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COMPARATIVE ANALYSIS OF ANTIOXIDANT POTENTIAL AND PHENOLIC COMPOSITION IN PEEL, PHLOEM, AND XYLEM OF RED CARROT (*DAUCUS CAROTA* L.)

Nabidad Bajkani[1], Tajnees Pirzada[2], Nazia Rind[3], Khalid Ahmed Bhutto[4], Qandeel Haider Hundal[5], Amjad Hussain Soomro[6], Hafizullah Mazari[7], Safeullah Bullo[8], Pooja Bai[9], Inam Ali Qadir[10], Ali Bahar Shahani[11], *Sanaullah Ansari[12]

[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]Institute of Chemistry, Shah Abdul Latif University, Khairpur Mirs, Sindh, Pakistan.

***Corresponding Author:** (sanaullah.ansari@salu.edu.pk)*

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Article Info

Abstract

This study investigates the distribution of phenolic compounds, hydroxycinnamic acid derivatives, and antioxidant activity in red carrot (*Daucus carota* L.) collected from two regions of Taluka Khanpur, District Shikarpur, Pakistan. Different parts, peel, phloem, and xylem, were separated and analyzed for assessment of their morphological and biochemical characteristics. Total phenolic contents (TPCs) and hydroxycinnamic acids were quantified using spectrophotometric methods with chlorogenic acid and caffeic acid as standards, respectively. Antioxidant activity was determined using the DPPH free radical scavenging assay and expressed as IC_{50} values. The results demonstrated significant variation among the tissues, with a consistent trend of peel > phloem > xylem in terms of phenolic content and antioxidant activity. The highest TPC (53.3 ± 2.9 mg/100 g) and hydroxycinnamic acid content (13.4 ± 1.1 mg/100 g) were observed in peel tissue from the K-1 region, while the lowest values were recorded in xylem tissue from K-2. Similarly, the peel exhibited the strongest antioxidant potential with the lowest IC_{50} value (31.643 µg/mL), whereas the xylem showed the weakest activity. Morphological analysis supported these findings, indicating structural and functional differences among tissues that influence phytochemical distribution. The strong correlation between phenolic content and antioxidant activity highlights the role of hydroxycinnamic acid derivatives as key contributors to the antioxidant potential of red carrots. The findings suggest that carrot peel, often discarded as waste, represents a valuable source of natural antioxidants and could be utilized in functional food and nutraceutical applications. This study provides important insights into the valorization of byproducts of agricultural industries and supports sustainable utilization strategies.

Keywords: *Red carrot (Daucus carota L.); Phenolic compounds; Hydroxycinnamic acids; Antioxidant activity; DPPH assay; IC_{50}; Peel valorization; Phytochemicals*

1. Introduction

The fruits and vegetables are essential components of a healthy diet due to the higher concentration of bioactive components, including phenolics, flavonoids, vitamins, and carotenoids. The phytochemicals show strong antioxidant properties and play a significant role to reduce the risk of chronic diseases, such as cardiovascular disease, cancer, diabetes, and neurodegenerative problems. Oxidative stress due to the excessive production of reactive oxygen species (ROS) contributes to cellular damage and affects lipids, proteins, and DNA. Hence, the intake of foods rich in antioxidants is crucial for the maintenance of human health and preventing disease (Iqbal *et al.,* 2019).

Among commonly consumed vegetables, red carrot (*Daucus carota* L.) is an important root vegetable, with nutritional values and properties that promote health. It is particularly rich in carotenoids, phenolic compounds, and dietary fiber to enhance its antioxidant potential. The red color of carrots is attributed to lycopene, a potential antioxidant with reduced risk of cancer and cardiovascular diseases. In addition, red carrots contain a significant amount of phenolic acids, especially hydroxycinnamic acid and its derivatives such as chlorogenic, caffeic, and ferulic acids, which are known as free radical scavengers (Maitlo *et al.,* 2023; Martínez-Saldarriaga *et al.,* 2025).

In recent studies, it has been shown that not all plants have a uniform distribution of bioactive elements. For carrots, each of the anatomical components, which include the periderm (peel), cortex (phloem), and core (xylem), has substantiated differences in its features. The outer, and particularly the peel, has been shown to contain the heightened amounts of phenolic compounds and higher amounts of antioxidants in relation to the inner components. For both nutrition and industry, the peel's patchy distribution warrants attention since it is usually thrown away (Bhandari *et al.,* 2022).

One of the large subdivisions of phenolic components is hydroxycinnamic acids. These elements are characterized by a structural formula of C6–C3 and are recognized for their many positive impacts, such as antihypertensive, anti-inflammatory, and cardioprotective. Chlorogenic acid is the predominant hydroxycinnamic acid in carrots and is a natural antioxidant. The health and nutritional impacts of carrots can be further enhanced by the study of the concentration and distribution of this component in various anatomical structures of carrots (El-Seedi *et al.,* 2012; Zhuravel *et al.,* 2026).

To address this, the study focuses on phenolic hydroxycinnamic acid and antioxidant capacity among the tissues of red carrot (*Daucus carota L.*). The validation for the antioxidant potential and phenolic content, along with their respective hydroxycinnamic acid derivatives, was done through the DPPH radical scavenging assay and UV-Visible spectrophotometric methods. The carrot was also subjected to a morphological study for a holistic evaluation of its structural and biochemical attributes (Sabahi *et al.,* 2024). The carrot peel has been demonstrated by this research to be a

valuable source of natural antioxidants. The findings will support the development of functional food and promote the sustainable usage of byproducts related to the agricultural industry.

2. MATERIAL AND METHOD

2.1. Area of Study

The study was conducted on red carrot (*Daucus carota* L.) collected from two agricultural regions of Taluka Khanpur, District Shikarpur, Sindh, Pakistan. The selected sites included Union Council (U.C.) Khanpur (K-1) and U.C. Rahimabad (K-2). The areas were chosen for evaluation of possible variations in phytochemical composition and antioxidant activity caused by the environment and geographical variances.

2.2. Chemicals and Reagents

All chemicals/reagents used were of analytical grade. Methanol, acetone, ethanol, hydrochloric acid (HCl), petroleum ether, and other solvents were obtained from standard commercial suppliers. 2,2-Diphenyl-1-picrylhydrazyl (DPPH) was used for free radical scavenging activity determination. Chlorogenic acid and caffeic acid were used as standards for the quantification of total phenolic concentration and derivatives of hydroxycinnamic acid, respectively. Ultra-pure distilled water was used throughout the experimental procedure.

2.3. Standards and Sample Preparation

Standard solutions of chlorogenic acid and caffeic acid were prepared using methanol as a solvent for calibration. The standards were used to construct calibration curves for the quantification of total phenolics and hydroxycinnamic acid derivatives.

For the preparation of samples, fresh red carrot tissues (peel, phloem, and xylem) were separated using a sterile blade and peeler. Each sample (10 g) was homogenized in 15 mL of acetone and allowed to extract for 2 hours. The homogenized mixture was centrifuged at 6000 rpm for 25 minutes. The supernatants were collected, and the residue was extracted twice using 60% acetone. The extracts were concentrated using evaporating acetone at 30 °C with the help of an environmental shaker. Lipophilic compounds such as pigments and fatty acids were removed using partitioning with petroleum ether (2:1, v/v). The remaining liquid was further concentrated to get crude extracts for analysis (Kurzawa *et al.,* 2022).

2.4. Sample Collection

Fresh samples of red carrot (*Daucus carota* L.) were collected from local agricultural fields (K-1 and K-2). The samples were transported to the laboratories under suitable conditions to prevent degradation. Samples were washed with distilled water to remove dirt and impurities. The edible root was carefully separated into peel (periderm), phloem (cortex), and xylem (core).

2.5. Analytical Methods

2.5.1. Determination of Total Phenolic Contents

Total phenolic contents (TPCs) were determined using a spectrophotometric method. The acidification of the extract was done to pH 2.0 and filtered through a 0.45 µm filter paper. The reaction mixture consisted of extract (0.25 mL), 0.1% HCl in ethanol (0.25 mL), and 2% HCl (4.5 mL). The absorbance was taken at 320 nm with a UV–Visible spectroscopy. Chlorogenic acid was used as a standard, and results were expressed as mg chlorogenic acid equivalents per 100 g (mg/100 g) (Suryawanshi *et al.,* 2026).

2.5.2. Determination of Hydroxycinnamic Acids and Derivatives

Hydroxycinnamic acid and its derivatives were also determined using spectroscopy. The absorbance was taken at 280 nm. Caffeic acid was used as the standard compound, and results were expressed as mg caffeic acid equivalents per 100 g (Hădărugă & Hădărugă, 2023).

2.5.3. Free Radical Scavenging Activity (DPPH Assay)

The antioxidant activity was evaluated using the DPPH radical scavenging assay. A 0.1 mM DPPH solution was prepared using methanol as solvent. An aliquot of sample extract (0.2 mL) was mixed with DPPH solution (4 mL) and incubated in the dark for 60 minutes. The decrease in absorbance was measured at 517 nm using a UV–Vi's spectrophotometer. A control sample blank was prepared using distilled water instead of the extract. The percentage inhibition of DPPH radicals was calculated, and the IC_{50} value (concentration required to inhibit 50% of DPPH radicals) was determined from the plotted graph (Gulcin & Alwasel, 2023).

2.5.4. Morphological Analysis

Morphological analysis of carrot tissues, i.e., peel, phloem, and xylem, was carried out using a microscope. Thin transverse and longitudinal sections of 2–5 nm were prepared and fixed in phosphate buffer (2.5% glutaraldehyde). Samples were dehydrated using ethanol solutions (30–100%) and stained using Safranin. Further treatment with xylene was performed before mounting. The prepared slides were observed using an electron microscope for identification of structural features such as deposition of lignin and distribution of fiber (Zhou *et al.,* 2023).

3. RESULTS AND DISCUSSION

3.1. Morphological Characteristics of Peel, Phloem, and Xylem Tissues of Red Carrot

The morphological analysis of different tissues of red carrot (*Daucus carota* L.), i.e., peel (periderm), phloem (cortex), and xylem (core), revealed clear structural distinctions corresponding to their physiological functions. The peel is the outermost protective layer, comprising peridermal cells stacked closely. Peel includes rich dietary fibers, which were identified with green staining

during the microscopic observation. Fibers give the peel a protective architecture and structure. The peel's protective layer is shown in Fig. 1a, and Fig. 1b shows the dietary fiber's stained networks. Metabolically, its active nature is due to its dense composition; the peel's higher accumulation of phenolic components explains the antioxidant activity and phenolic components in the later analyses (Kartika *et al.,* 2021). The phloem is present below the layer of peel, which is softer and less densely packed than the peel. A sieve-like tubular structure is formed, allowing it to transport sugars and other organic matter. Through the root, these tubes connect and elongate to create a transport system. The morphology of the phloem is shown in Fig. 2a, and its tubular structure is shown in Fig. 2b. The role of phloem in the transport of nutrients is directly related to its concentration of phytochemicals.

The xylem is the central core of the carrot. Its composition of tracheary elements shows a well-organized structure that is the compositional core of the carrot root. The core allows the vessels to transport and connect the minerals and water. They also have thick and lignified cell walls. The general structure of xylem tissue is given in Fig. 3a, while Fig. 3b highlights the presence of lignin by means of red staining of the cell walls. The rigid and lignified nature of xylem contributes to support with lower metabolic activity and reduced accumulation of bioactive components.

Overall, the morphological observations demonstrated a clear structural gradient from the peel to the xylem tissue. The peel is rich in fibrous and active metabolic cells, the phloem functions in nutrient transport, while the xylem provides structural support and water transportation. These anatomical differences strongly correlate the variation in phenolic content and antioxidant activity among the tissues, this supports the results obtained in subsequent analyses.

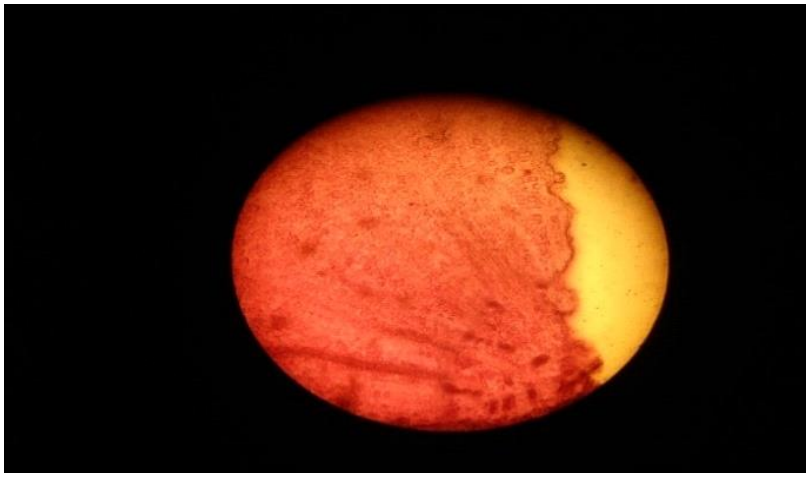

Fig. 1a Morphological structure of peel (periderm) tissue of red carrot (*Daucus carota* L.)

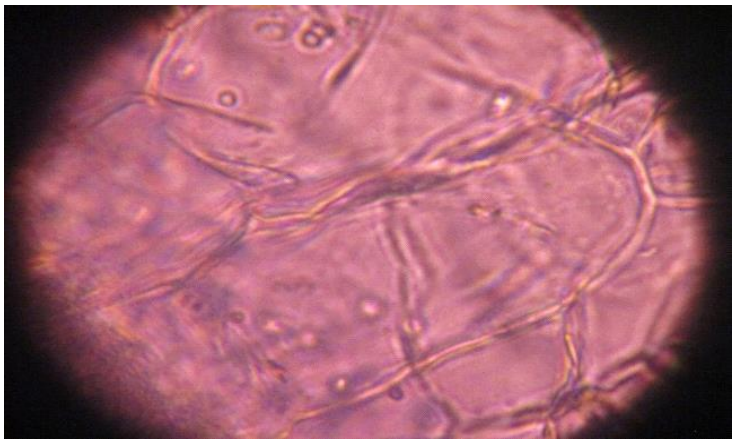

Fig. 1b Microscopic visualization of dietary fibers in peel tissue after green staining

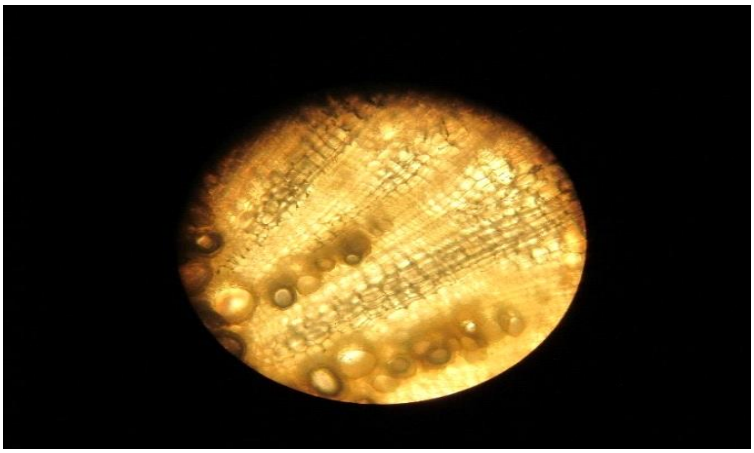

Fig. 2a Morphological structure of phloem (cortex) tissue of red carrot

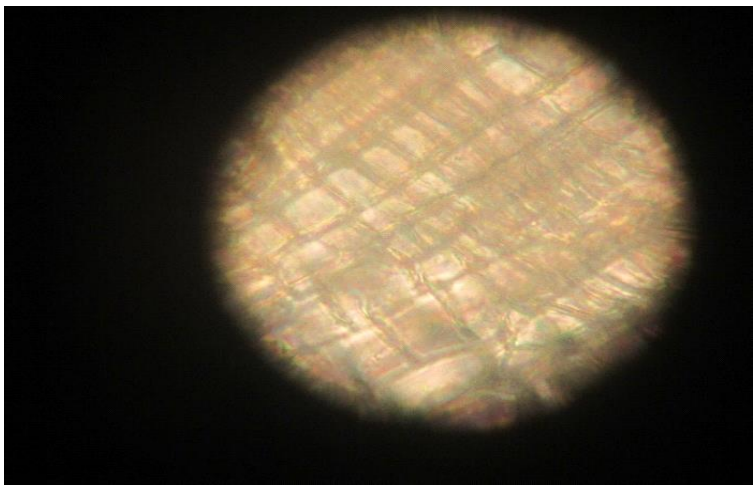

Fig. 2b Microscopic view of sieve tube elements in phloem tissue showing nutrient transport structures

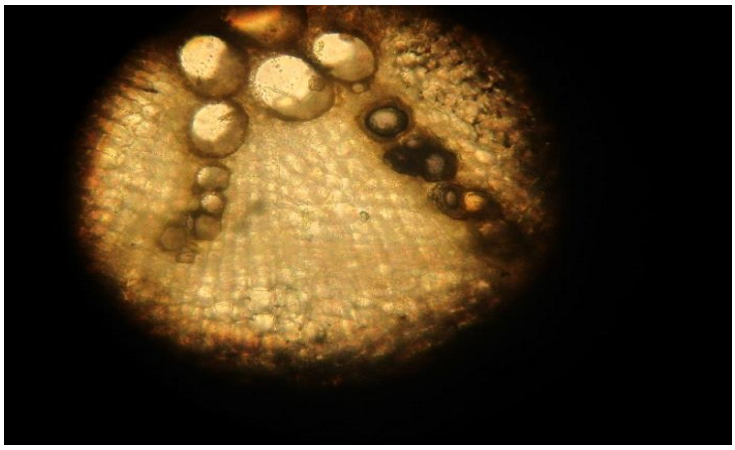

Fig. 3a Morphological structure of xylem (core) tissue of red carrot

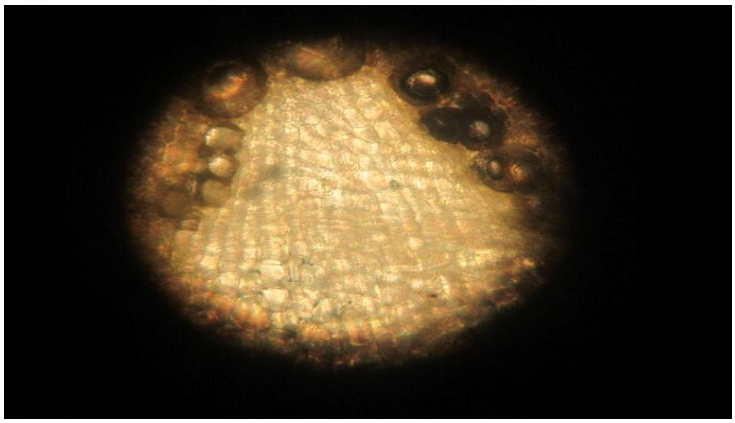

Fig. 3b Microscopic visualization of lignified xylem vessels after red staining

3.2. Physical Parameters of Red Carrots from the Khanpur Region

The physical characteristics of red carrot (*Daucus carota* L.) were evaluated for assessment of distinctions in morphological characteristics influenced by variation in environmental conditions. The measurement results, including root length, diameter, weight, and appearance, are shown in Table 1.

The results show that there is an inconsistency in the physical characteristics of the carrot plants collected at the two different sampling locations. It has been found that the carrots collected at K-1 have uniform size and appearance, with a larger average length and higher weight of root when compared to the carrots collected from the K-2 sampling site. The difference in physical characteristics may be attributed to the differences in the characteristics of soils used for cultivation, nutrient availability, irrigation practices, and weather conditions. Environmental variables like soil quality, temperature, and moisture availability, among others, have a major impact on the growth and development of roots. Favorable agricultural conditions lead to cell growth and expansion, leading to improvements in the physical qualities of roots. Moreover, the

differences found in physical qualities have implications for the composition of the carrot roots. Improved physical features, especially the presence of larger and better-developed roots, increase bioaccumulation of compounds and nutrients, but this is subject to tissue types and environmental stressors (Dehghani *et al.,* 2025). The findings suggest that geographic location and conditions can play an important role in the physical quality of the carrots. Such variations must be considered while evaluating nutritional values, processing suitability, and potential industrial applications.

Table 1. Physical parameters of red carrot (*Daucus carota* L.)

Sample	Length (cm)	Diameter (cm)	Weight (g)
Peel-K1	18.5 ± 1.2^{a}	3.2 ± 0.3^{a}	95.4 ± 5.6^{a}
Phloem-K1	17.8 ± 1.0^{a}	3.0 ± 0.2^{a}	90.2 ± 4.8^{a}
Xylem-K1	16.9 ± 1.3^{b}	2.8 ± 0.3^{b}	85.6 ± 6.1^{b}
Peel-K2	17.2 ± 1.4^{b}	3.0 ± 0.4^{a}	88.3 ± 5.2^{b}
Phloem-K2	16.5 ± 1.1^{b}	2.9 ± 0.3^{a}	83.7 ± 4.9^{b}
Xylem-K2	15.8 ± 1.2^{c}	2.6 ± 0.2^{b}	79.5 ± 5.4^{c}

Values are expressed as mean ± standard deviation (n = 3). $^{a–c}$ indicate statistically significant differences ($p < 0.05$).

3.3. Total Phenolics and Hydroxycinnamic Acids and Their Derivatives

Table 2 shows the total phenolic contents (TPC) in red carrots *(Daucus carota L.).* An evident variation in phenolic content was found in various parts, where the peel contained more phenolic compounds compared to the xylem, which had the least content of phenols. The peel of the plant from K-1 (Peel-K1) displayed the highest phenolic content (53.3 ± 2.9 mg/100 g), whereas the xylem sample of K-2 (Xylem-K2) showed the lowest phenolic content (29 ± 3.9 mg/100 g). The data is illustrated in Fig. 4, which clearly reveals the descending order of phenolic content, i.e., Peel > Phloem > Xylem.

Table 2. Total phenolic content of peel, phloem, and xylem tissues of red carrot (*Daucus carota* L.) (expressed as mg chlorogenic acid equivalents per 100 g)

Sample	Total Phenolic Content (mg/100 g)
Peel-K1	53.3 ± 2.9[a]
Phloem-K1	47.6 ± 3.1[b]
Xylem-K1	35.8 ± 2.7[c]
Peel-K2	49.2 ± 2.5[b]
Phloem-K2	42.5 ± 3.3[c]
Xylem-K2	29.0 ± 3.9[d]

Values are expressed as mean ± standard deviation (n = 3). [a–d] indicate statistically significant differences ($p < 0.05$).

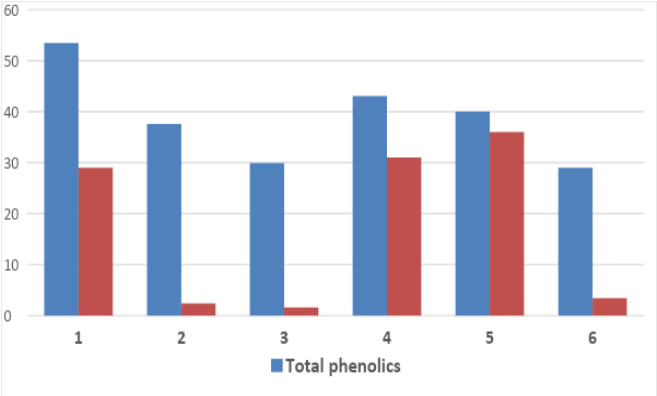

Figure 4 Variation in total phenolic content among different tissues of red carrot

The distribution of phenolic content can be explained by the different characteristics of the tested tissues. As the most external tissue, the peel receives more exposure to the environmental stress factors, which causes the synthesis of phenolic substances as an adaptive strategy of plants. On the contrary, the internal parts, like the xylem, receive little exposure to these stressful conditions; therefore, they accumulate fewer phenols. Intermediate concentrations measured in the phloem confirm the transitional anatomical and metabolic nature of the tissue (Ahmad *et al.,* 2019).

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therefore, they accumulate fewer phenols. Intermediate concentrations measured in the phloem confirm the transitional anatomical and metabolic nature of the tissue (Ahmad et al., 2019).

In addition, the concentration of hydroxycinnamic acids, as well as their derivatives, representing the largest portion of the total phenolic content, has been measured in carrots. The results are provided in Table 3. As in the case of total phenols, there is a considerable difference between tissues. The maximum content of hydroxycinnamic acids was observed in Peel-K1 (13.4 ± 1.1 mg/100 g), and the minimum concentration in Xylem-K2 (6.6 ± 1.0 mg/100 g). The relative distribution of hydroxycinnamic acids in various tissues is illustrated in Fig. 5, which follows the same decreasing trend, i.e., Peel > Phloem > Xylem.

Table 3. Concentration of hydroxycinnamic acids and their derivatives in peel, phloem, and xylem tissues of red carrot (*Daucus carota* L.) (expressed as mg caffeic acid equivalents per 100 g)

Sample	Hydroxycinnamic Acids (mg/100 g)
Peel-K1	13.4 ± 1.1^{a}
Phloem-K1	11.2 ± 0.9^{b}
Xylem-K1	8.5 ± 1.0^{c}
Peel-K2	12.1 ± 1.0^{b}
Phloem-K2	9.8 ± 0.8^{c}
Xylem-K2	6.6 ± 1.0^{d}

Values are expressed as mean ± standard deviation (n = 3). $^{a–d}$ indicate statistically significant differences ($p < 0.05$).

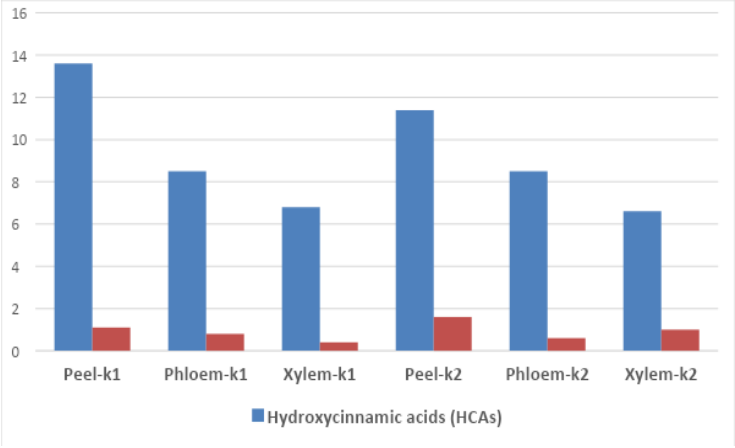

Figure 5 Comparative distribution of hydroxycinnamic acids and derivatives in peel, phloem, and xylem tissues of red carrot

Hydroxycinnamic acids, such as chlorogenic, caffeic, and ferulic acids, are known to have antioxidative functions and occur in plant tissues. The higher concentration in the peel proves the high potential of this tissue in the antioxidation of red carrots. The findings confirm the earlier research, which showed that phenolic acids are primarily accumulated in the external parts. The lower concentration in xylem could be explained by its structure and less active metabolism (Khawula *et al.,* 2024).

The study showed that there was a clear dependence of the type of tissue on the accumulation of phenolic compounds. The peel tissue had the highest content of total phenolic and hydroxycinnamic acids, proving its potential as an antioxidant. This study confirmed that the peel tissue could be used for different purposes due to its properties.

3.4. Free Radical Scavenging Activity of Red Carrot

Evaluation of antioxidant activity involved the use of the DPPH free radical scavenging activity test. Antioxidant activity was measured in terms of IC_{50} values (µg/mL). A lower IC_{50} value implies better antioxidant activity. Comparative IC_{50} values are presented in Table 4.

Table 4. IC_{50} values (µg/mL) of DPPH free radical scavenging activity of peel, phloem, and xylem tissues of red carrot (*Daucus carota* L.)

Sample	IC_{50} (µg/mL)
Peel-K1	31.64 ± 1.8^{a}
Peel-K2	34.85 ± 2.1^{a}
Phloem-K1	57.65 ± 2.6^{b}
Phloem-K2	59.70 ± 2.9^{b}
Xylem-K2	68.35 ± 3.2^{c}
Xylem-K1	86.83 ± 3.8^{d}

Values are expressed as mean ± standard deviation (n = 3). $^{a–d}$ indicate statistically significant differences ($p < 0.05$).

The results revealed a clear variation in antioxidant activity among different tissues. The peel tissue exhibited the highest free radical scavenging activity, as indicated by its lowest IC_{50} value. Among all samples, Peel-K1 showed the strongest antioxidant potential with an IC_{50} value of 31.643 µg/mL. The graphical representation of concentration versus percentage inhibition for Peel-K1 is shown in Fig. 6a, while the corresponding IC_{50} determination curve is presented in Fig. 6b. Similarly, Peel-K2 also demonstrated high antioxidant activity, although slightly lower than Peel-K1, as depicted in Fig. 7a and Fig. 7b.

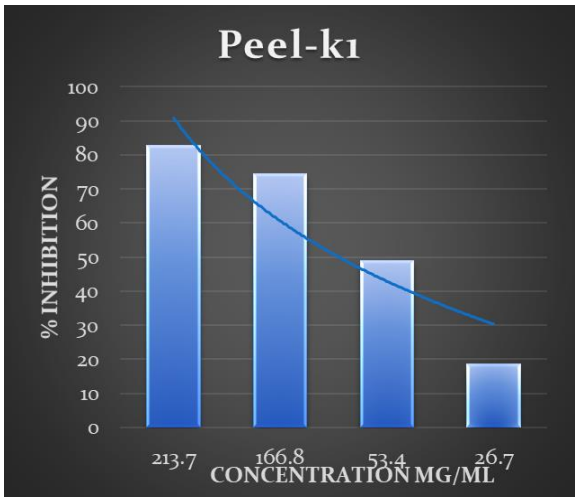

Figure 6a DPPH radical scavenging activity (% inhibition) of Peel-K1 at different concentrations

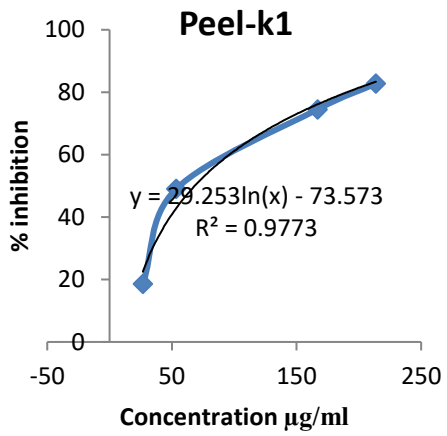

Figure 6b Determination of IC_{50} value for Peel-K1 using DPPH assay

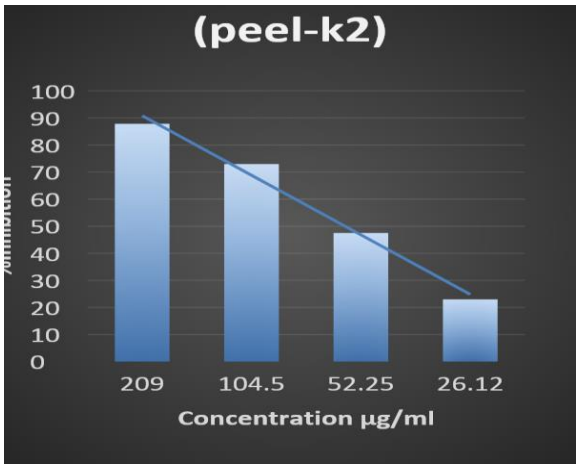

Figure 7a DPPH radical scavenging activity (% inhibition) of Peel-K2 at different concentrations

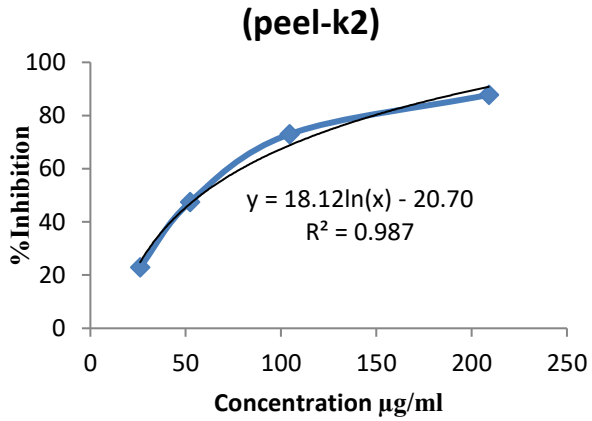

Figure 7b Determination of IC_{50} value for Peel-K2 using DPPH assay

The phloem tissues showed moderate antioxidant activity compared to peel. The IC_{50} value for Phloem-K1 was recorded as 57.65 µg/mL, while Phloem-K2 exhibited a slightly higher value of 59.698 µg/mL, indicating relatively lower scavenging efficiency. The graphical trends for these samples are illustrated in Fig. 8a and Fig. 8b for Phloem-K1, and Fig. 9a and Fig. 9b for Phloem-K2. The moderate antioxidant activity of phloem can be attributed to its intermediate position and functional role in nutrient transport.

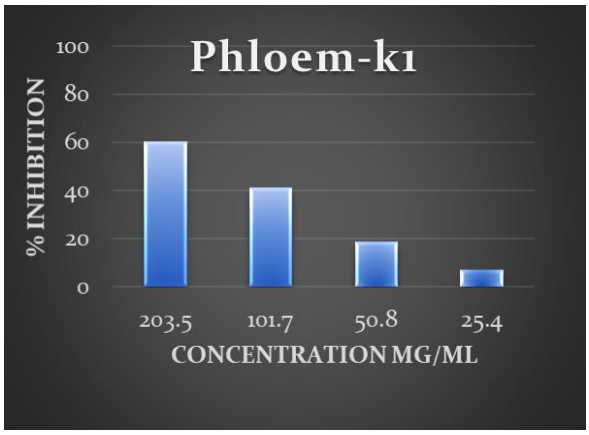

Figure 8a DPPH radical scavenging activity (% inhibition) of Phloem-K1 at different concentrations

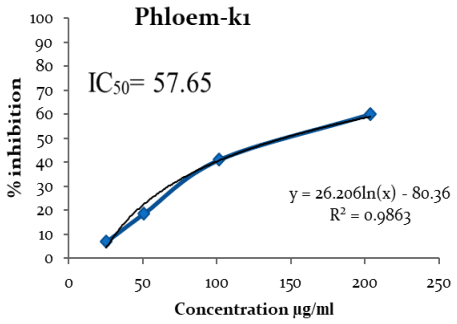

Figure 8b Determination of IC_{50} value for Phloem-K1 using DPPH assay

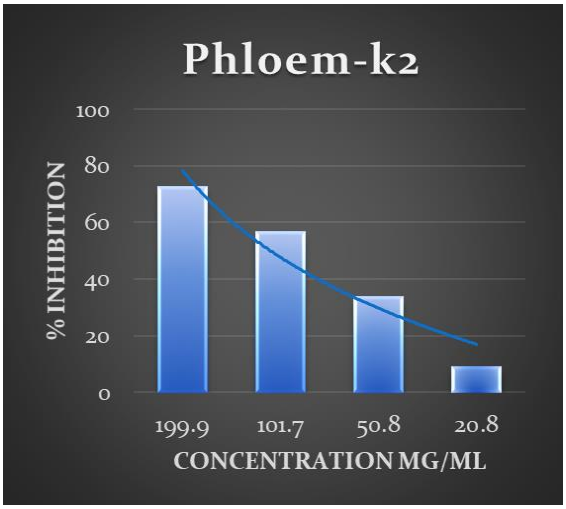

Figure 9a DPPH radical scavenging activity (% inhibition) of Phloem-K2 at different concentrations

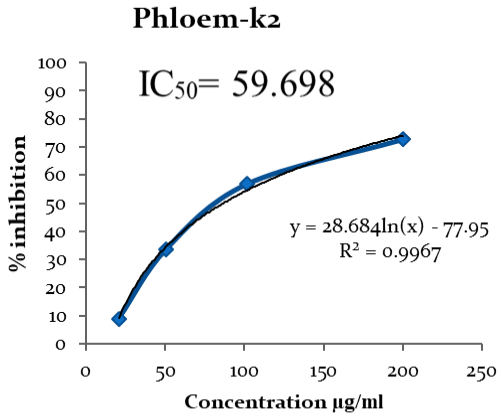

Figure 9b Determination of IC_{50} value for Phloem-K2 using DPPH assay

In contrast, the xylem tissues exhibited the lowest antioxidant activity among all samples, as indicated by their higher IC_{50} values. Xylem-K1 showed the highest IC_{50} value of 86.831 µg/mL, suggesting the weakest free radical scavenging ability, whereas Xylem-K2 exhibited a comparatively lower IC_{50} value of 68.347 µg/mL. The respective activity curves and IC_{50} determinations are shown in Fig. 10a and Fig. 10b for Xylem-K1, and Fig. 11a and Fig. 11b for Xylem-K2. The reduced antioxidant activity of xylem may be due to its highly lignified structure and lower metabolic activity.

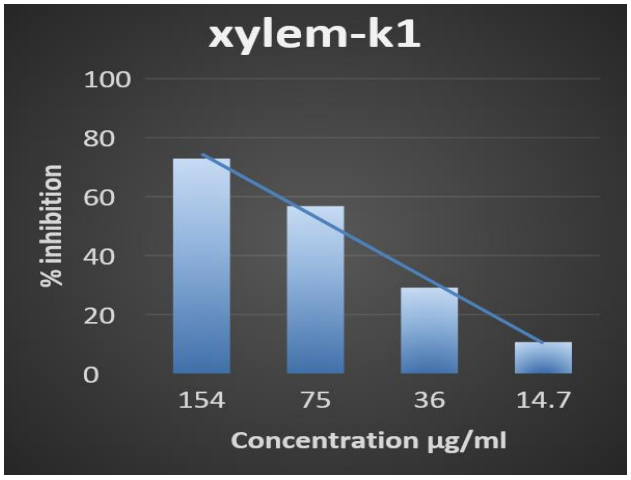

Figure 10a DPPH radical scavenging activity (% inhibition) of Xylem-K1 at different concentrations

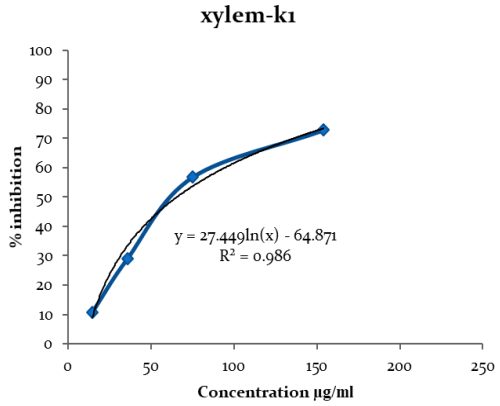

Figure 10b Determination of IC_{50} value for Xylem-K1 using DPPH assay

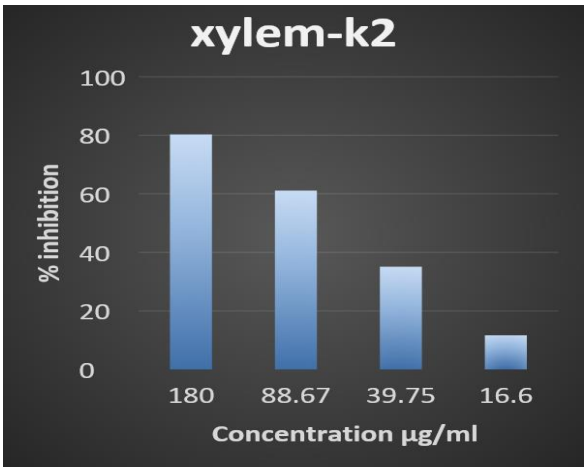

Figure 11a DPPH radical scavenging activity (% inhibition) of Xylem-K2 at different concentrations

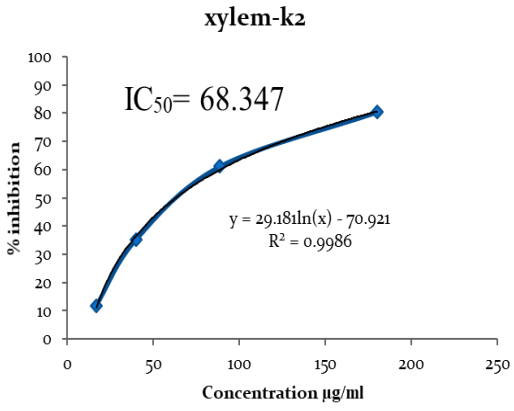

Figure 11b Determination of IC_{50} value for Xylem-K2 using DPPH assay

A comparative overview of antioxidant activity across all tissues is presented in Fig. 12, which clearly demonstrates the trend of decreasing antioxidant potential in the order: Peel > Phloem > Xylem for both regions (K-1 and K-2). Furthermore, Fig. 13 illustrates the comparison of IC_{50} values of all samples with ascorbic acid, used as a standard antioxidant, highlighting the relative efficiency of carrot tissues.

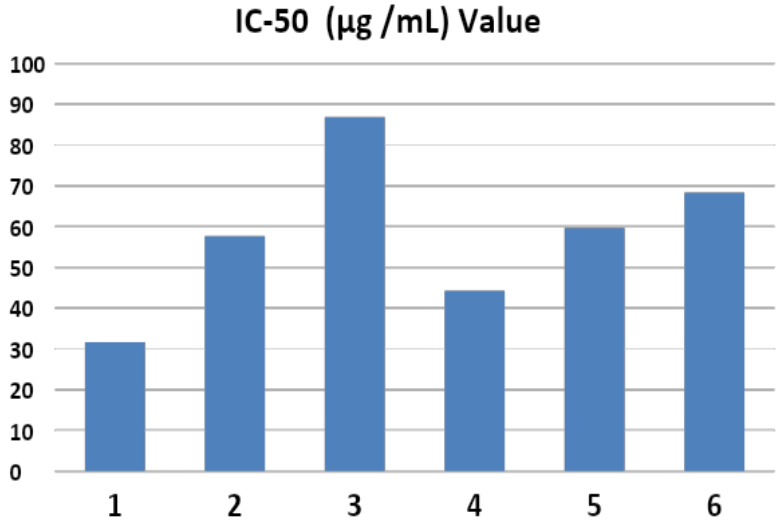

Figure 12 Comparative IC_{50} values of peel, phloem, and xylem tissues of red carrot

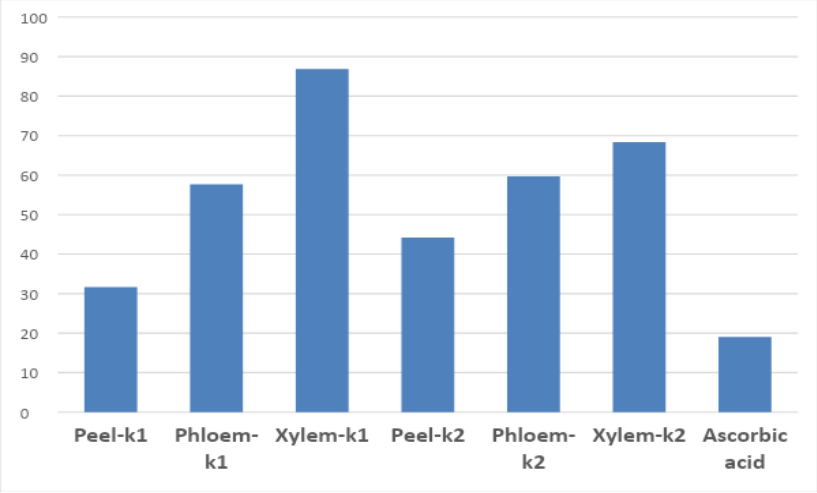

Figure 13 Comparison of IC_{50} values of red carrot tissues with standard antioxidant (ascorbic acid)

The results demonstrated that the peel tissue possesses pointedly higher antioxidant activity as compared to phloem and xylem tissues. This study indicates a very close relationship with the presence of phenols and hydroxycinnamic acids in the peels, and thus it is evident that phenolic antioxidants have an important role to play in scavenging activities of free radicals. This study

indicated that red carrot peels may be used as sources of natural antioxidants, and thus, this could be used in food products rather than wasting the peels.

4. CONCLUSION

The present study comprehensively evaluated the morphological characteristics, phenolic composition, hydroxycinnamic acid derivatives, and antioxidant potential of different tissues (peel, phloem, and xylem) of red carrot (*Daucus carota* L.) collected from two regions of Taluka Khanpur, District Shikarpur. The morphological analysis confirmed distinct structural differences among the tissues, where the peel was rich in fibrous components, the phloem consisted of sieve-like transport structures, and the xylem exhibited lignified tubular elements responsible for water conduction and mechanical support. These anatomical differences were found to be closely associated with variations in biochemical composition and antioxidant activity.

The quantitative analysis revealed that the distribution of total phenolic compounds and hydroxycinnamic acids varied significantly among the tissues, following a consistent trend of peel > phloem > xylem. The peel tissue, particularly from the K-1 region, exhibited the highest concentrations of phenolics and hydroxycinnamic acid derivatives, whereas the xylem tissue showed the lowest values. This variation can be attributed to the exposure of outer tissues to environmental stress, which enhances the synthesis of protective phytochemicals.

Similarly, the DPPH free radical scavenging assay demonstrated that antioxidant activity was highest in the peel and lowest in the xylem, as indicated by IC_{50} values. The strong correlation between phenolic content and antioxidant activity confirms that phenolic compounds, especially hydroxycinnamic acid derivatives, play a crucial role in the antioxidant potential of red carrot tissues.

The findings of this study highlight that the peel of red carrots, which is often discarded as processing waste, is a rich source of natural antioxidants and bioactive compounds. Therefore, it holds significant potential for value-added applications in the development of functional foods, nutraceuticals, and pharmaceutical products. The utilization of carrot peel can contribute to waste reduction and promote sustainable use of agro-industrial by-products.

Future research should focus on advanced analytical characterization of individual phenolic compounds and explore their bioavailability, as well as evaluate their potential health benefits through in vivo studies.

Declarations

Ethical Approval and Consent to Participate

Not applicable. This study did not involve human participants or animals.

Consent for Publication

Not applicable.

Availability of Data and Materials

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

Competing Interests

The authors declare that they have no competing interests.

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Authors' Contributions

All authors contributed to the conception and design of the study. Material preparation, data collection, and analysis were performed by the primary author. All authors contributed to writing, reviewing, and editing the manuscript and approved the final version.

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Conflict of Interest

The authors declare no conflict of interest.

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