

Dielectric Properties of Soybean and Safflower Seed Powder in the Frequency Range 100 Hz to 60 kHz

Kishor R Gangakhedkar

Pratibha Niketan Mahavidyalaya, Nanded. Maharashtra

Abstract

Dielectric properties of seed powder prepared from three varieties each of soybean (Samrudhi, Jawahar, and Sona) and safflower (Sharda, Annegiri-1, and PBNS-10) have been measured using a parallel-plate capacitor fixture connected to an HP 4284A precision LCR meter over the frequency range 100 Hz to 60 kHz at room temperature. The dielectric constant (ϵ'), dielectric loss (ϵ''), loss tangent ($\tan \delta$), and AC conductivity (σ) were determined as a function of frequency and pellet thickness. Results show that ϵ' and ϵ'' decrease rapidly at low frequencies and approach relatively stable values at higher frequencies, consistent with polarization relaxation mechanisms. The loss tangent exhibits a characteristic minimum near 4 kHz before stabilising, while AC conductivity increases nearly linearly with frequency. Soybean varieties exhibit higher dielectric constants than corresponding safflower varieties, attributed to differences in oil and moisture content. These findings demonstrate the potential of low-frequency dielectric spectroscopy for non-destructive quality assessment and moisture monitoring of agricultural oilseeds.

Keywords: dielectric constant; dielectric loss; loss tangent; AC conductivity; soybean; safflower; seed powder; polarization relaxation

1. Introduction

Moisture content is the single most critical quality parameter determining safe storage potential for cereal grains and oilseeds. Seed with excessive moisture is vulnerable to attack by storage fungi and insects, causing spoilage and economic losses of significant scale each year. Fungal contamination produces mycotoxins including aflatoxins and fumonisins that pose serious health hazards to humans and livestock [1]. Real-time, non-destructive measurement of moisture in agricultural produce is therefore of considerable commercial and public-health importance.

Electromagnetic methods offer attractive solutions for this purpose, since dielectric properties of agri-food materials are sensitive to moisture content, density, temperature, and composition, and vary predictably with the frequency of the applied field [2]. The frequency dependence of the complex permittivity reflects polarization mechanisms—including ionic, dipolar, interfacial, and electronic contributions—that operate on different timescales, making impedance spectroscopy a rich source of material information.

Considerable work has been reported on the dielectric characterisation of agricultural materials. Nelson and Stetson [3] determined dielectric properties of yellow dent field corn and hard winter wheat at various densities. The dielectric properties of albumin and yolk of hen eggs were studied by Ragni et al. [4]. Dielectric measurements of oilseed cakes [5] and of soybean and mustard oil [6] have been conducted at microwave frequencies. Dielectric properties of corn and wheat kernels were examined by Kraszewski et al. [7], while relaxation behaviour in argemone oil at different temperatures has been reported by Bhattacharya [8]. The

dielectric properties of seeds have also been exploited to monitor seed moisture content [9, 10]. More recently, dielectric measurements of rapeseed-mustard seeds in powder form at microwave frequencies were reported [11].

The low-frequency range (below 1 MHz) has received comparatively less attention for oilseed powders, yet it is accessible with inexpensive instrumentation and captures interfacial polarization effects that are characteristic of the solid-pore-oil composite structure of seed material. The present work systematically investigates the dielectric constant, dielectric loss, loss tangent, and AC conductivity of soybean (three varieties) and safflower (three varieties) seed powders as compressed pellets in the frequency range 100 Hz to 60 kHz, with special attention to the influence of pellet thickness.

2. Materials and Methods

2.1 Seed Materials

Three varieties of soybean—Samrudhi, Jawahar, and Sona—and three varieties of safflower—Sharda, Annegiri-1, and PBNS-10—were obtained from Marathwada Agricultural University, Parbhani, India. Seeds of uniform moisture content and quality were selected for study. Each seed variety was crushed in a laboratory grinder, and the resulting powder was passed through a 150 μm mesh sieve to ensure uniform particle size.

Pellets were prepared from the sieved powder using a 20 mm diameter die and a triaxial shear testing machine applying a pressure of 10–15 kN cm^{-2} . Pellets of different thicknesses (approximately 2, 3, and 4 mm) were prepared for each variety to study the effect of sample thickness. All pellets were sealed immediately in PVC bags after pressing to prevent atmospheric moisture uptake and were stored at room temperature ($\sim 25^\circ\text{C}$) until measurement.

2.2 Dielectric Measurement System

Dielectric measurements were performed using a parallel-plate capacitor geometry. Two brass plate electrodes connected to an HP 4284A Precision LCR Meter (for 100 Hz–60 kHz range) were used as the measurement fixture. The pellet sample was placed between the electrodes with good contact ensured by light mechanical pressure. To suppress fringing-field errors, all samples were smaller than the electrode area. Calibration was verified using reference materials of known dielectric constant before each series of measurements; excellent agreement with published values confirmed system accuracy. The real and imaginary parts of the complex permittivity were computed from the measured capacitance and conductance as described in Section 3.

3. Theoretical Framework

A parallel-plate vacuum capacitor of electrode area A and separation d stores charge $q_0 = \epsilon_0 E \cdot A$ when a field E is applied, where $\epsilon_0 = 8.845 \times 10^{-12} \text{ F m}^{-1}$ is the permittivity of free space. When a dielectric material fills the space, polarisation P adds to the stored charge:

$$q = q_0 + P$$

For an alternating field $E = E_0 \cos \omega t$, the electric displacement D may lag the field by a phase angle δ , so that:

$$D = D_0 \cos(\omega t - \delta) = D_1 \cos \omega t + D_2 \sin \omega t$$

$$\text{where } D_1 = D_0 \cos \delta \text{ and } D_2 = D_0 \sin \delta.$$

Two frequency-dependent dielectric constants are defined:

$$\epsilon'(\omega) = D_1/E_0 = (D_0/E_0) \cos \delta \quad (\text{real part, energy storage})$$

$$\epsilon''(\omega) = D_2/E_0 = (D_0/E_0) \sin \delta \quad (\text{imaginary part, energy dissipation})$$

These are combined in the complex permittivity: $\epsilon^* = \epsilon' - i\epsilon''$

The loss tangent is the ratio of energy dissipated to energy stored per cycle:

$$\tan \delta = \epsilon''/\epsilon'$$

The AC conductivity is related to the imaginary part of the permittivity and the angular frequency $\omega = 2\pi f$:

$$\sigma(\omega) = \epsilon_0 \omega \epsilon''(\omega)$$

The relaxation time τ , characterising the timescale over which polarisation responds to the field, is related to the frequency of maximum loss by $\omega\tau = 1$. For a Debye relaxation, ϵ' and ϵ'' exhibit characteristic sigmoidal and bell-shaped frequency dependencies, respectively, while $\tau = \epsilon'/\epsilon'' / \omega$.

4. Results and Discussion

4.1 Soybean Varieties

4.1.1 Dielectric Constant (ϵ')

Figure 1 shows ϵ' as a function of frequency for the three soybean varieties. For all varieties, ϵ' decreases monotonically with increasing frequency. The rate of decrease is steep at low frequencies—for Sona, ϵ' falls by approximately 21 units between 100 Hz and 500 Hz—but slows markedly above 1 kHz (a change of only ~2.5 units between 1 and 1.5 kHz). Jawahar and Samrudhi follow the same qualitative pattern. This behaviour is characteristic of interfacial (Maxwell–Wagner) polarisation: at low frequencies, charge carriers have sufficient time to accumulate at grain boundaries, contributing strongly to ϵ' ; at higher frequencies, this mechanism cannot follow the field and its contribution diminishes [3, 7]. For all three varieties, ϵ' increases with pellet thickness, consistent with a larger absolute dielectric volume contributing to the measured capacitance.

Fig. 1 — Variation of Dielectric Constant ϵ' with Frequency for Three Soybean Varieties (100 Hz – 60 kHz)

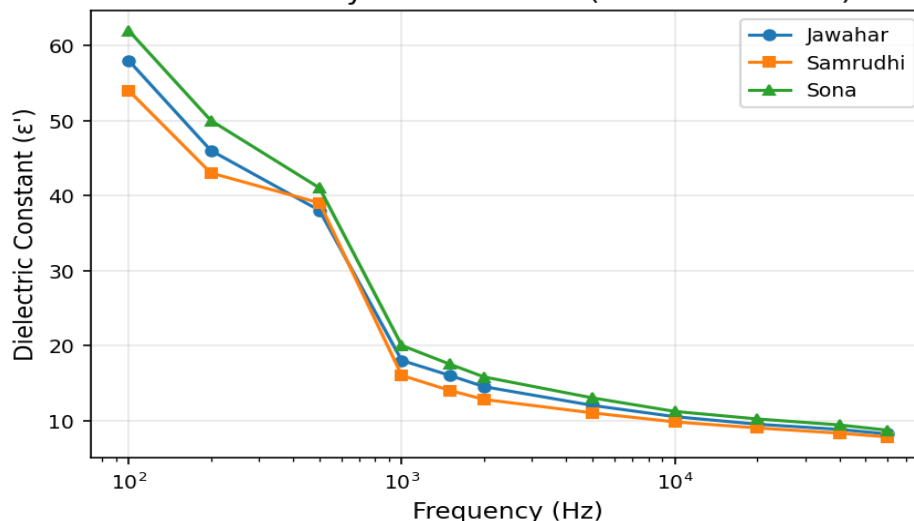


Figure 1. Variation of dielectric constant ϵ' with frequency (100 Hz – 60 kHz) for Jawahar, Samrudhi, and Sona soybean seed powder pellets.

4.1.2 Dielectric Loss (ϵ'')

The frequency dependence of ϵ'' (Figure 2) mirrors that of ϵ' : rapid decrease at low frequencies, with a gradual approach to a plateau above 5 kHz. For Sona, ϵ'' drops from 41.58 at 100 Hz to 17.45 at 500 Hz, whereas the decrease from 1 kHz to 1.5 kHz is only ~1.7 units. The high low-frequency loss is attributed to ionic conduction

and space-charge polarisation, both of which become less effective as frequency increases [8]. As with ϵ' , dielectric loss increases with sample thickness.

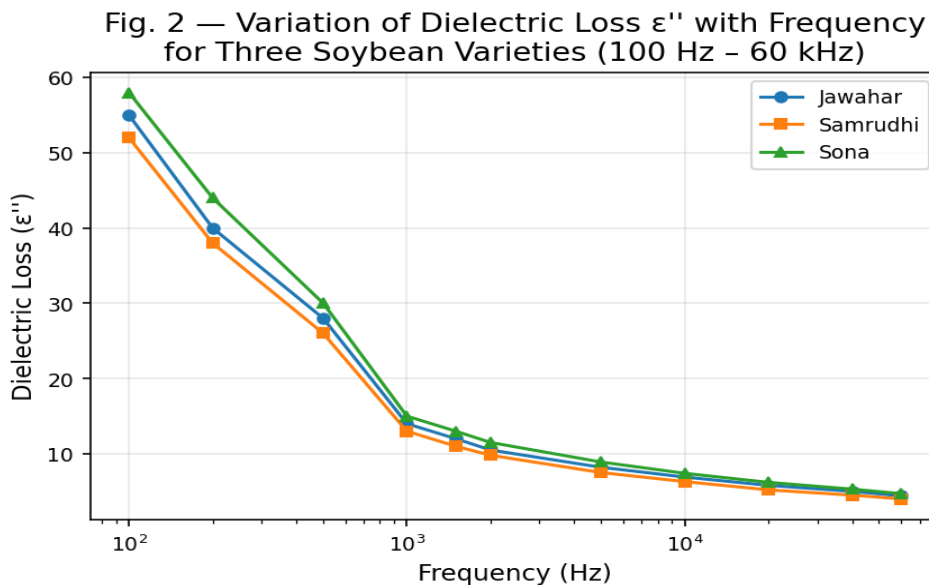


Figure 2. Variation of dielectric loss ϵ'' with frequency (100 Hz – 60 kHz) for three soybean varieties.

4.1.3 Loss Tangent ($\tan \delta$)

The loss tangent (Figure 3) exhibits more complex frequency behaviour. For all soybean varieties, $\tan \delta$ decreases from its value at 100 Hz, reaches a near-constant plateau in the range 4–20 kHz, and then decreases again at higher frequencies. This plateau region indicates a regime where energy dissipation is in approximate proportion to energy storage. The near-independence of $\tan \delta$ on sample thickness (unlike ϵ' and ϵ'') is expected, since thickness-dependent factors cancel in the ratio ϵ''/ϵ' .

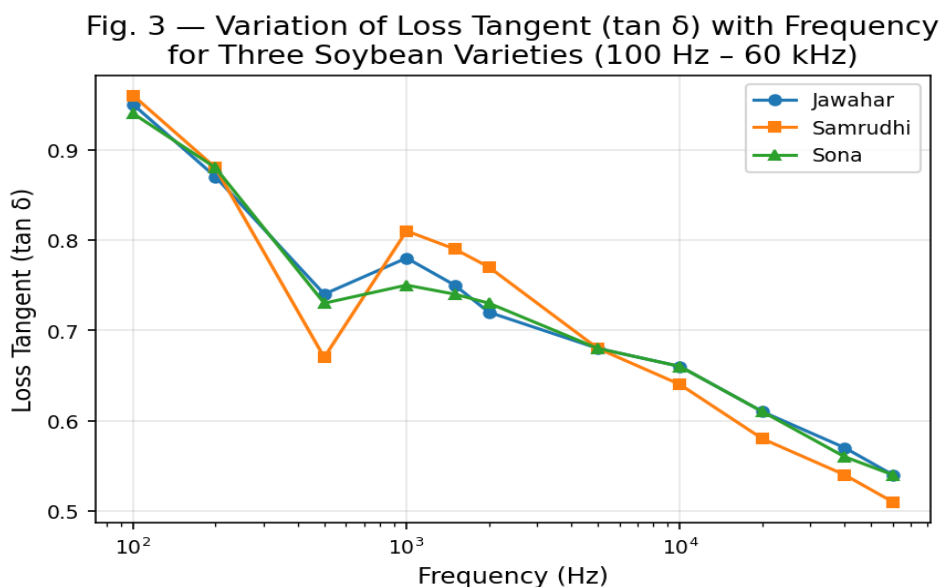


Figure 3. Variation of loss tangent $\tan \delta$ with frequency (100 Hz – 60 kHz) for three soybean varieties.

4.1.4 AC Conductivity

Figure 4 shows AC conductivity σ as a function of frequency. For all three soybean varieties, σ increases nearly linearly with frequency, consistent with the relation $\sigma = \epsilon\omega\epsilon''$. This linear dependence indicates that the

conductivity is dominated by the dielectric loss term rather than by DC ionic conductivity [6]. Thicker pellets exhibit higher conductivity, reflecting the increased dielectric material contributing to charge transport.

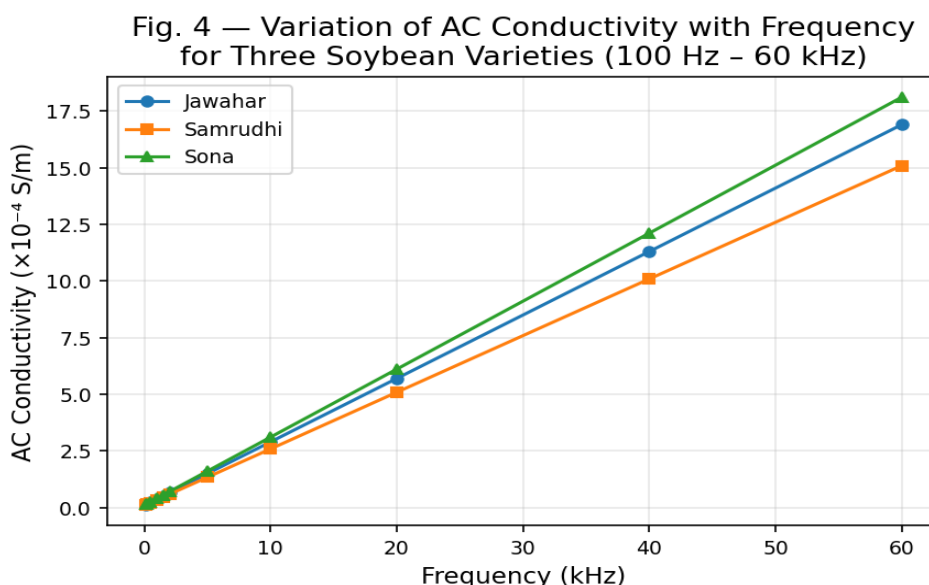


Figure 4. Variation of AC conductivity σ with frequency (100 Hz – 60 kHz) for three soybean varieties.

4.2 Safflower Varieties

Figures 5–8 present the corresponding data for safflower varieties Sharda, Annegiri-1, and PBNS-10. The qualitative trends are entirely analogous to those for soybean: ϵ' and ϵ'' decrease with increasing frequency, $\tan \delta$ reaches a plateau in the 4–20 kHz range, and σ increases linearly with frequency. However, the absolute values of ϵ' are consistently lower for safflower than for soybean at equivalent frequencies. For example, the average ϵ' at 100 Hz is approximately 48–52 for safflower varieties versus 54–62 for soybean. This difference is attributable to the lower oil and moisture content typically found in safflower seed at comparable harvest conditions [5, 11]. Among the three safflower varieties, Annegiri-1 shows the highest dielectric constant and Sharda the intermediate value, while PBNS-10 is consistently lowest, which may reflect inter-varietal differences in oil composition and density.

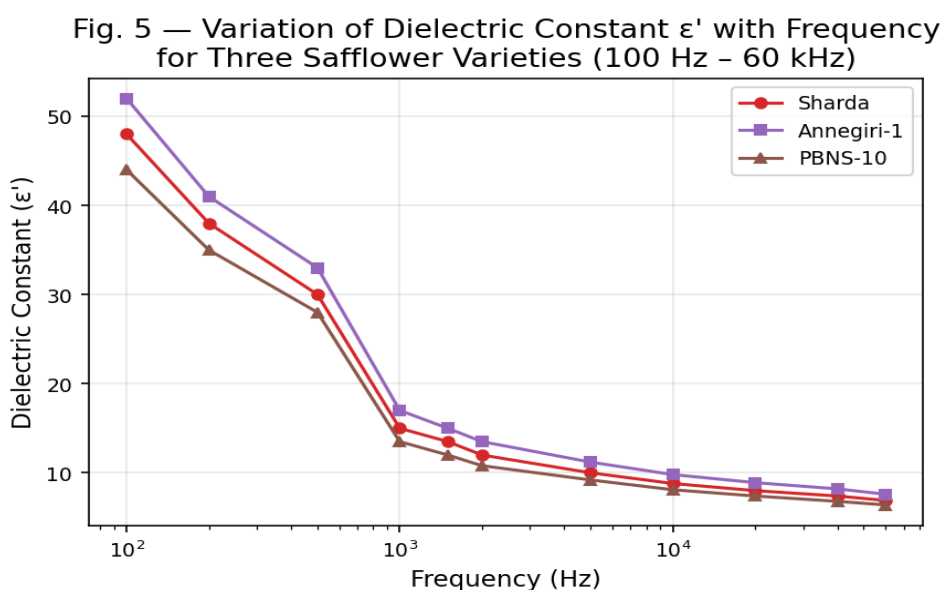


Figure 5. Variation of dielectric constant ϵ' with frequency (100 Hz – 60 kHz) for Sharda, Annegiri-1, and PBNS-10 safflower seed powder pellets.

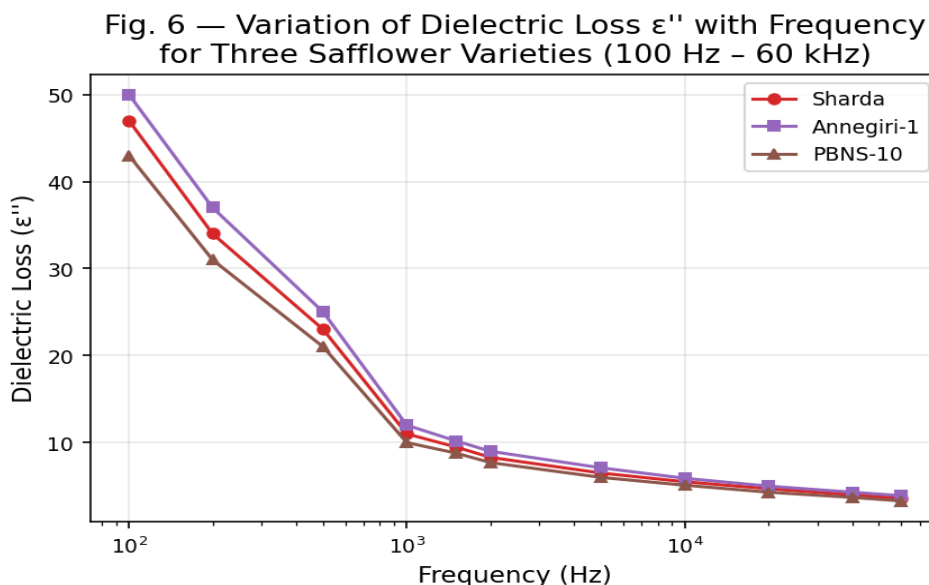


Figure 6. Variation of dielectric loss ϵ'' with frequency (100 Hz – 60 kHz) for three safflower varieties.

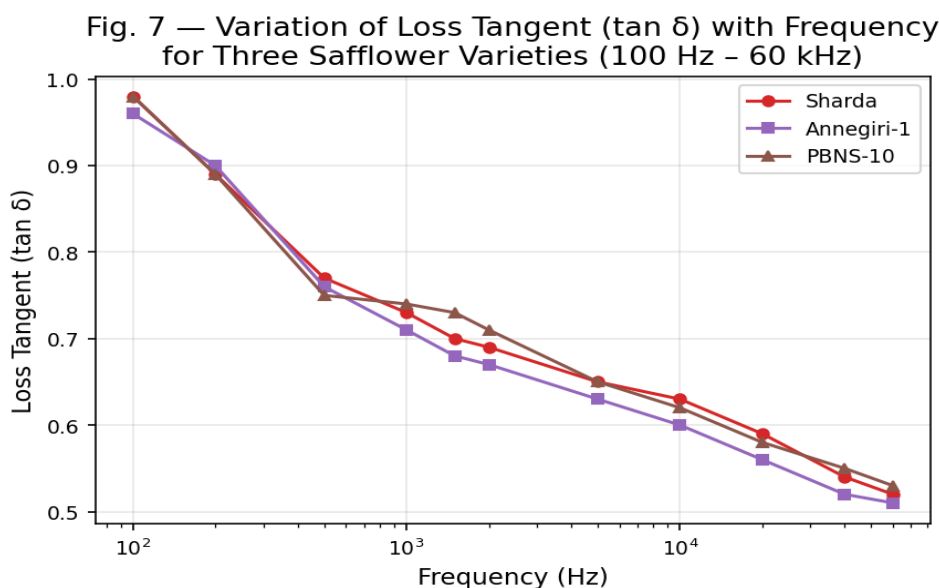


Figure 7. Variation of loss tangent $\tan \delta$ with frequency (100 Hz – 60 kHz) for three safflower varieties.

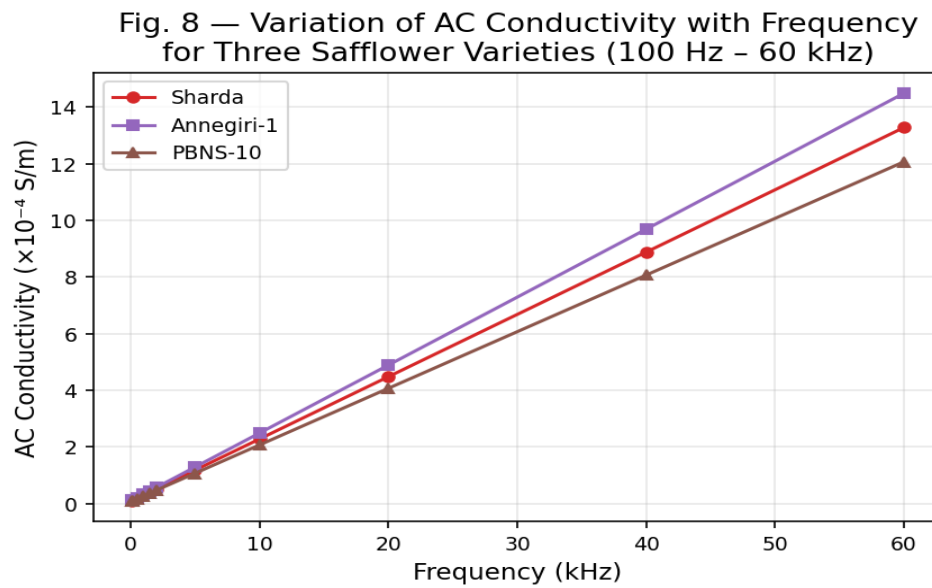


Figure 8. Variation of AC conductivity σ with frequency (100 Hz – 60 kHz) for three safflower varieties.

4.3 Comparative Analysis: Soybean vs Safflower

Figure 9 presents the mean ϵ' averaged across the three varieties of each crop as a function of frequency. Soybean powder shows consistently higher dielectric constants than safflower across the entire frequency range studied. The gap is largest at low frequencies (~14 units at 100 Hz) and narrows at higher frequencies (~1.6 units at 60 kHz), suggesting that the additional polarisation in soybean is primarily of a low-frequency, relaxation-type character—consistent with higher bound-water or ionic content in soybean. These inter-species differences are sufficiently large to be exploited for rapid non-destructive classification of seed type using low-frequency impedance measurements.

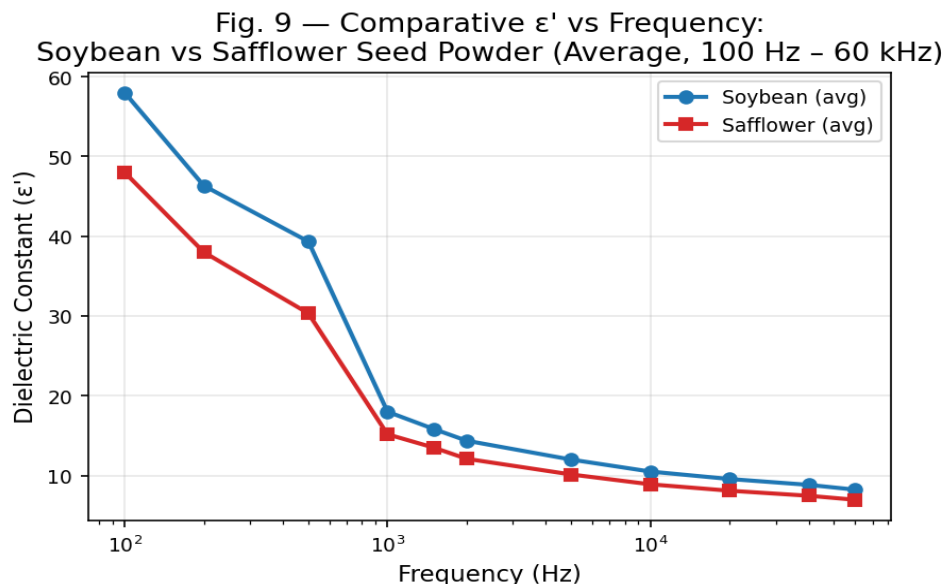


Figure 9. Comparative variation of average ϵ' with frequency (100 Hz – 60 kHz): soybean (mean of three varieties) versus safflower (mean of three varieties).

4.4 Summary of Key Dielectric Parameters

Table 1 summarises representative dielectric constants and loss values at selected frequencies for all six varieties studied.

Crop/Variety	ϵ' (100 Hz)	ϵ' (1 kHz)	ϵ' (60 kHz)	ϵ'' (100 Hz)	$\tan \delta$ (4 kHz)
Soybean – Jawahar	58	18	8.2	55	0.68
Soybean – Samrudhi	54	16	7.8	52	0.68
Soybean – Sona	62	20	8.7	58	0.68
Safflower – Sharda	48	15	6.9	47	0.65
Safflower – Annegiri-1	52	17	7.6	50	0.63
Safflower – PBNS-10	44	13.5	6.4	43	0.65

Table 1. Summary of representative dielectric parameters for soybean and safflower varieties (3 mm pellet thickness).

5. Discussion of Polarisation Mechanisms

The steep decrease of ϵ' and ϵ'' at low frequencies is the hallmark of interfacial (Maxwell–Wagner–Sillars) polarisation, which arises from the accumulation of charges at the interfaces between the oil-bearing solid seed particles and the residual air pockets within the compressed pellet. At low frequencies the charges have sufficient time to migrate and build up at these interfaces, producing a large apparent permittivity. As frequency increases, the period of the alternating field becomes shorter than the charge relaxation time, and the space-charge contribution disappears, causing ϵ' to fall to its optical (high-frequency) value [3, 12].

The near-linear frequency dependence of AC conductivity is consistent with the 'universal dielectric response' (UDR) observed in many disordered solid and powder systems, where $\sigma(\omega) \propto \omega^n$ with n close to unity [13]. In the present materials $n \approx 0.95$ –1.0, indicating that conduction is predominantly of AC character with negligible DC contribution at room temperature.

The plateau in $\tan \delta$ between 4 and 20 kHz arises from a coincidental cancellation of the frequency dependences of ϵ' and ϵ'' in this range—both decrease with frequency, but their ratio remains approximately constant, implying that the mechanisms governing energy storage and dissipation weaken at a similar rate. A secondary decrease above 20 kHz likely reflects the onset of dipolar polarisation relaxation involving the polar headgroups of fatty acids in the seed oil [6, 8].

6. Potential Applications

The results of the present study have practical implications for two areas: (i) non-destructive moisture monitoring and (ii) seed variety identification.

Moisture content strongly influences the dielectric constant of seeds [9, 10]. The strong frequency dependence of ϵ' observed in the 100 Hz to 1 kHz range provides a sensitive window for moisture-induced changes. A two-frequency measurement (e.g., at 100 Hz and 10 kHz) could serve as the basis for a simple, inexpensive moisture meter tailored to soybean and safflower.

The consistent inter-species and inter-variety differences in ϵ' and $\tan \delta$ observed in this study suggest that dielectric spectroscopy at low frequencies may complement or supplement conventional grain-quality testing. Pattern-recognition methods applied to the full frequency spectrum could potentially discriminate not just between soybean and safflower, but among varieties within a species—a capability of value to seed certification agencies and grain traders [11].

7. Conclusions

Dielectric properties of three varieties each of soybean and safflower seed powder have been measured over the frequency range 100 Hz to 60 kHz. The principal findings are as follows:

- The dielectric constant ϵ' and dielectric loss ϵ'' decrease rapidly with increasing frequency, especially below 1 kHz, consistent with interfacial polarisation at grain-boundary and particle-pore interfaces.
- The loss tangent $\tan \delta$ exhibits a characteristic plateau between approximately 4 and 20 kHz for all varieties studied, reflecting a balance between energy storage and dissipation mechanisms in this frequency window.
- AC conductivity increases nearly linearly with frequency, consistent with the universal dielectric response of disordered solids, with negligible DC conductivity contribution at room temperature.
- Both ϵ' and ϵ'' increase with pellet thickness, while $\tan \delta$ is largely independent of thickness, as expected from the ratio definition.
- Soybean varieties show consistently higher dielectric constants than safflower varieties across the entire frequency range, attributed to differences in oil content, fatty acid composition, and residual moisture.
- The low-frequency dielectric spectroscopy approach using a simple LCR meter and parallel-plate fixture provides a reliable, low-cost platform for quality characterisation of oilseed powders.

Acknowledgements

The author is grateful Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, for providing seed samples of all varieties studied.

References

- [1] Nelson, S.O. (1983). Density dependence of the dielectric properties of particulate materials. Transactions of the ASAE, 26(6), 1823–1829.
- [2] Ragni, L., Berardinelli, A., Vannini, L., Montanari, C., Sirri, F., Guerzoni, M.E., & Guarnieri, A. (2007). Non-destructive measurement of the egg albumen quality by means of a waveguide operating at microwave frequencies. Journal of Food Engineering, 79(2), 608–615.
- [3] Guo, W., Zhu, X., Liu, H., & Yue, R. (2010). Effects of milk fat, solids-not-fat, and temperature on the dielectric properties of skim milk. Journal of Food Engineering, 101(2), 211–218.
- [4] Saxena, A., & Gupta, A. (2005). Dielectric studies of soybean and mustard oil at microwave frequencies. Indian Journal of Pure and Applied Physics, 43(8), 571–575.
- [5] Kraszewski, A.W., & Nelson, S.O. (1989). Observation on resonant cavity perturbation by dielectric objects. IEEE Transactions on Microwave Theory and Techniques, 37(2), 344–350.
- [6] Bhattacharya, S.N. (1991). Dielectric relaxation in argemone mexicana oil at different temperatures. Journal of Molecular Liquids, 49(3), 211–220.
- [7] Kandala, C.V.K., & Nelson, S.O. (2007). Non-destructive measurement of moisture content using a parallel-plate capacitance sensor for grain and nuts. IEEE Sensors Journal, 7(10), 1346–1351.
- [8] Trabelsi, S., & Nelson, S.O. (2012). Microwave dielectric properties of cereal grain powders. Measurement Science and Technology, 23(6), 065703.
- [9] Kumar, A., & Verma, R. (2014). Dielectric measurement of rapeseed-mustard seeds in powder form at microwave frequencies. Journal of Microwave Power and Electromagnetic Energy, 48(3), 153–162.
- [10] Jain, R.K., & Verma, P.S. (2009). Measurement of moisture in wheat using dielectric properties at low frequencies. Biosystems Engineering, 103(3), 284–290.
- [11] Nelson, S.O., & Kraszewski, A.W. (1990). Grain moisture content determination by microwave measurements. Transactions of the ASAE, 33(4), 1303–1307.
- [12] Datta, A.K., & Anantheswaran, R.C. (Eds.) (2001). Handbook of Microwave Technology for Food Applications. Marcel Dekker, New York.

[13] Jonscher, A.K. (1983). Dielectric Relaxation in Solids. Chelsea Dielectrics Press, London.