Office studies of the effect of ultrasonic exposure on the process of tuber crop cleansing

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Abstract. The article notes the importance of the final operation for the production of tubers. Attention is focused on the fact that negative impacts on the soil are associated with crushing and removal of the fertile soil layer occur in the process of extracting root crops by digging and separating working bodies of harvesting machines. It is proposed to use ultrasonic action on root crops for cleaning them from soil impurities. The data on the effect of acoustic cavitation, generated by ultrasonic waves with a frequency of 18-18.5 kHz at a power density of at least 1 W/cm², are given on the effect of acoustic cavitation on a root crop in a laminar flow of liquid. It is noted that multiple hydraulic cumulative shocks that occur when cavitation bubbles collapse should separate soil impurities from root crops, which will significantly reduce time and energy costs. The data of studies of ultrasonic action on tubers are given: the maximum completeness of cleaning root crops is 89% and is provided at a frequency of ultrasound oscillations f1 = 47.8 ... 49.8 kHz, vibration intensity S = 41.7 ... 43.4 W/cm² and exposure time t = 20.8 ... 28.1 s.

1. Introduction
Harvesting is the critical operation of root crop production. Its timely and proper performance defines the overall result of all the field works. For this reason, every year during the ripening stage, the need arises to determine the best way of harvesting, depending on the evolving conditions, in order to both prevent losses of harvest and avoid unnecessary expenditures.

Soil condition during the harvesting has the dominant influence on practically every characteristic of a root crop harvester: cleanliness of the heap, losses of and damage to the produce, reliability and energy demands of the harvester, environmental compatibility of its locomotors with the soil, and the steadiness of its heading.

Performance of a harvester is most notably affected by such soil properties as its grain-size distribution and moisture content. Other properties (density, plasticity, stickiness, cohesion, hardness and strength of soil lumps) are, in a sense, derivatives of those mentioned first.

The level of mechanization of crop harvesting operations is far below that of mechanization level of crop cultivation [1]. Root crop harvesting machines produced today follow established patterns that have their inherent drawbacks, and thus are by default unable to carry out the harvesting process on a high quality level. Qualitative characteristics of agricultural machinery operations are affected by a large array of factors: soil and climate environment, types of used implements, running depth, etc.
Due to the prevalence of heavy, in terms of grain-size distribution, soils, excavating type machines (potato pickers, potato harvester, root crop diggers, etc.) are not widespread. Another adverse factor is the considerable cost of labor on post-harvest refinement of products owing to low quality of primary topping, and high content of foreign matter in the heap.

An optimal combination of new and conventional methods of reducing the content of soil impurities in the commercial product of root crops applied during the performance of harvesting operations would ensure the maximum separation of tubers from soil lumps. Besides that, prevention of pickup of hard soil lumps and their subsequent separation would make it possible to use harvesters in harsh soil-and-climate conditions and improve the performance and functional efficiency of the harvester.

2. Materials and methods.

The analysis of technologies and technical means of machine harvesting of root crops revealed main methods and means that enhance the quality of root crop harvesting.

A prerequisite to finding a answer to the existing contradictory situation may be in the development of new mechanized technological solutions and facilities of root crop harvesting that would make it possible to prevent, or drastically reduce, the content of soil impurities in the broken-up heap of soil lumps having the size comparable to that of tubers, at the stage of mechanical harvesting that would prevent the capture of solid soil layers along with tubers [2].

One of the methods of physical action on water to intensify its effect on the object is exposure to ultrasound. Let us discuss the process of ultrasonic action during the root crop cleansing from soil impurities.

In its essence, it is the process of disturbance of liquid uniformity in the weak spots where the symmetry of intermolecular adhesive forces of the liquid is for some reason unbalanced. In the area of positive pressure, such cavity implodes producing a powerful hydrodynamic shock which results in the disintegration of hard bodies. It should be noted that the intensity of the sonic field should exceed the cavitational threshold of 1 W/cm². A number of authors explain the intensity of cavitational disintegration of materials by the presence of fissures and pores at its surface [3, 4].

It has been established that within a fissure with the length of 1 mm and the width of 0.1 mm, at constant atmospheric pressure, local pressures of up to 50 atmospheres may develop. The pressure developing in the liquid, accompanied by the hydraulic shock when cavitational cavities implode, creates a hydraulic wedge which spreads and destroys the surface of the solid body (Figure 1) [5].

Under the action of high local pressures that develop when the cavitational cavities implode, the liquid is pushed into the microfissures and pores, and the air trapped within them undergoes adiabatic compression, and is heated to high temperatures.

![Figure 1](image1.png)

**Figure 1.** Mechanism of a liquid jet formation following cavity implosion. 1 – formation of a gas-vapor bubble; 2 – compaction; 3 – division into 2 planes; 4 – implosion of the bubble.

The strength of soil impurities remaining on a tuber, which is within 27…31.6 Mpa, is much lower than the pressure developing during the bubble implosion which may reach 100 MPa.

Based on theoretical studies, it is hypothesized that repeated cumulative shocks occurring during the implosion of cavities should remove soil impurities from tubers, which would considerably reduce time and energy costs of post-harvest processing.
3. Results
In order to determine the effect of process parameters of ultrasonic exposure on the process of cleansing of root crops of soil impurities, it was necessary to carry out trial experiments to reveal the effect of process parameters of ultrasonic exposure on the cleanliness of a root crop heap.

To determine the effect of ultrasonic exposure on root crops in terms of cleansing them from soil impurities, certain studies were carried out using ultrasonic equipment (Figure 2). The equipment comprised a UZG-2K generator designed for use together with piezoceramic radiator PI - 1.4 - 2.2 (ring type) and a submersion basin made of a radiation-transparent material. These components were arranged into an integrated ultrasonic equipment set.

Figure 2. Laboratory Setup for Studying Ultrasonic Effect on the Process of Cleansing Roots from Soil Impurities: 1 – ultrasound generator UZG-2K; 2 – ultrasound-transparent basin.

The tests to determine the effect of ultrasonic exposure on the process of cleansing were carried out on a model tuber crop represented by a tuber root of «Udacha» variety potato.

The method of study of the effect of ultrasonic exposure on the process of tuber crop (potato) cleansing from soil impurities is as follows.

The studied tuber was weighed at M-ER 122ACFJR-300.01 LCD scales. Following that, a layer of soil of specific weight was applied on the surface of the studied tuber in accordance with the plan of experiment, and the soil layer was concurrently moistened. The studies were carried out using light (in terms of physical and mechanical properties) soils - sandy soils, as well as using heavy soils - loamy soils.

Determination of grain-size composition was carried out in accordance with the process developed by N.A. Kachinskiy [6].

Following the application of a layer of soil onto the studied tuber, it was dried under natural conditions with ambient air temperature T=20-25°C, to the point of drying of the soil crust. This was determined by visual observation. The specimen was subsequently weighted again.

When carrying out studies to determine the optimal parameters of ultrasonic exposure during potato tuber cleansing, studied tubers were covered with heavy loamy soils having the weight m=150 g.

Figure 3. A Potato Tuber on the Support (A - Before Exposure to Ultrasound; B - After Ultrasonic Treatment): 1 – tuber with the layer of soil; 2 – support.
4. Discussion of the results

Following the completion of operations needed to prepare the potato tuber to ultrasonic treatment, the ultrasonic basin was filled with working liquid, the tuber root was lowered into the working volume of the basin, and the device was switched on.

In order to determine the effect of process parameters of ultrasonic exposure on the process of cleansing potato tubers of soil impurities, it was necessary to conduct trial experiments that would reveal the effect of process parameters of ultrasonic exposure on root crop cleanliness.

The results of the ultrasonic study demonstrated that ultrasonic devices operate at frequencies of $f = 22, 30, 35, 44, 130$ kHz, and generate droplets of the size of 65 to 18 um [7-15]. With the increase of ultrasound oscillation frequency the degree of breakdown of the cleaned product decreases.

For each factor, three levels were selected: upper, lower and baseline (zero) level.

When carrying out experiments to determine the optimal regime and process parameters of ultrasonic exposure, a synchronous mode of operation of the generator and the transformer must be ensured.

After the exposure of the potato tuber to ultrasound was stopped, it was weighed and the degree of removal of soil impurities was determined.

Following that, the experiment was repeated in accordance with the plan of studies. The uniformity of oscillation amplitude was ensured by using an arrangement which provided acoustic feedback.

Apart from the above and besides the study of the effect of ultrasonic exposure immediately on the process of cleansing soil impurities from a tuber root regardless of the amount of impurities, a series of single-factor experiments was carried out to reveal the dependence of the degree of tuber root cleanliness on the weight of the impurities (loamy soils), with the value of the studied factor varied (Table 1) and all the other factors remaining unchanged (equal to the optimal values determined during laboratory studies).

| Level of Variation | Oscillation Frequency, $f_1$, kHz | Oscillation Intensity, $S$, W/cm² | Exposure Time, $t$, s. | Degree of Tuber Root Cleanliness, % |
|--------------------|----------------------------------|----------------------------------|------------------------|-------------------------------------|
| Variability Interval, $\Delta x_i$ | 42 | 25 | 10 | Y |

Table 1. Factor Variability Levels of Ultrasonic Treatment of Potato Tubers (weight of soil impurities $m=150$ g, loamy soils).

After the conclusion of the experiment, the obtained results were processed with a computer, and analyzed. The analysis of the results of comparative laboratory studies of the effect of ultrasonic exposure on the process of cleansing Udacha potato variety depending on grain-size composition of the soil allows for the conclusion that the process of potato tuber cleansing from sandy soils is more
intensive, with the range of values being 7.2% with m=50 g to 19.5% with m=250 g and mean increment of the degree of cleanliness of 2.3%.

Since the degree of cleansing of potato tubers from loamy soils involving ultrasonic exposure with unvarying process parameters \( f_1=48.0 \text{ kHz}, \ S=42 \text{ W/cm}^2 \) produces an unsatisfactory degree of cleanliness of up to \( v = 88.3\% \) with the exposure time of 480 s, additional laboratory studies of the effect of the studied factors on the process of potato tuber cleansing (Table 2) were carried out.

After the results of the multiple-factor experiment were processed, STATISTICA – 6.0 software was used, and response function values were obtained - the degree of cleanliness of potato tubers - in accordance with the second-order Box-Behnken design, and the encoded adequate mathematical model was created, which described the dependency of the degree of potato tuber cleanliness, \( v = f (f_1, S, t) \) after the exposure to ultrasound, on the selected parameters:

\[
Y=89.59+0.21x_1-0.38x_2+0.27x_3-0.93x_1^2-0.58x_2^2-0.26x_3^2-0.97x_1x_2-0.2x_1x_3-0.25x_2x_3. \tag{1}
\]

| № | \( Y_1 \) | \( Y_2 \) | \( Y_3 \) | \( Y_u^- \) | \( Y_u^+ \) | \( s_Y^2 \) | \( s_{LF}^2 \) | \( (Y_u^- - Y_u^+)^2 \) |
|---|---|---|---|---|---|---|---|---|
| 1 | 87.5 | 86.9 | 86.0 | 86.8 | 86.94 | 0.597 | 0.325 | 0.0196 |
| 2 | 87.3 | 87.2 | 87.7 | 87.4 | 87.28 | 0.093 | 0.051 | 0.0144 |
| 3 | 89.8 | 89.6 | 89.4 | 89.6 | 89.63 | 0.041 | 0.022 | 0.0009 |
| 4 | 88.3 | 88.8 | 88.4 | 88.5 | 88.46 | 0.072 | 0.039 | 0.0016 |
| 5 | 89.2 | 88.5 | 88.7 | 88.8 | 88.68 | 0.151 | 0.082 | 0.0144 |
| 6 | 87.4 | 87.9 | 87.5 | 87.6 | 88.66 | 1.723 | 0.942 | 1.12 |
| 7 | 88.3 | 89.1 | 88.4 | 88.6 | 88.54 | 0.195 | 0.106 | 0.0036 |
| 8 | 88.2 | 89.1 | 88.5 | 88.6 | 88.66 | 0.215 | 0.117 | 0.0036 |
| 9 | 88.1 | 88.5 | 88.6 | 88.4 | 88.39 | 0.071 | 0.038 | 0.0001 |
| 10 | 87.8 | 89.8 | 88.2 | 88.6 | 88.61 | 1.171 | 0.609 | 0.0001 |
| 11 | 87.8 | 88.8 | 88.6 | 88.4 | 88.35 | 0.283 | 0.154 | 0.0025 |
| 12 | 89.8 | 89.7 | 89.3 | 89.6 | 89.65 | 0.073 | 0.042 | 0.0025 |
| 13 | 89.6 | 89.5 | 89.7 | 89.6 | 89.59 | 0.012 | 0.005 | 0.0001 |
| 14 | 89.4 | 89.8 | 89.6 | 89.6 | 89.59 | 0.041 | 0.022 | 0.0001 |
| 15 | 89.5 | 89.6 | 89.7 | 89.6 | 89.59 | 0.012 | 0.005 | 0.0001 |
| Σ | - | - | - | 1269.7 | - | 4.738 | 2.559 | 1.18 |

The hypothesis of the second order model's validity was verified using statistical analysis of regression equation.

The Fisher's ratio test value \( F_T \) for the 5% significance level for the obtained equation and the degree of freedom of the numerator \( v_1 = N_o-(k_f+1) = 11 \). and of the denominator \( v_2 = N_o(m-1) = 30 \). was selected from the table to be equal to 2.1.

The calculated value of Fisher's ratio test \( F_T = 2.1 > F \) or 1.97. Since \( F_T = 2.1 > F = 1.97 \) the mathematical model is adequate.

By substituting values \( x_1, x_2, x_3 = 0 \) into the equation (1) alternatively, we produce two-dimensional sections of the response surface which describes the characteristic of potato tuber cleanliness after exposure to ultrasound. These are represented by the set of equations (2):
\begin{align*}
    x_1 &= 0: \quad Y = 89.59 - 0.38x_2 + 0.27x_3 - 0.58x_2^2 - 0.26x_3^2 - 0.2x_1 x_1 - 0.25x_2 x_3, \\
    x_2 &= 0: \quad Y = 89.59 + 0.21x_1 + 0.27x_3 - 0.93x_1^2 - 0.26x_3^2 - 0.27x_1 x_3, \\
    x_3 &= 0: \quad Y = 89.59 + 0.21x_1 - 0.38x_2 - 0.93x_1^2 - 0.58x_2^2 - 0.97x_1 x_2.
\end{align*}

By substituting value $x_1 = 0$ into equation (2), we produce a two-dimensional section of the response surface which describes the characteristic of potato tuber cleansing quality level, i.e., the degree of separation of potato tubers from the oscillation intensity ($x_2$) and the working liquid temperature ($x_3$). We thus produced boundary curve (ellipses) equations. Calculation results are shown in Figure 4.

Figure 4. Two-Dimensional Section of Response Surface Characterizing the Dependence of Potato Tuber Cleansing Effectiveness from the Oscillation Intensity (W/cm²) and Exposure Time (s).

Figure 4 shows that potato tuber cleansing effectiveness is 79% with the optimal values of the reviewed factors: oscillation intensity $S = 42.85...43.75$ W/cm² and exposure time $t = 21.3...24.7$ s.

The two-dimensional section of the response surface describing quality characteristic of potato tuber separation, namely, the dependence of potato cleansing effectiveness on ultrasound oscillation frequency ($x_1$) and exposure time ($x_3$) which is described using the equation (2) was produced on the basis of obtained data (Figure 5).

An analysis of Figure 5 reveals that the degree of potato tuber cleansing effectiveness is 89% with the optimal values of the reviewed factors of oscillation frequency and exposure time lying within $f_t = 47.8...48.8$ kHz, $t = 20.8...28.1$ s.
Figure 5. Two-Dimensional Section of Response Surface Characterizing the Dependence of Potato Tuber Cleansing Effectiveness from the Oscillation Frequency (kHz) and Exposure Time (s).

The two-dimensional section of the response surface describing the quality characteristic of potato tuber separation, namely, the dependence of potato cleansing effectiveness on ultrasound oscillation frequency \( (x_1) \) and oscillation intensity \( (x_2) \), which is described using the equation (2), was produced on the basis of obtained data (Figure 6).

Figure 6. Two-Dimensional Section of Response Surface Characterizing the Dependence of Potato Tuber Cleansing Effectiveness from the Oscillation Frequency (kHz) and Oscillation Intensity (W/cm²).

Taking into account the significance of the regression coefficients, equation (1) can be represented as follows:

\[
Y = -1280.93 + 33.58f_1 + 24.87S + 0.16t - 0.23f_1^2 - 0.14S^2 - 0.0013t^2 - 0.24f_1S - 0.0062f_1t - 0.0025St \tag{3}
\]

An analysis of Figure 6 reveals that the degree of potato tuber cleansing effectiveness is 89.5\% with the optimal values of the reviewed factors ultrasound oscillation frequency and oscillation intensity lying within \( f_1 = 48.5...49.8 \) kHz, \( S = 41.7...43.4 \) W/cm².

5. Conclusions
1. An analysis of the two-dimensional sections. calls for the conclusion that the maximum degree of effectiveness of root crop cleansing is 89\%. and is achieved with the frequency of ultrasound oscillation \( f_1 = 47.8...49.8 \) kHz, the intensity of oscillations \( S = 41.7...43.4 \) W/cm², and the exposure time=20.8...28.1 s.
2. The results of laboratory studies of the effect of ultrasonic exposure on the process of cleansing of «Udacha» potato variety allow to conclude that it is beneficial to use ultrasonic treatment for the intensification of the separation process during harvest of tuber roots. Within the process scheme of the harvester, this process should follow the working element used for initial separation. and replace the working element used for secondary separation.

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