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Research Article

Calculation of the Height of the Drying and Separation Chamber in a Fluidized (Spouted) Bed

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Abstract

This study is devoted to improving the drying process of paddy rice using microwave (electromagnetic) energy in a spouted bed. The main objective is to determine the optimal height of the drying and separation chamber based on theoretical analysis and experimental validation. The influence of key process parameters, including electromagnetic wave power density, grain moisture content, and temperature evolution, was investigated. Experimental results showed good agreement with theoretical predictions, indicating that the heating time of the grain layer is approximately 2.1 s, with a nearly uniform temperature increase rate. It was established that the grain temperature should not exceed 50°C in order to preserve its germination properties, which limits the heating duration under fixed-bed conditions. Furthermore, an increase in grain moisture content leads to higher heat capacity and enhanced absorption of electromagnetic energy (up to $\eta \approx 0.8$), resulting in accelerated heating. Although the magnetron generates a power density of up to 80 W/m², the effective absorbed power by the grain was found to be approximately 16 W/m². The analysis also revealed that electromagnetic radiation intensity is the dominant factor influencing mass reduction, closely correlated with temperature rise. Based on the obtained results and the application of Duval's approach, a theoretical framework is proposed for determining the rational height of the drying chamber, ensuring sufficient residence time for complete drying while preventing premature particle entrainment. The findings can be used for the design and optimization of efficient microwave-assisted grain drying systems.

Keywords

Microwave Drying, Spouted Bed, Paddy Rice, Grain Moisture, Electromagnetic Heating, Drying Chamber Height, Mass Reduction, Thermal Optimization

1. Introduction

Farmers in the past have traditionally harvested crops according to the type of crop, climatic conditions, availability of labor, and similar factors. For example, vegetable crops and cereals such as rice were harvested after the final autumn frost. Currently, climate change, significant demographic growth, and the demands of a market economy have accelerated the production of agricultural crops. Consequently, in many cases, due to the shortened vegetative period of modern crop varieties and unfavorable weather conditions in some years, crops must be harvested without waiting for ideal conditions or following traditional schedules. Each crop has its own technologies for long-term storage. For instance, rice grains intended for storage must have a moisture content of 13–15%. Newly harvested and threshed rice grains have a moisture content of

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25–30%, so drying is necessary to reduce them to the required moisture level. This drying process is critical to preserving grain quality and protecting it from microbiological contamination [1-3].

Various drying methods, including microwave drying, have been investigated to improve the efficiency of rice drying. Microwave drying offers advantages over conventional convective drying in terms of effective internal moisture removal and reduced energy consumption [5-7]. Moreover, studies have shown that hybrid drying methods can further improve drying efficiency and product quality [7, 8].

In microwave drying, it is important to ensure that grains achieve uniform internal temperature and moisture distribution. This requires recirculation of grains within the drying chamber, allowing high-moisture grains to undergo additional heat exposure, thereby ensuring even drying and minimizing energy consumption.

The aim of this study is to enhance the efficiency of microwave drying of rice grains, improve the uniformity of internal moisture distribution, develop a drying device with an effective recirculation pathway, and optimize the height of the drying chamber both theoretically and practically. Factors such as microwave field distribution, air flow, and residence time of grains in the chamber are considered. The results of this study are expected to contribute to the development of energy-efficient and quality-preserving innovative drying technologies [4-8].

2. Materials and Research Results

There are numerous methods for drying hygroscopic materials and cereal crops in agriculture, which primarily differ in the way heat is supplied and in how moisture is removed along with heat. In the drying of rice grains, the separation of dried grains during the drying process itself using a vertical tube with pressurized drying agent is a novel approach, offering several advantages. For example, it eliminates the need for a separate separation operation, and with minor modifications to the design, it is possible to simultaneously clean the grains and separate them based on weight [9-11].

The structure, operation, and movement of rice grains within this device, capable of drying and simultaneously separating the grains during the drying process, were studied in detail. The device was developed by researchers at Namangan State University of Engineering. In addition to investigating the operational parameters and modes of the device, its theoretical basis was also formulated.

To address the problem, a grid was installed at the bottom base of the simulated boiling chamber to support the material (grains) being dried. A magnetron was placed beneath the grid in the center of the air supply chamber, with the wave propagation front directed upwards. The volume of the chamber housing the magnetron was connected to a vacuum pump outside the chamber to drive atmospheric air under pressure. Two windows were installed at the top of the chamber to separate dried grains from undried material, allowing efficient segregation during the drying process.

The device operates as follows. The lid 2 of the loading hopper 1 is opened, and the bulk material to be dried is loaded into the hopper, after which the lid is closed. Then, the lever gate 3 of the hopper is opened, followed by switching on the microwave-emitting magnetron 4 and the pump 5. Pressurized air supplied by the pump creates high pressure in the air supply chamber 6. The airflow passes through the grid 8 and lifts the material upward in the fluidized bed chamber 7, bringing it into a suspended fluidized state. At the same time, the microwave radiation emitted by the magnetron penetrates the material, reflects from the cylindrical walls of the chamber, and re-enters the material. This process continues until the microwave energy is dissipated.

Rice grains that are not fully dried return through the recirculation pipe to the grid of the drying chamber, where they are again exposed to electromagnetic radiation. This cycle is repeated continuously until the grains are completely dried. The atmospheric air supplied under pressure by the pump passes through the bulk material, carrying away the released heat and moisture, and is discharged into the atmosphere through the outlet pipe 9. The airflow exiting the outlet pipe entrains the dried material and delivers it into the collection container 10, after which the air is released into the atmosphere. The undried material is returned to the fluidized bed chamber through the recirculation pipe 11. The pressure in the fluidized bed chamber is regulated by the damper 12 installed in the outlet pipe (Figure 1).

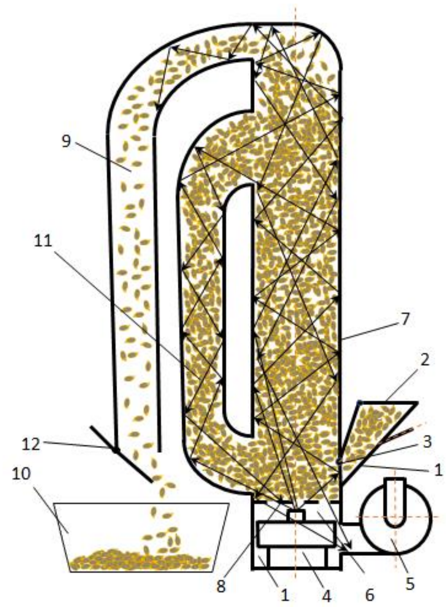

Figure 1. *Schematic diagram of a microwave-assisted fluidized bed drying device for rice grains.*

1 – loading hopper; 2 – hopper lid; 3 – lever gate; 4 – magnetron; 5 – air pump; 6 – air supply chamber; 7 – fluidized bed chamber; 8 – grid; 9 – discharge pipe; 10 – collection container; 11 – recirculation pipe; 12 – control damper.

In the proposed device, the motion of rice grains is mathematically described using Newton's second law.

$$m\frac{d^2x}{dt^2} = F_a - G. \quad (1)$$

Here, m is the mass of the rice grain, kg;

F_a is the driving force, i.e., the pressure force of the drying agent supplied under pressure, N;

G is the gravitational force acting on the rice grain, N.

During the analysis of the drying process, it was determined that the driving force F_a remains constant, while the weight of the rice grain decreases as drying progresses. Taking these changes into account, Newton's second law can be expressed in the following form:

$$m\frac{d^2x}{dt^2} = F_a - G(t). \quad (2)$$

Considering that the weight is equal to the product of mass and gravitational acceleration, it can be written as follows:

$$m\frac{d^2x}{dt^2} = F_a - m(t)\cdot g. \quad (3)$$

Due to the decrease in mass during the drying process, the equation of motion (the general form of Newton's second law) takes the following form:

$$m\frac{d^2m\vartheta}{dt} = F_a - m(t)\cdot g. \quad (4)$$

If the rate of moisture evaporation is low and the released vapor does not generate a reactive force, the equation can be simplified as follows:

$$m(t)\frac{d\vartheta}{dt} = F_a - m(t)\cdot g, \quad (5)$$

Or

$$\frac{d\vartheta}{dt} = \frac{F_a}{m(t)} - g$$

The decrease in the weight of rice grains depends on several factors, including the initial moisture content of the grains, the moisture level required for long-term storage, the temperature, humidity, and velocity of the drying agent, the intensity of electromagnetic waves or the power of the magnetron, and the duration of the drying process.

$$m(t) = f(i, w_b, w_o, \vartheta, T_b, T_o). \quad (6)$$

All of these parameters vary with time, velocity, and distance. Therefore, Newton's second law must be solved with respect to the parameters mentioned above. For this purpose, it is necessary to determine the variation laws of the parameters listed and relate them to the decrease in the weight of rice grains.

A formula for determining weight loss during the cleaning and drying of cereal crops was proposed by the American researcher George Duval.

$$X_M = \frac{100\cdot(w_b - w_o)}{100 - w_o}, \quad (7)$$

Here, X_M is the mass loss;

w_b is the initial moisture content;

w_o is the final moisture content.

$$X_M = \frac{100\cdot(30-15)}{100-15} = 17{,}64\%$$

If we assume that the weight of the rice taken for the experiment is equal to 100 kilograms, Duval's formula gives the mass of impurities and moisture removed during cleaning and drying. Accordingly, the weight of the cleaned and dried rice is 82,36 kilograms. Substituting this result into a differential equation could yield some outcome. However, it does not indicate how much of the mass has been lost or how much weight remains. Therefore, applying the obtained result directly into the differential equation does not provide the desired information. This is because the influence laws of the parameters mentioned above vary, and their effect on moisture content, as well as on the weight of the grain, must be standardized into a uniform law before applying them to the differential equation. Since the movement velocity of the grain and the path it traverses depend on the remaining mass, the weight of the clean rice is considered relative to the initial weight. The remaining parameters of the device should also be expressed according to this law. Considering these observations, it can be concluded that the influence of the process parameters in the device on mass loss should be represented as coefficients ranging from zero to one [12-14].

The analysis of the drying process with heat supplied by electromagnetic waves in a fountain-like boiling layer leads to the following conclusions:

A lower initial temperature of the drying agent reduces the drying time, while a higher temperature increases it. This is because a drying agent (atmospheric air) with a higher temperature contains more moisture, which absorbs less moisture released from the rice grains. In some cases, the amount of moisture released from the grain may exceed the moisture-holding capacity of the air.

One of the main parameters of the drying agent is its velocity. If the agent's velocity is lower than the lifting velocity of the grains, the drying time increases, as the mass transfer between the drying agent and the grains decreases. Conversely, an increase in velocity accelerates this process, thereby reducing the drying time.

An increase in the density of electromagnetic waves raises the temperature of the grains and rapidly converts the moisture inside them into vapor. This leads to an increase in the vapor pressure gradient within the grain, which accelerates mass transfer. As a result, the time required for grain drying significantly decreases.

The expression proposed by George Duval is applied with respect to the parameters listed above.

The suspended flight velocity of grains in a fluidized bed is considered a key parameter. Exceeding the critical velocity in the drying chamber can cause partially dried grains to leave the chamber prematurely. Additionally, in order to complete the drying process, the undried grains must circulate within the chamber for a certain period. The contribution of the drying agent's velocity to the drying of the grain mass is determined using a widely used empirical formula proposed in cereal drying practice.

$$X_m^{\vartheta} = \frac{\vartheta_h - \vartheta_{ch}}{\vartheta_h} = \frac{15-12}{15} = 0{,}2$$

Here,

ϑ_h denotes the velocity of the drying agent, m/s.

ϑ_{ch} denotes the suspended flight velocity of the grains, m/s.

In addition to the factors previously calculated for the rice grains introduced into the drying chamber, another crucial factor for the drying process is the provision of heat to the grains, which is achieved through electromagnetic radiation. Since the direct measurement of the amount of heat absorbed by the rice grains during this process is extremely difficult, an indirect method is employed.

The amount of heat supplied to the rice grains and the temperature difference are described using the classical expressions of thermodynamics.

$$Q = c \cdot m \cdot \Delta T, \quad (8)$$

Here,

c is the specific heat capacity of the rice grains, J/kg°C;

m is the mass of the rice grains, kg;

ΔT is the temperature change, in°C or K.

In order to determine the density of electromagnetic radiation in the drying chamber, the given formula is related to the magnetron's power using the power expression $Q = P_{abs} \cdot t$.

$$P_{abs} \cdot t = c \cdot m \cdot \Delta T, \quad (9)$$

If the expression is used to raise the temperature of the rice grain by one degree, the formula simplifies.

$P_{abs} = c \cdot m.$

Next, to transition to the radiation density, we introduce the following relationship,

$$i = \frac{P}{S} \quad (10)$$

Here,

P is magnetron power, W;

S is area over which the power is distributed,m^2.

If we aim to determine the electromagnetic wave intensity per second, the expression simplifies to the following form:

$$i = \frac{c \cdot m}{s \cdot t \cdot \eta}, \quad (11)$$

Here,

η is the efficiency coefficient of heat absorption, which is not always equal to 100% in microwave ovens, since a portion of the waves is absorbed by the chamber walls.

The calculation for rice grains is complex due to the porosity of the grains and their husks, as well as their low moisture retention. Additionally, it is related to characteristics such as the improved absorption of microwave energy by water molecules. By calculating for one kilogram of grains, we can determine the parameter limits.

The specific heat capacity of rice depends on its moisture content and ranges between 1600–1800 J/kg°C For a device with a rice layer surface area of 0.05 m² and a magnetron power of 800 W, the resulting radiation intensity was 16 W/m^2. As mentioned earlier, due to the lower absorption of microwaves by rice compared to water (η = 0.3–0.5 – the heat absorption efficiency), the heating time can be 2–3 times longer. However, considering the instantaneous effect of electromagnetic waves, the simultaneous removal of heat and moisture, and the fact that drying time is measured in seconds, the obtained result does not have significant practical importance [15, 16].

Taking into account the thickness of the rice layer poured into the reception chamber, the formula for the electromagnetic wave radiation intensity for the device is expressed as follows:

$$i = \frac{c \cdot m \cdot h}{s \cdot t \cdot \eta}, \quad (12)$$

Here,

h represents the thickness of the rice layer in the reception chamber, m.

When working with individual grains or a rice layer of a given thickness, the following two factors must be taken into account:

Dielectric properties of the rice husk: The husk is primarily composed of silicon and cellulose. Therefore, it is "transparent" to electromagnetic waves and has poor thermal conductivity. Heating occurs due to the moisture content and the limited heat transfer through the husk.

Temperature gradient: Because the husk conducts heat poorly, the heat becomes trapped inside the grain. At high electromagnetic wave intensity, the internal vapor pressure can exceed the husk's strength, potentially causing it to rupture (puffing effect).

3. Results

If it is necessary to determine the electromagnetic radiation intensity required to raise the temperature of rice grains by one degree, the resulting expression takes the following form:

$$i = \frac{c \cdot \rho \cdot h \cdot \Delta T}{t \cdot \eta}, \tag{13}$$

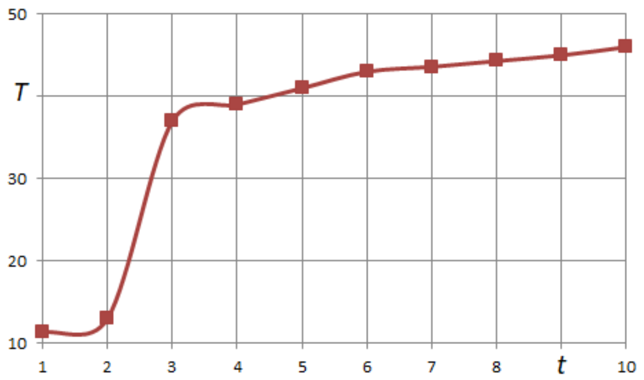

Figure 2. *Temporal variation of the rice layer temperature at the magnetron's maximum power.*

The experimental results confirmed the theoretical calculations. Heating the rice layer requires 2,1 seconds, and the changes in rice temperature per second at the given wave intensity showed negligible differences. Additionally, considering that the rice temperature should not exceed 50 °C to prevent sprouting, it was determined that the rice layer in a stationary state cannot be heated for more than 10 seconds. Furthermore, if the rice moisture content is high, its specific heat capacity increases, and it absorbs more electromagnetic waves (η rises up to 0.8), causing the rice layer to heat up more quickly (Figure 2).

At full power of the magnetron, the electromagnetic wave intensity generated in the receiving chamber was 80 W/m^2. Due to the intrinsic properties of the rice grains, the intensity they could effectively absorb was 16 W/m^2.

Since the heat transfer method is based on electromagnetic radiation, the temperature increase in the rice layer depends on the radiation intensity. Considering these characteristics, among the factors affecting the mass reduction of the grains, we retain the effect of either the electromagnetic radiation intensity or the temperature increase in the layer. When analyzed separately, their effects yield nearly identical results. To determine the contribution of factors affecting the mass reduction of rice grains, we utilize the expression proposed by George Duval.

$$m(t) = m \cdot \left(\frac{100 \cdot (w_b - w_o)}{100 - w_o} + \frac{i_{max} - i_d}{i_{max}} + \frac{\vartheta_h - \vartheta_{ch}}{\vartheta_h}\right) \tag{14}$$

The calculations showed that the remaining mass of the rice grains after drying corresponded to 97.2% of the mass of the wet rice grains.

From the processes described above, the following conclusion can be drawn: in bringing rice grains to the storage moisture content, electromagnetic radiation and the velocity of the drying agent were found to be the decisive factors, while the effect of moisture content is so small that it can be neglected.

When determining the height of the drying channel, the majority of studies have established that the velocity of the drying agent under pressure in the channel and the flight velocity of the rice grains significantly affect the separation process. Accordingly, to determine the grain velocity, we integrate the differential equation of grain motion. During integration, we adopt the following condition: the driving force F_a is assumed to be constant or unchanging, and the integration is carried out over the time interval from 0 to t.

$$\int_{\vartheta_0}^{\vartheta} d\vartheta = \int_0^t \left(\frac{F_a}{m(t)} - g\right) dt, \tag{15}$$

and we obtain the expression for the current velocity.

$$\vartheta(t) = \vartheta_0 - gt + F_a \int_0^t \frac{1}{m(t)} dt, \tag{16}$$

If we assume the change in mass is linear, that is, $m(t) = m_0 - kt$, the integral takes a logarithmic form. However, if the channel height is small, the mass changes by a very small amount; therefore, it is possible to use the average value of the mass.

The height of the channel represents the distance that the rice grains must traverse during the drying period t_f. Considering the velocity formula $\vartheta = \frac{dh}{dt}$ and integrating once again, we obtain an expression for determining the height of the channel.

$$H = \int_0^t \vartheta(t)\, dt, \tag{17}$$

If the expression for ϑ(t) is substituted, the result of the integration takes the following form:

$$H = \int_0^{t_f} \left(\vartheta_0 - gt + F_a \int_0^t \frac{1}{m(\tau)} d\tau\right) dt. \tag{18}$$

After performing the elementary integrations, the expression for determining the height of the channel takes the following form:

$$H = \vartheta_0 t_f - \frac{g t_f}{2} + F_a \int_0^{t_f} \int_0^t \frac{1}{m(\tau)} d\tau dt. \tag{19}$$

To calculate the minimum height of the channel, it is necessary to specify the laws governing the changes in the mass and the parameters of the medium.

Due to the high sphericity coefficient of rice grains and their low suspended flight velocity, they are considered “light” compared to other grain products. Therefore, given that the suspended flight velocity of rice grains ranges from 5 to 6.5 m/s, to separate the wet rice from the dried grains, the drying agent velocity in the drying chamber is assumed to be 3 m/s, and the mass loss rate of the grains is taken as 5% per second.

To simplify calculations related to the aerodynamic force F_as as a function of relative velocity, the suspended flight velocity is typically taken as the relative velocity for this purpose.

$$F_a = m_0 \cdot g \cdot \frac{\vartheta_h^2}{\vartheta_{ch}^2}, \quad (20)$$

In this case, when the mass changes linearly as $(t) = m_0(1 - \alpha t)$, the equation for the channel height takes the following form.

$$H(t) = \int_0^t \left(\left(\int_0^\tau \frac{g \cdot \vartheta_h^2}{\vartheta_{ch}^2 \cdot (1-\alpha\tau)} - g \right) d\tau \right) dt, \quad (21)$$

After integrating this equation, an expression for determining the channel height is obtained.

$$H(t) = \frac{g \cdot \vartheta_h^2}{\vartheta_{ch}^2 \alpha^2}[(1 - \alpha t)ln(1 - \alpha t) + \alpha t] - \frac{gt^2}{2}. \quad (22)$$

Based on the calculations according to Equation (22), the distance traveled by the rice grains in the channel during the given time was 0.81 meters in 0.8 seconds, and the flight distance of the grains per second reached 1.32 meters (Figure 3).

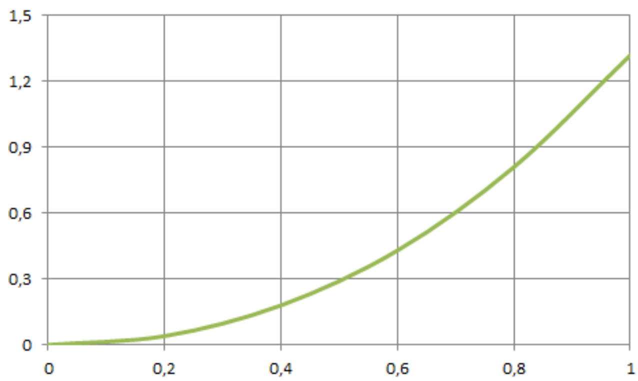

Figure 3. *Maximum distance traveled by a single rice grain at the initial moment.*

The residence time of the rice grain in the channel is determined to ensure that it does not exit the channel before drying is complete.

$$H(t) = \frac{k \cdot g \cdot}{\alpha^2}[(1 - \alpha t)ln(1 - \alpha t) + \alpha t] - \frac{gt_f^2}{2}, \quad (23)$$

Here,

$$k = \vartheta_h^2 / \vartheta_{ch}^2$$

According to the calculated formula, the time was found to be three seconds. This means that the residence time of the rice grain in the drying channel should not exceed three seconds. Therefore, by determining the distance the rice grain travels in the drying channel within these three seconds, it becomes possible to establish the constructive dimensions of the drying channel's height.

To determine the required height of the drying channel so that the rice grain does not exit before being dried, the logarithm in the previous formula can be simplified using a Taylor series expansion under the condition αt<3, resulting in a simplified working formula.

$$H_{min} = \frac{g}{2} t_f^2 \left(\left(\frac{\vartheta_b^2}{\vartheta_{kp}^2} \right) \cdot \left(1 + \frac{2}{3} \alpha t_f \right) - 1 \right). \quad (24)$$

Based on the obtained expression, calculations were performed, and the minimum required height of the channel for each fraction of a second was determined. On this basis, the constructive dimensions of the device's height were established (Figure 4).

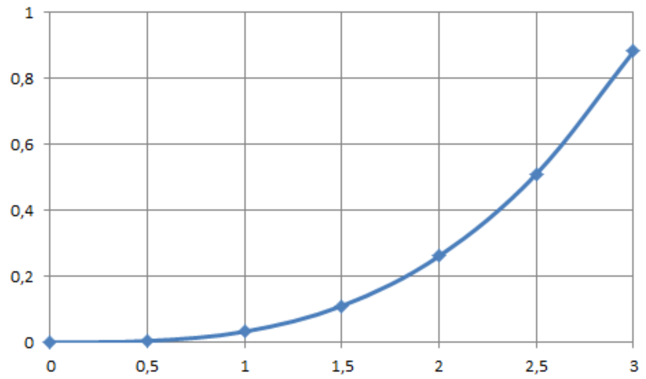

Figure 4. *Relationship between the required drying time of rice grains and the channel height.*

4. Conclusions

The study analyzed the minimum height of a drying channel for paddy grains $= 9{,}81\ m/s^2$. The relationship $H_{min} = 0{,}0327 \cdot t_f^3$ demonstrates a cubic increase of the channel height over drying time. For a drying time of $t_f = 3$ seconds, the required channel height to prevent grains from leaving the drying zone is 0.8829 m, while the return path for moist grains requires a height of 0.2616 m. The channel height was found to be critical for ensuring balanced grain motion and efficient drying. Grain movement, velocity, and moisture content are interdependent, and optimal height selection enhances both drying and separation performance. In microwave-assisted drying, temperature and moisture variations are influenced by channel height, directly affecting drying rate and duration. These results provide a scientific basis for optimizing drying equipment and designing effective systems for paddy grain drying, ensuring process efficiency while preserving grain quality.

Abbreviations

w_b The Initial Moisture Content

w_o The Final Moisture Content

ϑ_h The Velocity of the Drying Agent, m/s
ϑ_{ch} The Suspended Flight Velocity of the Grains, m/s

Author Contributions

Abdulkhayev Khurshed: Project administration, Methodology, Supervision, Writing – review & editing
Otakhanov Bakhrom: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft
Sodikov Makhammadjon: Investigation, Resources, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Abdulkhayev Khurshed is a Doctor of Technical Sciences and a professor at the Department of Technological Machines and Equipmets, Namangan State Technical University. Since 2023, he has been serving as a professor in this department. He was born on August 9, 1978, in Kosonsoy district, Namangan region. He holds a higher education degree, having graduated from Namangan Engineering-Pedagogical Institute (full-time) in 2000. He holds the academic degree of Doctor of Technical Sciences and the academic title of Professor.

Otakhanov Bakhrom is an Associate Professor at the Department of Technological Machines and Equipment, Faculty of Mechanics, Namangan State Technical University. He has authored 2 books, holds 5 patents, and has published approximately 40 articles in international and national journals. He has 43 years of professional experience in academic and pedagogical fields. His research focuses on the operation of rotary tillage machines for surface soil cultivation.

Sodikov Makhammadjon is currently a PhD student at Namangan State Technical University. He conducts scientific research in the specialization of Agricultural and Melioration Machinery, as well as the mechanization of agricultural and land reclamation processes. To date, he has published more than 8 scientific articles in international and national journals related to his research area, and based on his research work, he has obtained 2 software copyright certificates and 1 invention patent.

Research Field

Abdulkhayev Khurshed: Technological machines and equipment, manufacturing technology, machine science, machine parts, theory of machine mechanisms, creation of new-generation mechanisms, agricultural and melioration machinery, mechanization of agricultural and land reclamation processes.

Otakhanov Bakhrom: Technological machines and equipment, manufacturing technology, machine science, machine parts, theory of machine mechanisms, creation of new-generation mechanisms, agricultural and melioration machinery, mechanization of agricultural and land reclamation processes.

Sodikov Makhammadjon: Technological machines and equipment, manufacturing technology, machine science, machine parts, theory of machine mechanisms, development of new-generation mechanisms, agricultural and melioration machinery, mechanization of agricul-tural and land reclamation processes.