PHYSICOCHEMICAL MEASUREMENTS

Effect of wheat bulk density on the accuracy of moisture measurement via the microwave method

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Abstract
The article examines the effect of wheat bulk density (grain material density) on the accuracy of microwave moisture measurement. The method of microwave moisture measurement is based on amplitude dielectric metrology that analyzes the attenuation of an electromagnetic wave passing through grain material. A single-parameter moisture meter designed for use in grain processing was developed to operate at microwave frequencies. A block diagram of the moisture meter is provided, and its operating principles are described. The design of the instrument implements a mathematical model that takes into account the electrophysical properties of grain material and the features of its interaction with microwave radiation at a fixed frequency. A prototype of the instrument was manufactured and tested under actual production conditions. Grain material of various densities was analyzed: 87, 116, and 145 kg/m^3. It was experimentally found that with decreasing grain density, the relative moisture measurement error increases, especially at moisture levels of above 14%: at 18% moisture content and grain densities of 145 and 87 kg/m^3, the relative measurement error amounted to 9.8% and 44.7%, respectively. The calculated partial derivatives of the measurement signal amplitude with respect to density are significantly higher at high moisture levels, which indicates that moisture meter readings are highly dependent on material density under these conditions: at high moisture levels, even a small change in density can significantly increase the measurement error. Graphs are presented showing the dependence between the signal amplitude and moisture at different densities, as well as the results of regression analysis confirming the need to take density into account during instrument calibration. The absolute and relative moisture measurement errors were estimated depending on grain material density. The study confirmed the effectiveness of the microwave method for rapid moisture assessment and the developed moisture meter, provided that the effect of density is corrected.

Keywords Grain · Moisture · Monitoring · Dielectric method · Microwave method · Single-parameter moisture meter

Introduction

Moisture measurement constitutes an essential part of the storage, transportation, and processing of agricultural products, in particular, grain material. The agro-industry uses various moisture measurement methods: from

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conventional gravimetric to modern dielectric methods, including the microwave method [1] based on the interaction between the electromagnetic field and material. The idea is that moisture has high permittivity, which causes microwave signal attenuation. Thus, the amplitude of the signal passing through the sample can be used to determine its moisture content [2].

The transition from the long wavelength region (medium, short, and intermediate radio waves) to the centimeter range (microwave range) holds promise for moisture measurement since the interaction between electromagnetic radiation and water is more active in the centimeter range: at a higher moisture level, signal attenuation is more pronounced. The use of microwave radiation in moisture meters improved several of their characteristics: increased the sensitivity of the device to changes in moisture and measurement accuracy; reduced measurement time (enabling rapid analysis); reduced the effect of material composition and temperature on measurement results; and increased resistance to external electromagnetic interference.

The microwave method relies on the laws of electrodynamics described by Maxwell's equations, which establish the relationship between electric and magnetic fields in a medium. As microwave waves pass through moist material, the amplitude, phase, and energy of the electromagnetic field change depending on the radiation wavelength and the dielectric properties of the material. A shorter wavelength (to the millimeter range) enables more accurate detection of changes caused by the presence of moisture.

Unlike low-frequency capacitance methods, the microwave method offers several advantages: high sensitivity; non-contact operation; the ability to perform rapid analysis without destroying the sample; weak dependence on the chemical composition of the material. However, measurement accuracy can significantly decrease with changes in the physical parameters of the material, especially density and temperature.

One of the key factors affecting the accuracy of grain moisture measurement via the microwave method is the density of a grain sample (grain bulk density). Under real conditions, the density of grain material may vary depending on the variety, compaction degree, and loading conditions. These variations affect the dielectric properties of the medium and, as a result, the results of measurement. Previous studies [3] show that without taking density into account, the measurements of grain moisture may contain systematic errors, especially within a high moisture range. However, in most practical applications of microwave moisture meters, this factor is not taken into account, which limits the accuracy and repeatability of the results.

Therefore, it is relevant to study the effect of grain density on the accuracy of moisture measurement via the microwave method, as this will improve monitoring validity and ensure the metrological reliability of moisture meters under development.

The study aims to determine the extent to which the bulk density of wheat grain affects the accuracy of moisture measurement with the use of a single-parameter moisture meter implementing the microwave dielectric method and to justify the need to factor in grain material density in the calibration of microwave moisture meters.

To this end, it was necessary to measure the moisture content of grain material at three density values (87, 116, and 145 kg/m^3); to assess the accuracy of measurements based on the calculation of absolute and relative errors, as well as standard deviations; to examine the relationship between the true and measured moisture values and determine the degree of correlation between them; to plot the dependences of the signal amplitude on moisture and density, perform regression analysis of the obtained data, and identify trends; to assess the sensitivity of the device to changes in the density of grain material.

Microwave method of grain moisture measurement

The limited capabilities of the high-frequency method for measuring the moisture content of grain and grain products using capacitance moisture meters led to the need to develop moisture meters operating at microwave frequencies of no more than $3 \cdot 10^{10}$ Hz. In spite of the difference in frequency spectra (since high-frequency moisture meters operate at no more than $5 \cdot 10^{7}$ Hz), measurements performed via both methods yield approx-

imately the same values for the dielectric parameters of dehydrated materials. However, the unique property of water to maximally attenuate microwave signals prompted the development of the microwave method for measuring the moisture content of agro-industrial materials.

In addition to the specified microwave method, which uses signal attenuation, an optical method is available. In this method (known as the reflection method), moisture is determined from the reflection coefficient of electromagnetic waves. At a low moisture content in the material, the attenuation-based method has an advantage over the reflection method. Similar conclusions were made by other researchers [3]: the reflection method has not found wide application in the practice of microwave moisture measurement since the accuracy of moisture determination is relatively low, especially within a low-moisture range.

As described above, when microwave radiation interacts with moist material, a significant signal attenuation is observed, which can be attributed to the dipole polarization of molecules: water molecules placed in alternating electromagnetic fields begin to rotate, aligning themselves with the lines of force (dipole polarization), which leads to the attenuation (absorption) of electromagnetic pulses [4]. For example, a 1 cm thick layer of water attenuates radio signals (microwave range) by a factor of 10,000[1], while layers of sand, clay, and limestone measuring several hundred meters in thickness are practically radio-transparent. Attenuation is inversely proportional to the transmitted energy and depends on the moisture content, density, and temperature of the material.

Although moisture has the greatest effect on attenuation, at high moisture levels (over 14% for wheat grain), the sensitivity of readings to density increases significantly, which should be taken into account. The method is implemented at a fixed microwave signal frequency and enables rapid analysis without destroying the sample [5].

The results of studies [6–8] by the present authors laid the foundation for the development of microwave moisture meters, which can be used to measure the moisture content of various agro-industrial products and which meet the requirements for reliability and measurement accuracy acceptable for grain processing enterprises.

In order to measure the moisture content of grain samples, this study used a single-parameter moisture meter developed by the present authors to implement the amplitude dielectric method in the microwave range. The instrument registers the attenuation of an electromagnetic wave passing through the analyzed sample. Signal attenuation (decrease in amplitude A) depends on the moisture content W and density ρ of the material, as well as on its permittivity and microwave radiation frequency.

In order to reduce the effect of other factors, such as changes in ambient temperature and particle (grain) shape, the device is calibrated using samples with known moisture content and density. The method is implemented as a single-parameter algorithm, with the density of the grain material considered to be a variable correction in the interpretation of measurement results.

Design and operating principle of the microwave moisture meter

The developed moisture meter is a single-parameter measurement system. The measurement process is controlled by an integrated comparator circuit and a logic gate. The measurement results are displayed digitally. A distinctive feature of the instrument consists in its structural arrangement that minimizes the effect of external interference and ensures rapid recalibration with due consideration for the density of the analyzed material. The operating principle of the moisture meter is based on comparing the level of a microwave signal before and after it passes through the grain material. The instrument records the amplitude of the propagating wave and interprets it into a moisture value, taking density into account. The moisture meter can be used both under laboratory and industrial conditions. The development is protected by a utility model patent, which specifies

[1] Physics of Moisture Measurement. https://www.microradartest.com/svch.htm (accessed: 03/07/2025).

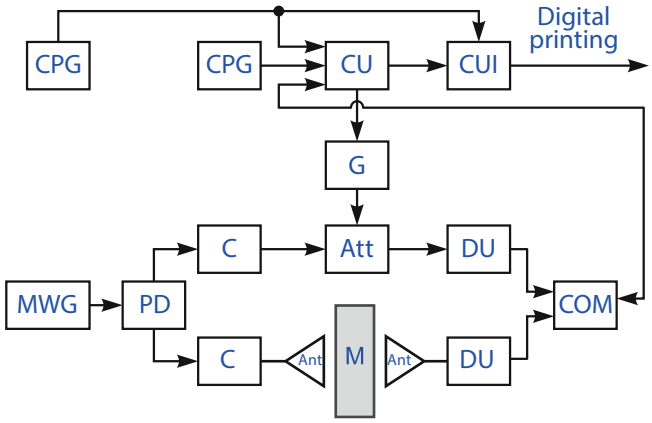


Fig. 1 Block diagram of the microwave moisture meter: *MWG*—microwave generator; *PD*—power divider; *Att*—attenuator; *DU*—detection units; *Ant*—antennas; *M*—material; *COM*—comparator; *CU*—control unit; *CPG*—counting pulse generator; *CPG*—clock pulse generator; *G*—generator; *CUI*—computing unit using indexing; *C*—circulators

both the technical characteristics of the instrument and the implementation features of the measurement method [9].

At the stage of developing the single-parameter microwave moisture meter, we analyzed several moisture meter diagrams that differed in the configuration of sensing elements and the microwave section. As a result, the diagram with the lowest sensitivity to external interference and a high signal stability was selected.

A block diagram of the moisture meter is presented in Fig. 1. Microwave radiation was produced by a generator *MWG*—a prismatic waveguide resonator containing a gallium arsenide Gunn diode. The microwave components were decoupled using ferrite circulators *C*, which allow electromagnetic waves to pass in the forward and reverse directions at a ratio of 1:20. Here, a power divider *PD* based on waveguide tees with short-circuiting pistons was used as the microwave energy splitter. By changing the position of the pistons, the signal power can be redistributed in the reference and measurement microwave channels. The reference channel includes an attenuator *Att*, a directional coupler, and a phase shifter (the latter two are not shown in Fig. 1), which ensure the formation and adjustment of the reference signal. The measurement channel includes a measurement cell with the analyzed sample of material *M*, as well as matching devices and a detector that records the propagating signal (not shown in Fig. 1).

Microwave energy was controlled using a balancing attenuator with 2A510A *p–n–p* diodes, which consisted of a waveguide section. In both channels, the conversion of microwave energy into a direct current signal took place in detection units *DU* equipped with D405A mixer diodes. The balancing attenuator was controlled using a current generator, which constitutes a synchronizable op-amp integrator and a voltage-to-current converter.

The moisture measurement result was displayed as a percentage using a three-digit binary-coded decimal counter, whose outputs were connected to a digital display via decoders. The signals of the reference and measurement channels of the microwave section were compared using an MK4804 comparator (Mikropribor, Ukraine). The measurement results were processed according to a specified algorithm in the computing unit controlled by an integrated circuit device.

The moisture measurement range of 6–30% is limited by the linearity of the attenuator characteristic. At a temperature of (20±2)°C, the measurement error is $\delta W = 5\%$, increasing by $0.0038W$ for every 1°C change in grain temperature.

The prototype of a microwave moisture measurement instrument was tested under industrial conditions at a grain processing plant (GallaAlteg, Republic of Uzbekistan).

Results and discussion

The experiment used wheat grain samples of three different densities ρ: 87, 116, and 145 kg/m^3. The natural moisture content of grain *W* varied between 7.13 and 18.00%. A total of 30 grain samples with different, evenly

distributed density and moisture values were prepared and tested. In order to determine the moisture content W_{avg} of grain samples having a specific density, the attenuation of the moisture meter signal passing through them was measured. The value of W_{avg} was determined from the calibration function obtained experimentally by comparing the conventional true moisture values (measured via a gravimetric method) and the corresponding values of signal attenuation A at fixed densities. The reading W_{avg} constituted the average moisture value in a series of measurements with an estimate of the standard deviation.

The moisture meter measured the attenuation of the propagating microwave signal and converted it into a moisture value using a regression model (quadratic polynomial). The empirical dependence of attenuation on the moisture content of a grain sample takes the following form:

$$A = 0.0844W_{avg}^2 - bW_{avg} + c.$$

The coefficients b and c were found from the results of regression analysis for the selected density range. At $b = -1.2103$ and $c = 11.1842$, attenuation is described as follows:

$$A = 0.0844W_{avg}^2 - 1.2103bW_{avg} + 11.1842.$$

Figure 2 presents the experimental dependences of attenuation A on grain sample moisture content W= 7.13–18.00% at densities ρ of 87; 116; 165 kg/m^3.

In order to assess the accuracy of moisture determination, absolute ΔW and relative δW errors were estimated, as well as standard deviations of measurement results in a series. In addition, the repeatability of attenuation measurements (standard deviation) was estimated. A regression analysis of the dependence $A(\rho)$ was performed to estimate the numerical derivatives $\partial A/\partial\rho$ reflecting the sensitivity of the instrument to changes in material density. Taking the calibration function $W = f^{-1}(A, \rho)$ into account, the effect of density on the final error in moisture determination was evaluated. Table 1 provides the calculated errors in determining moisture content W_{avg} (moisture meter reading as the final recorded result) from the measured attenuation of the microwave signal (primary measured parameter), as well as the standard deviation of the measurement result σW_{avg} (with and without the correlation coefficient R for samples with different densities being taken into account) at a confidence level of 0.95.

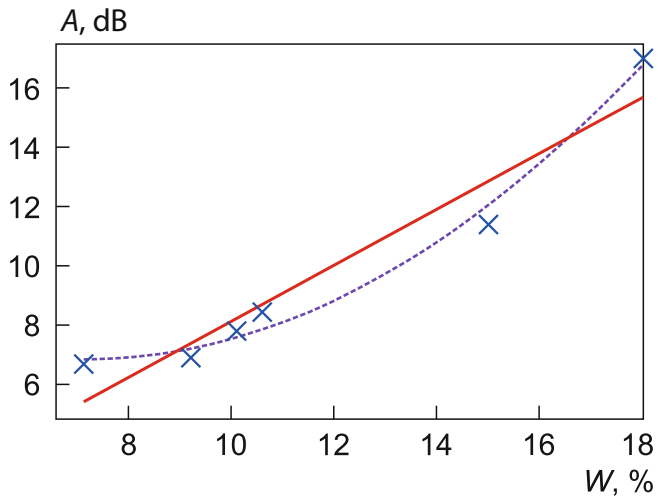


Fig. 2 Dependence of microwave wave attenuation A on material moisture content W

Table 1 Results of moisture measurement in wheat samples with different densities

ρ, kg/m^3	W, %	(W_{avg}±ΔW_{avg}), %	σW_{avg}, %, factoring in R	σW_{avg}, %, not factoring in R	δW_{avg}, %
145	7.13	7.5±0.54	0.24	0.24	7.20
145	9.20	8.8±0.56	0.26	0.24	6.40
145	10.1	9.7±0.49	0.24	0.20	4.90
145	10.6	10.8±0.49	0.25	0.26	5.30
145	15.5	15.3±0.61	0.36	0.29	3.90
145	18.0	18.1±1.79	0.82	1.33	9.80
116	7.13	7.5±0.56	0.25	0.25	7.47
116	9.20	8.3±0.70	0.31	0.31	8.43
116	10.1	8.8±0.76	0.33	0.33	8.64
116	10.6	9.8±0.64	0.30	0.30	6.50
116	15.5	8.3±0.95	0.42	0.42	11.45
116	18.0	1.7±0.76	0.88	0.88	44.71
87	7.00	6.7±0.55	0.24	0.24	8.21
87	9.10	6.9±0.54	0.26	0.26	7.83
87	10.1	7.8±0.66	0.24	0.24	8.46
87	10.6	8.4±0.27	0.12	0.12	3.21
87	14.5	11.4±0.80	0.36	0.36	7.02
87	18.0	17.0±0.85	0.82	0.82	5.00

The coefficient of correlation between the moisture measurement results obtained using the microwave moisture meter and the standard values as per GOST 13586.5-2015[2] was calculated using Pearson's formula:

$$R = \frac{\sum_{i=1}^{n} \left(W_i - \overline{W}\right)\left(W_{\text{avg}i} - \overline{W}_{\text{avg}}\right)}{\left[\sum_{i=1}^{n} \left(W_i - \overline{W}\right)^2 \sum_{i=1}^{n} \left(\overline{W}_{\text{avg}i} - \overline{W}_{\text{avg}}\right)^2\right]^{1/2}},$$

where $\overline{W}$, $\overline{W}_{\text{avg}}$ — sample mean values; n—number of experiments.

The value of $R = 0.987$ calculated for the entire measurement range indicates a high linear dependence between the results obtained using the microwave moisture meter and reference data. This confirms the adequacy of the selected measurement method and the developed design.

Without R being taken into account, the standard deviation σW_{avg} characterizes only the scatter of experimental data around the mean value. In this case, the degree of consistency with the reference results is not taken into account. Conversely, with the correlation coefficient R taken into account, the standard deviation reflects not only the scatter but also the consistency of the obtained data with the model (standard measurements), which enables a more objective performance evaluation of the moisture meter.

The error in measuring electromagnetic wave attenuation, as well as the error in determining moisture content, decreases with increasing bulk density ρ; therefore, attempts were made to increase the density to 165 kg/m^3. However, in order to obtain a sample with a density of over 145 kg/m^3, special compaction mechanisms should be used, which significantly complicates the design of the instrument, as well as increasing its specific metal consumption and the analysis time. Also, two samples having different masses and the same bulk density were analyzed to test the effect of mass on the measurement result. At a fixed value of ρ, no significant effect of mass

[2] GOST 13586.5-2015. Grain. Method of Moisture Content Determination.

was observed, so only density was further analyzed as the main factor within the considered moisture range of 7–18%.

With increasing sample density, the scatter of measurement results caused by uneven grain distribution decreases. A higher loading density ensures greater uniformity in the dielectric properties of the medium and, as a result, increases the accuracy in determining the moisture content of the wheat sample.

According to [10–12], grain density is understood to be the bulk (volume) density of a batch (sample) of grain material, which ranges from 750 to 770 kg/m^3. In this study, we analyzed samples with significantly lower ρ values (145, 116, and 87 kg/m^3), which is attributed to the conditions of their formation in the resonator cavity of the microwave moisture meter. Noteworthy is that the partial derivative $\partial A/\partial\rho$ decreases with increasing bulk density ρ; therefore, the effect of density, as an interfering factor, on the measurement result can be quantitatively assessed using this derivative.

At high densities ($\rho \geq 140$ kg/m^3) of the analyzed samples, the derivative takes relatively low values (less than 0.03%/kg·m^3), which indicates a weak density dependence of readings and a minimal effect of this factor on the moisture measurement results; at low densities ($\rho \approx 87$ kg/m^3), the derivative reaches a value of 0.07%/kg·m^3, i.e., even small changes in density cause a noticeable change in instrument readings, which leads to an increase in the relative error.

Thus, an increase in the density of grain loading allows the influence of this interfering factor to be minimized and the accuracy of moisture measurement to be improved.

In order to accurately calibrate the moisture meter in the case of a large derivative $\partial A/\partial\rho$, it is necessary to factor in the density of the sample. If the dependence $A(\rho)$ is weak, then density can be considered a less critical parameter. The decrease in error with increasing bulk density is consistent with the results presented in [13–17].

Figure 3 shows the measured moisture content W_{avg} of grain material with different densities. In Fig. 4, the variations in the derivative $\partial A/\partial\rho$ are presented for two density ranges: 87–116 kg/m^3 and 116–145 kg/m^3. An increase in the sensitivity of the device to density is observed at higher moisture levels. This is particularly evident at moisture levels of over 14% where density has a significant effect on moisture meter readings. For most W values within the density range of 87–116 kg/m^3, the derivative is positive and small: approximately 0.03–0.05% moisture per 1 kg/m^3. However, at $W = 14.5;18.0\%$, sudden shifts into the negative region are observed within the first density interval, and a significant shift into the positive region is observed within the range of 116–145 kg/m^3. This fact may indicate data instability or measurement features. In the second density interval, the derivatives are generally positive and slightly higher than in the first, which indicates an increase in the sensitivity of the device to density within the range of 116–145 kg/m^3.

Prospects for the development of microwave moisture measurement

In spite of their simple design and ease of use, single-parameter moisture meters are not sensitive enough to changes in material density and temperature, have a limited measurement range, and low noise immunity, which reduces measurement accuracy and operational stability. The influence of interfering factors on such an informative indicator as moisture content has prompted the search for new technical solutions that meet the ever-increasing requirements for determining the quality characteristics of grain and grain products. The present authors are currently developing a two-parameter microwave moisture meter with improved metrological characteristics.

The study [18] reports that the use of two-parameter microwave methods for bulk materials can improve measurement accuracy if the effect of density is taken into account; however, this method is effective only for comparatively small density fluctuations within a relatively narrow moisture range. The works [19, 20] show that in the microwave moisture measurement of bulk materials, special attention has been paid in recent years to determining the feasibility of measurements whose results are independent of material density.

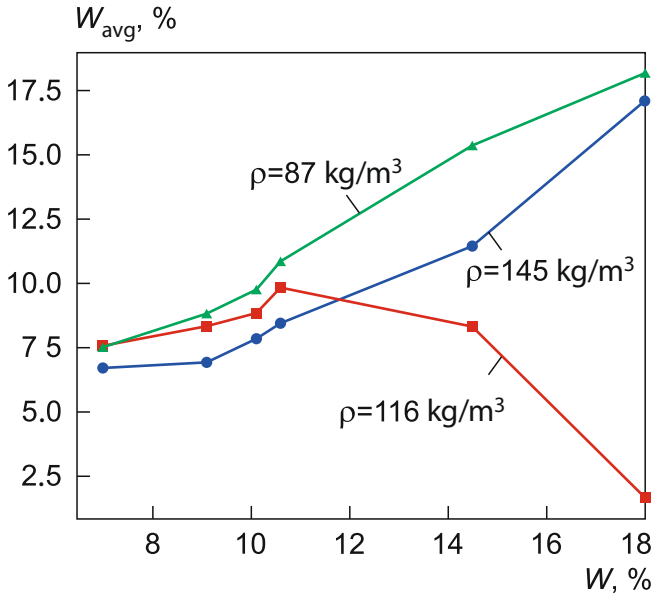


Fig. 3 Results of moisture measurement W_{avg} in wheat samples with different densities

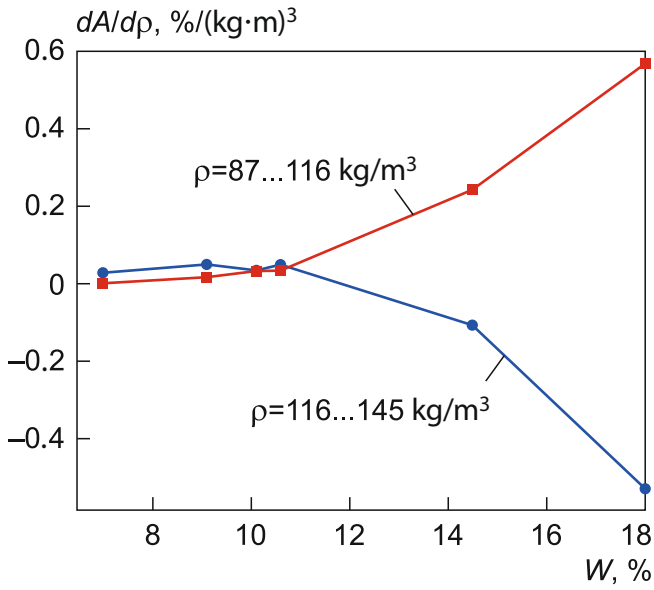


Fig. 4 Derivative $\partial A/\partial\rho$ with respect to density

For optimal results, it is necessary to select the microwave radiation mode for each type of product. In the process of microwave heating, grain material undergoes numerous physicochemical changes, as well as changes in dielectric parameters, which affect measurement accuracy. These factors should be taken into account to achieve the best results in the design of microwave moisture meters.

Conclusion

The results of this study can be used to improve the theory and practice of microwave moisture measurement and create instruments measuring various parameters of processed agricultural products by drawing on the systematic methodology for studying the electrophysical parameters (permittivity) of materials—objects of moisture measurement—in relation to noninformative parameters (temperature and density) in microwave fields.

The conducted experiment confirmed the significant effect of wheat grain bulk density on the results of its moisture measurement by means of the developed microwave moisture meter. This effect is particularly pronounced in a high moisture region (over 14%). The measured moisture values differ depending on density, which requires this parameter to be taken into account during data interpretation. The sensitivity of the moisture meter to density increases at higher moisture levels. At a density of 145 kg/m^3, the minimum relative measurement error is achieved. The study results highlight the importance of a comprehensive approach to grain moisture measurement, including consideration of the physical and mechanical characteristics of the sample, specifically its density, in order to ensure data reliability and repeatability.

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Author Contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by P. I. Kalandarov, L. F. Saidoripov, and B. P. Iskandarov. The first draft of the manuscript was written by P. I. Kalandarov. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of interest The authors declare no potential conflict of interest with respect to the research.

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