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Clean technologies

PRESOWING TREATMENT OF SEEDS USING ULTRASOUND: DEVELOPMENT OF TECHNOLOGY AND INDUSTRIAL EQUIPMENT

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Abstract. The objective of this study is to analyse the possibility of using the dry-air ultrasonic method of presowing treatment of barley seeds in the agricultural industry and to develop semi-industrial equipment for technology implementation. In the case of dry-air ultrasonic treatment, there is no environmental contamination by harmful substances and there is a possibility of using the remains of seed grain as raw materials for producing foodstuffs or feedstuffs, since the nutritional qualities of seeds do not decrease at all as a result of the effect of ultrasound. As a result of calculations by the finite element method, sections with a disk radiator for dry-air ultrasonic treatment of barley seeds were developed that made it possible to assemble waveguide systems by adding sections without changing the resonance frequency of the entire system. It was found that the ultrasonic treatment of barley grains can cause both suppression and stimulation of their vitality. High-intensity ultrasonic treatment can inhibit the growth of plants. The modes of ultrasonic treatment have been determined that are the most favourable for the intensification of barley seed germination. In these modes, plants sprout and develop better. The effect of ultrasound on the dynamics of water absorption by barley seeds in the course of swelling was studied. It was shown that by changing the intensity and duration of ultrasonic treatment, it is possible to control the dynamics of water absorption and to affect the process of barley germination.

Keywords: ultrasound, barley seeds, intensification of barley seed germination, growth of plants, presowing treatment, water absorption by seeds.

AIMS AND BACKGROUND

In 2010 the United States Congress issued a law, in accordance to which barley was included into the list of medicinal products. This is due to the fact that barley seeds contain useful substances necessary for maintaining good health: amino acid-balanced protein (8–12%), starch (62–68%), crude fibre (up to 5.2%), minerals (2.9%), lipids (2.4%), ash substances, mucilage, enzymes, and vitamins.

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Barley sprouts have medicinal properties due to the activity of vitamins (C, B12, K, and provitamin A) and microelements (Zn, Cu, Mn, Fe, and others). Barley sprouts normalise the acid-base balance and increase stamina. Commercially, seed germination is carried out for malt production. Since malt is the main component in brewing, the use of chemical methods for growth enhancement is limited. As it was shown[1], the addition of fertilisers has a long-term effect on the soil and, consequently, the production of cereal. However, organic agriculture becomes increasingly important[2], taking into account the overall policy related to environmental protection. Thus, the study of the possibility of using physical methods for the intensification of this process is of importance.

Numerous experiments show that biological objects react to physical influence even with a comparably low applied power. This is due to the fact that biological objects are very complex systems containing a large number of feedback loops that strive to reduce the effect of external action to zero. However, this does not mean that such action does not stimulate a system, promoting the processes of its development. According to the latest data, it is the low-intensity action that is the most promising both with respect to induced biological effects and with respect to the safety of application. Among such methods, ultrasonic stimulation has a special place. Ultrasound is successfully used for the intensification of a number of processes[3–7].

Yaldagar et al.[8,9] have performed a series of experiments study to the effect of ultrasound on the rate of barley germination, in which ultrasonic vibrations were transmitted through an aqueous medium. Such treatment raises the level of barley yield by up to 20%. Apart of that, an increase in the enzymatic activity of the malt produced from this barley, an increase of extractivity, the Kolbach index and the amount of soluble nitrogen is observed.

The mechanism of the influence of ultrasound on plants is mainly attributed to cavitational effects arising in a liquid medium that causes the destruction of various associates in cells (lipid-lipid, protein-lipid, etc.). In a number of studies, it is pointed out that low-intensity ultrasound can affect the structure of biomembranes, thus leading to an increase in their permeability. In particular, after ultrasonic stimulation, the penetration of water and nutrients into seed is enhanced, which increases the degree of swelling. As a consequence, the rate of physiological processes, first of all, biochemical reactions in a grain, can be increased, which is associated with the activation of a number of enzymes. The effect of ultrasound on seeds (in stimulating doses) does not lead to mutations, as is the case when they are stimulated by ionising radiation.

A positive biological effect of ultrasound is observed in the case of a short-term stimulation with a low intensity, when power does not exceed 2 W/cm^2. An increase in the power (higher than 3 W/cm^2) and duration of treatment leads to negative biological effects associated with irreversible damage at tissue, cellular, and molecular levels.

Ultrasonic treatment of seeds can be performed both through an aqueous medium and by the dry-air method. In the case of the sonication of large volumes of seeds in an aqueous medium, it is difficult to control the modes of treatment and in some cases after treatment seeds should be dried to the normal moisture content. Thus, a dry-air method for presowing treatment of seeds has a number of advantages over other methods and can easily be used for the treatment of large volumes of grain. The objective of this study is to analyse the possibility of using the dry-air method in the agricultural industry and to develop semi-industrial equipment for technology implementation.

EXPERIMENTAL

To perform experiments we assembled the laboratory setup shown in Fig. 1. The main requirement, which we had to take into account during the development of the setup, was the possibility of its scaling by adding a number of waveguide sections to the vibration system. The plant consisted of an ultrasonic generator with a power of up to 1 kW, a magnetostrictive transducer with a resonance frequency of 20 kHz, and a waveguide section with a disk radiator on the surface of which the seeds being treated were located. The waveguide system was placed in a special tubular casing closed by a cover. Between the lateral surface of the radiating disk and the casing, there was a 0.3 mm gap, which, on the one hand, ensured the acoustic decoupling of the waveguide and the casing, and, on the other hand, did not allow the grains to slide off the radiating surface. A contact parametric vibrometer that operates on the principle of recording a change in the reluctance of the gap between the sensor and the radiating surface was developed to determine the vibration amplitude of the disk radiator.

The dimensions of a waveguide system should be calculated in such a way that the frequency of its mechanical resonance is in the frequency range of the electrical resonance of the generator – magnetostrictive transducer system. When the waveguide system is excited at the resonance frequency, the maximum values of vibration amplitudes are achieved on the surface of the disk radiator and the highest efficiency of ultrasonic treatment is ensured.

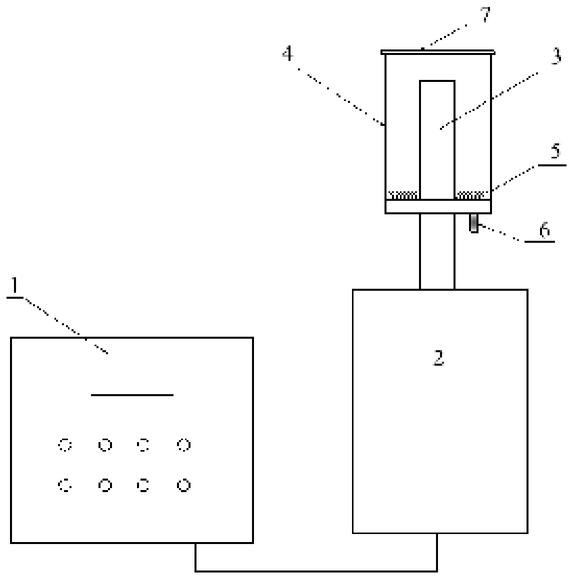

Fig. 1. Experimental setup
1 – ultrasonic generator, 2 – magnetostrictive transducer, 3 – waveguide section, 4 – casing, 5 – seeds being treated, 6 – sensor for amplitude measurement, 7 – cover

We have modelled the dimensions of waveguides using the finite element method in COMSOL Multiphysics. This software package makes it possible to simulate practically all physical processes that are described by partial differential equations. The use of this method allows one to calculate effective designs and to model acoustic phenomena. This method of calculations makes it possible to find the optimum shape and design without making trial parts, to construct graphical representations and animations, and not only to observe, but also to predict the results of experiments. All of this will make it possible to substantially speed up the design of ultrasonic equipment and the choice of the optimum modes of treatment. Figure 2 illustrates the shape of the oscillations of the waveguide, which was obtained using the modelling software. In our case, the length of the waveguide section was taken to be close to half the wavelength in the material at the resonance frequency of the magnetostrictive transducer. In this case, the resonance frequency of the system does not change when adding one or several waveguide sections that have dimensions determined by us. This makes it possible to use waveguide systems consisting of several sections, as is shown in Fig. 3, when conducting treatment on an industrial scale.

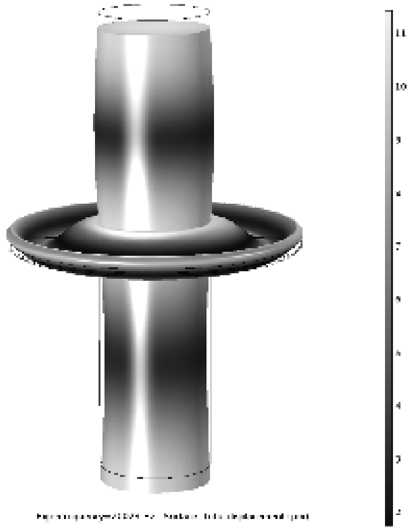

Fig. 2. Oscillation shape of the waveguide section with a disk radiator, obtained using the finite element method

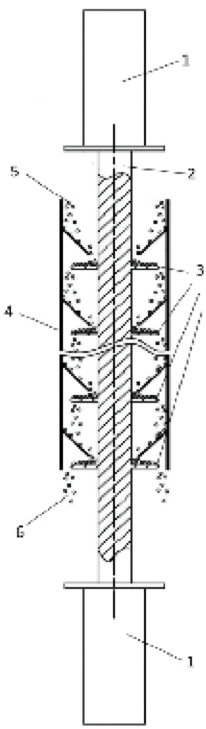

Fig. 3. Schematic diagram of a plant for ultrasonic semidry presowing treatment of seeds
1 – ultrasonic magnetostrictive transducer, 2 – waveguide system, 3 – disk radiator with a variable cross section, 4 – tubular casing with reflectors that ensures the directional movement of grain being treated, 5 – grain introduced for treatment, 6 – grain after treatment

During the experiments we have determined the moisture content of barley grain in the time interval of up to 60 h from the mass difference of a sample of ground grain. The moisture content of grain was calculated in weight % by formula (1), and the degree of grain swelling was calculated by formula (2):

$$W = 100 - (m_0/m)\,(100 - w_0), \tag{1}$$

$$\alpha = (m - m_0)/m_0, \tag{2}$$

where W is the moisture content of grain after steeping (%); w_0 – the initial moisture content of grain (%); m_0 – the weight of grain before steeping (kg); m – the weight of grain after steeping (kg); α – the degree of grain swelling.

The germinability of barley was estimated in percentage from the fraction of seeds that sprouted on the fifth day. Barley germination was performed in funnels in accordance with the standard laboratory version of the commercial process of malting in the following sequence: first steeping for 4 h, an air pause (16–20 h), second steeping for 4 h, and germination in a damp atmosphere for 5 days.

We have used the barley grade 'Ryadovoi' during the experiments. The dry grain of this grade contained 12 to 15% water, which is mainly bound with protein and starch. These grains were living biological objects that were at rest. The weight of 1000 grains was more than 45–50 g, the protein content was not more than 12%, the foreign grain content was not more than 2%, and the fine grain content was not more than 5%. Grain samples with high (90–92%) and low (68–70%) germinabilities – strong and week grain, respectively – were used.

RESULTS AND DISCUSSION

We performed the ultrasonic treatment of barley grains with vibration amplitudes of 2, 4, and 6 μm on the surface of the disk radiator. During experiments, the time of acoustic stimulation varied from 1 to 7 min. The results of the experiments are presented in Fig. 4.

It was found that the ultrasonic treatment of barley grains can cause both stimulation and suppression of their vitality. The treatment of weak grain with an amplitude of 2 μm for 4 min leads to a noticeable increase in the degree of germination.

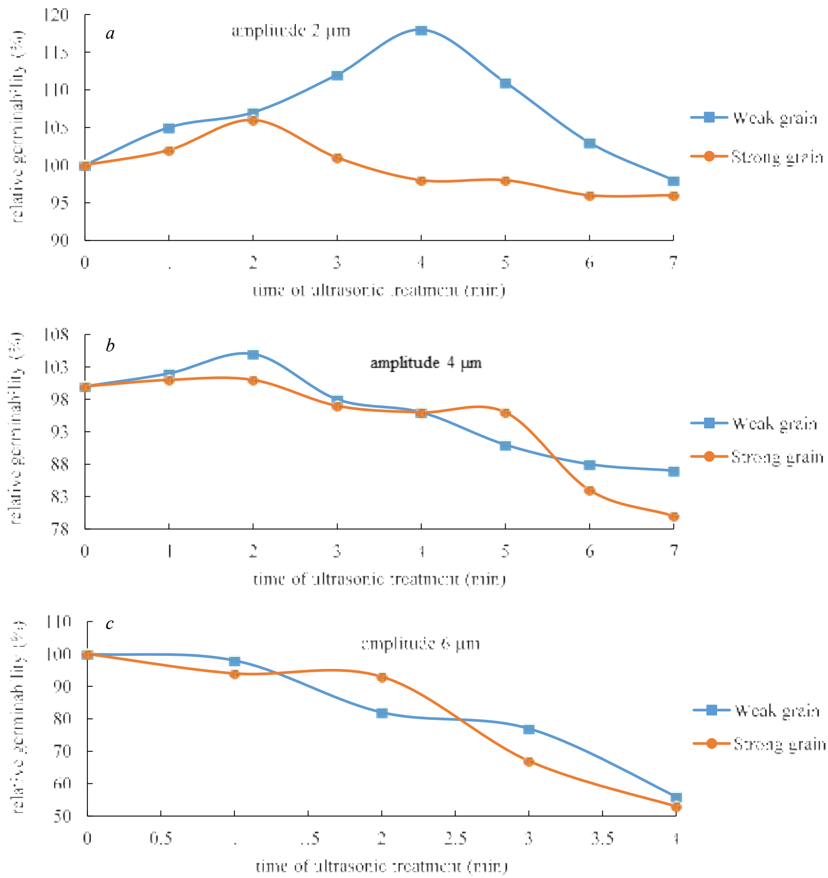

Fig. 4. Germinability of barley as a function of the duration of acoustic treatment (20 kHz) of weak and strong grain with different amplitudes on the surface of the disk radiator: with amplitude of 2 µm (*a*); with amplitude of 4 µm (*b*); with amplitude of 6 µm (*c*)

Thus, both the duration of ultrasonic treatment and its intensity affect seed germination processes. Under the conditions of harmonic vibrations, the total energy of vibrations is proportional to the square of the displacement amplitude. In this connection, the high sensitivity of a grain as a biological system to the amplitude of mechanical vibrations is quite explainable. At vibration amplitudes of more than 4 µm, grain damage can occur even at small treatment times. The damage to seeds reduces their germinability. Damage leads to the functional incoordination of the individual organs of seed due to the breakage of the lines of nutrient transport from the endosperm to the embryo. The defects of protective coats and films facilitate the washout of nutrients and biologically active substances from seed, which impoverishes the nutrition of the embryo in the germination stage. There is also the washout of compounds that have antibiotic and bactericidal properties. As a result, the resistance of seeds and sprouts to parasitic microflora decreases.

To study the mechanisms of the effect of ultrasound on the germinability of barley seeds, we investigated the dynamics of water absorption by seeds before (control experiment) and after low intensive (with the amplitude of 2 μm) and high intensive (with the amplitude of 6 μm) acoustic treatment. The time of acoustic treatment in this experiment was 3 min. We have used swelling curves, which are the function of variation in the weight of the grain being germinated with the time of its contact with water, to analyse the dynamics of water absorption. The character of the curves is affected by structural changes that occur in seeds and have an influence on the transport of water and nutrients to the embryo. Results of this experiment are shown in Fig. 5.

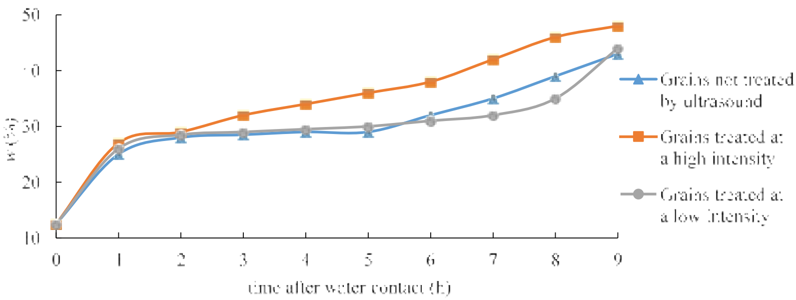

Fig. 5. Water absorption by seeds before and after ultrasonic treatment

For all the cases most intensive water absorption occurred during the initial stage immediately after the immersion of the grain into water, i.e. in the first minutes after the contact of seeds with water. The rapid absorption of water in the first stage is caused by its free penetration into the cavities under the husk and into capillary and intercellular space within the embryo and endosperm.

During the next stage in case of the grains, not treated by ultrasound a minimum increase in the moist mass is observed. That can be called a lag period. As demonstrated by Akopyan and Ershov[10] in 2005 during this second stage, the duration of which is ≈ 2–7 h, the preparation of 'building materials' for the initiation of cell growth takes place and energy is produced for cell growth. According to Danko et al.[11], the lag period can be considered to be the time during which the primary stimulus (the factor that initiates germination – rapid water penetration into a grain) causes a metabolic response – the activation or synthesis of hormones and the subsequent action of these hormones on the genetic apparatus.

The rate of water absorption by grain depends not only on its grade, ripening conditions, and storage, but also on the presence of defects. The loss of seed germinability leads to sharp acceleration of the periods of intensive water absorption and a decrease in the duration of the subsequent lag periods or even to their disappearance. Danilchuk showed that in the swelling of dead seeds, the physicochemical properties of the capillary-porous structure of grains are mainly manifested: wetting, swelling of biopolymers, release of hydration heat, variation of thermal conductivity, etc. In this case, biochemical processes manifest themselves weakly[12]. It was earlier reported by Ovcharov[13] that dead seeds have the ability to absorb water more rapidly and to release various substances into the surrounding medium to a greater extent, which was explained by the disturbance of the structure of seed coats and cell walls. It is known that the rapid penetration of water into grains at the initial stages of steeping is a stress for seeds, at which there can be damage to cell membranes. As can be seen from Fig. 5, weakened or flawed seeds, in our case those seeds, which were affected by high intensity ultrasound, are easier damaged during hydration.

Stress loads on the embryo decrease with an increase in the time of water absorption in the initial stage and the duration of the lag period. This is accomplished, as is shown in Fig. 5, by low-intensity acoustic treatment. Such treatment led, on the one hand, to a certain increase in the duration of the period of intensive water absorption and, on the other hand, to an insignificant increase in the weight of absorbed moisture. A noticeable increase in the duration of the lag period was simultaneously observed. As a result of the observed variations, the amount of absorbed moisture to the beginning of the period of intensive growth of cells was less than that in control samples. However, the further increase in the weight of grains in this third stage was higher than that for grains that were not subjected to acoustic treatment. Thus, a comparative analysis of the swelling of barley with different germinabilities makes it possible to reveal the connection between the dynamics of water absorption and the qualitative characteristics of grain and to develop practical recommendations for germination. Thus, low-intensity acoustic treatment does not lead to an increase in the degree of seed damage and raises seed germinability.

CONCLUSIONS

In the case of dry-air ultrasonic treatment, there is no environmental contamination by harmful substances and there is a possibility of using the remains of seed grain as raw materials for producing foodstuffs or feedstuffs, since the nutritional qualities of seeds do not decrease at all as a result of the effect of ultrasound. The main acoustic element for an industrial setup for presowing treatment of seeds in dry conditions was developed and manufactured. The acoustic element consisted of a disk radiator that made it possible to assemble waveguide systems by adding sections without changing the resonance frequency of the entire system.

The effect of ultrasound on the dynamics of water absorption by barley seeds in the course of swelling was studied. It was shown that by changing the intensity and duration of ultrasonic treatment, it is possible to control the dynamics of water absorption and to affect the process of barley germination.

It was found that the ultrasonic treatment of barley grains can cause both suppression and stimulation of their vitality. High-intensity ultrasonic treatment can inhibit the growth of plants. The modes of ultrasonic treatment have been determined that are the most favourable for the intensification of barley seed germination. In these modes, plants sprout and develop better. The optimum treatment time for barley seeds is 3 min if the amplitude of the oscillations is 2 μm.

REFERENCES

1. N. LUPASCU, M. DUMITRU, N. MARIN, M. TANC: Influence of Organic and Mineral Fertilization on Long-term Production of Wheat Grown on Chernozem. J Environ Prot Ecol, **18** (2), 533 (2017).
2. S. DEACONU, D. DANULETIU, D. ADINA, S. ADELA, C. MOISA: Sustainable Development through Conversion to Organic Agriculture – Implications on the Financial Indicators of Firms. J Environ Prot Ecol, **18** (2), 1514 (2017).
3. V. O. ABRAMOV, F. SOMMER, O. V. ABRAMOV, O. M. GRADOV, O. M. SMIRNOV: Surface Hardening of Metals by Ultrasonically Accelerated Small Metal Balls. Ultrasonics, **36** (10), 1013 (1998).
4. V. O. ABRAMOV, M. S. MULLAKAEV, A. V. ABRAMOVA, I. B. ESIPOV, T. J. MASON: Ultrasonic Technology for Enhanced Oil Recovery from Failing Oil Wells and the Equipment for Its Implementation. Ultrason Sonochem, **20**, 1289 (2013).
5. V. O. ABRAMOV, A. V. ABRAMOVA, P. P. KEREMETIN, M. S. MULLAKAEV, G. B. VEXLER, T. J. MASON: Ultrasonically Improved Galvanochemical Technology for Remediation of Industrial Wastewater. Ultrason Sonochem, **21** (2), 812 (2014).
6. P. P. KEREMETIN, P. S. PARILOV, M. S. MULLAKAEV, G. B. VEKSLER, N. E. KRUCHININA, V. O. ABRAMOV: Determination of the Technological Parameters for the Sonochemical Purification of Oily Water. Theor Found Chem Eng, **45** (4), 568 (2011).
7. F. SOMMER, O. V. ABRAMOV, D. ORLOV, V. O. ABRAMOV: Properties of Al-Pb Base Alloys Applying Electomagnetic Forces and Ultrasonic Vibration during Casing. Mater Lett, **23** (1–3), 17 (1995).
8. M. YALDAGAR, S. A. MORTAZAVI, F. TABATABAIE: Influence of Ultrasonic Stimulation on the Germination of Barley Seed and Its Alpha-Amylase Activity. Afr J Biotechnol, **7** (14), 2465 (2008).
9. M. YALDAGAR, S. A. MORTAZAVI, F. TABATABAIE: The Effect of Ultrasound in Combination with Thermal Treatment on the Germinated Barley's alfa-Amylase Activity. Korean J Chem Eng, **25** (3), 517 (2008).
10. B. V. AKOPYAN, Yu. A. ERSHOV: Fundamentals of the Interaction of Ultrasound with Biological Objects. Bauman Moscow State Technical University, Moscow, 2005.
11. S. F. DANKO, T. N. DANILCHUK, D. N. YURYEV, V. V. EGOROV: Germination of Barley after Sonication with Different Frequencies. Beer and Beverages, **3**, 22 (2000).
12. T. N. DANILCHUK: Dynamics of Water Absorption by Barley in Different Modes of Steeping. Beer and Beverages, **4**, 6 (2009).
13. K. E. OVCHAROV: Physiology of Seed Formation and Germination. Kolos, Moscow, 1976.

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