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Effect of storage conditions on the dietary and pharmaceutical values of ginger oil, and modeling its dielectric properties

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SUMMARY: This research was conducted to evaluate the impact of the storage conditions of ginger rhizomes on the nutritional and therapeutic properties of the ginger oil (GO). The physicochemical and phytochemical properties, fatty acid contents and dielectric constant (ε′) of the GO were analyzed in accordance with standard guidelines. The findings revealed that the storage temperature significantly impacted the quality of GO ($p < 0.05$). Notably, the oil contains a significant amount of acid value (AV), free fatty acid (FFA), saponification value (SV), iodine value, vitamin C, phenolic compounds, and polyunsaturated fatty acids (PUFAs). Furthermore, the findings demonstrated a strong correlation between the GO's ε′ and its AV, FFA and saturated fatty acid contents. A predictive model was developed using Stepwise Linear Regression to forecast the GO dielectric properties based on its measured physicochemical properties. Comparison of the model's predictions with the experimental results revealed reliable forecasting, indicating the usefulness of the model for evaluating the oil quality and electrical properties.

KEYWORDS: *Electrical installations; Electrical properties; Health risks; Nutritional value; Oil quality.*

RESUMEN: ***Efecto de las condiciones de almacenamiento sobre los valores dietéticos y farmacéuticos del aceite de jengibre y modelado de sus propiedades dieléctricas***. Esta investigación se realizó para evaluar el impacto de las condiciones de almacenamiento de los rizomas de jengibre en las propiedades nutricionales y terapéuticas del aceite de jengibre (GO). Se analizaron las características fisicoquímicas, fitoquímicas, de los ácidos grasos y la constante dieléctrica (ε′) del GO de acuerdo con las pautas estándar. Los resultados mostraron que la temperatura de almacenamiento afectó significativamente la calidad del GO (p <0,05). En particular, el aceite tiene valores altos de acidez (AV), ácidos grasos libres (FFA), índice de saponificación (SV), índice de yodo, vitamina C, compuestos fenólicos y ácidos grasos poliinsaturados (PUFA). Además, los resultados demostraron una fuerte correlación entre el ε′ del GO y su contenido de AV, FFA y ácidos grasos saturados. Se desarrolló un modelo predictivo utilizando la regresión lineal escalonada para pronosticar las propiedades dieléctricas del GO en función de sus propiedades fisicoquímicas medidas. La comparación de las predicciones del modelo con los resultados experimentales reveló un pronóstico confiable, lo que indica la utilidad del modelo para evaluar la calidad del aceite y las propiedades eléctricas.

PALABRAS CLAVE: *Calidad del aceite; Instalaciones eléctrica;s Propiedades eléctricas; Riesgos para la salud; Valor nutricional.*

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1. INTRODUCTION

The high demand for functional foods has made intensive research into edible food items containing essential compounds with significant health benefits and other engineering applications necessary (Sabra *et al.,* 2021). Edible oil is an important dietary component, derived from plants and animals, which is necessary for a balanced diet and tissue development. Oils provide the body with energy, carotenes, vitamins, essential phytonutrients and polyunsaturated fatty acids which help prevent various chronic diseases and support proper functioning of bodily systems (Rabiej-Kozioł *et al.,* 2023). The physicochemical, phytochemical, and fatty acid profiles of oils depend on plant variety, storage conditions, and processing methods. These attributes determine the utilization and functionality of the oils (Khalili Tilami and Kouřimská, 2022; Uguru *et al.,* 2023). Fatty acids in oils are primarily classified into saturated and unsaturated fatty acids; and the unsaturated fatty acids (UFAs) are generally considered more health-friendly than saturated fatty acids (SFAs). Some UFAs such as eicosapentaenoic, linolenic, arachidonic and adrenic acids have the potential of producing low-density lipoprotein (LDL) cholesterol; hence reducing the chances of cardiovascular diseases and neurological disorders.

The utilization of vegetable oils has been increasing rapidly due to their consistent applications in medical, dietary, engineering, and other essential sectors worldwide (Tian *et al.,* 2023). The rise in deficiency-related and food-borne diseases has spurred a demand for essential oils that contain a balanced composition of fatty acids, phytosterols, phytochemicals, carotenoids, and tropocepols. These essential compounds have the ability to retard cardiovascular diseases, cancer, diabetes, kidney and liver diseases. They also possess antimicrobial, anti-inflammatory, and antitumorigenic qualities (Sabra *et al.,* 2021; Siddiqui *et al.,* 2023). The use of oils in the medicinal and nutritional sectors is primarily influenced by their profiles of anti-nutrients, saturated fatty acids, and antioxidants (Esfarjani *et al.,* 2019). The atherogenicity index (AI), thrombogenicity index (TI), and hypercholesterolemic index (HH) are health indicators used to evaluate the tendency of oils to form clots in blood vessels, which can consequently lead to cardiovascular diseases (Khalili Tilami and Kouřimská, 2022).

Dielectric properties play a vital role in human nutrition and pharmaceuticals. Oils that have higher dielectric constant (ε') values are usually absorbed and utilized by the body more rapidly. Apart from the nutritional and medical sectors, oils with a greater ε' are primarily suitable for the production of high energy storage capacitors (Lim *et al.,* 2023). Oils with higher ε' and dielectric loss (ε'') are more likely to contain more dissolve as saturated fatty acids. Additionally, impurities like water and metal particles may inhibit the oil's basic insulating properties, causing rapid dielectric breakdowns and electrical insulation failures; thereby affecting the oil's performance and reliability (Lizhi *et al.,* 2008; Koutras *et al.,* 2022). Transformer oil with a high dielectric constant improves transformer efficiency by increasing the insulation between the windings and other components (Rafiq *et al.,* 2020). Additionally, the dielectric properties of oils are essential parameters to consider in the production of electrical cables. Due to the environmental toxicity of traditional oil, there is a growing demand for eco-friendly bio-oil with lower eco-toxicity potential for electrical applications (Salama *et al.,* 2020). The phenolic compounds present in oils, in varying concentrations, help maintain their electrical properties by inhibiting the formation of conductive degradation products that can compromise their performance (Tian *et al.,* 2023).

Ginger (*Zingiber officinale* Roscoe) rhizomes contain large amounts of phytochemical compounds and UFAs; hence, displaying an outstanding antioxidant activity (Oforma *et al.,* 2019; Aremu *et al.,* 2023). Ginger oil (GO) is rich in bioactive compounds with health-promoting qualities (Ramadan, 2020). Ginger leaves and rhizomes contain significant amounts of minerals, phenolic compounds, vitamins, PUFAs, and phytochemical compounds, enhancing their health benefits and expanding their prospects for engineering applications. The bioactive compounds in ginger rhizomes make them a potential food item for managing severe ailments such as cardiovascular diseases, cancer, diabetes mellitus, and respiratory disorders (Mao *et al.,* 2019). Derivatives from ginger rhizomes have the capability to inhibit the formation of reactive oxygen species (ROS) and lipid peroxidation. These make ginger a potentially valuable dietary supplement aimed at combating oxidative damage, thereby supporting the proper functionality of bodily systems (Ramadan, 2020; Aremu *et al.,* 2023). From comprehensive literature review, the physiochemical, phytochemical and fatty acid compositions of oils derived from most crops have been exclusively studied. However, the correlation between the physiochemical, fatty acids, and dielectric properties of ginger rhizome oil and their nutritional profiles have not been fully reported. Consequently, this research aimed at investigating the relationship between GO storage duration, functional properties, and its dielectric properties, with major focus on its nutritional and pharmaceutical applications.

2. MATERIALS AND METHODS

2.1. Materials

Ginger (cultivar UG1, also known as "white variety") rhizomes were harvested at their peak maturity and thoroughly washed under running water to remove any foreign materials. Thereafter, the rhizomes were manually sorted to remove all pest-infested ones and divided into four batches to await storage treatment.

2.2. Methods

2.2.1. Treatments

The four rhizome batches were cut into small pieces and subjected to four treatment procedures as outlined here:

Natural condition = ambient temperature 30 ± 6 °C, 80 ± 5 % RH

Treatment 1 (T1) = the rhizomes were kept at a temperature of 20 °C

Treatment 2 (T2) = the rhizomes were kept at a temperature of 30 °C

Treatment 3 (T3) = the rhizomes were kept at a temperature of 40 °C

The cut rhizomes were kept at these temperatures until they were dried, enabling the extraction of their oil using the solvent method.

2.2.2. Oil extraction

Ginger rhizome oil (GO) from each batch was produced following the solvent (n-hexane) extraction method, in strict adherence to the American Oil Chemists' Society (AOCS) procedures as explained by Uguru *et al*. (2023).

2.3. Laboratory analysis

All the reagents used for the laboratory tests were of analytical grade, manufactured and mainly produced by Merck KGaA Company in Germany. The tests were conducted in triplicate and the mean values documented accordingly. The recovery rates for the Certified Reference Materials (CRMs) fell within the range of 91 and 103%.

2.3.1. Peroxide value (PV) determination

The peroxide value content in the oil was determined in accordance with the American Oil Chemists' Society (AOCS, 2011), as explained by Aremu *et al*. (2023).

2.3.2. Acid value (AV) and free fatty acid (FFA) determination

The acid value was measured by using the titration technique in agreement with AOCS recommendations. Additionally, the FFA level of the GO was determined in harmony with AOCS procedures, through simple titration as described by (Esfarjani *et al.,* 2019), and the results were expressed as mg KOH/g.

2.3.3. Iodine value (IV) determination

The GO iodine concentration was measured by adopting the Wijs technique, using a blank value of 40.0 and the result was expressed as gI_2/100 g.

2.3.4. Saponification value (SV)

The SV of the oil was determined in accordance with AOCS guidelines (AOCS 2021). The SV was calculated based on a blank value of 127.3, and the saponification value was expressed as mg KOH/g of oil sample.

2.3.5. Kinematic viscosity (KV) measurement

The ginger oil KV level was measured at a temperature of 40 °C in accordance with AOCS procedures (AOCS, 2011).

2.3.6. Vitamin C determination

The oil vitamin C level was determined through the spectrophotometric method, by using a spectrophotometer (model: UV-5300, manufactured in India), and adopting AOCS guidelines. The absorbance was compared to a standard curve to determine the vitamin C concentration in the oil.

2.3.7. Phytochemical properties

The phytochemical compositions of the GO were determined by employing the High-Performance Liquid Chromatography (HPLC) technique, using the HPLC Machine (model LC-W100B, manufactured by Wincom Company Ltd in China). The chromatographic column length of the machine was 0.1 m, using methanol as the solvent. The quantification limit of 0.001 mg/kg was used to quantitatively measure the phytochemical compounds in the oil at a constant temperature of 35 ºC and run time of 12 minutes.

2.3.8. Fatty acids profile

The GO fatty acid analysis was conducted using gas chromatography (GC-model Agilent 6890N manufactured in USA) equipped with a flame ionization detector in accordance with the AOCS guidelines, as explained by Oforma *et al.* (2019).

2.3.9. Dielectric constant (ε') determination

The oil ε′ was measured in accordance with ASTM D1531 procedures, using the Impedance Analyzer (model 1260A, manufactured by AMETEK scientific equipment, USA), as explained by Elmosalami *et al*. (2022) at a frequency on 1 MHz. The GO dielectric constant value was computed through Equation 1.

$$\varepsilon' = \frac{C_{aps}}{Co} \qquad \text{Eq.1}$$

Where Co is the empty cell capacitance, and C_{aps} is the loaded cell capacitance (Elmosalami *et al.,* 2022).

2.4. Oil nutritional quality index evaluation

The atherogenicity index (AI), thrombogenicity index (TI), and the ratio of hypocholesterolemic to hypercholesterolemic (HH) of the fatty acids, were computed from Equations 2, 3 and 4. These indices are used to evaluate the health benefits of the oil in relation to cardiovascular and heart diseases (Aremu *et al*. 2023; Rabiej-Kozioł *et al.,* 2023).

$$AI = \frac{C12{:}0 + 4(C14{:}0) + C16{:}0}{\sum MUFA + \sum\omega6 + \sum\omega3} \qquad \text{Eq. 2}$$

$$TI = \frac{C14{:}0 + C16{:}0 + C18{:}0}{0.5x\sum MUFA + (0.5x\sum\omega6) + (3x\omega3) + (\sum\omega3/\sum\omega6)} \qquad \text{Eq. 3}$$

$$HH = \frac{C18{:}1 + C18{:}2 + C18{:}3 + C18{:}4 + C20{:}4}{C14{:}0 + C16{:}0} \qquad \text{Eq. 4}$$

2.5. Statistical analysis

The SPSS (version 20.0) and Matlab (version 20.0) were used to carry out the statistical analysis and modeling of the experimental results. The effects of rhizome storage temperature on physiochemical parameters, vitamin C, phytochemical properties, fatty acid composition and dielectric parameters were determined by one-way analysis of variance; while the means were separated into significance levels of 0.05, using the Duncan’s Multiple Range Test (DMRT)

3. RESULTS AND DISCUSSION

3.1. Physiochemical properties and vitamin C level

The results of the vitamin C contents and physiochemical properties of the various GO batches are presented in Table 1. It was seen that apart from the moisture content, the heat treatment had a significant effect on the remaining GO physiochemical parameters investigated. Notably, the GO SV ranged from 164.07 to 216.81 mg KOH/g, acid value varied from 3.79 to 4.16 mg KOH/g, FFA content ranged from 1.90 to 2.08 mg KOH/g, peroxide value varied from 10.40 to 13.90 meq O_2/kg, MC value ranged from 0.73 to 0.75%, iodine value varied from 82.37 to 101.13 gI_2/100 g, and the KV ranged from 122.00 to 164.00 mm^2/s. The high AV and FFA recorded in the GO is similar to the observation by Aremu (2023) and Prasad and Tyagi (2015), who stated that ginger oil contains significant amounts of organic acids. FFA, PV, and AV are crucial physiochemical factors which affect the phytochemical properties of oils (Abdiani *et al.,* 2024). However, the results show that the GO iodine value decreased as the AV, PV and FFA in the

Table 1. Physiochemical properties and vitamin C level in ginger oil

Parameter	Natural	Treatment 1	Treatment 2	Treatment 3
Physiochemical properties				
SV(mg KOH/g)	$191.43^{c} \pm 1.62$	$164.07^{a} \pm 2.22$	$181.26^{b} \pm 1.50$	$216.81^{d} \pm 2.91$
AV (mg KOH/g)	$4.03^{b} \pm 0.05$	$3.79^{a} \pm 0.08$	$3.96^{b} \pm 0.06$	$4.16^{c} \pm 0.06$
FFA (mg KOH/g)	$2.03^{b} \pm 0.03$	$1.90^{a} \pm 0.05$	$1.99^{b} \pm 0.05$	$2.08^{c} \pm 0.03$
PV (meq O_2/kg)	$12.73^{c} \pm 0.36$	$10.40^{a} \pm 0.35$	$11.73^{b} \pm 0.26$	$13.90^{d} \pm 0.65$
MC (%)	$0.74^{a} \pm 0.03$	$0.73^{a} \pm 0.02$	$0.75^{a} \pm 0.02$	$0.74^{a} \pm 0.02$
IV (gI_2/100 g)	$88.13^{b} \pm 1.61$	$101.13^{c} \pm 5.17$	$92.91^{b} \pm 3.08$	$82.37^{a} \pm 4.41$
KV mm^2/s	$152.60^{c} \pm 6.19$	$122.00^{a} \pm 3.54$	$137.80^{b} \pm 5.54$	$164.00^{d} \pm 8.19$
Vitamin				
Vitamin C	$72.58^{b} \pm 2.33$	$86.99^{c} \pm 2.24$	$76.15^{b} \pm 3.67$	$63.34^{a} \pm 3.10$

± mean and standard deviation, n(replication) = 5, rows with the same letter (superscript) indicate that the results are not significantly different ($p \leq 0.05$) using the DMRT. SV = Saponification value, AV = Acid value, FFA = free fatty acids, IV = Iodine value, MC = moisture content, KV = Kinematic viscosity

oil underwent a continuous increase. Elevated FFA, PV and AV contents are indicators of poor oil quality as they signify that the oil is highly susceptible to oxidation and rancidity (Esfarjani *et al.,* 2019). Oils with high PV are linked to cardiovascular diseases, cancers, and obesity, reducing their suitability for dietary use.

Remarkably, the rhizomes stored under T1 produced the GO with the lowest concentrations of SV, AV, FFA, PV and KV; while rhizomes stored under T2 produced GO with the highest concentration of SV, AV, FFA, PV and KV. Likewise, the rhizomes kept at lower temperature (T1) yielded oil with highest IV. This is an indication that the elevated temperature accelerated the process of rancidity and the degradation of glycerides within the ginger rhizomes' oil cells. High temperatures facilitated the UFAs oxidation, leading to the formation of peroxides and other oxidation by-products. These substances further degraded into smaller molecules such as free fatty acids, thereby altering the oil's acidity and electrical properties (Tian *et al.,* 2023; Abdiani *et al.,* 2024). Iodine, saponification, peroxide, and acid values are essential parameters used to assess oil quality. The SV and AV offer reliable insights into the molecular weight and the carboxylic acid groups of fatty acids present in oil. The IV and SV indicate the level of unsaturation in oil, while the PV reflects the degree of oxidative deterioration. Additionally, the AV and IV are commonly used to predict the electrical and fuel properties of oils.

With respect to the vitamin C content in the oil, it was observed that the vitamin C levels in the Natural, T1, T2 and T3 oil samples were 72.58, 86.99, 76.15 and 63.34 mg/L, respectively. It was noted that the storage temperature had a significant impact on the GO's vitamin C level, with the highest and lowest vitamin C contents recorded in the rhizomes stored at 20 °C and 40 °C, respectively (Table 1). Vitamin C is a heat and UV radiation sensitive water-soluble vitamin; hence, the higher temperature could be linked to the depleted vitamin C concentration in the oil produced from Natural and T4 storage conditions. High temperatures facilitate the oxidation of vitamin C to dehydroascorbic acid and other inactive substances (Abdiani *et al.,* 2024). Also, the lower AV, PV and FFA values recorded in the T1 oil specimen can be linked to the higher vitamin C content documented in the T1 oil, as those physiochemical parameters have the ability to degrade and oxidize natural vitamins and antioxidants. Vitamin C is a major antioxidant which plays a critical role in defending the body against oxidative stress by scavenging reactive oxygen species (Kim *et al.,* 2017).

3.2. Phytochemical properties of ginger oil

Table 2 presents the results of the GO phytochemical analysis. It was observed that the concentration of phytochemical compounds depreciated as the environmental temperature rose. Generally,

Table 2. Phytonutrient levels during storage (mg/kg)

	Natural	T1	T2	T3
Lunamarin	$0.78^{a} \pm 0.14$	$1.03^{b} \pm 0.07$	$0.99^{b} \pm 0.05$	$1.10^{c} \pm 0.03$
Anthocyanin	$2.58^{a} \pm 0.25$	$3.01^{c} \pm 0.23$	$2.81^{b} \pm 0.07$	$2.40^{a} \pm 0.15$
Flavonones	$4.91^{b} \pm 0.20$	$6.71^{d} \pm 0.43$	$5.33c \pm 0.30$	$4.46^{a} \pm 0.18$
Kaempferol	$3.11^{a} \pm 0.12$	$3.89^{c} \pm 0.12$	$3.40^{b} \pm 0.34$	$3.11^{a} \pm 0.12$
Epicatechin	$6.14^{b} \pm 0.23$	$6.88^{c} \pm 0.19$	$6.36^{b} \pm 0.41$	$5.62^{a} \pm 0.43$
Flavone	$4.88^{b} \pm 0.16$	$5.85^{c} \pm 0.21$	$4.93^{b} \pm 0.12$	$4.66^{a} \pm 0.20$
Catechin	$9.17^{b} \pm 0.29$	$9.99^{d} \pm 0.11$	$9.32^{c} \pm 0.16$	$8.82^{a} \pm 0.17$
Resveratrol	$3.87^{b} \pm 0.12$	$4.17^{c} \pm 0.21$	$3.90^{b} \pm 0.15$	$3.36^{a} \pm 0.19$
Genistein	$2.19^{a} \pm 0.13$	$3.06^{c} \pm 0.32$	$2.50^{b} \pm 0.38$	$2.12^{a} \pm 0.20$
Quercetin	$4.36^{a} \pm 0.08$	$6.08^{c} \pm 0.85$	$5.42^{b} \pm 0.17$	$4.10^{a} \pm 0.01$
Luteolin	$1.20^{a} \pm 0.03$	$1.94^{c} \pm 0.18$	$1.55^{b} \pm 0.25$	$1.12^{a} \pm 0.07$
Ferulic acid	$1.24^{a} \pm 0.05$	$2.19^{c} \pm 0.32$	$1.65^{b} \pm 0.06$	$1.19^{a} \pm 0.03$
Artemetin	$7.72^{b} \pm 0.20$	$8.90^{d} \pm 0.17$	$8.19^{c} \pm 0.24$	$7.49^{a} \pm 0.40$
Gallocatechin	$0.22^{a} \pm 0.07$	$0.46^{c} \pm 0.06$	$0.33^{b} \pm 0.01$	$0.21^{a} \pm 0.03$
Retusin	$0.39^{a} \pm 0.03$	$0.73^{c} \pm 0.09$	$0.53^{b} \pm 0.03$	$0.35^{a} \pm 0.05$
Nobeletin	$1.99^{a} \pm 0.31$	$2.78^{c} \pm 0.25$	$2.30^{b} \pm 0.16$	$1.89^{a} \pm 0.19$
Ellagic acid	$1.38^{a} \pm 0.07$	$2.23^{c} \pm 0.24$	$1.84^{b} \pm 0.40$	$1.34^{a} \pm 0.03$
Tangeretein	$1.57^{a} \pm 0.04$	$1.86^{c} \pm 0.12$	$1.69^{b} \pm 0.21$	$1.51^{a} \pm 0.14$
Vanillic acid	$7.36^{a} \pm 0.48$	$8.86^{c} \pm 0.64$	$8.29^{b} \pm 0.31$	$6.76^{a} \pm 0.56$
Hesperidin	$0.80^{b} \pm 0.09$	$0.90^{c} \pm 0.06$	$0.82^{b} \pm 0.22$	$0.74^{a} \pm 0.03$
Butein	$0.31^{b} \pm 0.03$	$0.42^{c} \pm 0.08$	$0.42^{c} \pm 0.08$	$0.29^{a} \pm 0.02$
Apigenin	$5.10^{b} \pm 0.04$	$6.09^{d} \pm 0.25$	$5.68^{c} \pm 0.34$	$4.99^{a} \pm 0.16$
Naringenin	$0.60^{a} \pm 0.11$	$0.81^{c} \pm 0.05$	$0.69^{b} \pm 0.19$	$0.57^{a} \pm 0.11$
Myricetin	$9.89^{b} \pm 0.58$	$11.91^{c} \pm 0.43$	$10.33^{bc} \pm 0.50$	$9.40^{a} \pm 0.26$
Hesperidin	$0.50^{b} \pm 0.11$	$0.77^{d} \pm 0.16$	$0.66^{c} \pm 0.06$	$0.47^{a} \pm 0.10$
Daidzin	$0.48^{b} \pm 0.07$	$0.69^{d} \pm 0.09$	$0.55^{c} \pm 0.10$	$0.46^{a} \pm 0.06$
Isorhamnetin	$0.39^{b} \pm 0.05$	$0.59^{c} \pm 0.03$	$0.54^{bc} \pm 0.09$	$0.38^{a} \pm 0.04$

± mean and standard deviation, n= 3, rows with the common letter (superscript) are not significantly different ($p \leq 0.05$) using the DMRT.

the oil produced from rhizomes kept at 20 °C (T1) tended to have the highest percentage of phytochemical compounds, while from rhizomes stored at 40 °C (T3) produced GO with the lowest percentage of phytochemical compounds. According to Mao *et al*. (2019), heat treatment and storage duration can alter the phytochemical compositions of ginger rhizomes' essential oil.

Interestingly, 25 out of the 26 phytochemical compounds analyzed in ginger oil are phenolic compounds with potential antioxidant properties, highlighting the remarkable antioxidant potential of ginger oil. It was noted that Lunamarin was the only non-phenolic and non-antioxidant compound detected in the ginger oil. Also, it was noted that catechin, artemetin, epicatechin, quercetin, vanillic acid and myricetin were the predominant compounds present in the GO, regardless of the treatment applied. Remarkably, while heat treatment leads to a reduction in essential phenolic compounds, it effectively detoxifies the lunamarin content in the oil by accelerating its hydrolysis, thereby reducing the oil's cyanogenic potential.

The total phenolic compound (THC) contents in the ginger oil ranged from 78.91 to 102.56 mg/kg, which is within the THC range reported for cottonseed oil (Zhao *et al.,* 2021). The THC level in the GO was greater than the THC values documented for walnut (*Juglans regia* L.) oil, palm kernel oil, rice (*Oryza sativa*) bran oil, and maize (*Zea mays*) oil (Mikolajczak *et al.,* 2021); but was lower than the amount reported for pomegranate (*Punica granatum*) seed oil (Drinic *et al.,* 2020) and grape (*Vitis vinifera* L.) seed oil (Mikolajczak *et al.,* 2021). The wide variation in THC observed in the investigated oils could be attributed to the total number of quantified phenolic compounds, prevailing climatic conditions, as well as the processing, storage, and testing methods used (Tian *et al.,* 2023; Uguru *et al.,* 2023). Phenolics are essential natural compounds that help slow the oxidative degradation of oils, thereby preserving their nutritional values, functional properties and electrical properties.

3.3. Fatty acids profile

The fatty acids profile results of the GO are presented in Table 3. It was observed that the considerable initial amount of SFA tended to increase as the storage temperature increased. The Natural, T1, T2 and T3 GO sample SFA values were 41.91, 36.37, 39.13 and 45.47 ppm, respectively. Palmitic, oleic and linoleic acids were the most prominent SFA, MUFA and PUFA in the oil, respectively. Apart from palmitic acid, other notable SFA in the GO were caprylic, capric, lauric and myristic acids; while other PUFA present in the GO in appreciable amounts were linolenic, arachidonic, osbond, and docosahexaenoic acids. The substantial presence of linoleic, oleic

Table 3. The CRO fatty acid profile (mg/kg)

Acid		Natural	T1	T2	T3
SFA					
Caprylic acid	C8:0	$3.01^{c} \pm 0.15$	$1.95^{a} \pm 0.17$	$2.86^{b} \pm 0.17$	$3.36^{c} \pm 0.17$
Capric acid	C10:0	$4.69^{c} \pm 0.15$	$4.11^{b} \pm 0.10$	$4.28^{b} \pm 0.30$	$5.12^{d} \pm 0.20$
Lauric acid	C12:0	$1.98^{b} \pm 0.04$	$1.72^{a} \pm 0.10$	$1.80^{a} \pm 0.28$	$2.14^{c} \pm 0.11$
Myristic acid	C14:0	$4.62^{b} \pm 0.14$	$4.25^{a} \pm 0.25$	$4.35^{a} \pm 0.15$	$4.90^{c} \pm 0.08$
Palmitic acid	C16:0	$21.17^{c} \pm 0.75$	$19.31^{a} \pm 0.34$	$20.22^{b} \pm 0.08$	$22.64^{d} \pm 1.08$
Stearic acid	C18:0	$2.68^{b} \pm 0.18$	$2.15^{a} \pm 0.07$	$2.21^{a} \pm 0.21$	$3.10^{c} \pm 0.12$
Arachidic acid	C20:0	$0.95^{b} \pm 0.07$	$0.83^{a} \pm 0.09$	$0.87^{a} \pm 0.04$	$1.08^{c} \pm 0.13$
Behenic acid	C22:0	$0.97^{c} \pm 0.01$	$0.83^{a} \pm 0.05$	$0.90^{b} \pm 0.04$	$1.10^{d} \pm 0.10$
Lignoceric	C24:0	$1.84^{c} \pm 0.16$	$1.22^{a} \pm 0.03$	$1.64^{b} \pm 0.08$	$2.03^{d} \pm 0.06$
ΣSFA		**41.91 ± 1.41**	**36.37 ± 1.20**	**39.13 ± 1.35**	**45.47 ± 2.05**
UFA					
Oleic acid	C18:1	$16.23^{b} \pm 0.92$	$17.76^{c} \pm 0.43$	$16.74^{b} \pm 1.07$	$15.42^{a} \pm 1.29$
Linoleic acid	C18:2	$25.03^{b} \pm 0.51$	$26.95^{c} \pm 0.95$	$25.35^{b} \pm 0.26$	$24.19^{a} \pm 0.07$
Linolenic acid	C18:3	$6.37^{b} \pm 0.07$	$7.81^{c} \pm 0.37$	$6.83^{b} \pm 0.07$	$6.01^{a} \pm 0.22$
Eicosenoic acid	C20:1	$0.34^{c} \pm 0.01$	$0.26^{ab} \pm 0.05$	$0.23^{a} \pm 0.01$	$0.30^{b} \pm 0.01$
Eicosadienoic Acid 6	C20:2	$2.16^{a} \pm 0.03$	$2.86^{c} \pm 0.15$	$2.34^{b} \pm 0.04$	$2.04^{a} \pm 0.12$
Arachidonic Acid 6	C20:4	$4.76^{b} \pm 0.08$	$5.62^{c} \pm 0.31$	$5.25^{c} \pm 0.12$	$4.18^{a} \pm 0.06$
Adrenic acid 6	C22:4	$3.29^{b} \pm 0.18$	$3.88^{c} \pm 0.17$	$3.41^{b} \pm 0.12$	$2.97^{a} \pm 0.17$
Osbond acid 3	C22:5	$4.82^{b} \pm 0.01$	$5.06^{c} \pm 0.20$	$4.90^{b} \pm 0.03$	$4.18^{a} \pm 0.08$
Docosahexaenoic Acid 3	C22:6	$4.31^{b} \pm 0.04$	$4.90^{d} \pm 0.20$	$4.46^{c} \pm 0.22$	$3.94^{a} \pm 0.16$
ΣMUFA		**16.57 ± 0.93**	**18.02 ± 0.48**	**16.97 ± 1.08**	**15.72 ± 1.3**
ΣPUFA		**50.74 ± 0.92**	**57.08 ± 2.35**	**52.54 ± 0.86**	**47.51 ± 0.88**
PUFA/SFA		**1.21**	**1.57**	**1.34**	**1.04**
AI		**0.66**	**0.54**	**0.61**	**0.75**
TI		**0.48**	**0.38**	**0.43**	**0.55**
HH		**2.03**	**2.47**	**2.21**	**1.81**

± mean and standard deviation, n(replication) = 3, the same letter (superscript) within a row indicates that the means are not significantly different ($p \leq 0.05$) using the DMRT.

and palmitic acids found in the current study's GO closely aligns with the findings reported by Ramadan (2020) and Oforma *et al.* (2019). Additionally, The SFA quantity recorded in this research waslower than those documented for palm oil (Choudhary and Grover, 2019) and coconut oil (Dorni *et al.,* 2018), but greater than the results reported for pumpkin, sunflower and pomegranate seed oil (Drinic *et al.,* 2020; Khalili Tilami and Kouřimská, 2022).

It was also observed that amount of lauric acid in the GO was lower than the value reported for coconut oil (Dorni *et al.,* 2018). Lauric acid is an UFA known for its strong antimicrobial and anti-inflammatory properties, and it may also support cardiovascular and skin health. The palmitic acid value of the GO was lower than the result recorded for palm oil (Choudhary and Grover, 2019). Palmitic acid is a significant SFA which is crucial for ATP production and possesses antimicrobial properties. However, its toxicity is linked to an increased risk of cardiovascular disease. Linoleic acid, a key essential omega-6 fatty acid abundantly found in GO, has the potential to exhibit anti-inflammatory properties, lower blood LDL levels, and boost the body's immune system (Tian *et al.,* 2023).

Furthermore, it was noted that the ginger oil's AI, TI and HH values ranged from 0.54 to 0.75, 0.38 to 0.55, and 1.81 to 2.47, respectively. Although the ginger oil TI and AI values increased with rising storage temperatures, their values remained below 1. Furthermore, the HH values were greater than 1.0, regardless of the treatment applied. The results of this research GO's AI and TI values were less than the values (AI ~0.91, TI ~0.80) recorded by Aremu *et al.* (2023) for ginger oil; but were higher than the values (AI ~0.04, TI ~0.23) for cold-pressed sunflower oil (Rabiej-Kozioł *et al.,* 2023). Similarly, the HH values recorded in this study were lower than those documented for cold-pressed pumpkin oil (6.47) and sunflower oils (13.23) by Rabiej-Kozioł *et al*. (2023).

Atherogenicity index, TI, and HI are nutritional indices used to evaluate the suitability of oils for human consumption, as their values are used to determine the possibility of oil causing health hazards, such as blood clots and thrombus conditions. From a nutritional perspective, low values of AI and TI are preferred in the human diet. Additionally, oils with higher HH values are more beneficial for human health (Aremu *et al.,* 2023). Remarkably, though the SFA value of the oil was relatively high, the higher PUFA: SFA and HH values (>1), coupled with lower AT and TI values (<1), are indications that GO is beneficial for heart health and preferred in the human diet. Oils with lower PUFA: SFA and HH values (<1), and elevated AT and TI values (>1) are linked to increased risk of heart disease, through increased cholesterol levels (Rokosik *et al.,* 2020; Khalili Tilami *et al*, 2022).

3.4. Electrical properties

The results of the GO dielectric constant are presented in Figure 1. It was observed that the ε′ of the natural condition, T1, T2 and T3 were 3.152, 3.052, 3.128 and 3.258, respectively, which is an indication that the heat treatment had a substantial effect on the electrical properties of the oil. Interestingly, the ε′ values of the GO were comparable to those reported by Elmosalami *et al*. (2022) for olive and corn oils. The increase in the GO's ε′ values with rising storage temperatures can be attributed to the oxidation of the oil components in the ginger rhizomes, resulting in oil with higher AV, FFA and PV parameters of the oil (Table 1). This process is accompanied by increased acidity of the oil, which consequently leads to a rise in the dielectric constant (Šegatin *et al.,* 2020). It was observed that the oil's ε′ value tended to increased unevenly as the SFAs content in the oil increased. A high acid value is an indication of oil degradation through the hydrolysis and oxidation of the unsaturated fatty acids (Table 3). This generates more saturated fatty acid (a more polar compound) which produce more dielectric constant charges within the oil (Inoue *et al.,* 2002).

The GO ε′ values recorded in this study were higher than the values reported for safflower and sunflower oils, but smaller when compared to the documented corn oil ε′ values (Lizhi *et al.,* 2008). The higher ε′ value of T3 GO will enhance the oil's capacity to minimize electrical discharges, thereby upholding the reliability of the electrical equipment in which it is used. A high ε′ generally increases the insulating and electrical energy storage competences of oil, further improving its effectiveness in high voltage and capacitance applications (Lim *et al.,* 2023). The dielectric constant value is dependent on the acids and structural compositions, moisture level, viscosity and temperature of the oil

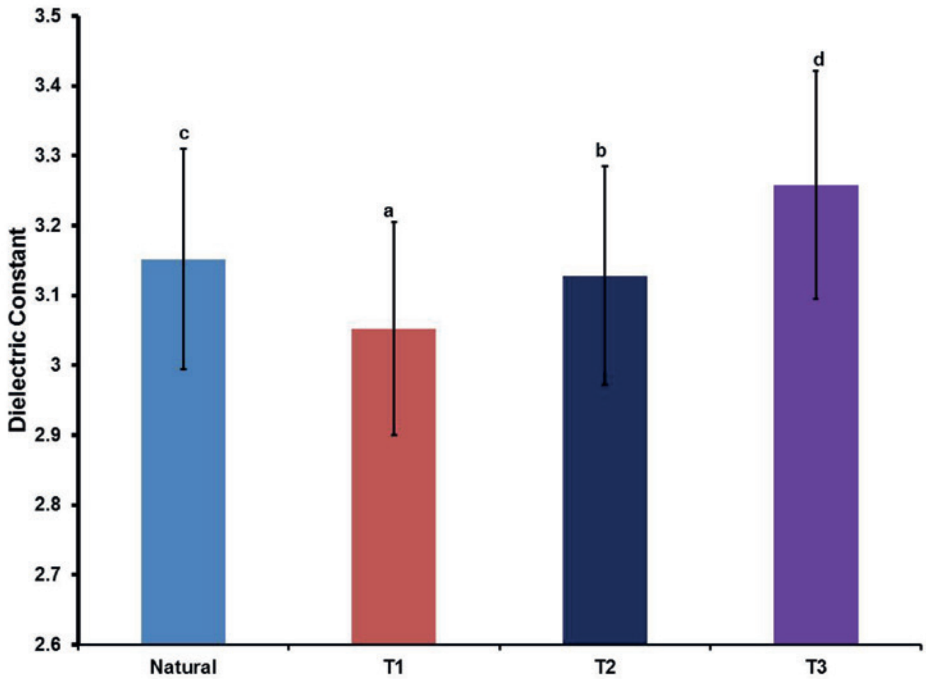

Figure 1. The dielectric constant of the oil
n = 5, bars with the same letter indicate that the results are not significantly different ($p \leq 0.05$) using the DMRT.

(Lizhi *et al.,* 2008). According to Elmosalami *et al*. (2022), in addition to their relevance in the electrical sector, dielectric properties are essential for assessing the nutritional and pharmaceutical qualities of edible oils.

3.4.1. Modeling of the dielectric constant

The Stepwise Linear Regression appears to hold promise for forecasting the dielectric constant of oil through the physiochemical properties, due to its loweRMSE value. The model properties of the stepwise linear regression are presented in Table 4. Generally, the low RMSE value (0.046) indicates a strong correlation between the predicted and observed values of the dielectric constant measurement, reflecting the excellent performance of the developed model.

Table 5 compares the experimental versus the predicted value of the ginger oil ε′ for the frequency 7 GHz. It was noted that the mismatch between the calculated ε′ and the predicted ε′ values in this model is less than 5%, which is considered as acceptable convergence between the two values. Figures 2 and 3 illustrate the plots depicting the effects of prediction error on the dielectric constant of the oil and the fit-

Table 4. Model properties of the stepwise linear regression

Property	Value
Number of Observations	20
Degree of Freedom of Error	18
R Square	0.692
Adjusted R Square	0.675
AIC	-64.723
AICc	-64.017
BIC	-62.732
CAIC	-60.732
P value	6.04E-35
Log Likelihood	34.362
SSR	0.085
SST	0.122
SSE	0.038
RMSE	**0.046**
MSE	0.002
Prediction speed	170 obs/sec
Training time	31.734 sec
Model size (Compact)	5kB
Maximum no of steps	1000

AIC is Akaike information criterion. AICc is Akaike information criterion with a correction. BIC is Bayesian information criterion. CAIC is Consistent Akaike information criterion. SSR is Sum of the Squared Residuals. SST is Total sum of squares. SSE is Sum of the Squares of Errors. RMSE is Root mean square error. MSE is square error. MAE is Mean absolute error.

Table 5. Model fitting using the generated code for the same data

Temperature	Replication	Moisture content	Iodine value	Free fatty acid	Kinematic viscosity	Dielectric	
						Actual	Predicted
Natural air temperature	1	0.74	87.73	2.01	157	3.15	3.19
	2	0.78	88.98	2.02	150	3.18	3.17
	3	0.75	90.23	2.04	161	3.17	3.20
	4	0.71	85.91	2.07	149	3.12	3.17
	5	0.74	87.78	1.99	146	3.14	3.16
20 degrees	1	0.71	101.23	1.95	121	3.09	3.06
	2	0.73	109.39	1.85	120	3.04	3.04
	3	0.69	95.42	1.87	128	3.03	3.09
	4	0.74	100.94	1.95	119	3.02	3.05
	5	0.75	98.65	1.88	122	3.08	3.06
30 degrees	1	0.75	90.83	1.95	134	3.11	3.11
	2	0.77	91.29	1.98	131	3.14	3.10
	3	0.74	97.04	2.06	141	3.09	3.13
	4	0.76	95.31	1.95	138	3.17	3.12
	5	0.72	90.06	2.02	145	3.13	3.15
40 degrees	1	0.77	81.21	2.05	168	3.22	3.24
	2	0.74	80.9	2.08	163	3.28	3.22
	3	0.81	89.45	2.08	151	3.29	3.17
	4	0.76	77.47	2.14	173	3.23	3.26
	5	0.78	82.83	2.07	165	3.27	3.23

ness of the model, respectively. Table 5, Figures 2 and 3 show the potential of measuring the dielectric constant of the oil through the AV, FFA, PV and SV of the oil, regardless of the storage temperature. It was noted that the ε′ calculated and the predicted value in this model is less than 5%. These findings depicted that a Partial Least Squares analysis can be used to forecast the ε′ of the GO based on its physicochemical properties.

4. CONCLUSIONS

Food quality is a crucial component for achieving food security. This study was conducted to assess the impact of the storage temperature of ginger rhizomes on the quality of the extracted ginger oil. The levels of vitamin C, physicochemical properties, phytochemicals, fatty acids, and dielectric constant (ε′) of ginger rhizome oil (GO), extracted using the solvent extraction technique from rhizomes stored at varying temperatures, were determined in accordance with approved procedures. This study's outcomes indicated that iodine value, vitamin C, phytochemical and PUFA of the oil decline non-linearly as the storage temperature increases; while the AV, SV, PV, SFA and dielectric content level of the oil increases at the temperature at which the ginger rhizomes were stored. Remarkably, the oil contains significant amounts of essential phytonutrients and UFAs. The calculated values of the atherogenicity index, thrombogenicity index, and ratio of hypocholesterolemic to hypercholesterolemic of the fatty acids revealed that GO possesses significant medicinal and nutritional qualities. Furthermore, the Partial Least Squares analysis revealed that the GO ε′ can be reliably predicted based on its physicochemical properties. The findings of this research have shown that ginger oil is an essential oil with numerous applications in both the medical and engineering sectors.

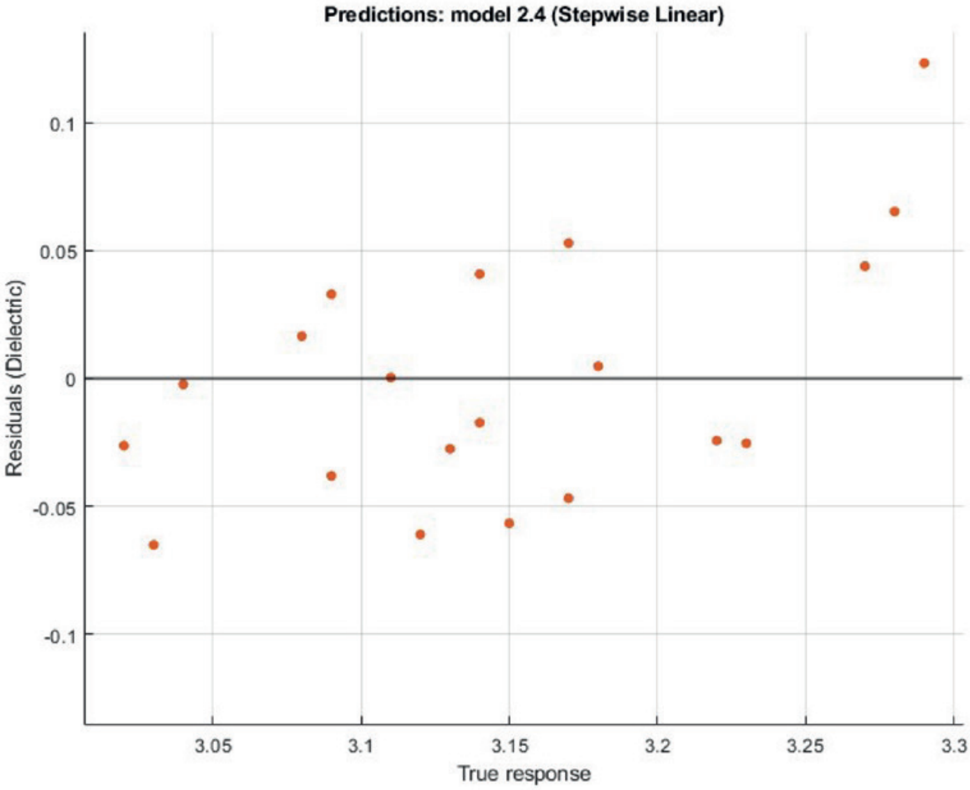

Figure 2. Effects of error of prediction on dielectric constant

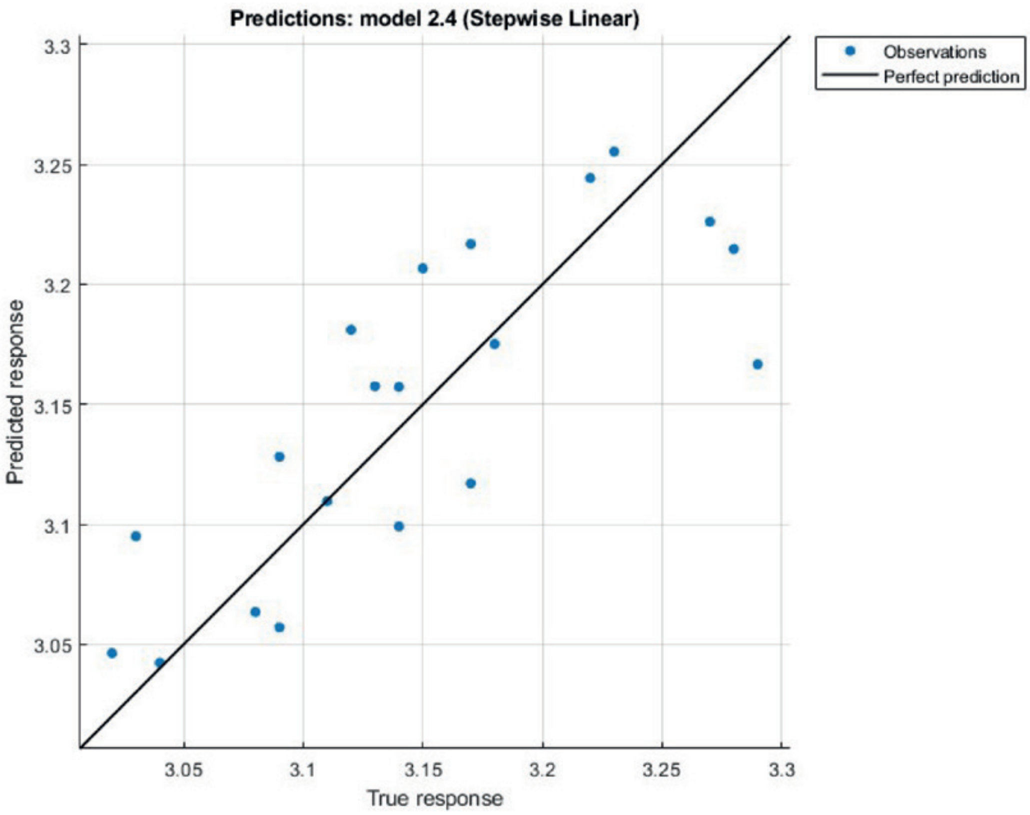

Figure 3. The fittest of the model

RESEARCH DATA POLICY DATA AVAILABILITY

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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DECLARATION OF COMPETING INTEREST

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

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AUTHOR CONTRIBUTION

A.S.A., A.A.M., Conceptualization, Formal analysis, Funding acquisition, H.U., Data analysis, Writing – original draft, A.O., K.A., Investigation, Methodology, R.S., A.A.G., M.H., A.W.A Project administration, Writing – original draft, Writing – review & editing

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