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USE OF TDR TECHNIQUE TO MEASURE GRAIN MOISTURE CONTENT

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Abstract

The Time Domain Reflectometry (TDR) technique is widely employed across various industrial sectors due to its high speed and measurement selectivity. It is mainly used for measuring soil moisture or electrical conductivity. In this paper, the possibility of using this technique to measure moisture content of various seeds is analyzed. For this purpose, a commercial TDR meter – FOM2/mts with FP/mts – field TDR probe was used to measure dielectric permittivity for different seed species. The obtained results were then correlated with seed moisture content and calibration curves were proposed for each seed species. In addition, the effect of temperature on the dielectric permittivity readout was studied and a correction factor was proposed.

Keywords: TDR probe, grain, moisture, measurements.

1. Introduction

One of the basic parameters describing the quality of a seed is its moisture content. This parameter is crucial at many stages of seed processing. The first stage in which moisture plays a significant role is the timing of harvesting. In order to be able to store seeds for an extended period of time, the right storage temperature and seed moisture content must be ensured [1]. Depending on the plant species, there are differences in the optimal seed moisture content for storage. For rapeseed it is below 7% [2], for corn it is below 13.5% [3] while for wheat it is below 14% [4]. When seeds are stored with moisture contents higher than recommended, storage time is significantly reduced due to the possibility of mold or fungal growth [5]. Another stage of seed processing in which moisture content plays a significant role is seed trading. The price of seeds offered by buyers is negatively correlated with the seeds' moisture content.

Many methods and techniques for measuring seed moisture are available on the market. The gravimetric method is used as the reference method. It involves weighing a sample of seeds before and after drying and then the seed moisture content is obtained from the difference in weight. In this case, it is necessary to adjust the drying parameters (time and temperature) appropriately for the seed species. These parameters are described in PN-EN ISO 665:2020-09 [6,7]. There are also

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moisture analyzers that use infrared radiation to heat the sample [8]. Unfortunately, this method, although accurate, is time-consuming. In practice, other methods are being sought that give an almost immediate reading of the moisture content. Among these methods, the most noteworthy are the so-called indirect methods in which the moisture content measurement is based on the measurement of another parameter that is correlated with the seed moisture content.

Due to the speed of the readout, as a rule, these methods use electrical parameters of seeds such as resistance, electrical capacitance or dielectric permittivity [1, 9, 10]. These parameters are also used, for example, in medical diagnostics for early detection of diseases [11]. Electrical parameters are also used to measure humidity in petroleum products. In the case of indirect measurements, prior calibration of the device is necessary [12, 13]. There are also works that describe the shape of the signal generated by a piezoelectric plate to determine the moisture content of rapeseed [7, 14].

The *Time Domain Reflectometry* (TDR) measurement technique was developed in the 1920s to locate faults in transmission as well as in telecommunications cables [15]. The method involves forcing a voltage step or a needle pulse at the input of a given line, which propagates along the line and then the return pulse reflected from the impedance discontinuity is recorded. The principle of TDR measurement is shown in Figure 1.

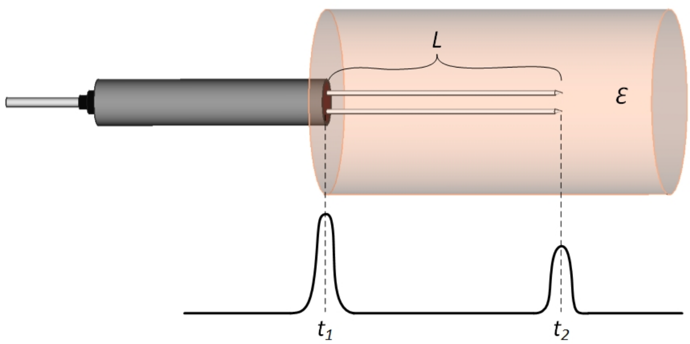

Fig. 1. Principle of TDR measurement in a medium with apparent dielectric permittivity ε. L is the length of the probe, t_1 and t_2 are the recorded time of the pulse reflected from the beginning and the end of the probe rods, respectively.

The parameter that is used in the TDR technique is apparent dielectric permittivity ε. Dielectric permittivity is in general a frequency-dependent complex number consisting of a real part (ε') and an imaginary part (ε''), where the real part ε' is sometimes called the dielectric constant and the imaginary part ε'' represents the loss factor [7, 16]. In the case of an electrical pulse, which can be regarded as a superposition of waves in a broad frequency spectrum, its propagation time in a given medium depends on ε of this medium. As depicted in Figure 1, apparent dielectric permittivity of a measured material can be determined according to the following formula:

$$\varepsilon = \left(\frac{c\,(t_2 - t_1)}{2L} \right)^2, \tag{1}$$

where L is the length of the probe, t_1 and t_2 are the recorded time of the pulse reflected from the beginning and the end of the probe rods, respectively, and c is the speed of light in vacuum. Thanks to the development of electronic circuits used to shape the input pulse, the measurement resolution of this technique has significantly increased, which makes it possible to detect impedance discontinuities within a distance of several mm [17, 18].

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The TDR technique is used to measure moisture content of materials in many industrial branches. Studies on the use of the TDR technique for measuring soil moisture are widely reported in the literature [19–24]. There are known studies in which the TDR technique is used to analyze the occurrence of capillary rise in composites that are components of exterior walls [25], or for measuring the volumetric water content in weathered granitic bedrock [26]. The paper [27] presents the use of the TDR technique to monitor the moisture content of food products including corn. This technique is also used by quality control inspections to assess the quality of octopus and verify compliance with regulations [28].

The literature also describes attempts to use the TDR technique to measure the moisture of cereal grain. For this purpose, the authors constructed a cylinder-shaped sensor with a centrally placed electrode [29]. Despite achieving high selectivity of measurements, this system has the disadvantage of having to pour a sample of material into the sensor. This makes random inspections of cereal grain moisture more difficult.

The idea behind this work is that one may use a commercial TDR meter to easily measure the moisture of various plant species, directly from a larger sample (*e.g.* when harvesting plants or during storage).

The purpose of the study is: i) to evaluate the possibility of using a commercial TDR meter to measure the moisture content of seeds, ii) to test the accuracy of the proposed solution using selected seeds as an example, iii) estimate the effect of temperature on the accuracy of the measurement.

2. Materials and Methods

2.1. Preparation of the samples

The following seed species collected in 2022 were used for the study:

- Wheat (*Triticum* L.) – Euforia variety
- Rapeseed (*Brassica napus* L.) – Bellevue variety
- Mustard (Sinapis alba L.) – MHR Palma variety
- Millet (*Panicum miliaceum* L.) – Jagna variety
- Common buckwheat (*Fagopyrum esculentum Moench* L.) – Panda variety
- Red clover (*Trifolium pratense* L.) – Dajana variety
- Mixed alfalfa (*Medicago media Pers* L.) – Radius variety
- Tansy phacelia (*Phacelia tanacetifolia Benth*. L.) – Stala variety
- Maize (*Zea mays* L.) – Brenton variety
- Flax (*Linum* L.) – Olivin variety
- Persian clover (*Trifolium resupinatum* L.) – Nitra Plus variety
- Cannabis (*Cannabis sativa* L.) – Rajan variety
- Soybean (Glycine max L.) – Acardia variety

In the case of TDR measurements, the factors that influence the measurement are seed diameter, thousand seed weight and density. These parameters determine the volume of empty spaces between individual seeds (Table 1). They were obtained for the lowest moisture levels (according to Table 2).

As presented in paper [30], the diameter of the seeds depends on the species and even within the same species the seeds may have different diameters. In addition, the moisture of the seeds affects the weight of a thousand seeds and thus the density. Therefore, in order to best reflect the conditions during harvesting, a given seed species was measured without division into granulometric composition.

Table 1. Physical parameters of individual seeds.

Type of grain	**Thousand seed mass [g]**	**Sample weight [g]**	**Density [g cm^{-3}]**
Wheat	36	260	0.719
Rapeseed	2.4	232	0.641
Mustard	5.9	261	0.721
Millet	6.1	263	0.727
Common buckwheat	16.9	213	0.589
Red clover	4.2	283	0.782
Mixed alfalfa	1.6	270	0.746
Tansy phacelia	1.9	183	0.506
Maize	301.1	231	0.639
Flax	5.5	189	0.522
Persian clover	1.3	279	0.771
Cannabis	14.7	192	0.531
Soybean	183	232	0.641

Table 2. A compilation of prepared seed samples with different moisture contents.

Type of grain	**Obtained moisture content of individual samples [%]**
Wheat	10.5, 11.8, 12.9, 13.5, 15.3, 17.6, 17.8, 18.4, 20.9, 22.3
Rapeseed	8.3, 8.8, 9.9, 10.9, 12, 13.1, 15.3, 15.8, 16.4, 19.8
Mustard	9.4, 10.8, 11.3, 12.8, 14.2, 14.7, 15.5, 16.3, 16.9, 17.4
Millet	9.8, 10.7, 12, 13.4, 14.3, 14.6, 17.5, 18.5, 20, 25
Common buckwheat	12.8, 13.9, 14.1, 14.5, 15.6, 16.8, 17.8, 18.1, 20.1, 20.9
Red clover	9.6, 10.1, 12.4, 12.5, 14.1, 15, 16, 17.5, 20.2, 22.7
Mixed alfalfa	9.3, 9.9, 11, 12.2, 13, 14.1, 15.3, 16.4, 19.5, 22.3
Tansy phacelia	8.4, 8.6, 9.3, 10.8, 10.7, 12.9, 14.2, 15.1, 16.9, 17.3
Maize	11.1, 12.4, 13.6, 15.8, 17.8, 21.4, 21.5, 25.4, 27.1, 29.7
Flax	3.4, 4.4, 5.4, 6.5, 8.5, 8.5, 11, 11.6, 11.9, 15.8
Persian clover	10.5, 10.7, 12.7, 13.5, 15.6, 16.2, 17, 20.5, 24.7, 26.2
Cannabis	5.3, 5.4, 5.6, 6.8, 8.7, 9, 10.7, 11.1, 12.1, 12.7
Soybean	12.6, 14.5, 16.4, 15.7, 15, 16.3, 17.5, 19.5, 19.7, 21.4

To obtain the appropriate desired moisture content, the seeds were conditioned before measurements. An appropriate amount of demineralized water was added to the seeds, then the seeds were closed in airtight containers. The seeds were placed in a Pol-Eko type KK 115 TOP+ climate chamber for 72 h at 7°C. The seeds were mixed every 6h to achieve an even distribution of moisture in the sample. The seeds were then removed from the climate chamber and kept at room temperature (21 ± 0.5°C) for 6h. This was to eliminate the effect of temperature on the measurements. Before each measurement, seed moisture was measured. For this purpose, a Radwag WPS 30 S weighing dryer and the gravimetric method were used, in which the seed weight before and after drying was measured. Then, seed moisture was calculated based on the following formula:

Metrol. Meas. Syst., Vol. 31 (2024), No. 3, pp. 565–576
DOI: 10.24425/mms.2024.150288

$$sm = \left(\frac{wbd - wad}{wbd}\right) \cdot 100\%, \tag{2}$$

where:

sm – seed moisture;

wbd – seed weight before drying;

wad – seed weight after drying.

Since the usable moisture range for each seed is different, therefore the prepared seed moisture content varied by species. The range of moisture contents is summarized in Table 1.

The next step was to check the effect of temperature of the test material on the accuracy of the dielectric permittivity reading for three selected seed species: rapeseed, mustard and millet. Seeds with different moisture contents were placed in the climate chamber for 12h and the following temperature values were set: 0, 5, 10, 15, 20, 25, 30, 35, 40°C. The seeds were mixed every 4h to ensure an even distribution of temperature. Immediately after removing the seeds from the chamber, the seed moisture was measured and then 10 series of dielectric permittivity measurements were performed for each sample. The obtained results made it possible to determine the average value and standard deviation for individual measurements using the MATLAB R2021a application.

2.2. Measurement setup

A commercial field-operated TDR meter – FOM2/mts – was used for the study. This meter is dedicated to field measurements of soil moisture, temperature and electrical conductivity. The manufacturer's catalog note shows that the meter has the following technical parameters:

– soil moisture (accuracy: ±2%),
– bulk electrical conductivity (accuracy: ±0.01 S/m)
– temperature (accuracy: ±0.5°C) [28].

A dedicated FP/mts meter – field TDR probe was used for the study. The measuring part of the probe consists of two 10 cm long steel rods with 2 mm in diameter. The rods are 14 mm apart from

a) b)

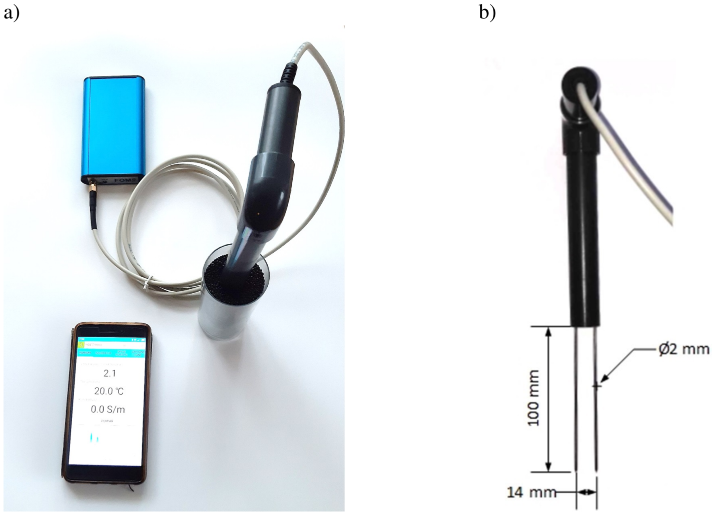

Fig. 2. a) Measurement setup, b) dimensions of the measuring probe.

each other. The utilized TDR system operates with a sin2-like needle pulse with 200 ps rise-time, 500 ps width at the base, bandwidth of 1.75 GHz and the amplitude of 1 V [31]. The measurement results are read out using the FOM2/meter application. It provides a direct reading of the dielectric permittivity of the material under test. The probe was placed in a cylindrical container with a diameter of 58 mm and a height of 200 mm. Figure 2 shows the measurement setup.

3. Results and Discussion

3.1. Influence of moisture on TDR times

Although the aim of this work is to determine seed moisture from a large sample, the sensitivity zone of a given TDR probe was also examined. The aim was also to select an appropriate container in which the seed moisture would be tested. Figure 3 shows the measurement results of dielectric permittivity for rapeseed with a moisture content of 5.2% taken from samples placed in several containers of various diameters, from 27 to 98 mm.

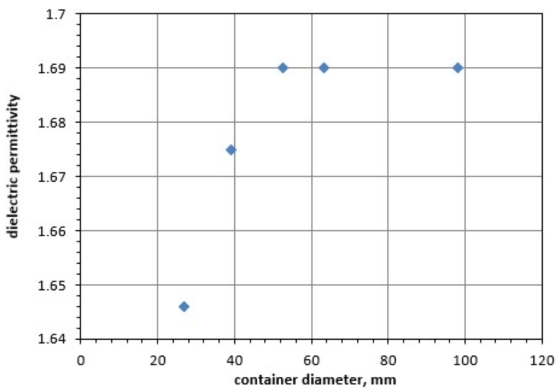

Fig. 3. Dependence of dielectric permittivity as a function of the diameter of the container for rapeseed with moisture of 5.2%.

As can be seen from the results presented in Fig. 3, the minimum diameter of the container should be 50 mm in order to obtain representative measurement results of a large sample. Therefore, for the main experiment, samples were placed in containers of 58 mm in diameter

The second experiment consisted of measuring apparent dielectric permittivity with a TDR meter for different seed species and for different moisture contents. The meter was calibrated before each series of measurements according to the manufacturer's description (the probe was placed in two media: air and water). In order to perform appropriate statistical analysis, measurements for each sample were repeated 10 times, with consecutive insertion and removal of the probe. Figure 4 shows the results of dielectric permittivity measurements for different seed species.

Each measurement point represents an arithmetic average of 10 measurements and error bars represent standard deviation. One can notice that, due to large air gaps between the seeds, the measured DP displayed relatively small changes with moisture content, which also depended on the species. Nevertheless, generally small standard deviation of the given measurements with respect to the respective average values was observed. For each seed species, the relation between apparent dielectric permittivity and soil moisture has been determined by testing various polynomial and exponential models. On each graph, the best model with the highest coefficient of determination

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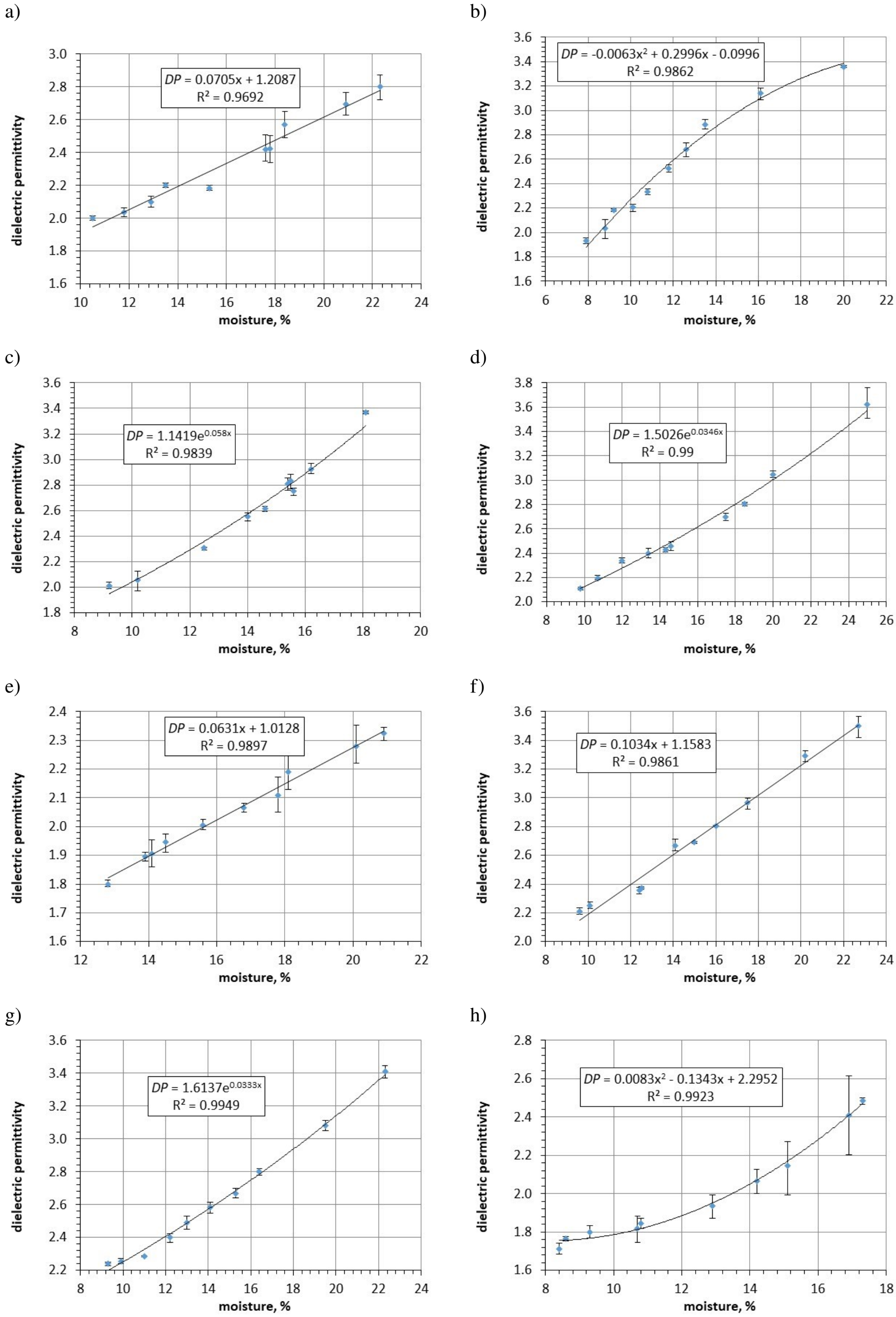

Fig. 4. Dependence of apparent dielectric permittivity (designated *DP* on the graphs) on seed moisture for: a) wheat, b) rapeseed, c) mustard, d) millet, e) common buckwheat, f) red clover, g) mixed alfalfa, h) tansy phacelia, i) maize, j) flax, k) Persian clover, l) cannabis, m) soybean. Fitted models with R^2 were presented on the graphs.

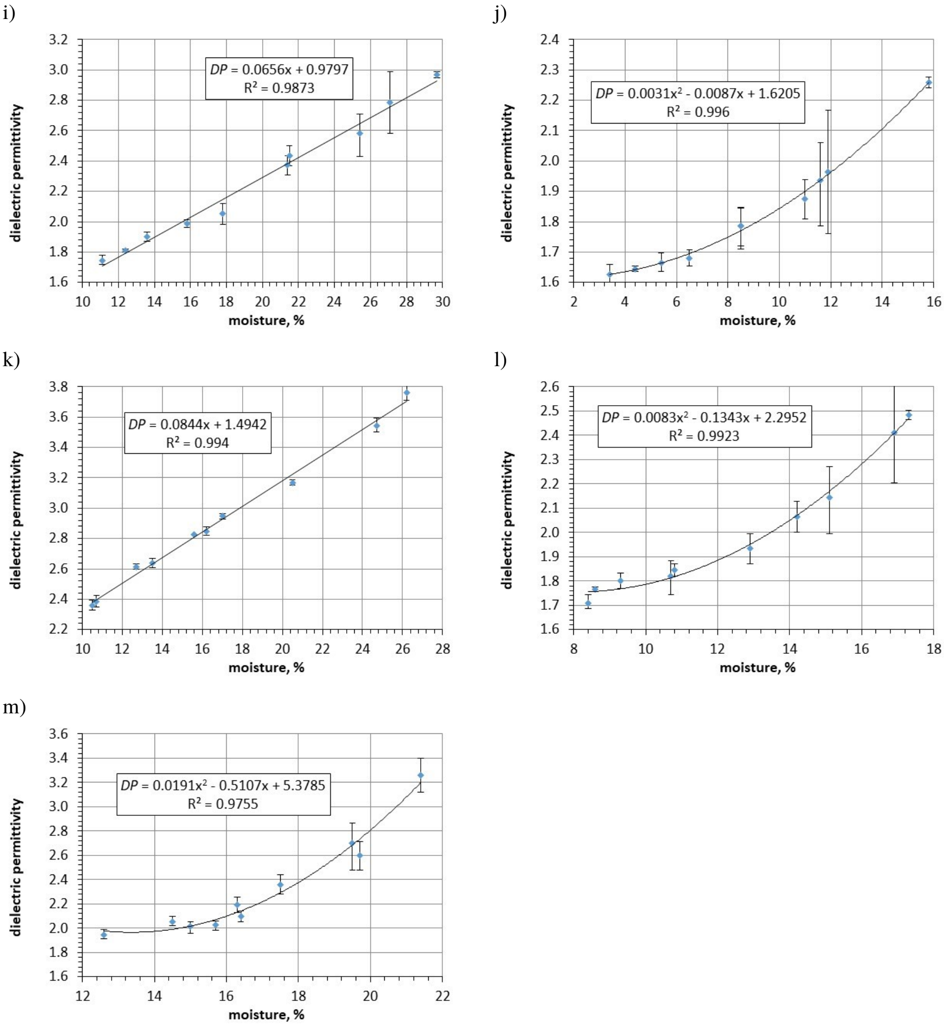

Fig. 4 [cont.]

(R^2) has been presented. For every seed species, the optimal model exhibited high R^2, greater than 0.96. Finally, one can conclude that despite the small permittivity range, the measurement of seed moisture content by the TDR technique has a high resolution.

There are also other works in which similar conclusions were obtained using the TDR technique to measure grain moisture. Paper [29] presented the measurement of moisture of several varieties such as: wheat, rape, vetch, barley, triticale, maize. The authors determined the seed moisture characteristics from $\sqrt{\varepsilon}$ and obtained R^2 coefficients greater than 0.95.

3.2. Influence of temperature on TDR reflection times

Generally, TDR measurements can be sensitive to changes in the temperature of the material under test due to the influence of temperature on its dielectric properties. In the case of moist materials, this is caused on one hand by the fact that the dielectric permittivity of water decreases

Metrol. Meas. Syst., Vol. 31 (2024), No. 3, pp. 565–576
DOI: 10.24425/mms.2024.150288

with increasing temperature, and on the other hand by the increase in permittivity due to the release of bound water [32, 33]. Therefore, in the case of soil moisture measurement with a TDR meter, correction factors can be introduced [34–36].

To test the effect of temperature on the accuracy of seed measurement, an experiment was performed for three selected seed species. Figure 5 shows the results of the tests.

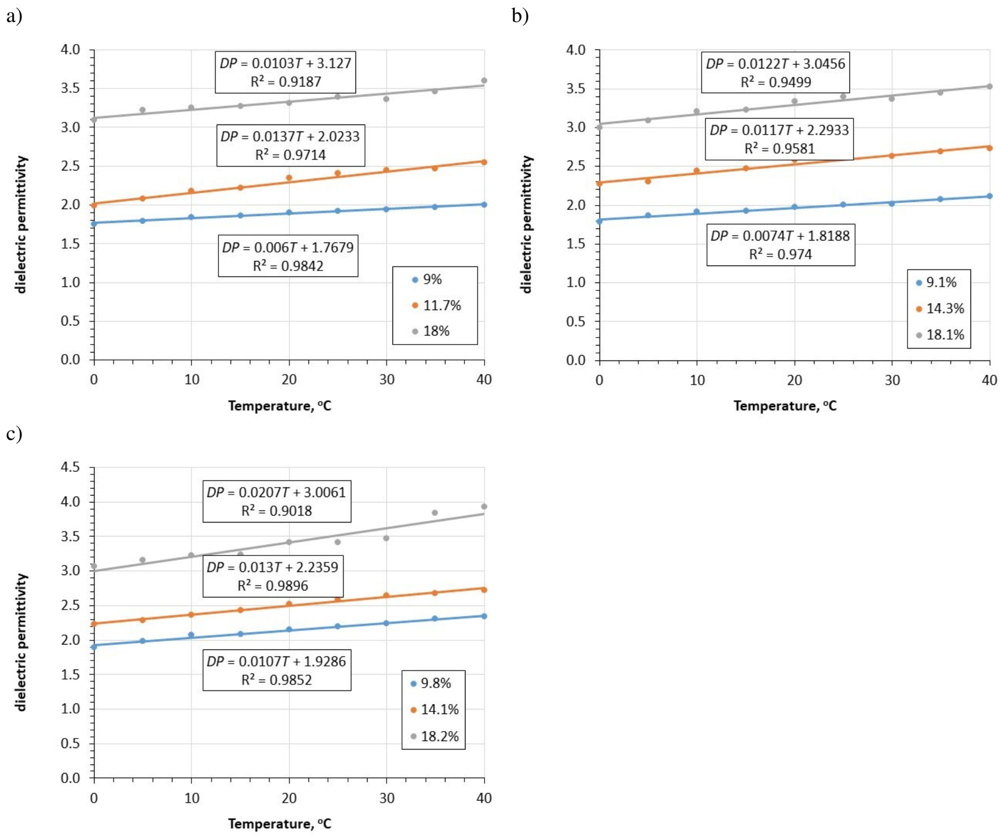

Fig. 5. Influence of temperature on dielectric permittivity for three levels of moisture content of three seed species: a) rapeseed, b) mustard, c) millet.

The study shows that the obtained apparent dielectric permittivity increases with increasing temperature in all tested cases, which indicates that the impact of temperature on water dipole relaxation is not the dominant driver of temperature influence on apparent dielectric permittivity of the seeds. This relationship can be written using the linear function $DP = aT + b$. With the coefficients a and b to be determined for each seed species. This is due to the different shape of each seed and its different size.

4. Conclusions

In the presented study, the impact of moisture content and temperature on TDR-measured apparent dielectric permittivity of selected seed species was examined. It turned out that for each tested seed, a specific dielectric permittivity-moisture content relation can be determined. The impact of temperature was quantified and a correction method has been presented. Based on the obtained results, it can be concluded that the commercial TDR meter, after prior calibration, can be used to accurately measure moisture content of various seed species.

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