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Radio Frequency Treatment of Sesame Oilseed for Quality Assessment

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ABSTRACT

Background: Agricultural products are essential for human beings and maintaining their quality and storing them under optimal conditions is important. Sesame is a widely used cooking oil. Oil production and quality are important aspects of the food industry. However, during storage, the quality of sesame seeds can be greatly affected by factors such as moisture content, microbial growth and pests. Conventional techniques for eliminating pests and drying frequently entail the use of chemicals or high temperatures, which could cause health hazards and diminish the nutritional value of the seeds. However, dielectric measurement is a low-cost, rapid and effective technique for the detection and quality assessment of agricultural products.

Methods: A specially designed coaxial sample holder was connected to an LCR Meter by using a computer-controlled interface. It operates on the principle of a cylindrical capacitor and is based on the cavity perturbation technique. The sample was contained in the cavity of a cylindrical sample holder and a specifically constructed temperature controller sensor assembly was used to regulate the temperature. Five different moisture concentrations of sesame oilseeds were prepared to study their dielectric permittivity, electrical conductivity and penetration depth over the frequency range of 100 Hz to 5 MHz.

Result: This study indicates that the dielectric constant tends to change in a more regular and understandable manner as the frequency and moisture content vary, whereas the behaviour of the dielectric loss factor was less predictable and more irregular in response to the same changes. A linear regression model was developed to investigate the impact of the dielectric constant and loss on frequency and temperature. An R^2 value of 0.705 indicates that the model is well explained, with 27.6% of the variance in temperature and frequency.

Key words: Dielectric constant, Dielectric loss, Electrical conductivity, Moisture content, Penetration depth.

INTRODUCTION

The agricultural sector is significantly affected by oilseed crops, which fall under the category of field crops, second only to cereals (Rani and Singh, 2022). The shortage of edible oils, which accounts for 60% of the country′s requirements (2016-17:14.01 million tons were imported at a cost of Rs. 73,048 crore), makes it impossible to sustain the oilseed self-sufficiency gained during the ″Yellow Revolution″ in the early 1990s for an extended period (Singh and Ahmad, 2019). Oilseeds are essential for the production and sale of edible oils and edible vegetable which are the main sources of energy and necessary fatty acids in the body.

The two oilseeds that are most often farmed in Uttar Pradesh, India are sesame and mustard (Rai *et al*., 2016). Sesame (*Sesamum indicum L*.), often known as benniseed, is the oldest oilseed crop in India (Nagar and Agrawal, 2022). Sesame seeds are a good source of minerals, vitamins E, A and B-complexes and energy. As sesame seeds contain 50% oil, 25% protein and 15% carbohydrates, they are used in the food industry (Tirgarian *et al*., 2019). The best alternative to breast milk, particularly for those who are allergic to milk, is sesame oil (Aydar *et al*., 2020). It is also highly useful for treating heart diseases and lowering cholesterol (Dalibalta *et al*., 2020).

With 16.73 million hectares and 6.5 million tons, India is one of the largest producers of sesame, but its average yield is just 391 kg per hectare, which is low compared with other countries (Chauhan *et al*., 2021). Recently a correlational study on yield of rapeseed for different morphological, physiological, biochemical and quality parameters (Chintey *et al.,* 2024), also storage behavior, dormancy and germination pattern of Tabernaemontana pandacaqui Lam. seeds were reported (Cejalvo *et al.,* 2023). The lack of high-quality seed varieties, antiquated farming methods, improperly managed rained farming and

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planting during the kharif season are the main causes of the low output (Kumar *et al*., 2020). Sesame crops are well known to produce 1200-1500 kg/ha under irrigation and 800-1000 kg/ha under rainy conditions with adequate management (Nagarjuna *et al*., 2022). Despite producing the fifth-largest number of oilseed crops globally, India is currently one of the top importers of vegetable oil (Kumar and Boraiah, 2022).

To understand how agricultural materials respond to electromagnetic fields during microwave cooking, storage, or other procedures that require radio frequency (RF) or microwave dielectric heating, it is vital to understand their dielectric characteristics (Venkatesh and Raghavan, 2004).

In some materials, particularly conductors, there is a concept called ″skin depth.″ It refers to the depth at which the amplitude of an electromagnetic wave is reduced to approximately 37% of its surface value. The skin depth decreased as the frequency increased, which could be a factor in the observed trend for certain materials. Finally, the declining trend of penetration depth with increasing frequency can be attributed to a combination of wave absorption, interactions with the material's internal structures, temperature dependencies and inherent material properties, such as skin depth. This understanding is crucial for industries and applications in which the depth of penetration and frequency are vital parameters, such as telecommunications, medical imaging and material testing.

These characteristics must also be understood when using radio frequency and microwave sensors for quality sensing. The apparatus designed to immediately sense or quantify the moisture content of grains and other food items is the most anticipated example (Nelson and Bartley, 2002). The design of equipment for radio frequency or microwave dielectric heating applications, as well as potential agricultural uses such as grain drying, seed treatment to improve germination and insect control in stored grain using high-frequency and microwave electric fields, all depend on the dielectric properties of the agricultural materials (Nelson, 1992). Nuclear magnetic resonance (NMR), NIR (near infrared) techniques, distillation and gas chromatography can be used for different analyses (Yanti *et al*., 2023), of which dielectric measurement is a low-cost, rapid and effective technique for the detection and quality assessment of agricultural products.

MATERIALS AND METHODS

Material

The study used sesame (*Sesamum indicum* L.) oilseed of the GT-10 variety, samples of which were obtained from ICAR-NBPGR, New Delhi. The seeds were manually cleaned to remove foreign objects and contaminants. The seeds were initially kept under sunlight to maintain equal moisture levels. After this process, the moisture concentration was adjusted by adding a certain amount of distilled water to each sample. All samples were often stirred to ensure uniform distribution of moisture levels and samples were stored in sealed glass bottles at 5°C for 3 days. For the necessary observations, five samples with varying moisture content at concentrations of 4.5%, 9.5%, 13.2%, 15.2% and 20.5% (w.b.) were generated.

Experimental method

Dielectric measurements were performed by using an LCR Meter (*nf: ZM2376*) with a measurement range of 100 Hz–5 MHz, which is inferred in Fig 1. A specially designed coaxial sample holder was connected to the LCR Meter using a computer-controlled interface. It operates on the principle of a cylindrical capacitor and is based on the cavity perturbation technique. After calibrating the sample holder, the sample is filled in the cavity of the cylindrical sample holder and required measurements were taken. In Fig 2, a specifically constructed temperature controller sensor assembly was used to regulate the temperature of the sample holder. Researchers have fabricated similar devices based on the capacitive sensing principle (Soltani *et al*., 2014). All experiments were performed in the research laboratory, Amity Institute of Applied Sciences, Amity University Noida during June 2023 to September 2023.

Permittivity describes the dielectric behavior that affects the electromagnetic wave reflection at interfaces and wave energy attenuation within materials. It was discussed in our earlier studies that the relative permittivity (εr) of a dielectric

Fig 1: LCR meter setup for dielectric measurement.

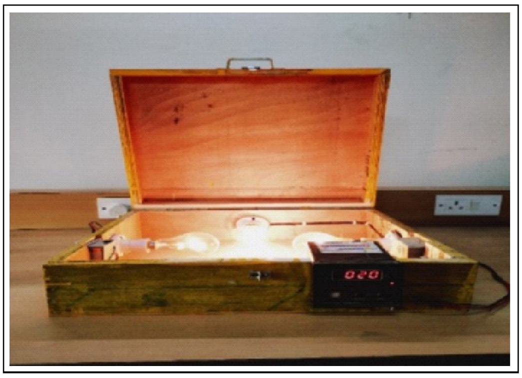


Fig 2: Temperature controller-sensor device.

material consists of the dielectric constant as a real term and the dielectric loss as an imaginary term (Mishra *et al*., 2023), (Mishra *et al.*, 2024b) which can be written in complex form as follows:

$$\varepsilon = \varepsilon' - i\varepsilon'' \tag{1}$$

The real and imaginary parts of the relative permittivity equation indicate that, response of material on applied electric field to store energy which is known as dielectric constant (ε′), whereas its ability to dissipate the energy is known as its dielectric loss (ε″) (Wang *et al*., 2003).

Wet-basis moisture content

The term ″wet basis moisture″ is used to define the amount of water present in the products. In the food industry, the phrase ″moisture content″ typically refers to the moisture content on a wet basis. This provides a significant illustration where the moisture content of whole grains is assessed at each stage of the marketing process as the grain changes hands. It was calculated using the following equation (Ghosal and Rath, 2020).

$$Q = \frac{W_i(M_f - M_i)}{(100 - M_f)} \tag{2}$$

Where,
Wi= Initial sample mass.
M_i and M_f= Initial and final moisture contents of the sample (% w.b.), respectively.
Q= Mass of added water.

The percentage moisture content was verified using an automated grain moisture meter (Smart Sensor, AR991) in our research laboratory.

The sample was then removed from the refrigerator and allowed to stand at room temperature for at least 3 h before observation. Calibration of the sample holder was performed using benzene by performing a few preliminary measurements with an empty (air-filled) sample holder. Tests for each combination of moisture content and temperature were performed at frequencies between 5 and 5 MHz. The LCR meter was synchronized and fixed-interval measurements with 100 data points of frequencies ranging from 5 kHz to 5 MHz were taken on a logarithmic scale.

The dielectric properties were calculated by measuring the dielectric constant, dielectric loss, electrical conductivity and penetration depth which have been previously discussed by our research group (Chandel *et al*., 2014), (Singh *et al*., 2018), (Khan *et al*., 2021a, 2021b), (Khan and Chandel, 2011):

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{3}$$

$$\text{Electrical conductivity} = \omega\varepsilon_0\varepsilon'' \tag{4}$$

$$D_P = \frac{\lambda_\circ \sqrt{\varepsilon'}}{2\pi\varepsilon''} \tag{5}$$

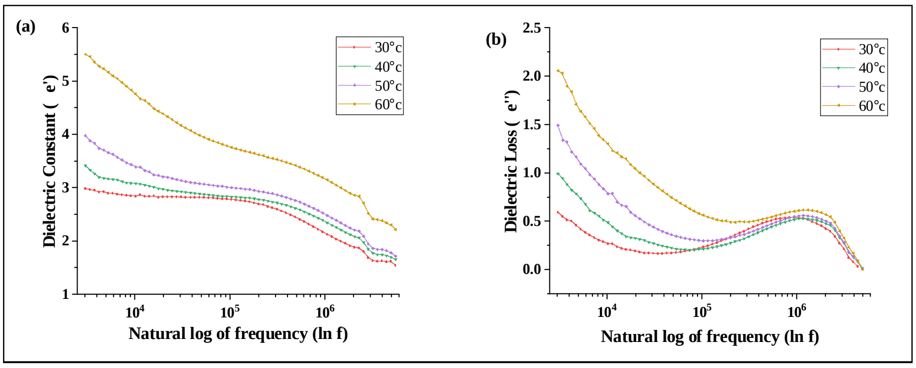


Fig 3 (a) and 3 (b): Frequency dependence of the dielectric constant and dielectric loss of sesame oilseed at the indicated temperatures and moisture content of 4.5%.

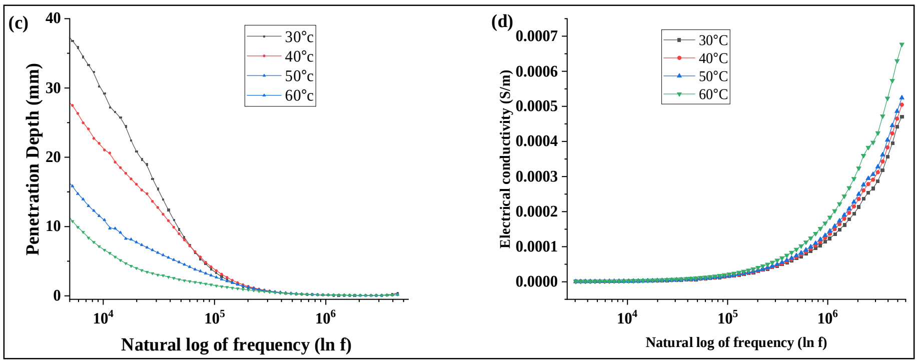


Fig 3 (c) and 3(d): Frequency dependence of penetration depth and electrical conductivity at the indicated temperatures.

Statistical analysis

Design-expert 7.1 was used for regression analysis of the observed dielectric permittivity data and to describe the mathematical relationships for the dielectric constant and loss factor of sesame oilseeds as a function of temperature at selected frequencies.

RESULTS AND DISCUSSION

Frequency dependence on dielectric constant and dielectric loss

The variation in the dielectric constant and dielectric loss of sesame oilseed at 4.5% moisture content is shown in Fig 3(a) and 3(b) for the frequency range of 5 kHz to 5 MHz at the indicated temperature. The figures show that the dielectric constant decreased from 5.558 to 1.478 and the dielectric loss decreased from 2.501 to 0.046 when the frequency was increased from 5 kHz to 5 MHz. This finding was consistent with that reported by (Auksornsri *et al*., 2018). The decreasing trend of the dielectric constant was more regular than that of the changes in the dielectric loss factor at each temperature. According to the frequency-dependent variations in the dielectric constant and corresponding variations in the dielectric loss, the irregularities observed in the dielectric loss may be due to the complex structure of dielectric relaxation and dispersion events.

Frequency dependence on penetration depth and electrical conductivity

Fig 3(c) shows the relationship between the frequency and penetration depth of sesame oilseeds at the indicated temperatures. The value of the penetration depth decreased constantly with increasing frequency. At higher frequencies, the waves tend to be absorbed more by the materials. This absorption translates to energy loss in the form of heat or other forms of energy. As a result, as the frequency increases, more of the wave energy might be absorbed by the material, allowing less of it to penetrate deeper. It has also been reported that higher frequencies correspond to shorter wavelengths (Singh *et al*., 2021). Shorter wavelengths may interact more with microstructures or particles within the material, leading to greater scattering or absorption. This is because of the longer wavelengths. The graph also illustrates that at higher temperatures, the penetration depth at any given frequency is generally lower than that at lower temperatures. This could be due to the increased molecular or atomic motion at higher temperatures, leading to more interactions and wave scattering, thereby reducing the penetration depth.

Fig 3(d) depicts the frequency dependence of the electrical conductivity at the indicated temperature, which shows that the electrical conductivity at the indicated temperature increased continuously with an increase in frequency.

Temperature dependence on dielectric constant and dielectric loss

Fig 4(a) and 4(b) show the variations in the dielectric constant and dielectric loss of sesame oilseed with temperature at the respective frequencies. It is evident that the nonlinear dielectric constant and dielectric loss of the effective complex permittivity increase with the temperature. Diverse frequencies also exhibit similar temperature-dependent dielectric characteristics (Wang *et al*., 2013). The molecular mobility and ionic conduction of the material increase with temperature and at lower frequencies, these phenomena become more significant in influencing the dielectric properties as the temperature increases, similarly temperature and light effects on germination behaviour of African Eggplant (*Solanum aethiopicum* L.) seeds were previously reported (Botey *et al.,* 2022).

Temperature dependence on penetration depth and electrical conductivity

The temperature dependence of the penetration depth of the sesame oilseed at the indicated frequency is shown in Fig 4(c). The interaction between ionic and dielectric loss causes the penetration depth to decrease significantly as the temperature increases. With the inclusion of loss from ionic conduction, the Cole-Cole relation can theoretically explain this pattern (Feng *et al*., 2022).

The temperature dependence of electrical conductivity at the relevant frequency is shown in Fig 4(d). The electrical conductivity increased significantly with an increase in

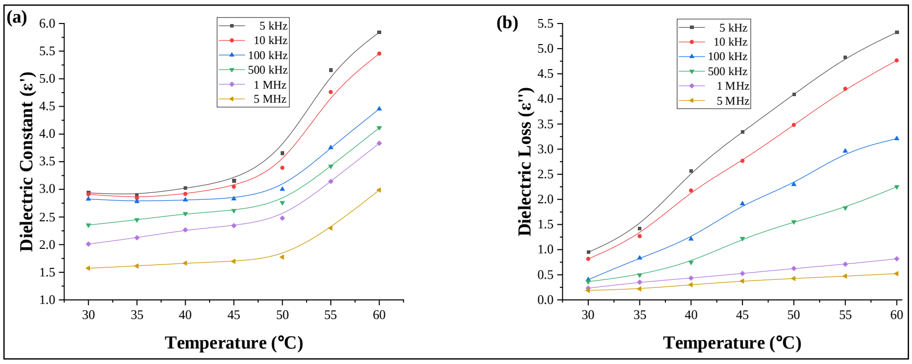


Fig 4 (a) and 4(b): Temperature dependence of dielectric constant, dielectric loss of sesame oilseed at indicated frequencies.

temperature and the increase was relatively large for higher frequencies and nearly linear for lower frequencies.

Moisture dependence on dielectric constant and dielectric loss

Fig 5 and 6 depict the variation in the dielectric constant and dielectric loss factor for the sesame oilseed sample at various moisture contents and 30°C. It was found that the dielectric constant and dielectric loss both showed an increasing trend as the moisture content increased and when the percentage of moisture content exceeded 13.2%, both parameters increased steeply. The rising rates of the dielectric constant and dielectric loss with moisture content were noticeably high at low frequencies, particularly at 5 kHz and 10 kHz. More water dipoles contribute to polarization at high moisture levels because of the higher water mobility, which shows how easily water dipoles follow applied field variations (Ozturk *et al.*, 2016). Below a moisture content of 9.5%, the dielectric constant and dielectric loss of the complex permittivity are both moderate. This is a result of the strongly bound water state (monolayer), in which the cell walls and water molecules are strongly attracted to one another while being relatively close to one another. As a result, both the dielectric loss and constant are quite low.

When the moisture content exceeds 9.5%, the change from the first bound water state-monolayer) to the second type-multilayer) could be responsible for the increase in the dielectric constant and dielectric loss of complex permittivity. When the moisture content was greater than 15.2%, there was a definite increase in frequency. With a high moisture content, particularly at a moisture content of 20.5% and frequency of 10 kHz, oilseeds exhibit extraordinarily high dielectric constant and dielectric loss values. The transition from the second (multilayer) type of bound water to the third (osmotic tension) type, or from

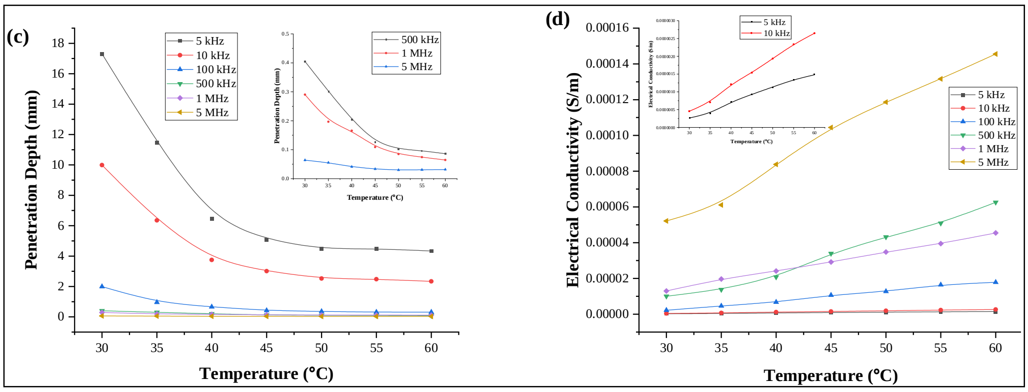


Fig 4 (c) and 4(d): Temperature dependence of the penetration depth and electrical conductivity of the sesame oilseed at the indicated frequencies.

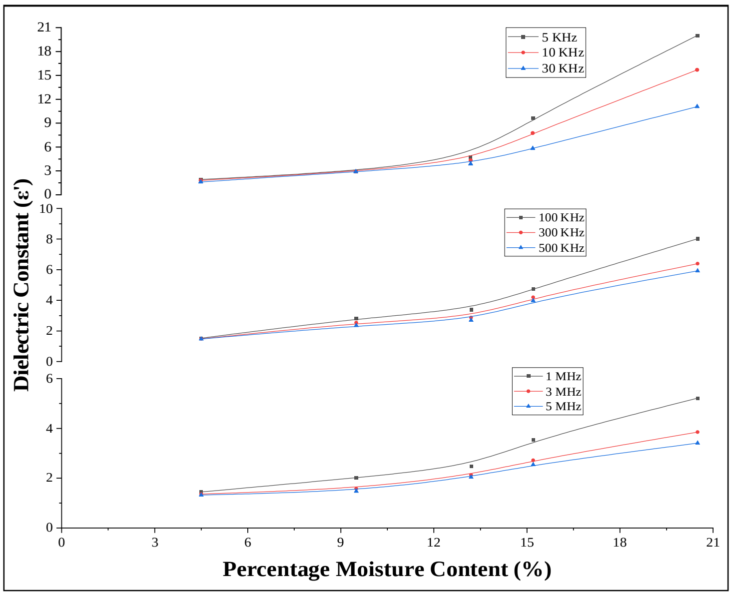


Fig 5: Moisture dependence of the dielectric constant of sesame oilseed at indicated frequencies.

free-state water, is the cause of this behavior. Large moisture levels and low frequencies result in strong ionic conductivity; hence, the dielectric losses are notably large under these conditions.

Effect of moisture content (%) on electrical conductivity

At a temperature of 30°C, experimental data on electrical conductivity with changes in moisture content percentage were gathered over the frequency range of 5 kHz to 5 MHz. Fig 7 shows how the electrical conductivity of sesame oilseed varies with moisture content at the indicated frequency and demonstrates how the electrical conductivity of each oilseed sample increases with increasing moisture content and frequency. At the indicated minimum and maximum moisture contents of the seeds, at 30°C temperature and over the frequency range of 5 kHz to 5 MHz, the electrical conductivity values of the sesame oilseed samples were found to range between 1.526×10^{-7} S/m and 2.601×10^{-4} S/m. This demonstrates that the electrical conductivity increases with moisture content. The electrical conductivity steeply increased for moisture contents greater than 13.2%. This behavior is similar to the dependency of moisture content on the dielectric

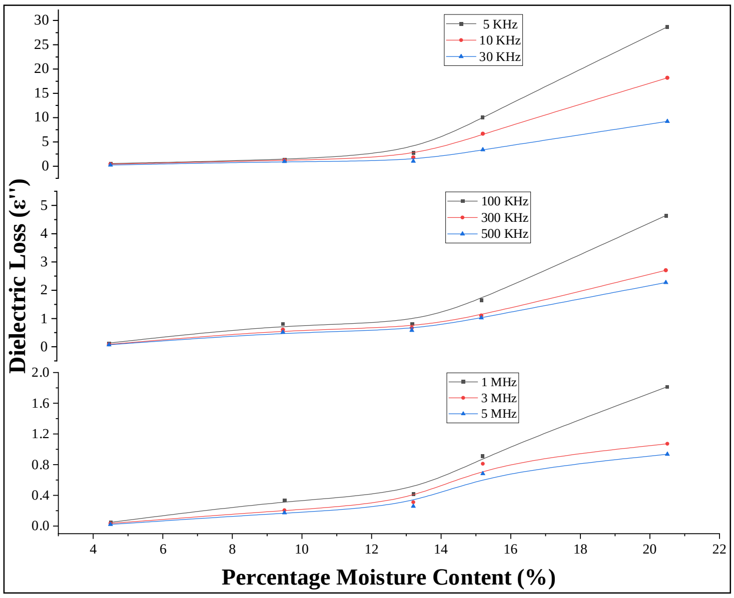


Fig 6: Moisture dependence of the dielectric loss of sesame oilseed at indicated frequencies.

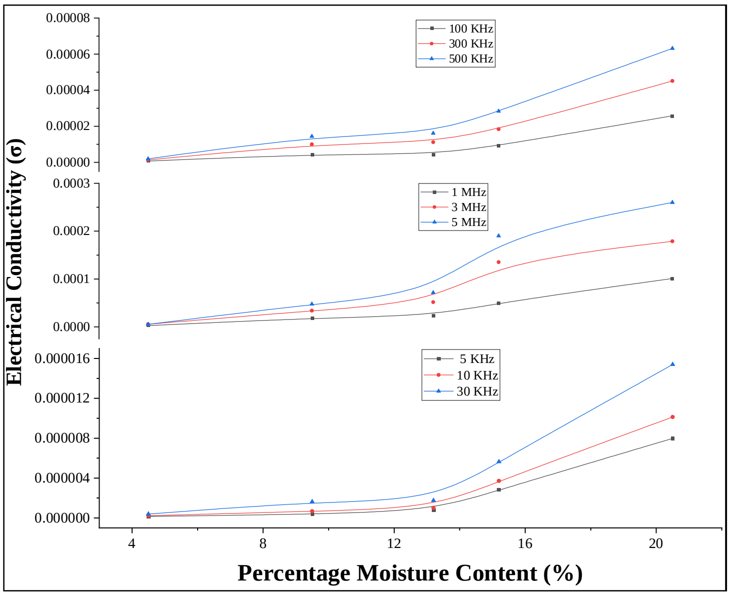


Fig 7: Moisture dependence of the electrical conductivity of sesame oilseed at the indicated frequencies and at a constant temperature of 30°C.

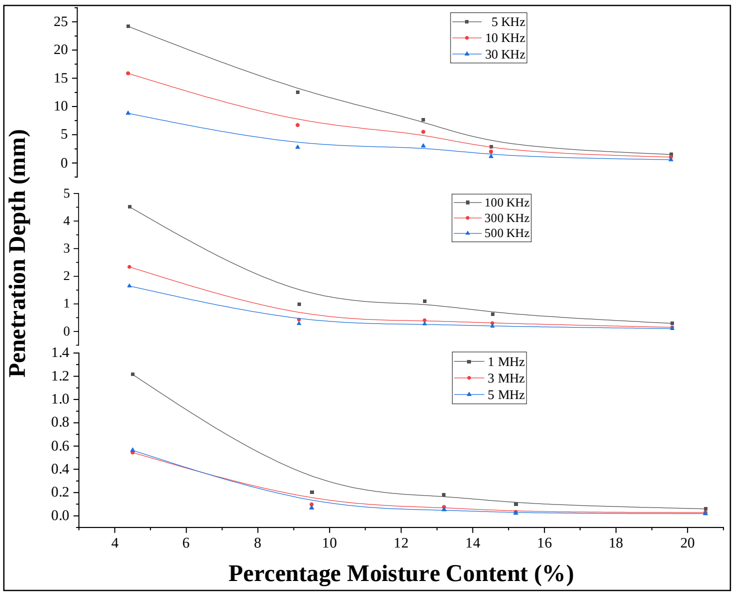
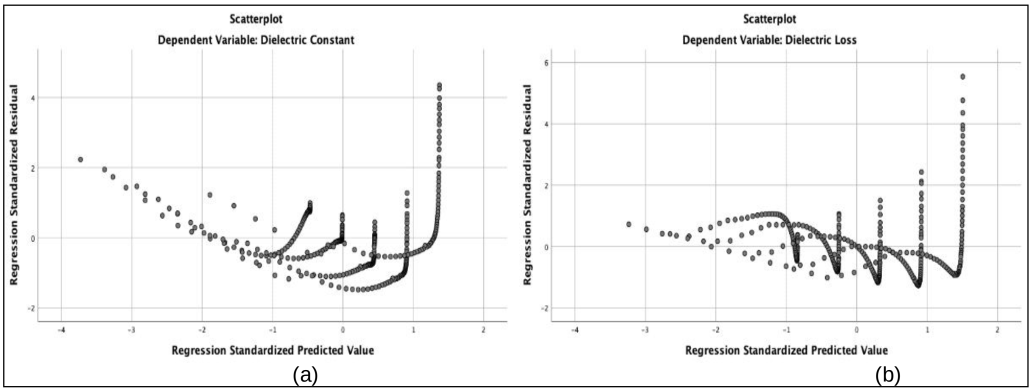


Fig 8: Moisture dependence of the penetration depth of sesame oilseed at the indicated frequencies and at a constant temperature of 30°C.



(a) (b)

Fig 9 (a) and (b): Scatterplot of regression-standardized predicted value versus regression-standardized residual for Dielectric constant and Dielectric loss.

constant and dielectric loss factor, which means that all these factors are related to each other.

Effect of moisture on penetration depth

At a temperature of 30°C, experimental data on penetration depth with varying moisture content percentages were gathered over the frequency range of 5 kHz to 5 MHz. Sesame oilseed sample penetration depth values ranged from 0.02 mm to 24.18 mm. Fig 8 demonstrates that the value of the sesame oilseed penetration depth constantly declined as moisture content increased at the observed specified set of frequencies between 5 kHz and 5 MHz at a constant temperature of 30°C. These results are consistent with those of a previous study (Tripathi *et al*., 2015). With an increase in the moisture content percentage, the decrease in the penetration depth was due to strong ionic interactions and dielectric loss. This decreasing trend could also be explained by the Cole-Cole relation with the addition of loss from ionic conduction.

Statistical analysis

In this study, a linear regression model was developed to investigate the impact of the dielectric constant and loss on frequency and temperature in Fig 9 (a) and 9(b). It was hypothesized that the dielectric constant would have a significant impact of the applied frequency and temperature. To test this hypothesis, a regression was executed for the dielectric constant on the predicted variables, frequency and temperature (Zuo *et al.,* 2023). The results indicate that the dielectric constant can be significantly predicted with varying frequency and temperature (F = 408.4, p<0.001) similar to the previous study (Mishra *et al.,* 2024a). This suggests that the applied frequency and temperature play significant role in shaping the dielectric constant ($b = -0.0000003$, $p<.001$). An R-squared value of 0.705 indicates that the model explained 27.6% of the variance in temperature and frequency.

CONCLUSION

This study demonstrates a significant relationship between the dielectric properties of sesame oilseeds and their moisture content, frequency and temperature. When the frequency increased, a decreasing trend was observed in the dielectric constant and the loss factor. A similar decreasing trend was observed with increasing temperature and moisture concentration.

At higher temperatures (more than 45°C), the effect of frequency on the dielectric constant and dielectric loss factor was observed to increase considerably. Lower frequencies and higher moisture content enhanced the influence of frequency on the dielectric constant and dielectric loss factor, whereas a higher moisture content enhanced the effect of frequency fluctuation on the quantities. The electrical conductivity showed an increasing trend at higher percentages of moisture content, such as the dielectric constant and dielectric loss factor. The fact that lower frequencies have higher penetration depth values suggests that using this range of radio frequencies rather than microwave frequencies is preferable. Therefore, to design manufacturing and storage instruments, as well as handling and processing operations, knowledge of electrical properties such as dielectric constant, dielectric loss, penetration depth and electrical conductivity is important.

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Author contributions

Venkatesh Mishra: Writing-original draft, Software, Methodology. Satyendra Pratap Singh: Conceptualization, Project administration, Investigation, Formal analysis and funding acquisition. Mamta Singh: Formal analysis, data curation, Vishal Singh Chandel- Resources, Project administration and Rashmi Yadav: Supervision.

Conflict of interest

All authors declared that they have no conflict interest or personal relationships that could have appeared to influence the work reported in this paper.

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