor costs [5, 6]. Therefore, in many countries, increased attention is paid to the search for technical means [7-9] and mechanization of harvesting processes [10-12]. At the same time, with introduction of mechanized technologies for harvesting cabbage its preservation has become an acute problem due to mechanical damage to heads. Thus, the studies [13] have established that when placing damaged heads for storage their losses can be up to 50%. In this regard, the task of development of new technological methods that allow machine harvesting of head cabbage in the non-damaging mode is to be solved.

The goal of this study is the scientific justification of the new technology and devices for cabbage machine harvesting in the non-damaging mode as well as their main parameters.

2. Materials and methods

The results of observations have demonstrated that during machine harvesting cabbage heads sustain significant damage when loaded in bulk into the body of an accompanying vehicle. In order to identify
the causes of the specified negative phenomenon we shall study the geometry of the process in more
detail.

The scheme of loading cabbage heads into the vehicle body by the harvester elevator is shown in
figure 1. It allows seeing that when loaded to the bottom of the body the heads can have a maximum
fall height determined by the formula (1):

\[ H = D_2 + h_2 + \Delta_{\text{min}} + h_1 \]  

(1)

where \( h_1, h_2, D_2 \) – elevator and body geometry shown in figure 1; \( \Delta_{\text{min}} \) – the required minimum
distance between the edge of the body side and the elevator scraper in order to prevent them from
touching during operation of the units due to field irregularities.

In this case, cabbage heads will also have an initial falling speed determined according to the
expression (2):

\[ v_{oy} = -v \left( 1 + \frac{D_1}{D_2} \right) \cdot \sin \Theta \]  

(2)

where \( v \) – elevator blade speed, \( D_1 \) – head diameter; \( \Theta \) – scraper inclination angle at the moment a
head moves off the elevator.

In this case, on the basis of the energy conservation principle it is possible to imagine the head
falling without initial speed over vertical from a fictitious height conditionally (3):

\[ H' = H + \frac{v^2(1 + D_1/D_2)^2 \sin^2 \Theta}{2g} \]  

(3)

Using the real values of the parameters of modern cabbage harvesting machines and vehicles in this
formula we make sure that the fictitious fall height \( H' \) significantly exceeds the fall height allowed for
cabbage heads \( [H] = 0.15-0.6 \) m depending mainly on their mass and size.

Thus, machine harvesting of cabbage is accompanied by significant dynamic impacts on the heads,
in particular when loaded into the vehicle body by the elevator. Therefore, the main task during
machine harvesting of head cabbage is to provide a non-damaging mode for loading heads with a
harvesting unit and to exclude their reloads during placement for storage.

Taking into account the revealed fact, a new method [14] for careful cabbage harvesting is
proposed and is implemented on the basis of the experimental cabbage harvester MKK-1 developed by
us earlier.

A new way of harvesting cabbage is presented schematically in figure 2. It is performed as follows.
During operation the harvesting unit (a tractor with a combine) moves along the harvested part of the
field, the cutter bar 1 is headed along a row of cabbage. First, it evens out the lodged cabbage plants,
and then simultaneously cuts heads and frame leaves. The cut heads and leaves are fed by the external and pressure conveyors [1] through the roller leaf separator to the bulkhead conveyor cutter 2.

![Figure 2](image_url)

**Figure 2.** New method to harvest cabbage: 1 – cutter bar; 2 – conveyor cutter; 3 – flexible flooring; 4 – vehicle; 5 – removable containers.

Cabbage heads are inspected on the bulkhead conveyor cutter. Workers pick out heads with long stumps and insert them into the holes of the conveyor cutter in which they are cut again when reaching a passive knife. As a result the frame leaves are separated from heads and the cut stumps roll down the tray to the ground [1].

Then the flow of cabbage goes to the raddle chain where most of the cabbage leaves are screened out immediately and the heads are sent for unloading.

In this case, unlike the traditional method of harvesting, the heads are unloaded by the cabbage harvester in the non-damaging mode to a flexible soft flooring 3 of a trough-shaped form installed with the help of a special rack on the platform of the vehicle 4 above the removable containers 5. Then, being on the platform, workers carefully put heads from the flooring to the containers. After filling the containers, the vehicle is driven to the storage where, using a forklift, the containers loaded with heads are replaced by empty ones leaving the flexible flooring 3 with a rack on the platform for the next cycle of work.

It should be noted that for harvesting cabbage according to the described method, the cabbage harvester is equipped with a special device [15] for laying heads on a flexible flooring.

The device contains a rigid base 1 (figure 3) mounted under the elevator 2 parallel to the trajectory of its scrapers 3, an elastic tray 4 and a flexible apron 5 which form a wedge-shaped slot.

The device operates as follows. Heads and loose leaves move on the rods in the upper branch of the elevator 2 to the discharge end. At the same time, a part of loose leaves of cabbage falls onto the base 1. At the discharge end of the elevator, the heads come off from the scrapers 3 and fall on the inclined part of the elastic tray 4. In this case the impact is significantly softened. Then the heads roll into a
wedge-shaped slot between the tray 4 and the apron 5. Here, the heads significantly lose their speed, so they are unloaded to the flexible flooring in the non-damaging mode.

Figure 3. Scheme of the loading device to the cabbage harvester:
1 – base; 2 – elevator; 3 – scrapers; 4 – elastic tray; 5 – flexible apron.

It should be noted that this loading device will function effectively when the heads falling onto the elastic tray immediately roll into the wedge-shaped slot. Otherwise, they will be fed by the next scraper 3 to the base 1 disrupting the technological process.

Let us find out in which sections of the elastic tray the cabbage head begins to roll after the fall immediately. To do this, we have to consider the position of the head (figure 3) where the inclination angle of the tangent to the tray relative to the horizon is \( \alpha \).

As can be seen from figure 3, in the equilibrium position, the head is under the influence of gravity \( G \) and reaction \( N \) shifted towards possible rolling from the center of the head by \( k \).

Then from the equality (4) of moments

\[
RG \sin \alpha = kN
\]  

(4)

where \( R \) – head radius.

Or taking into account \( N = G \cos \alpha \)

\[
G \sin \alpha = (k/R)G \cos \alpha
\]  

(5)

From expression (5) we find the equality (6)

\[
tg \alpha = \frac{k}{R} = \mu
\]  

(6)

where \( \mu \) – head rolling friction coefficient.

It follows that the heads will immediately roll into the wedge-shaped slot after falling onto the elastic tray in those sections where the following condition is met (7):

\[
tg \alpha \geq \mu
\]  

(7)

In order to determine the coordinates of those sections we shall write the differential equation of the sagging line of the tray as for an elastic plate (8):

\[
EI \frac{d^2 y}{dx^2} = M(x),
\]  

(8)

where \( EI \) – tray flexural rigidity; \( M(x) \) – bending moment in the tray section with the coordinate \( x \).
The value of the bending moment when the weight $G'$ of the tray is evenly distributed along the length $l$ (9):

$$M(x) = -\frac{G'(l-x)^2}{2l}$$  \hspace{1cm} (9)

Then the expression (8) takes the form of:

$$EI \frac{d^2y}{dx^2} = -\frac{G'(l-x)^2}{2l}$$  \hspace{1cm} (10)

From the expression (10) we obtain:

$$EI \frac{dy}{dx} = -\int \frac{G'(l-x)^2}{2l} \, dx + C$$  \hspace{1cm} (11)

here at $x = 0$, $C = 0$.

Then

$$\frac{dy}{dx} = -\frac{G'}{2EI} \left(lx - x^2 + \frac{x^3}{3l}\right)$$  \hspace{1cm} (12)

The tangent of angle $\alpha$, as is known, is equal to $dy/dx$.

This implies that

$$tg\alpha = -\frac{G'}{2EI} \left(lx - x^2 + \frac{x^3}{3l}\right)$$  \hspace{1cm} (13)

Then the condition (7) takes the final form:

$$tg\alpha = \left| -\frac{G'}{2EI} \left(lx - x^2 + \frac{x^3}{3l}\right) \right| \geq \mu$$  \hspace{1cm} (14)

3. Results and discussion

The dependence of $tg\alpha$ on the coordinate $x$ of the head falling point at various bending rigidity of the elastic tray is shown in figure 4 (the zone where the condition (14) is met is hatched).

Therefore, when the heads fall on the elastic rubberized tray in the sections with coordinates $x$ meeting the condition (14) the loading device will function successfully. Values of the coordinates $x$ meeting the condition (14) will correspond to the design parameter of the loading device $\Delta = 0.100-0.150$ m (figure 3) when the tray is made of an elastic rubberized plate with bending rigidity $EI = 16-20 \text{ MN} \cdot \text{m}^2$.

The objective of further study is to find rational values of the parameters of the flexible flooring mounted on the vehicle body.

To do this, we shall first note the following.

In order to avoid mechanical damage to heads in the course of their unloading to the flexible flooring its sagging line should be such that the heads after unloading immediately roll off the place of falling in order to avoid their collision with each other. At the same time, it would also be desirable for them to gather in the area accessible to service personnel.

The fulfillment of this condition mainly depends on the shape of the flooring sagging line, perhaps when installing its edges at different levels with the difference $h$ as shown in figure 5 [16].

In order to determine the shape of the flooring sagging line we shall consider its equilibrium taking into account the acting forces (figure 5).
Figure 4. Values of $tga$ depending on the coordinates $x$ of the elastic tray at $E I$ equal to 8(1), 12(2), 16(3), 20(4) $H \cdot m^2$.

The forces acting on the flooring are the distributed load $q$ and the reactions $R_A$ and $R_B$. Here $T(z)$ and $M(z)$ are internal force factors.

In this case the equilibrium equations [16]:

for the whole flooring

$$
\begin{align*}
-R_{Ax} + R_{Bz} &= 0, \\
-R_{Ay} - R_{By} + ql &= 0, \\
R_{Az} h - R_{Ay} l + \frac{ql^2}{2} &= 0.
\end{align*}
$$

(15)

for its part

$$
\begin{align*}
-R_{Ax} + T_z(z) &= 0, \\
-R_{Ay} + T_y(y) &= 0, \\
-R_{Az} y + R_{Az} z + \frac{qz^2}{2} + M(z) &= 0
\end{align*}
$$

(16)

For absolutely flexible flooring $M(z) = 0$. Then, solving together expressions (15) and (16) we find the sagging line equation:

$$
y = \left(\frac{ql}{2 T_z(z)} + \frac{h}{l}\right) z - \frac{qz^2}{2 T_z(z)}
$$

(17)

where $T_z(z)$ – horizontal component of the internal force $T(z)$ identical in all sections, $l$ – span length.

It should be noted that heads will be gathered near the lowest point. We find the coordinate of the lowest point of the flooring sagging line equating the derivative $\frac{dy}{dz}$ of the function (17) to zero and solving relative to $z$:

$$
z = a = \frac{l}{2} + \frac{T_z(z) h}{ql}
$$

(18)

Analyzing the expression (18), we verify that the position of the greatest sagging point depends on the tension $T_z(z)$. For example, if $T_z(z) = \frac{ql^2}{2h}$ the greatest sagging point coincides with the support point $B$ (figure 6,a). In this case the heads can fall out of the flooring.
Figure 6. Layout options for the lowest sagging point of the flooring: a – the point of greatest sagging coincides with the support point; b – the point of greatest sagging is between the supports.

If $T_{sl}(z) = \frac{q_0 l^2}{4h}$ the lowest sagging point $C$ is within the flooring span at the distance of $a = \frac{3}{4}l$ from the support $A$ (at the distance of $b = \frac{1}{4}l$ from the support $B$) which is the most preferable condition (figure 6,b) since it will be convenient for workers to reach cabbage heads when reloading them into the containers, in particular if $l = 1$ m, $b = 0.25$ m.

The new technology and the developed technical means for harvesting head cabbage in the non-damaging mode have been tested in the field (figure 7).

Figure 7. Fragment of a study of a new technology for harvesting cabbage in LLC ‘Chapaevskoe’ of the Republic of Mari El (Russian Federation): 1 – harvesting unit with a special shipping device; 2 – vehicle with containers and flexible flooring on racks.

As a result, it is established that quality of the obtained products meets agrotechnical requirements. In particular, the damage rate of the heads has decreased to the level of 5-7% of the total mass of the received products. At the same time with traditional cabbage harvesting technology it averaged about 30%.
4. Conclusion

It has been established that the main cause of damage to cabbage heads during machine harvesting is their fall during unloading from a considerable height exceeding the permissible value ([H]=0.15-0.6 m).

The methods for reducing damage to cabbage heads during machine harvesting are represented which consist of unloading them onto the flexible flooring using an elastic tray and an apron that form a wedge-shaped slot between themselves. The new technology for cabbage machine harvesting in the non-damaging mode is proposed.

The theoretical study has established the laws of the processes of interaction of heads with an elastic tray, an apron and a flexible flooring and revealed the nature of influence of their main parameters on the process quality.

As a result of the theoretical study the following rational parameters of the devices are determined:
- the places where heads fall on the elastic tray and on the flexible flooring;
- the bending rigidity of the tray $EI=16$-$20$ H·m²;
- the difference in height of the flooring edges $h=0.25$ m.

As a result of production tests, the consistency of the proposed new technology for machine harvesting of cabbage and the possibility of reducing the damage to the heads to a level not exceeding 5-7% of the total mass of the resulting products were established.

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