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Characterization and stability of carrot root oil (D. *carota subsp. Sativus*) with predictive modelling

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SUMMARY: This research was conducted to determine the influence of storage duration on the stability of carrot root oil (CRO). Chemical analyses of the CRO produced through the solvent extraction technique and stored in the dark at 30±5 °C for 150 days, were carried out in line with standard procedures. The results revealed that CRO contains an appreciable amount of unsaturated fatty acids, phytochemicals and physiochemical properties. Moreover, the phytochemical analysis indicated that ephedrine, epicatechin, and lunamarin were the most prevalent compounds in the CRO. The oil quality (unsaturated fatty acids and phytochemicals) declined non-linearly during storage. The acid value content increased from 0.49 to 1.04 mgKOH/g; while the carotenoids, iodine, tocopherol and polyunsaturated fatty acids levels decreased by 15, 27, 21 and 28 %, respectively, after 150 days. These findings clearly demonstrate that CRO contains appropriate concentrations of essential compounds, making it a sustainable fixed oil for medical and nutritional applications.

KEY-WORDS: *Antioxidant effects; Cardiovascular health; Fixed oil; Micronutrients; Shelf-life.*

RESUMEN*: Caracterización y estabilidad del aceite de raíz de zanahoria (*D. carota subsp. sativus*) con el modelado de predicción*. Esta investigación se realizó para determinar la influencia del tiempo de almacenamiento en la estabilidad del aceite de raíz de zanahoria (CRO). Los análisis químicos del CRO extraido mediante solventes y almacenado en condiciones de oscuridad a 30 ± 5 ºC durante 150 días, se realizaron en armonía con los procedimientos estándar. Los resultados mostraron que el CRO contiene una cantidad apreciable de ácidos grasos insaturados y fitoquímicos. Además, el análisis fitoquímico indicó que efedrina, epicatequina y lunamarina fueron los compuestos más abundantes en el CRO. Es de destacar que la calidad del aceite (ácidos grasos insaturados y fitoquímicos) disminuyó de forma no lineal durante el almacenamiento. El contenido ácido aumentó de 0,49 a 1,04 mgKOH/g; mientras que los niveles de carotenoides, yodo, tocoferol y ácidos grasos poliinsaturados disminuyeron en un 15, 27, 21 y 28 %, respectivamente, después de 150 días. Estos resultados demuestran claramente que el CRO contiene concentraciones adecuadas de compuestos esenciales, lo que lo convierte en un aceite a tener en cuenta para aplicaciones médicas y nutricionales.

PALABRAS CLAVE: *Aceite de raíz de zanahoria; Efecto antioxidante; Micronutrientes; Salud cardiovascular; Vida útil.*

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1. INTRODUCTION

Carrots (*Daucus carota*), a member of the Apiaceae carrot family, are widely grown edible taproot crops which are valued for their industrial, medicinal and nutritional properties around the world. Carrot root comprises large amounts of important nutrients, including antioxidants, phytochemicals, minerals, vitamins A, C and E, and dietary fiber, with low amounts of calories, saturated fatty acids and cholesterol (Musa Özcan and Chalchat, 2007). Carrots contain a high carotene concentration, but lower than the quantity present in palm oil fruits (Ranalli *et al.,* 2004; Ojha *et al*., 2024). A further limitation of carrot roots is their perishability, making them susceptible to microbial growth during storage and potentially harmful to human health. Effective storage and processing techniques are essential in the carrot food chain to minimize the challenges associated with carrot root perishability (Musa Özcan and Chalchat, 2007; Sharma *et al*., 2012; Arthur *et al.,* 2021). The nutritional quality of carrots depends on factors such as variety, cropping method, processing technique and storage conditions (Arthur *et al*., 2021).

Antioxidants, vitamins and minerals play vital parts in the human body and are crucial for maintaining overall human health (Duru and Enyoh, 2020; Matthäus *et al*., 2021; Mikolajczak *et al.,* 2021; Kalinowska *et al*., 2022). Carrots are rich in carotenoids and tocopherols (Musa Özcan and Chalchat, 2007), and these contribute immensely to combating deficiency diseases and optical system performance. The consumption of food items which are rich in natural antioxidants provides numerous benefits against the actions of free radicals. Carotenoids and tocopherols have potent antioxidant properties, which help to deactivate reactive oxygen species (ROS), and exert pivotal functions in retinal performance and vision (Sharma *et al*., 2012; Kalinowska *et al*., 2022). The tocopherols content in carrots helps to boost the body's immune system and enhance the performance of skin cell membranes. The consumption of essential oils which are rich in aromatic compounds is increasing rapidly, driven by their perceived medicinal and cosmetic benefits. Lavender (*Lavandula* angustifolia) and peppermint (*Mentha xpiperita*) oils are used in aromatherapy to reduce internal stress and facilitate relaxation (Jomova *et al*., 2022); while, carrot seed oil and tea tree (*Melaleuca alternifolia*) oil are commonly incorporated into skincare products because of their nurturing and anti-inflammatory characteristics, and aiding in cellular rejuvenation (Arthur *et al*., 2021).

Plant-based oils are characterized by high concentrations of phytochemicals, phenolic compounds, and essential fatty acids. Notably, carrot root contains a substantial amount of oil due to its moderate fat content (Tian *et al.,* 2023). Carrot root oil has been shown to possess a notable concentration of beta-carotene and minerals, thereby facilitating maintenance of the bodily electrolyte levels, suppressing free radical activities and improving vision health, reducing inflammation and enhancing immune functions. Oil obtained from carrot roots is a fixed oil, in contrast to carrot seed oil, primarily because carrot root oil (CRO) contains a high level of fatty acids and fat-soluble nutrients (Sharma *et al*., 2012; Tian *et al.,* 2023). The presence of phytochemical compounds in plant-based oils is essential, as they significantly enhance the stability and versatility of these bioactive substances, thereby conferring antioxidant, antimicrobial, anti-inflammatory, and protective properties. As a result, these oils are used as fortifying agents to enhance the nutritional value and stability of other vegetable or animal oils by optimizing their functional properties (Mikolajczak *et al*., 2021; Tian *et al*., 2023). Globally, carrot oil is widely utilized in the cosmetic, pharmaceutical, and food industries, resulting in a rapid increase in its demand due to its diverse applications.

The degradation of oils during storage is a complex phenomenon that can be exacerbated by multiple external factors, including high storage temperatures, contaminants, initial acid value and prolonged storage periods. These factors collectively exert a significant influence on the quality of the stored oil, ultimately compromising its overall integrity and shelf life (Abdiani *et al*., 2024). Oils with higher antioxidant concentrations and lower acid values exhibit greater stability during storage, as they are better equipped to resist oxidative degradation. Most antioxidants, functioning as free radical scavengers, effectively inhibit the oil oxidation rate and prevent the formation of unpleasant flavors and odors associated with rancidity (Omozuwa *et al*., 2023; Tian *et al.,* 2023; Uguru *et al*., 2023). Proper understanding of the oil's deterioration pattern during storage helps in quality control, logistics planning, and public health safety. This will result in supply chain management and consumer preference optimization, thus positively impacting both the oil industry and health considerations (Kalinowska *et al*., 2022)

A review of previous literature has revealed that numerous studies have investigated the effects of storage methods on oil quality (Nwakodo *et al*., 2019; Asemave *et al.,* 2012; Abdiani *et al.,* 2024; Uguru *et al*., 2023), yet a significant knowledge gap exists regarding the impact of storage duration on the quality of carrot root oil. Carrot oil is one of the promising fixed oils used for various nutritional and medicinal applications due to its enriched vitamin, mineral, and antioxidant contents, which contribute to its therapeutic effects (Arthur *et al.,* 2021; Ranalli *et al*., 2024). Consequently, the focal aim of this research was the chemical characterization (iodine value, total carotenoid content, acid value, tocopherol, fatty acid profile and phytochemical profile) of oil extracted from carrot roots, and to comprehensively examine the effect of storage duration on the quality of carrot root oil. Additionally, a model was created to forecast alterations in the physicochemical properties of carrot oil as it is subjected to storage over time. The results of this study will contribute immensely to enhancing the quality, stability, and marketability of carrot root oil-based products. Furthermore, employing prediction modeling will aid researchers in forecasting the oil's behavior during extended storage, hence promoting sustainable practices in oil processing and human safety.

2. MATERIALS AND METHODS

2.1. Sample collection and oil preparation

The aims of this research were achieved through the following experimental procedure: Sample collection and preparation, oil extraction process using the solvent (n-hexane) approach, chemical characterization of the carrot root oil, stability evaluation of the oil, prediction modeling, and conclusion.

Twenty kilograms of orange carrot (D. *carota subsp. Sativus*) roots were obtained from a market in the Delta State of Nigeria. The carrots were placed in a perforated bag and taken to the laboratory immediately. In the laboratory, the roots were chopped, sun-dried and ground using an electric grinder (model RT-04, manufactured by Mill Powder Technology, Taiwan). Thereafter, the oil was extracted by n-hexane at 70 oC for 5 hours, and the oil was recovered via the evaporation technique to obtain the carrot root oil "CRO" (Abdiani *et al*., 2024).

The fat yield (content) from the dried carrot roots was calculated through Equation 1 (Arthur *et al.*, 2021).

$$Fat\ yield = \frac{Weight\ of\ the\ extracted\ oil}{weight\ of\ the\ carrot\ material} \times 100 \qquad \text{Eq. 1}$$

2.1.1. Oil storage

The oil was preserved using plastic containers in a dark environment at a temperature of 30±5 oC for 150 days. The samples were prepared in triplicate to ensure the consistency and accuracy of the results. The essential parameters were analyzed every 30 days.

2.2. Chemical analyses

All chemical analyses of the oil were carried out in agreement with the American Oil Chemists' Society (AOCS) and American Society for Testing and Materials (ASTM) standard procedures. All the materials and chemicals used were of analytical grade, mainly produced by Merck KGaA (manufactured in Germany), and were procured through Merck in Nigeria. The measurements were made in triplicate, attaining a relative standard deviation lower than 4%. Additionally, the Certified Reference Materials recovery percentages ranged from 92 to 100%.

2.2.1. Iodine value (IV)

The oil's IV was determined through the titration technique (Wijs' method), and the results were computed in grams of iodine per 100 g of CRO (Nwakodo *et al*., 2019).

2.2.2. Total carotenoid content (TCC)

Approximately 3 g of oil were mixed with 30 mL hexane, 20 mL ethanol, and 2 mL NaCl (2%), and the product was poured into a separating funnel. The TCC in the oil was determined by spectrophotometry at 450 nm as explained by Nwakodo *et al*. (2019).

2.2.3. Acid value (AV)

The CRO's AV was determined using the titrimetry technique, employing phenolphthalein (3 drops) as the indicator, and the AV was computed through Equation 2 (Negash *et al.,* 2019; Omozuwa *et al*., 2023).

$$acid\ value = \frac{V \times N \times M}{W} \quad \text{Eq. 2}$$

Where: V ~ standard KOH volume, N ~ KOH solution normality, W ~ CRO weight, M ~ KOH molecular weight

2.2.4. Vitamin E (Tocopherol)

The tocopherol level in the oil was determined by using the Ultra-Performance Liquid Chromatography (UPLC) system with Photodiode Array Detector (PDA), equipped with an Acquity CSH C18 column (model SKU: 186005296; produced by Waters Corporation, USA). Methanol was used as carrier gas at a flow rate of 0.5 mL/min, injection volume was 10 µL and column temperature was set at 40 °C. The UV Detection for tocopherols was 292 nm, with a retention period of 5 minutes. The calibration curve was produced by linear regression ($R^2 > 0.99$), and the limit of detection was 0.05 µg/mL (Matthäus *et al*., 2021).

2.2.5. Fatty acid profile

The fatty acid profile of the CRO was determined by employing a Gas chromatography (GC) with flame ionization detector (FID), equipped with a fused silica capillary column (size: 15 m x 0.25 mm x 0.10 µm; manufactured by Chromatography Direct Ltd, United Kingdom). The injector volume was 2 µL at a temperature of 250 °C, while the detector (FID) temperature was 300 °C. The oven was set at initial, intermediate and final temperatures of 50, 150 and 250 °C, respectively; the initial, intermediate and final holding periods were 2, 5 and 10 minutes, respectively; while ramp rates 1 and 2 increased by 10 and 5 °C per minute, respectively. The fatty acid composition was determined by comparing the oil's retention times and peak areas with approved fatty acid standards (Matthäus *et al*., 2021).

2.3. Statistical analysis and modeling

Data analysis was conducted on the laboratory results using the statistical analysis in social science "SPSS" statistical software (version 20.0). Analysis of Variance (ANOVA) was used to evaluate the impact of storage duration on the quality of carrot oil. The means were separated using the Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$. All experiments were done in triplicate, and the average results documented.

Predictive modeling was carried out using the Minitab version 2019 software. The modeling procedure basically involved the collection of experimental data on the physiochemical properties of the CRO and the model was evaluated using independent data to determine its accuracy.

3. RESULTS AND DISCUSSION

3.1. Physiochemical properties

The results of the physiochemical properties and vitamin contents in the carrot root oil (CRO) during the experimental period are presented in Table 1. It was noted that the storage duration had a significant effect on the oil's physiochemical behavior during storage ($p \leq 0.05$). Notably, the oil quality deteriorated rapidly after 60 days of storage. This could be associated with an increase in storage temperature, microbial contamination, and other factors which contribute to higher acidity and oxidation of the oil as storage progressed. Microbial infection and high temperature play significant roles in accelerating the degradation process of oils (Uguru *et al.,* 2023).

TABLE 1. The physiochemical properties and vitamin levels of the oil

Days	FC (%)	AV (mgKOH/g)	IV (g/100 g)	Carotenoids (ppm)	Vitamin E (mg/kg)
0	5.17	0.49a±0.02	92.39f±0.24	8.04f±0.08	75.79f±1.11
30	ND	0.54a±0.02	91.82e±0.24	7.64e±0.23	72.67e±1.08
60	ND	0.69b±0.02	89.17d±0.05	7.11d±0.16	68.40d±0.21
90	ND	0.81c±0.03	85.89c±0.14	6.67c±0.04	65.64c±0.30
120	ND	0.97d±0.04	82.50b±0.29	6.39b±0.02	63.08b±0.59
150	ND	1.04d±0.02	78.29a±0.37	5.81a±0.02	59.59a±0.98

± mean and standard deviation, n = 3, columns with the same superscript indicate that the results are not significantly different ($p \leq 0.05$) using the DMRT, ND = not determined, FC = fat content or fat yield

3.1.1. Fat content (yield)

The information in Table 1 shows that 20.83 g of oil were extracted from 403 g of carrot roots, resulting in a fat yield of 5.17%. This result is within the range of results (0.83 - 7.84%) obtained by Musa Özcan and Chalchat (2007), but lower than the results recorded by Arthur *et al.* (2021) for carrot seeds. These differences in the oil content documented in this research compared to results from other studies could be attributed to the different plant materials (seeds and roots) tested, field practices and environmental factors. Fat content is one of the critical measurements used to determine the economic viability of vegetable oils.

3.1.2. Acid value (AV)

Table 1 shows that the CRO's AV increased significantly from 0.48 to1.04 mgKOH/g during the 150-day storage period ($p \leq 0.05$), resulting in low acid content. Oil with a low AV indicates high levels of freshness, stability, and nutritional quality, as well as lower levels of toxicity (Uguru *et al.,* 2023). The acid value helps evaluate the degree of triglyceride hydrolysis in oils, providing insight into the oil's freshness and quality. The increase observed in the CRO's AV as storage progressed could be associated with the oxidation of unsaturated fatty acids and micro-degradation. This leads to the subsequent formation of more oil acidity in the CRO. Remarkably, the AV of the CRO was found to be lower in this study than the acid values documented for carrot seed oil (Musa Özcan and Chalchat, 2007; Arthur *et al*., 2021), palm oil, groundnut oil, and soybean oil (Asemave *et al.,* 2012), regardless of their storage duration. The comparatively lower AV for CRO compared to other researchers' oils can be linked to its (CRO) elevated degree of unsaturated fatty acid proportion compared to the aforementioned oils.

Interestingly, the low percentage of AV documented in this study's CRO, particularly during the early storage period, highlights its suitability for dietary and medicinal uses. Oil AV value is one of the essential indices used in evaluating oil quality. Excessive acid values can compromise both the nutritional value and quality of oil, leading to limited applications in both the culinary and industrial sectors (and Arthur *et al*., 2021; Uguru *et al*., 2023). Hence, the lower AV values documented for the CRO reveal its suitability for various domestic, medicinal and commercial applications.

3.1.3. Carotenoid content

Table 2 presents the carotenoid levels of the oil during storage. These findings reveal that the carotenoid content decreased significantly from 8.04 to 5.81 ppm during the storage period ($p \leq 0.05$). This indicates a 28% reduction in the oil carotenoid concentration during storage. Carotenoids are fat-soluble compounds which exhibit high sensitivity to heat and are prone to enzymatic oxidation as well as photochemical reactions. These results are similar to the findings documented by Nwakodo *et al*. (2019), where the carotenoid content in palm oil decreased by 10.74% during storage.

Interestingly, the carotenoid content in CRO was higher than the results documented for corn oil, but lower than flaxseed oil (Yang *et al*., 2018). Carotenoids are fat-soluble compounds and are powerful antioxidants which have the ability to hinder the multiplication of cancer cells, promote immunity in the body and enhance eye performance (Yang *et al*., 2018).

TABLE 2. The Pearson correlation of the physiochemical properties

	IV	Acid value	Vitamin E	Carotenoids
IV	1			
Acid value	-.871**	1		
Vitamin E	0.915**	-0.953**	1	
Carotenoids	0.916**	-0.957**	0.980**	1

**Correlation is significant at the 0.01 level (2-tailed).

3.1.4. Iodine value (IV)

The findings indicate a non-linear decrease in IV from 92.38 to 78.29 g/100 g, representing a 15 % decrease after a five-month storage period (Table 1). Iodine value is one of the factors used to evaluate the quality of edible oil as it indicates the oil's unsaturated fatty acid content. Interestingly, it was noted that the CRO iodine value was greater than the value reported for carrot seeds, mayten tree (*Maytenus boaria*) seed oil, and palm oil (Arthur *et al*, 2021; Ginocchio *et al*., 2021), but lower than the values obtained for milk thistle (*Silybum marianu*) seeds and hemp seed oils (Kalinowska *et al*., 2022).

This study's findings are related to the observations of Omozuwa *et al.* (2023), who reported a substantial decrease in the iodine value of palm and groundnut oils during storage, but contrary to Nwakodo *et al.* (2019), who observed that palm oil IV increased non-linearly during storage. Oils with high contents of unsaturated fats are more resistant to oxidative rancidity due to the occurrence of the double bonds in unsaturated fatty acids (Arthur *et al*, 2021). The slight oxidation contributing to the decrease in iodine value will result in the formation of more acidic compounds, ultimately causing a rise in the oil's acid value.

3.1.5. The vitamin E (total tocopherol) content

The results in Table 1 reflect how the tocopherol content in the oil decreased significantly from 75.8 to 59.67 mg/kg during the storage period ($p \leq 0.05$). This shows that the CRO contains an appreciable amount of Vitamin E, which it tried to retain throughout the experimental duration. The Vitamin E level in carrot oil was within the range of values documented by Goffman and Böhme (2001) for maize (*Zea mays* L.) oils. Despite the wide variations in vitamin E concentration found in CRO compared to oils from other crops, these findings indicate that plant-based oils are rich sources of natural vitamin E. Tocopherol is a powerful fat-soluble antioxidant with vitamin E activity which helps in skin and immune system development (Ranalli *et al*., 2004).

3.2. Pearson correlation

The correlation results of the CRO physiochemical properties are presented in Table 2. The analysis results depicted that there was a positive relationship ($r \geq 0.900$) between the CRO IV and vitamin E concentration, and IV and carotenoid content during storage. Notably, a prefect positive correlation ($r = 0.980$) existed among the carotenoids and vitamin E concentrations in the CRO. In contrast, the Pearson correlation revealed that a strong negative relationship ($r \geq -0.900$) existed between the IV and AV in the CRO, and acid value and carotenoids. The Pearson correlation outcomes revealed that the IV, vitamin E and carotenoid contents varied inversely proportional to the AV concentration in the CRO. This is in agreement with Omozuwa *et al*. (2023), who observed that oils with high acid values tend to have lower iodine, vitamin E and carotenoids levels.

3.3. Phytochemicals properties of the oil

The results of the concentration of the phytochemical compounds analyzed in the oil are shown in Table 3. The results revealed that Epicatechin is the most abundant flavonoid present in the CRO, with appreciable phytate, lunamarin and sapogenin concentrations. Phytate has a strong tendency to bind with essential minerals, which will result in their deficiencies in the human body. Despite the anti-nutrient properties of phytate and oxalate, phytate has some pharmaceutical benefits, protecting the body against various cancers, enhancing gut microbiota, and inhibiting the formation of kidney stones (Nnabugwu and Uchenna, 2018). Epicatechin possesses antioxidant and anti-inflammatory potentials which help to reduce oxidative stress, lower the risk of neurodegenerative disorders, enhance blood flow, and manage arthritis symptoms (Alizadeh and Fattahi, 2021).

Table 3. The phytochemical levels in CRO during storage (mg/kg)

	Day 0	Day 30	Day 60	Day 90	Day 120	Day 150
Lunamarin	6.377±0.39	6.101±0.54	5.783±0.72	5.227±0.31	5.119±0.31	5.056±0.47
cardoac glycoside	1.837±0.04	1.749±0.07	1.703±0.15	1.680±0.09	1.575±0.12	1.463±0.09
Anthocyanin	3.072±0.16	2.918±0.11	2.704±0.09	2.668±0.04	2.596±0.05	2.503±0.07
Sparteine	4.859±0.27	4.717±0.52	4.562±0.15	4.484±0.31	4.284±0.12	4.113±0.22
Rutin	3.875±0.09	3.802±0.05	3.715±0.04	3.600±0.34	3.528±0.07	3.441±0.14
Flavonones	3.118±0.05	2.893±0.09	2.822±0.03	2.789±0.05	2.603±0.06	2.578±0.08
Steriods	5.594±0.29	5.522±0.31	5.483±0.31	5.412±0.02	5.377±0.22	5.305±0.43
Kaempferol	1.975±0.03	1.931±0.04	1.887±0.03	1.818±0.02	1.765±0.05	1.704±0.32
Epicatechin	9.483±0.81	9.419±0.66	9.328±0.53	9.240±0.27	9.164±0.53	9.103±1.01
Phytate	7.509±0.72	7.248±0.41	7.225±0.15	7.189±0.12	7.102±0.62	7.034±0.73
Flavone	2.897±0.07	2.748±0.05	2.416±0.25	2.391±0.03	2.225±0.07	2.168±0.41
Oxalate	6.675±0.31	6.621±0.33	5.588±0.33	5.501±0.16	5.472±0.44	5.403±0.51
Catechin	2.709±0.05	2.671±0.05	2.592±0.06	2.474±0.02	2.405±0.08	2.363±0.04
Resveratrol	2.708±0.11	2.627±0.02	2.613±0.09	2.599±0.02	2.535±0.19	2.482±0.05
Tannins	3.261±0.09	3.216±0.14	3.122±0.21	3.037±0.19	2.993±0.13	2.914±0.08
Sapogenin	5.505±0.51	5.479±0.84	5.412±0.43	5.300±0.22	5.235±0.32	5.189±0.14
Epihedrine	5.893±0.13	5.809±0.11	5.734±0.37	5.665±0.12	5.595±0.14	5.506±0.52
Quercetin	0.329±0.04	0.315±0.06	0.289±0.19	0.247±0.01	0.225±0.07	0.208±0.03

± mean and standard deviation, replication (n) = 3

Additionally, the CRO's anthocyanins, Sparteine and epicatechin levels were higher than the concentrations in Damask rose (*Rosa damascena*) oil, groundnut, lemon (*Citrus limon*) grass and tea seed (*Lahijan variety*) oils (Alizadeh and Fattahi, 2021; Duru and Enyoh, 2020; Uguru *et al*., 2023; Fazel *et al*., 2008). Notably, the oil's lunamarin and Flavonone concentrations were lower than the levels recorded for lemon and lemongrass oils (Duru and Enyoh, 2020). Anthocyanins are powerful water-soluble antioxidants which exhibit anti-inflammatory behavior, and sparteine has antiarrhythmic properties which help by enhancing the performance of the central nervous system (Uguru *et al*., 2023). Resveratrol and flavanones have a wide range of medicinal qualities and are known for their ability to manage blood sugar levels and cardiovascular diseases. Also, the tannin and oxalate concentrations in the CRO were lower than rosemary (*Rosmarinus officinalis* L.) oil's tannin concentration (Adris *et al*., 2019), and groundnut oil's oxalate concentration (Nnabugwu and Uchenna, 2018). Likewise, the oil's phytate concentration was lower than the concentration found in peanut hull oil (Nnabugwu and Uchenna, 2018).

Furthermore, the CRO's kaempferol and quercetin contents were higher than the values found for hemp (*Cannabis sativa*) and milk thistle (*Silybum marianu*) seed oils (Kalinowska *et al*., 2022). Flavanones have the ability to decrease arthritis and cardiovascular ailments, along with cancer risks. Kaempferol has proven anti-carcinogenic, anti-inflammatory and antimicrobial potential. Catechin is an antioxidant that belongs to the flavonoid category, known for its capability to control the multiplying of immune cells and regulate blood sugar levels (Kalinowska *et al*., 2022).

Remarkably, out of the 18 phytochemicals evaluated in the carrot oil, 10 (anthocyanin, rutin, flavonones, kaempferol, epicatechin, flavone, catechin, resveratrol, tannins and quercetin) are phenolic compounds. The total phenolic concentration (THC) of the phenolic compounds in the CRO amounts to 33.427 mg/kg and was higher than the values reported for walnut and palm kernel oils (Mikolajczak *et al*., 2021), but fell within the range of results obtained for perilla seed oil and evening primrose oil (Yang *et al*., 2018). The wide variation in the THC of the different plant oils could be linked to the number of phenolic compounds quantified, oil extraction technique, field practices, plant variety and storage method adopted (Tian *et al*., 2023). The depreciation in the phytochemical levels observed in the oil during the storage period could be linked to changes in environmental temperature and humidity, the presence of heavy metals, enzymatic oxidation, and other impurities (Nwakodo *et al.*, 2019). Despite the decline in the concentrations of phytochemical compounds, the oil still retains appreciable levels of these essential phytochemicals after 5 months. The high stability of the oil observed during the storage period could be attributed to its high concentration of total phenolic compounds.

3.4. Fatty acids profile

Table 4 displays the results of the fatty acid profile of the carrot root oil. The fatty acids analyzed varied from C16 (16 carbon atoms) to C24 (24 carbon atoms), including 4 saturated fatty acids (SFA), 2 monounsaturated fatty acids (MUFA), and 7 polyunsaturated fatty acids (PUFA). It was observed that stearic acid was the major SFA, while eicosapentaenoic acid was the highest unsaturated fatty acid in the oil. The fatty acid composition of the carrot root oil wase similar to the one reported by Ojha *et al*. (2024) for carrot seed oil. The oleic acid and linoleic acid levels recorded in this study were lower than the values obtained by Matthäus *et al*. (2021) for purple carrot seed oil. Musa Özcan and Chalchat (2007) reported a higher palmitic acid value but a lower stearic acid value for carrot seed oil, compared to this study's findings.

Table 5 shows that CRO is rich in unsaturated fatty acids. Interestingly, the PUFA level in CRO was higher when compared to the value obtained for groundnut hull oil, and tiger nut chaff oil (Nnabugwu and Uchenna, 2018), but lower than what was obtained for flaxseed oil (Yang *et al*., 2021). Additionally, the carrot root oil MUFA value was less than the results obtained by Yang *et al.* (2021) for almond oil, and olive oil, but greater than the values for jackfruit seed oil (Tian *et al.* 2023), and 2 extracted carrot root oil extracted with CO2 (Ranalli *et al*., 2004). High percentages of monounsaturated fatty acids (MUFAs) and PUFAs have several health benefits, such as lowering low-density lipoprotein (LDL) cholesterol levels and enhancing overall lipid profiles.

During storage, the composition of fatty acids in the oil changes dramatically. The fat content in the CRO samples was noted as follows: Day 0 (95.362 ppm), Day 30 (89.954 ppm), Day 60 (85.869 ppm), Day 90 (83.271 ppm), Day 120 (80.785 ppm), and Day 150 (78.937 ppm). The decline observed in the oil samples' fatty acid contents could be attributed to oxidation, hydrolysis, lipolysis, and volatilization of the oil during storage. Oxidation, hydrolysis, lipolysis, and volatilization increase the oil's acid value (AV) levels by rapidly degrading the unsaturated fatty acids. Consequently, these processes collectively contribute to the degradation of unsaturated fatty acids, thereby increasing the AV levels (Table 1) and reducing the overall fat contents in the oil samples (Arthur *et al.*, 2021). Despite the deterioration in CRO quality during storage, it maintained high levels of PUFAs, likely due to its high content of phenolic compounds (Table 3). This places CRO in the category of fixed oils with stable nutritional and medicinal qualities.

Table 4. The CRO fatty acids profile (ppm)

Acid		Storage period					
		Day 0	**Day 30**	**Day 60**	**Day 90**	**Day 120**	**Day 150**
SFA							
Palmitic acid	C16:0	4.341±0.32	4.743±0.22	5.634±0.43	6.146±0.08	6.849±0.11	7.093±0.26
Stearic acid	C18:0	6.021±0.34	6.554±0.45	7.058±0.52	7.450±0.43	7.741±0.09	8.383±0.14
Arachidic acid	C20:0	0.18±0.01	0.193±0.03	0.201±0.01	0.227±0.01	0.243±0.03	0.265±0.02
Behenic acid	C22:0	0.396±0.01	0.438±0.02	0.469±0.01	0.480±0.07	0.497±0.04	0.514±0.02
ΣSFA		**10.938**	**11.928**	**13.362**	**14.303**	**15.33**	**16.255**
UFA							
Oleic acid	C18:1	16.567±0.91	15.986±0.83	15.348±0.92	14.865±1.41	14.133±0.57	13.574±0.96
Linoleic acid	C18:2	10.429±0.73	9.872±0.39	9.472±0.48	8.924±0.08	8.544±0.31	8.116±0.87
Linolenic acid	C18:3	9.068±0.44	8.472±0.55	7.919±0.09	7.433±0.73	7.042±0.06	6.875±0.92
Eicosenoic acid	C20:1	0.240±0.02	0.220±0.02	0.210±0.32	0.190±0.02	0.180±0.01	0.160±0.01
Eicosadienoic acid	C20:2	0.096±0.01	0.091±0.01	0.086±0.02	0.079±0.01	0.077±0.02	0.073±0.01
Arachidonic acid	C20:4	7.104±0.61	6.530±0.71	5.918±0.51	5.680±0.09	5.332±0.07	5.243±0.09
Eicosapentaenoic acid	C20:5	23.796±1.44	21.364±0.85	19.049±1.02	18.608±0.81	17.582±1.42	16.845±0.72
Docosahexaenoic Acid	C22:6	15.873±1.01	14.338±0.73	13.402±0.91	12.112±0.36	11.629±1.10	10.934±0.83
Nervonic acid	C24:5	1.251±0.02	1.153±0.01	1.103±0.02	1.077±0.01	0.936±0.02	0.862±0.01
ΣMUFA		**16.807**	**16.206**	**15.558**	**15.055**	**14.313**	**13.734**
ΣPUFA		**67.617**	**61.82**	**56.949**	**53.913**	**51.142**	**48.948**
SFA:PUFA		**0.162**	**0.193**	**0.235**	**0.265**	**0.300**	**0.332**
Fatty acids content		**95.362**	**89.954**	**85.869**	**83.271**	**80.785**	**78.937**

± mean and standard deviation, replication (n) = 3

Based on these research findings, CRO could have several health benefits, as its high PUFA value tends to enhance cyclooxygenases, lipoxygenases and cytochrome P450 enzymatic reactions, which have proven protection against brain or renal disorders (Ginocchio *et al.,* 2021). Moreover, the oil's SFA:PUFA ratio ranged from 0.161 to 0.332 throughout the storage duration, further affirming its good nutritional and medicinal attributes. The World Health Organization (WHO) recommended that a good edible oil should have a SFA:PUFA ratio of no greater than one (Tian *et al.,* 2023). Notably, the SFA:PUFA values recorded for CRO were lower than the resulta reported for jackfruit (*Artocarpus heterophyllus* Lam) seed oil, custard apple (*Annona reticulate*) seed oil and pomegranate (*Punica granatum*) seed oil (Tian *et al.,* 2023). The results clearly depicted that CRO contains appropriate concentrations of essential compounds, making it effective in obesity, cancer, cardiovascular, neurodegenerative disorders and diabetic management.

3.5. Predictive modeling

The data obtained from the laboratory analysis were utilized to train various machine-learning predictive models. These models were evaluated to establish the best one which can be employed to forecast the status of the oil at different storage periods. Out of the 28 models evaluated, it was observed that the Gaussian Process Regression (Exponential GPR) was the most suitable model to be employed due to its smallest RMSE (Validation) value, (data not reported).

Figure 1 shows the correlation between the predicted and true response of the results. It can be observed that the results from Exponential GPR can be used to predict the quality status of the oil during storage with an accuracy of approximately 97 %. These findings will be valuable for monitoring the quality and toxicity of CRO during prolonged storage, as well as for its application in the food and pharmaceutical industries.

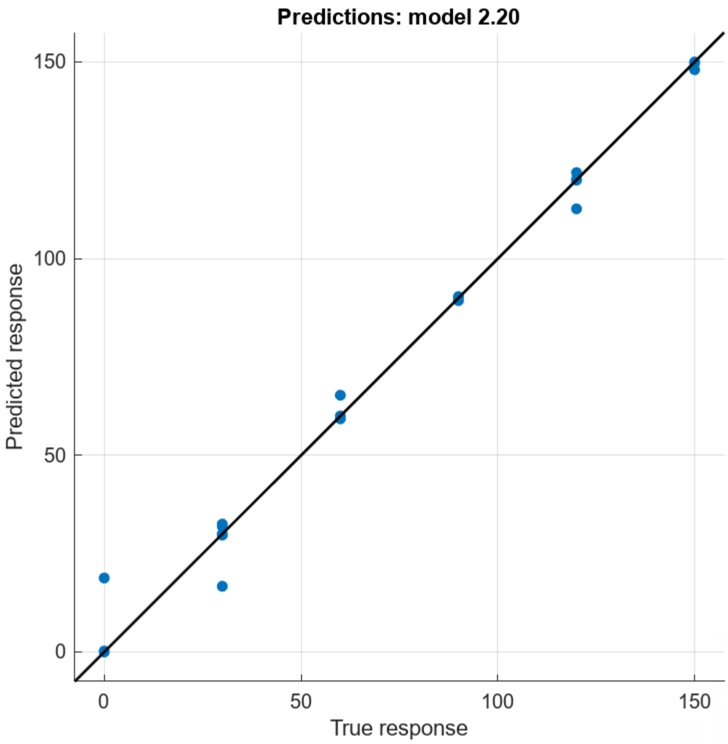

Figure 1. The relationship between the Predicted and True response

4. CONCLUSION

This study investigates the biochemical and nutritional stability of carrot root oil (CRO) during extended storage under ambient environmental conditions. It aims to provide valuable insights into the oil's quality and human safety over time. The CRO's physicochemical parameters, fatty acid profile, and phytochemical profile were determined in accordance with approved standard guidelines. The phytochemical profile analysis of the CRO showed that the oil predominantly contains ephedrine, epicatechin, lunamarin, and phytate. The fatty acid profile showed that the CRO has a high volume of polyunsaturated fatty acids compared to saturated ones, with notably high percentages of oleic, eicosapentaenoic, and docosahexaenoic acids. The information obtained from the physicochemical and mineral analyses of the CRO indicated that it has low acid value but moderate concentrations of iodine, carotenoids, and vitamin E. Remarkably, the quality of the CRO declined in a non-linear fashion during storage. The oil's acid values increased by 112 %, while levels of carotenoids, iodine, tocopherol, and polyunsaturated fatty acids decreased by 15, 27, 21, and 28 %, respectively, after 150 storage days. A model developed from Exponential Gaussian Process Regression

(Exponential GPR) can be effectively used to predict the quality status of the oil during storage, achieving an accuracy level of approximately 97 %. These findings demonstrate that CRO is a high-quality fixed oil, offering numerous health benefits with minimal risks, and making it a valuable addition for both medicinal and nutritional applications. This study was conducted using one storage condition, hence further research on real-world variations should be conducted on CRO. Also, comparing Exponential GPR to other machine-learning models will enhance predictive performance.

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DECLARATIONS CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

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

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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AUTHOR CONTRIBUTIONS

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S. Alharthi, A. AL-Farga, W.A. Alsanei, R. Sami, S.A. Abushal, M. Helal, H.M. Abo-dief,: Contributed to data collection.

H. Uguru, A.M. Almehmadi, O. Nyorere: Contributed to all data and statistical analysis and interpretation of data.

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All authors read and approved the final manuscript.

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