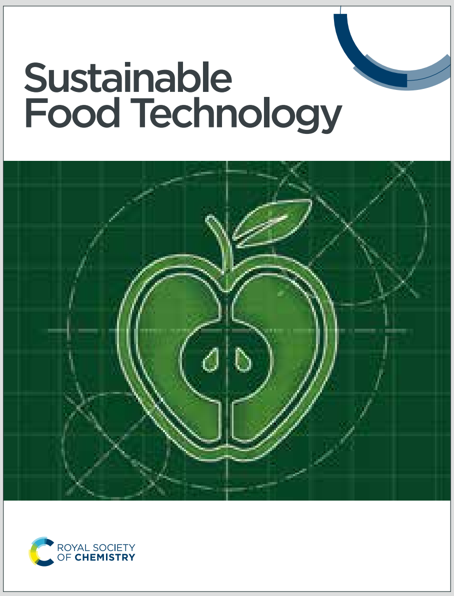
Sustainable Food Technology

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: A. Kaur, R. Kumar Tiwari, S. Singh Gaur and P. Choudhary, *Sustainable Food Technol.*, 2025, DOI: 10.1039/D5FB00493D.



View Article Online
DOI: 10.1039/D5FB00493D

- Carrot by-products offer cost-effective and sustainable formulation profits when incorporated into food products
- This holistic approach supports a transition toward circular economy practices by transforming waste streams into high-value applications
- It also aligns with the growing consumer demand for clean-label, functional alternatives and environmentally responsible products

View Article Online
DOI: 10.1039/D5FB00493D

Carrot and Its By-Products in the Circular Economy: A Review of Valorisation Pathways

Anmol Kaur[1], Ravindra Kumar Tiwari[2], Supriya Singh Gaur[1]*, Pintu Choudhary[3*]

[1]Department of Food Technology and Nutrition, Lovely Professional University, Phagwara, Jalandhar, Punjab, India-144411

[2]Department of Post Harvest Technology, College of Horticulture and Forestry, Rani Laxmibai Central Agricultural University, Jhansi, U.P.

[3]Department of Food Technology, College of Agricultural Engineering and Technology, Dr Rajendra Prasad Central Agricultural University, Pusa, Samastipur - 848 125, India

***Corresponding author:** Dr. Supriya Singh Gaur, Assistant Professor, Department of Food Technology and Nutrition, Lovely Professional University, Phagwara, Jalandhar, Punjab; E-mail: **supriya.27320@lpu.co.in**

Dr. Pintu Choudhary, Department of Food Technology, College of Agricultural Engineering and Technology, Dr Rajendra Prasad Central Agricultural University, Pusa, Samastipur - 848 125, India;

Email: choudharypintu14@gmail.com

DOI: 10.1039/D5FB00493D

Carrot and Its By-Products in the Circular Economy: A Review of Valorisation Pathways

Abstract

Carrots are one of the most widely consumed vegetables worldwide, owing to their nutritional benefits. They offer a wide range of prospects through utilization of all components of the plant. The carrot root, peel, pomace, and leaves represent values that contribute to product development in diversified uses: food processing, the pharmaceutical industry, cosmetics, and bioenergy. In addition, carrot coproducts-peel, leaves, and pomace-contain biologically active compounds that can be extracted for a range of value-added products. Besides, carrot peels are rich in fiber and antioxidant contents convertible to powder materials that can be extracted, hence suitable for functional foods and dietary supplement applications. More significantly, the integration of carrots and their by-products provide an avenue to reduce environmental waste amidst emerging consumers' demand for clean-label and functional products. The review discusses the potential benefits as a way of mitigating waste accumulation and enhancing sustainable practices across industries. This review examines how different residues of the carrot, including the roots, peels, pomace, and leaves, can be used to produce value-added products. Furthermore, this review provides a balanced perspective on how these coproducts can be processed to extract valuable compounds from them. Additionally, this review outlines values regarding plant-based products from carrots and points to valorisation of whole carrot biomass as one of the strategies to reduce waste and enhance environmental sustainability.

Keywords – Carrot, by-products, waste utilisation, sustainability, health benefits, nutritional profile.

1. Introduction

Carrot (*Daucus carota L.)* is widely consumed globally, both as a fresh and processed form, thus offering essential nutrients that contribute to human health and nutrition.[1] Carrots are valued not only for their colour and taste but also for their content of carotenoids (notably β-carotene), dietary fibre, vitamins and minerals. [2] Figure 1 illustrates the carrot along with its primary by-products in detail. Worldwide, the total production of carrots amounted to about 42 million tonnes in 2022 where China remained the dominant producer, followed by Russia and USA among the 125 nations.[3,4] Parallelly, processing industry data estimated commercial carrot processors to generate as much as 175,000 tonnes of carrot waste yearly that is

View Article Online
DOI: 10.1039/D5FB00493D

considered a great source of dietary fibre and bioactive substances.[5] Additionally, recent work indicated that carrot processing industries generate approximately 25 – 30 % of the input mass in the form of rejects, peels and pomace.[6] Despite these data, more precise breakdowns of the volumes of green tops, peel, pomace, etc., remain rather sparse in the literature, notably at global or even regional level. For instance, relatively few studies have systematically quantified the mass of carrot foliage (green tops) that is removed at harvest, along with subsequent routes of disposal and the valorisation potential. A study concerning the nutritional value of carrot whole tops for fodder indicated that the top can have high crude protein (~144 g kg^{-1}) and relevant mineral content, indicating its valorisation potential.[7]

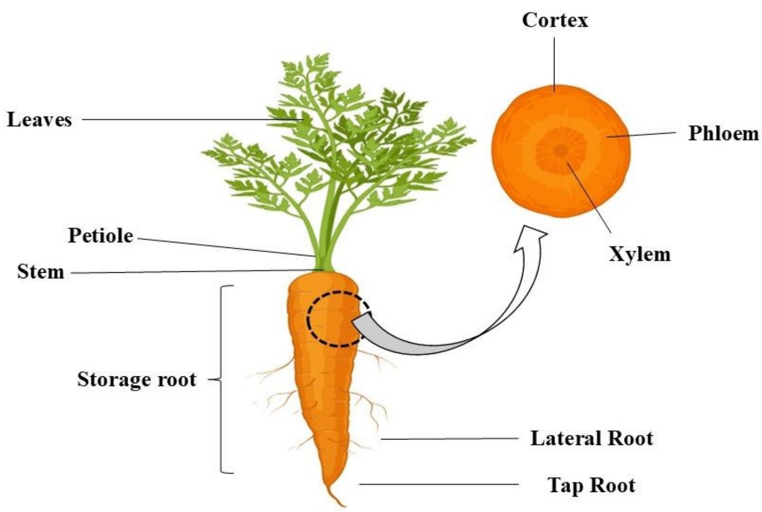


Figure 1. Illustration of carrot and its primary by-products

From the sustainability perspective, life cycle assessment (LCA) for carrot cultivation and processing opens the wider boundary of the system, including cultivation, harvest, processing, waste disposal and re-use.[8] Integrating LCA with by-product valorisation pathways would allow to quantify for the environmental benefits, such as waste reduction, reduced greenhouse gas emissions, and energy savings, offering far better justification for valorisation schemes.[9] Apart from the general opportunities of carrot by-products, a further emerging area is the presence of ice-binding proteins (IBP) or antifreeze-type proteins in carrots. However, the IBP present in carrot possess weak freezing point depression activity similar to grass protein. but is highly active at nanomolar concentrations in inhibiting ice recrystallization.[10] In all, the scale

View Article Online
DOI: 10.1039/D5FB00493D

of carrot processing has been associated with the generation of by-products including peel, pulp and pomace at a significant global level. Nonetheless, these by-products are considered a great source of carotenoids, dietary fibre, flavonoids and phenols that possess a beneficial effect on utilization in functional food products and medications.[11]

Carrot pomace has been added to bakery products like bread, cookies and cakes to enhance the fibre content, thereby, improving the nutritional value.[12] Similarly, cosmetic applications have utilized carrot seed extracts for their natural pigments and skin-protective antioxidants [13]. Despite the promising potential, here exists a significant gap in the holistic valorisation of carrot by-products. Comprehensive validation of each of its application in different sectors including bakery, cosmetics, ready to eat etc. are limited. Most of the literature reports deal with individual by-products in isolation or in one single category of products, without giving an overall view of the valorisation across various industries. This paper therefore bridges this gap by compiling and critically analysing the value creation possibilities of all major carrot by-products-peel, pomace, pulp, leaves and seeds-for different industries, such as bakery, beverages, ready-to-eat foods, cosmetics and nutraceuticals. Contrary to previous reviews, which focused on aspects related to composition or extraction, this work focuses on practical routes of utilization and cross-sectorial innovations that contribute to circular bioeconomy and waste minimization. By integrating fragmented research on carrot by-product valorisation, this review offers an overall framework for carrot by-product utilization and agro-waste management.

2. Nutritional and Phytochemical Composition of carrot and its by-products

Carrot and its by-products, such as seed oil, carrot peels, pulp, pomace, residue after the extraction of juice and tops (green leafy parts) contain high nutritional and bioactive compounds, particularly carotenoids, phenolic compounds, minerals, polyacetylenes and dietary fibre as depicted in Table 1.[14]

View Article Online
DOI: 10.1039/D5FB00493D

Table 1: Nutritional Composition of Carrot and its Byproducts

Nutrients	Whole carrot	Carrot peel	Carrot pomace	Carrot leaf
Protein (%)	0.9 -10.73	3.69 – 9.7	4 – 9.14	18.71
Fat (%)	0.2 – 6.09	1.30 - 1.54	0.70 - 1.30	3.19
Carbohydrate(%)	4.25- 58.67	32.98	46.55 – 58.95	
Dietary fiber (%)	1.2 – 80.94	45.45 - 52	20.09 – 48	15.69
Iron (mg/100g)	0.4 – 20,900	-	3050	16.25
β-carotene (mg/100g)	1.50 – 54.8	13.74 - 20.45	0.607 – 11.83	-
Calcium (mg/100g)	23.7- 80	32.06	110 – 300	49.3
Phosphorous (mg/100g)	25 - 2130	25.10	180	40.1
Potassium (mg/100g)	6.6 - 240	-	1860	9.72
References	[15–19]	[2,20–22]	[23,24]	[25–27]

2.1. Carrot

Carrot is one of the major root vegetables, rich in numerous bioactive compounds like dietary fibers and carotenoids that exerts significant health-promoting effects. The edible portion of the carrot contains soluble carbohydrates ranging from 6.6 to 7.7 g/100g[16]. Studies have revealed that the three varieties of carrot *i.e.,* Pamella, Kuroda and Americano exhibit high moisture (69.06 to 75.30%), protein and low carbohydrate level.[15] Moreover, carrot is packed with protein (0.6 to 2.0 %), fat (0.2 to 0.7%), sugars (5.4 to 7.5 %), fiber (0.6 to 2.9 %) monounsaturated fatty acids (MUFA) (160.0 mg), polyunsaturated fatty acids (PUFA) (921.7 mg) and saturated fatty acids (SFA) (693.4 mg).[2] Additionally, carrot is a great source of various minerals and vitamins, predominately calcium (34 to 80 mg/100g), iron (0.4 to 2.2 mg/100g), phosphorous (25 to 53 mg/100g), magnesium (9 mg/100 g), thiamine (B1) (0.04 mg/100g), riboflavin (0.02 mg/100g) and β-carotene.[28] Besides, the bioactive compounds present in the carrot are carotenoids (carotene, lutein, β-carotene, lycopene, zeaxanthin), phenolic acids (p-hydroxybenzoic, chlorogenic and caffeic acid), flavonoids (anthocyanins)

View Article Online
DOI: 10.1039/D5FB00493D

that exert various pharmacological properties, comprising hypolipidemic, anti-fungal, gastro and hepato-protective effect, antifungal, antibacterial, antipyretic, antioxidant and analgesic properties.[29,30]

2.2. Carrot pomace

Being a valuable source of significant nutrients, carrot pomace has incorporated for the development of food products owing to their nutritional profile.[31] Carrot pomace contains a healthy balance of both macro and micro-nutrients, such as total carbohydrates (71.60 %), protein (4 %), fat (1.30 %), crude fiber (20.90 %), cellulose (51.6 %), pectin (3.88 %), lignin (32.1%), hemicellulose (12.3%), reducing sugar (9%), calcium (3.00 mg/g), iron (30.50 mg/g), zinc (24.40 mg/g), phosphorous (1.80 mg/g), copper (4.00 mg/g) and potassium (18.60 mg/g) (Nazar et al., 2023). Parallelly, pomace is also rich in vitamins, such as vitamin A, vitamins B complexes, Vitamin C and K. The phytoconstituents present in the carrot pomace are polyphenols, carotenoids and antioxidants.[32] Thus, the utilization of carrot pomace provides an insight for the development of functional ingredients for the food industry and reduces the food waste[33].

2.3. Carrot Peel and leaves

Carrot peel, a major waste and by-product of carrot, can be engrossed for the value-added products owing to the high level of antioxidant and phenolics content (54.1%) [16]. Interestingly, carrot peel contains significant amount of β-carotene (204.5 µg/g) as compared with carrot pulp waste (39.2 µg/g) and carrot pomace (19.81 µg/g) [34]. Moreover, the peel has abundant amount of cations (+92%), carotenoids (+42%), phenolic acids (seven times) and organic acids (+103%) than root flesh [35]. Besides, carrot peel powder conserved increased content of beta-carotene, total carotenoids, lycopene and lutein and promotes their significant health benefits.[36]

Parallelly, carrot leaves are a remarkable source of macronutrients, like protein (18.71%), fibre (15.69%), oil (3.19%), vitamin C and phytochemicals, especially flavonoids, terpenoids, steroids, carotenoids, beta-carotene, tannins and phenolic compounds.[25] Importantly, orange carrots have high concentrations of α-carotene (67%) as compared with other vegetables[37]. Studies have demonstrated the anti-inflammatory, antioxidant, antimicrobial and anticancer effects of carrot leaves due to the presence of polysaturated fatty acids, α-pinene, germacrene, sabinene and luteolin.[38]

3. From Farm to Function: Utilization of Carrots

View Article Online
DOI: 10.1039/D5FB00493D

Carrots are progressively being utilized for the development of a wide spectrum of value-added products that not only enhances the nutritional and functional appeal of carrots but also contribute to its increased shelf life as well as consumer convenience.[39] This section outlines different carrot based value-added products that offers enhanced shelf life and convenience, as illustrated in figure 2.

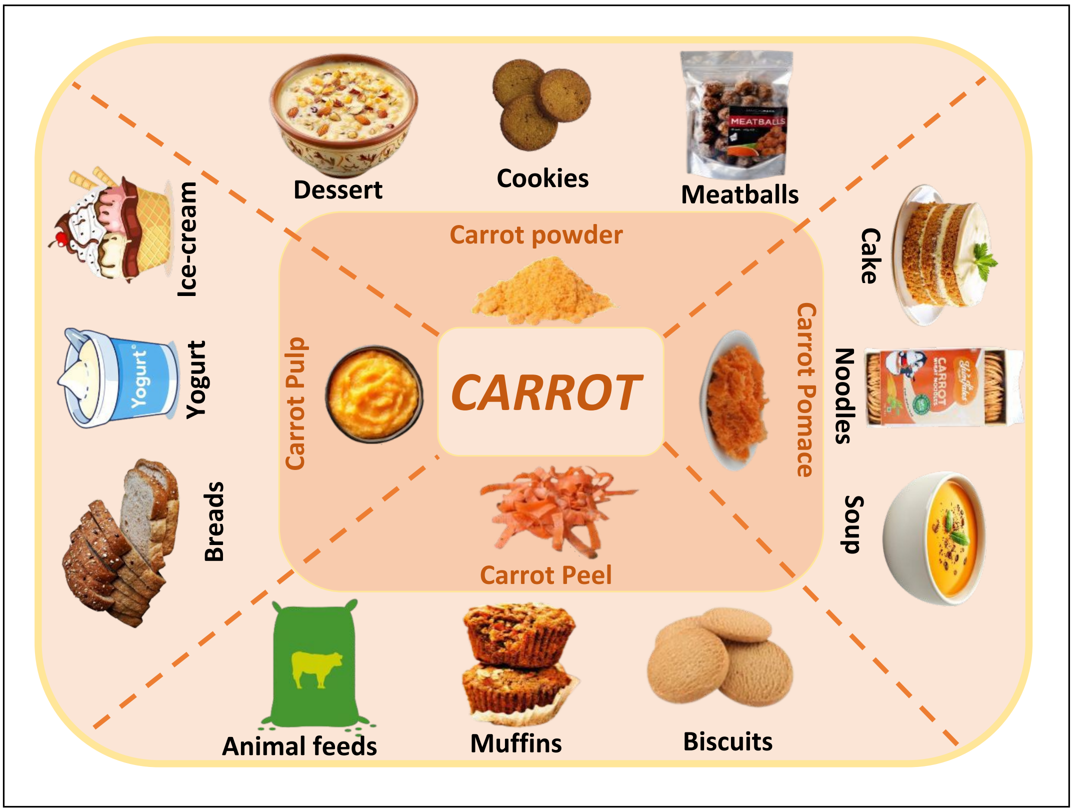


Figure 2: Utilization of Carrot and its By-products in various Industries

3.1. *Bakery Products*

Carrot, due to its rich nutritional and functional properties has been widely utilized in bakery products to enhance their health benefits and sensory appeal. The incorporation of carrot in bakery products such as biscuits, cookies, cakes and bread has shown a promising impact on both nutritional profile and consumer acceptability. Biscuits developed using a different concentration of carrot powder with white bean flour showed great enhancement in nutritional content compared to the control. These biscuits showed an increase in the antioxidant activity, with higher total phenolic content (66.20 – 210.30) and radical scavenging activity (30.50 – 52.5).[40] Likewise, in a similar study, carrot powder along with soy and wheat flour caused significant enhancement in the protein level in cookies, which reached as high as 21.60 percent with the incorporation of soy flour. The composite flour significantly enhanced the functional properties of the final product and contributed to better handling of dough and quality.[41] Besides this, the addition of black carrot powder in bread with the level of 2.5, 5.0 and 7.5 percent preserved the moisture, protein and fat content of the product and thus enhanced the crude fibre and total ash content. This was considered advantageous for increasing the antioxidant activity and mineral content of the bread.[42] Thus, it indicates that the amount of carrot in breads may vary according to the form of carrot used and its processing.[43] Moreover, layer cakes prepared by a 40 percent mixture of carrot and pumpkin puree obtained a significant enhancement in nutritional content, with protein reaching to 8.89 percent and fat content rising to 18.31 percent, beta carotene increasing to 54.41 g and moisture content at 48.18 percent[44]. Likely, Prajapati et al.[45] developed cake using carrot, which imparted unique flavour, colour and taste to the product. Moreover, the antioxidant activity, springiness and volume of the cake was excellent compared to normal cake.

3.2. Meat based products

Carrot, being a natural additive has lately exhibited immense potential for enhancing nutritional quality and oxidative stability in meat-based product production. Components derived from carrot used in various meat products have therefore shown good prospects to act like natural additives to enhance nutritional value, stability of oxidation and quality of the ultimate product [46]. According to report by Kaynakç, [47], purple carrot powder extract applied effectively reduced lipid oxidation of vacuum-packed meatballs stored at 4°C for seven days, with lower thiobarbituric acid reactive substances on day four. Besides, carrot and ginger extracts (12:1) had the highest sensory acceptability in chicken nugget formulations. However, flavour and juiciness had slightly declined during extended storage at -20°C, highlighting the need for improved storage stability [48]. Additionally, a study evaluated the impact of incorporating carrot in canned goat meat and its biological value, where increase in carrot content contributed to significant increase in fibre, β-carotene, select amino acids (histidine, lysine), vitamins (A, B5, B6, B9), minerals (potassium, magnesium, phosphorus) and a reduction in fat content [49]. Moreover, carrot incorporated fresh turkey sausages had excellent physicochemical properties and fatty acid profile. In particular, the addition of 20 and 30 percent carrot significantly reduced lipid content, energy value and sodium levels while enhancing the colour.[50]

3.3. Traditional food products

View Article Online
DOI: 10.1039/D5FB00493D

Carrot has emerged as a valuable ingredient in developing nutrient-rich, culturally relevant desserts with enhanced sensory and therapeutic attributes. Carrots are used to prepare various traditional food products including sandhesh, rasogolla, chamcham, rasamadhuri etc.[51] A shelf-stable, ready-to-cook carrot halwa mix showed reduced preparation time compared to the control halwa mix, without compromising the sensory and nutritional qualities.[52] In an effort to combat vitamin A deficiency in Indonesia, a modified traditional cake- carcake was formulated using different substitution levels of carrot flour. Among the tested variations, the formula containing 150 g of carrot flour emerged as the most preferred in terms of taste, aroma, color, and texture, indicating its suitability as an acceptable and nutritious alternative.[53] Other innovative approach was the development of carrot dessert/ payasam - an Indian food with rice balls - using different proportions of carrot puree, milk, rice flour, sugar and water. In this context, the prepared product was rich in β-carotene and bioactive compounds, showing prospective therapeutic applications against Vitamin A deficiency and cardiovascular diseases.[51] Significantly, incorporation of carrot with spinach and basella leaves showed a great potential in the traditional food industry for the development of nutrient-dense and shelf-stable products, like instant chutney powders. This exhibited an increase in micronutrients and bioactive molecules, thus, exhibited to solve the problem of micronutrient deficiency.[54]

3.4. Functional Beverages

Being a rich source of antioxidants, dietary fibres, vitamins and minerals, functional drinks has become popular among health-conscious consumers.[55] A functional beverage developed by blending carrot and cucumber juice in equal ratio enhanced the vitamin A, vitamin C and maximum antioxidant activity levels of the drinks.[56] Likewise, incorporation of pomegranate, beetroot and carrot concentrates in whey-based beverage resulted in an increased nutritional, antioxidant, physicochemical and sensory properties. The beverage with carrot concentrates exhibited the highest beta-carotene and anthocyanin content.[57] In addition, the bioactive profile of Kanji prepared from black carrot juice was excellent; the pH decreased from 6.0 to 3.47, lactic acid increased to 0.99 percent, and the lactic acid bacteria count increased significantly during fermentation, reaching up to 8.33 log CFU per millilitre. Besides this, the prepared beverage had a high antioxidant activity of 79.96 percent and high flavonoids and phenolic content.[58] In another approach, the limitations of conventional Kanji like limited shelf life and low microbial stability were overcome by the preparation of a ready-to-use Kanji mix using carrot powder. The reconstituted mix prepared from it showed either comparable or slightly

View Article Online
DOI: 10.1039/D5FB00493D

higher antioxidant activity (86.90%) and flavonoid content (43.91 mg/100 mL) compared to conventional Kanji, and consumer acceptability was also comparable.[59]

3.5. Dairy Products

Various carrot extract has been used for the fortification dairy products. A study by Baker et al.[60], added carrot powder to probiotic cream cheese in different concentrations. The product exhibited excellent mineral content, antioxidant activity, total phenol, β-carotene, sensory profile and functional properties, without affecting its basic composition. Besides that, CP supported the viability of probiotics (>6 log cfu/g) during storage, against typical changes in pH and acidity and carrots could be highlighted as a functional dairy additive. Similarly, utilization of black carrot juice to develop a whey drink initially exhibited an increased acidity and decreased anthocyanin content, though the resting period resulted in its enhanced phenolic content and colour. Inclusively, black carrot juice not only highlighted as a source of vibrant pigments and phenolic compounds but also a viable base for fermented functional drinks with probiotic potential.[61]

3.6. Carrot ice-binding proteins

Ice-binding proteins (IBPs) or anti-freeze proteins (AFPs) are specialized low temperature responsive proteins, not only reduces the freezing damage but also controls the growth of ice-crystals.[62] Notably, carrot (*Daucas carota*) antifreeze protein (*Dc* AFP) is considered as leucine-rich repeat protein with a molecular weight of 36.8 KDa. This protein demonstrates significant anti-crystallization ability, thermal hysteresis and provide softer texture with pleasant aroma.[63] Besides, the carrot antifreeze protein has a strong influence on textural properties of white salted noodles by increasing cooking absorption, reducing dry material loss, protecting the gluten network from the freezing and fluctuation of temperature.[64] Likewise, the protein reduces the depolymerization of glutenin macropolymers (GMP) and weakened the destruction of disulfide bonds, microstructure and secondary structures of hydrated gluten [65] . Studies have proven the fact that carrot antifreeze protein improves the textural properties and fermentation capacity of dough during frozen storage. However, their production is generally low due to the low-yield and extensive purification producers.[66]

4. Carrot Peel Utilization: A Sustainable Approach

Carrot peels have gained huge attention in the recent years for their potential development in value-added products from different sectors.[67] High in bioactive compounds and fiber, they are

View Article Online
DOI: 10.1039/D5FB00493D

being progressively used in bakery, ready-to-eat (RTE) foods, and serve as a sustainable component in animal feed-as discussed in this section.

4.1. Bakery Products

Mixed peel powder (MPP) was prepared using peels of banana, carrot and apple and was used to develop high-fibre whole-wheat biscuits. Based on the findings, carrot peel presented higher fibre, fat, ash and essential minerals, thus giving fortified biscuits a better nutritional profile.[68] In a similar study, the use of carrot and mango peel powder blends in biscuit formulations enhanced the antioxidant activity with 67.52 percent along with improving the sensory qualities of the product. The formulation containing 10 percent carrot and mango peel powder showed maximum colour, texture, taste and overall acceptability along with 9.63 percent of protein.[69]

4.2. Animal Feed:

The growing interest in sustainable livestock production has turned attention toward agricultural by-products, where fruit and vegetable peels are used as alternative feed resources. Among those, carrot by-products have emerged as sustainable, nutrient-rich alternatives in livestock and their feed, supporting animal health and environmental conservation. By diverting such organic waste from landfills, methane emissions can be significantly reduced and the pressure on resource-intensive grain production can be alleviated. It has been reported that vitamin E in carrot peel supports reproductive efficiency, calcium in it supports bone strength of livestock, and its nutrient-dense nature makes them ideal for meat-producing animals like ruminants and poultry.[70] In addition, vegetable wastes like carrot peel used as protein-based fishmeal alternatives in aquaculture shows promising results.[71] A study conducted by Rauf et al.[72] used carrot peel as carotenoid source in aqua feed for platy fish. It is known that pigments in the feed will result in improved pigments in ornamental fishes and the study concluded that platy fishes responded positively towards the carrot peel-based feed with improved pigments in passage of time. Also, including carrot peels cattle feed will improve nutrients in its milk such as omega-3 fatty acids and vitamins.[70]

View Article Online
DOI: 10.1039/D5FB00493D

5. Carrot Pulp: A Valuable Agro-Industrial Residue

Carrot pulp, a multipurpose by-product of carrot processing, has come into the spotlight due to its potential to increase the nutritional and functional qualities of different food commodities. Carrot pulp is progressively merged into cereal-based fermented foods, beverages, dairy products, baked goods and spreads, refining their fiber levels, antioxidant potential thereby, offering cost-effective and sustainable formulation profits.

5.1. Probiotic Fermented Products

The nutritional potentiality of fermented food products significantly depends on the probiotic strain present in it [73]. However, the matrix used can improve the probiotic count as well nutritional composition of the product. A study conducted by Suraj et al.[74] used 10 percent carrot pulp in tef based injera-a traditional fermented product. According to research, injera with tef alone lacks many vital nutrients. The results from carrot pulp incorporated injera showed good mineral content, crude fat, protein, sensory properties and optimum microbial content. Besides, a probiotic drink developed using carrot and mango pulp excellent probiotic viability along with optimum pH, colour, soluble solids and sensory acceptance. Among multiple probiotic strains used, *Lactobacillus plantarum* showed highest survival in gastrointestinal conditions, highlighting the positive role of carrot-mango pulp as matrix.[75] Similarly, functional yoghurt developed using black carrot pulp and arabic gum demonstrated excellent phenolic content, antioxidant activity, texture. Also, incorporation of carrot pulp improved probiotic viability and sensory properties with storage.[76] Carrot pulp fortified with Lassi- a traditional fermented beverage had improved viscosity, acidity, total soluble solids with decreased fat content. Moreover, the probiotic count increased from 8.50 to 8.68 log cfu/ml with an increase in concentration of carrot pulp in the product.[77]

5.2. Dairy based Products

Carrot pulp has been widely explored in dairy and frozen dessert formulations for its potential to enhance nutritional composition, functional properties and consumer appeal. A modified version of kulfi developed using carrot pulp exhibited excellent fibre content, optimum pH and the melting rate decreased with the addition of carrot pulp.[78] Likewise, the addition of pumpkin and carrot pulp into traditional ice cream where the product enriched with pulp demonstrated enhanced melting resistance and better sensory performance, antioxidant activity, especially at the 15 percent inclusion level.[79] Similarly, ice cream developed using carrot pulp and beetroot juice had higher levels of carotenoids, crude fibre, total phenolic compounds and antioxidant

View Article Online
DOI: 10.1039/D5FB00493D

activity, improved natural colour and flavour, indicating strong consumer acceptance.[80] In the case of yoghurt drink, incorporation of carrot and guava pulp at varying levels reported significant increase in fiber, phenolic compounds, ascorbic acid and antioxidant activity. Although acidity and syneresis increased over storage, carrot pulp addition enhanced nutritional value and product acceptability.[81] Similarly, carrot and orange pulp–fortified yogurt drink with 10 percent pulp showed higher antioxidant capacity and provitamin A content. Sensory evaluation showed favourable scores and microbial stability was maintained throughout the 35-day storage period.[82]

5.3. Confectionery and Bakery products

Carrot pulp is one of the best applicants which has exhibited potential for incorporation into a variety of spreadable products, especially when combined with other fruit pulps. A study conducted by Hanoğlu et al.[83] incorporated carrot pulp in preparing Turkish delight- a traditional soft confectionery. The product showed good phenolic profile, antioxidant activity and sensory qualities. Similarly, apple and carrot pulp-based jam was developed and its organoleptic quality was assessed. The jam retained most nutrients, showed negligible changes in all sensory attributes and all physicochemical properties remained comparable for a period of 90 days.[84] Additionally, vegetable based extruded pellets and snacks can be developed by incorporating carrot pulps to it and such addition of pulps will limit energy and water requirement during processing [85] Carrot pulp can be used to prepare bread with cereal flours as base material, which will have improved dietary fibre vitamins and sensory properties compare to regular bread.[43]

6. **Carrot Leaves: Green Gold in Agro-Waste**

Carrot leaves, once considered as a waste, are now known for their potential and rich nutritional profile. Being a rich source of several nutrients, these could be utilized as a new food supplement for the agriculture sector.[26]

6.1. Bakery Products

Incorporating carrot leaves into bakery products signifies an innovative approach to improving the nutritional value hence, reducing food waste. Carrot leaf and stem flour incorporated gluten free biscuit at a different concentration of 0, 10, 15, 20 and 25 percent possessed excellent nutritional composition, texture and sensory profile. Additionally, chewability and fracturability of the biscuits increased with an increase in the ratio of carrot leaf powder, thus,

View Article Online
DOI: 10.1039/D5FB00493D

reporting carrot by-products as the main component to maintain the textural characters of the developed biscuits.[86] Besides, researchers evaluated carrot leaves as a cheap source of abundant nutrients, thus, their addition in bakery products could be a beneficial food product for below poverty line consumers, highlighting the potential of carrot waste valorisation in food security.[87] Moreover, carrot leaf powder assessed as a fortifying ingredient in sponge cake exhibited high content of antioxidant, thus, enhancing the nutritional, sensory quality, and enhanced functional properties of the product.[88]

6.2. Instant Products

Incorporation of carrot with olive leaves showed a great potential in the instant food industry for the development of nutrient-dense pasta. This exhibited a significant potential by enhancing the functional and nutritional characteristics of the food product by raising the content of polyphenol and antioxidant activity in it [89]. Similarly, the potential of carrot leaves and oregano was shown to be used as functional food ingredients for formulating pasta, thus enhancing the bioactive compounds and nutritional composition of the product.[90,91] Besides, a study conducted by Joshi et al.[92] developed instant soup mix using vegetables leaves including carrot leaves. The antioxidant characters of the soup mix were exhibited to be maintained even after 60 days storage.

7. Carrot Seed: A Seed of Functional Innovation

Carrot seed oil has gained much attention with respect to its use in cosmetic and pharmaceutical applications due to its anti-aging, antioxidant, and photoprotective potentials [77]. More recent studies have focused on its application in emulsions, nano emulsions, and topical cream formulations, which have shown great promise in skin rejuvenation, sun protection, and as a suitable carrier that enhances the therapeutic competence of other drugs. This is an indication of carrot seed oil's great potential in both aesthetic and health-related spheres of application.

7.1. In Emulsion

The first support for the therapeutic relevance of carrot seed oil was developed by preparing a nano-emulsion prepared with carrot seed oil and the anticancer drug sorafenib, with a view to enhance efficacy and lessen toxicity for the said drug. In particular, the nano emulsions are characterized by small droplet sizes (10.27 ± 2.39 nm for drug-free nano emulsion and 68.92 ±10.6 nm for the sorafenib-loaded one). Additionally, antitumor activity along with the reduction in hepatotoxicity and hematotoxicity was improved with the use of this nano-

View Article Online
DOI: 10.1039/D5FB00493D

emulsion-sorafenib combination in a murine model of Swiss albino mice bearing Ehrlich ascites carcinoma, as compared to the control group. Such a formulation not only increased the therapeutic index of sorafenib but also demonstrated the versatility of carrot seed oil in pharmaceutical emulsions.[93] Recent research has focused on carrot seed oil as a natural, plant-derived ingredient in cosmetic emulsions for skin rejuvenation and protection. The formulations with 2-6% carrot seed oil showed stable emulsions, with high antioxidant and free radical scavenging action, the 6% formulation giving the highest SPF, promising anti-aging, and skin enhancement without irritation.[94]

7.2. In Cosmetics

Aging comprises several biological factors with physiological, psychological, and environmental influences. However, it is inevitable and irreversible process. Also, skin aging reveals the gradual telltale signs, especially through wrinkles, loss of elasticity, and uneven skin tone, as people regard them more negatively than positively.[95] Researchers investigated the topical cream formulations of carrot seed oil (3–9%) in oil-in-water emulsions and observed that all formulations were stable, compatible with skin, and did not cause any irritation. The greatest anti-aging activity was demonstrated by the 9% carrot seed oil cream through its hydration-enhancing action, wrinkle minimization, and reduction of dark spots, thus presenting this natural active compound as a vital ingredient for skin-improving cosmetic formulations [96]. A comparative study investigated the photoprotective potential of carrot seed oil and raspberry seed oil added to an SPF 30 sunscreen formulation. Results showed that adding carrot seed oil significantly enhanced UVB protection with statistical validation confirming it as a natural UV-protective additive that enhances the efficacy of sunscreen.[97]

8. Carrot Pomace: Valorising Juice Industry Waste

Carrot pomace, a nutrient-rich by-product of carrot processing, is a very desirable ingredient in a wide variety of food products. Value addition not only provides functional value to products but also helps in reducing food waste, hence promoting sustainability.[14] Various value-added products using carrot pomace are discussed here and are illustrated as Figure 3.

View Article Online
DOI: 10.1039/D5FB00493D

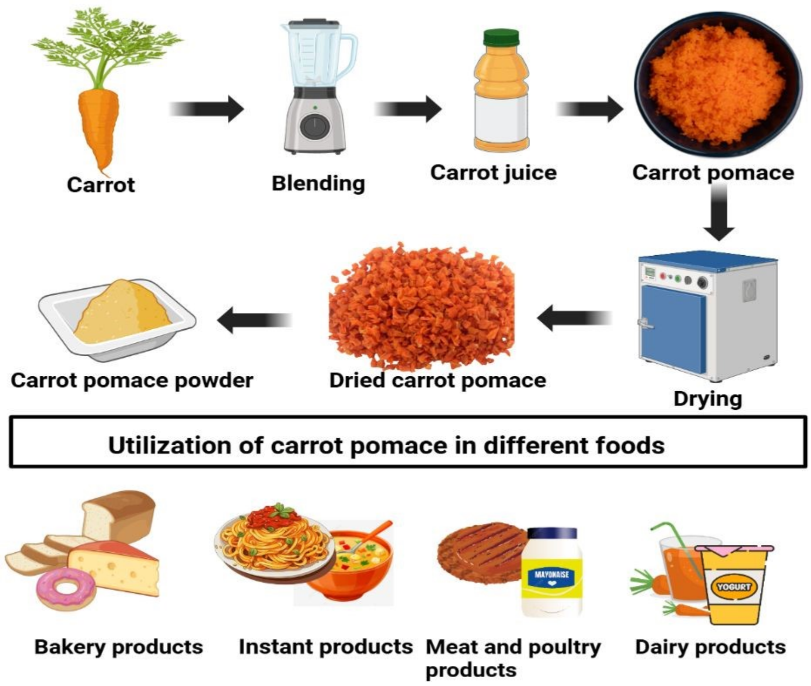


Figure 3: Processing of Carrot Pomace and its utilization in various food products.

8.1. Bakery products

Carrot pomace is being incorporated in different bakery products such as bread, muffins, cakes, cookies, biscuits, crackers etc. The usage of carrot pomace flour in bakery products is an effective sustainable approach.[98] Black carrot pomace at different concentration in cake showed enhanced total phenolics, antioxidant activities and anthocyanins.[99] Additionally, incorporation of 5 percent carrot pomace in 100g of bread enhanced the content of cellulose (0.37 mg) and β-carotene (5.44 mg). Notably, consumption of 277g carrot pomace enriched bread on daily basis fulfils 100 percent of carotene and 4.1 percent of daily dietary fibre.[100] Likewise, addition of 15 percent carrot pomace not only affected the characteristics of the dough but also led to the increase in lipid content and antioxidant activities.[101]

8.2. Instant/Ready to eat products

The addition of carrot waste to durum wheat pasta significantly enhanced its fat, protein, and ash value, organoleptic of the product. It was reported that addition of 25 percent pomace of carrots not only improved the dietary fibre and β-carotene content of the pasta, but also bridged the Vitamin-A deficiency.[102] In addition, incorporation of the carrot pomace powder with wheat flour in instant fried noodles at different concentration increased the protein content of the noodles. Among these preparations, noodles made from 5 percent of the carrot pomace had the highest overall acceptability for color, texture, flavor and odor.[103] Similarly, the higher

View Article Online
DOI: 10.1039/D5FB00493D

proportion of carrot pomace also affected the texture of noodles during thermal treatment.[104] Similarly, scientists demonstrated the nutritional improvement of soup mix from carrot pomace blended with other food items which led to the improvement of β-carotene, ascorbic acids, phenols, dietary fiber and minerals content.[105] Alike, freeze-dried carrot pomace on combination with groundnut meal exhibited to improve the colour, water absorption and swelling capacity of the pasta, consequently, reducing its cooking time [106]. Additionally, natural sweetness of carrot and corn minimized the requirement of artificial sweetener in the cooking of sweet corn and carrot pomace enriched porridge.[107]

8.3. Meat and Poultry

Carrot pomace powder incorporated with the emulsion based low fat chicken meatballs at the concentration level of 1, 2 and 3 percent, respectively, not only improved the dietary fibre content of the product but also sustained the sensory properties of the meatballs, thereby, proving carrot pomace powder as a valuable source of the residue.[108] Besides, addition of 6 percent dried carrot pomace into the chicken sausages supplied 1/7 of the daily requirement of dietary fiber.[109] Additionally, incorporation of dried carrot pomace into beef patties exhibited extra benefits such as enhancing the water holding capacity by 12 percent and cooking time by 5-15 percent. But the texture of beef patties remained unchanged. Thus, making carrot pomace as valuable by-product to enhance the quality of the product. Moreover, beef patties supplemented with 1 percent carrot pomace received highest overall acceptability compared to those prepared with 3 percent of carrot pomace.[33] Furthermore, incorporation into mayonnaise at varying concentrations was systematically investigated to assess developments in functional attributes and nutritional quality. The sample containing 4 percent carrot pomace showed the highest total phenolic content, firmness, and adhesiveness.[110]

8.4. Milk Products

Carrot pomace is highly valued for being an excellent source of carotene, ascorbic acid, dietary fibre and some essential minerals such as calcium, phosphorus, magnesium, iron, copper, all of which results in benefiting the health of individuals. Researchers observed an increase in the nutritional value and antioxidant compounds like flavonoids and carotenoids in the frozen bio yoghurt by incorporation of carrot pomace. Additionally, carrot pomace has been considered as a prebiotic as it supports the evolution of beneficial microorganisms especially probiotic bacteria. The incorporation of carrot pomace into such dairy-based systems contributed notably to the enhancement of ash content, thus elevating the product’s mineral profile and enhancing

DOI: 10.1039/D5FB00493D

its classification as a nutrient-dense food.[111] In a related study, carrot pomace was added to a milk-based beverage as a source of dietary fiber, using high methoxyl pectin as a stabilizer. Changing this formulation influenced the beverage not only in colour and viscosity but also maintained its acidity, turbidity and overall physical stability.[112] Above stated findings therefore highlight the multifunctional potential of carrot pomace in dairy-based applications mainly to enhance mineral fortification and dietary fiber content without adversely affecting product quality or consumer acceptability.

9. Valorization Pathways: Technologies and Products

Carrot is a good source of numerous bioactive constituents, such as flavonoids, vitamins (B1, B2, B6), minerals, carotenoids and phenolic compounds.[18] However, these compounds can be effectively extracted by employing various extraction methods, as illustrated in **Table 2**.

9.1. Physical And Thermal Processing:

Numerous studies have discussed the effect of thermal processing techniques, such as boiling, baking, steaming and microwave cooking. which have a major influence on the carotenoid composition, antioxidant properties, nutritional composition, phenolic content and sensory attributes, including texture, flavour and colour.[113] Studies have demonstrated that the thermal processing technique facilitates cell separation of vegetable tissues due to the pectin depolymerisation in the middle lamella through β-elimination.[114] The cell walls damage by thermal treatment is responsible for the enhanced release of phenolic compounds. It was observed that cooked carrot in water, steam and microwave contain higher phenolic compound compare to the uncooked carrot.[115] Similarly, has been reported that compare to hot water cooking, steam cooking, pressure cooking, microwave showed highest increase in phenolic compounds.[116] However, Thanuja et al., (2018)[117] reported that hot water cooking of carrot have no significant effect on phenolic compound content, while stir-frying and microwave cooking significantly reduced phenolic compound with microwave showed higher reduction of phenolic compound compare to stir-frying.

Notably, refractance window drying, a technology used to develop novel food products with excellent functional properties as compared with the conventional air-drying methods.[118] Moreover, the combination of microwave (MW) and microwave vacuum (MWV) technologies improved the quality of the carrot chips by reducing shrinkage characteristics and hardness, preserving phenolic compounds, color changes and β-carotene with acceptable nutritional and physical quality.[119] In addition to this, incorporation of freeze-dried carrot pomace powder in

View Article Online
DOI: 10.1039/D5FB00493D

the wheat bread enhances the nutritional value quality of the product with acceptable flavor and taste.[120] Overall, the mild and controlled thermal processing enhance phenolic compound however harsh thermal processing reduces the phenolic compounds additionally various other factor impacts the process such as temperature, pressure, treatment time and variety of carrot.

9.2. Green Extraction Techniques

Green extraction methods, like ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE) and enzymatic-assisted extraction (EAE), provide an effective and eco-friendly approach by preserving the bioactive compounds and reducing environmental impact.[121] For instance, the ultrasound extraction technique is employed for the extraction of carotenoids from carrot pomace by ultrasonic cavitation that may activate the chemical reaction and increase the extraction rate and efficiency while decreasing the extraction time and temperature.[122]

In the context of carrot waste, UAE has been successfully applied for the extraction of carotenoids such as β-carotene and lutein. The efficiency of UAE is influenced by various process parameters such as ultrasonic frequency, power intensity, extraction time, temperature, and solvent type. Studies have reported that that UAE significantly reduces extraction time (by up to 50–70%) and solvent usage while maintaining high antioxidant activity of the extracted compounds.[122,123] Additionally, UAE is particularly advantageous for heat-sensitive compounds due to its relatively low operating temperature.

Recently, Constantin et al.[124] investigated UAE based optimization for the valorization of carrot peels using ultrasonication combined with process optimization tools. The study reported a high carotenoid recovery (≈38.2 mg/g dry weight) along with strong antioxidant activity (≈1522 µmol TE/g), confirming that UAE not only improves extraction yield but also retain the functional properties of bioactive compounds. However, the authors have mentioned that ultrasound parameters are very important in extraction, excessive ultrasonication treatment may generate free radicals and that will be responsible for the degrading bioactive compounds

In addition, hybrid techniques combining ultrasound with other extraction methods have shown promising results. Sequential microwave–ultrasound-assisted extraction has been reported to further increase the recovery of bioactive compounds due to synergistic effects of thermal and mechanical disruption, achieving higher extraction yields than either method alone. This integration highlights the potential of UAE as a component of intensified and scalable extraction systems for industrial applications. Overall, these studies emphasize that UAE is a highly adaptable, efficient, and scalable green extraction technology. Its advantages include reduced extraction time, lower solvent requirements, improved yield, and better preservation of thermolabile compounds. However, optimization of process parameters particularly ultrasonic power, temperature, and extraction time is essential to balance enhanced extraction with the prevention of compound degradation.

Similarly, microwave-assisted extraction (MAE) is an effective technique used for the isolation of phenolic compounds and carotenoids from carrot peels, chiefly the efficiency depends on microwave power, treatment duration and ethanol concentration.[125] Microwave-assisted extraction (MAE) has emerged as a highly efficient technique for the recovery of bioactive compounds from carrot peels, which are a rich source of phenolic acids, flavonoids, and carotenoids. The effectiveness of MAE lies in its ability to generate rapid internal heating through microwave energy, causing dipole rotation and ionic conduction within the plant matrix. This results in localized pressure buildup, leading to cell wall rupture and enhanced release of intracellular compounds.[126,127]

In addition, MAE involves GRAS and food-grade solvents with high dielectric constants including ethanol, acetone and ethyl acetate, which boosts the antioxidant activity. Thus, highlighting MAE as a sustainable, energy-saving and high-performance extraction method having strong potential applications in food, medicine and nutraceutical industries [128,129]. Notably, enzyme-assisted extraction (EAE) is reported to enhance the total flavonoid and free radicals scavenging properties by 2-fold, while β-carotene and phenolic concentration improved by 5-fold as compared to conventional methods used for the extraction of phytochemicals from carrot waste [130]. Further, EAE in combination with cellulase (C) is revealed to be an eco-friendly technique replacing acid extraction, whereas EAE together with acid extraction improves the yield of pectin from carrot pomace.[131]

9.3. Encapsulation:

Various encapsulation techniques have been applied for carrot bioactives, among which spray drying is the most widely used due to its cost-effectiveness, scalability, and compatibility with food-grade materials. In this method, carrot extract is first emulsified with carrier materials such as maltodextrin, gum arabic, or modified starch, followed by rapid drying to form a stable powder. Studies have shown that spray drying can attain high encapsulation efficiency (70-95%) for β-carotene, while significantly reducing oxidative degradation.[132] The choice of wall

View Article Online
DOI: 10.1039/D5FB00493D

material plays a critical role in determining encapsulation efficiency, solubility, and release behavior. For instance, gum arabic provides better emulsification properties, whereas maltodextrin improves powder stability and reduces hygroscopicity. In addition to spray drying, advanced techniques such as freeze drying (lyophilization), coacervation, liposomal encapsulation, and nanoemulsification have been investigated to further improve the delivery of carrot bioactives. Freeze drying is particularly suitable for preserving heat-sensitive compounds, as it works under low temperature and pressure, which minimizing degradation of carotenoids and phenolics. However, its higher operational cost limits large-scale applications.[4] Further, for encapsulating carrot waste extract, free dried encapsulation shows significant hygroscopicity, oxidative stress, and color properties compared to spray drying, indicating the potential for creating functional foods with improved color, nutritional, and bioactive qualities.[11] For instance, carotenoids derived from carrot waste were encapsulated via electrostatic extrusion and incorporated into yoghurt at concentrations of 2.5 and 5 percent without affecting its microbiological and physicochemical attributes. In addition, both the samples remained stable for 28 days with enhanced antioxidant effect and fulfilled β-carotene requirements, hence demonstrating the effectiveness of encapsulation for the production of value-added products from carrot waste.[133] Likewise, encapsulation of anthocyanin-rich black carrot concentrates by employing whey protein-based microcapsules for the production of hydrogels having considerable retention of phenolic acids, flavonoids and anthocyanins. Additionally, these capsules imparted a uniform pink colour even when added at varying concentrations to yoghurt, thereby demonstrating microencapsulation as a useful method for delivering black carrot phytochemicals as a natural food colourant.[134] Moreover, carrot-derived carotenoids encapsulated in a chitosan-TPP complex improve their stability against oxidative stress and retain stability by 94 percent as compared to free carotenoids. Furthermore, the encapsulated form exhibited a better free radical neutralising effect and showed controlled release, thereby demonstrating chitosan-TPP encapsulation as a protective technique for carotenoids.[135]

Nanoencapsulation approaches, including nanoemulsions and solid lipid nanoparticles (SLNs), have gained increasing attention due to their ability to enhance the solubility and bioavailability of hydrophobic compounds such as β-carotene. Nanoemulsions typically consist of oil-in-water systems stabilized by emulsifiers, where carotenoids are solubilized in the oil phase. These systems provide improved dispersion, protection against oxidation, and enhanced intestinal absorption.[136] Similarly, liposomal encapsulation involves phospholipid bilayers that can

View Article Online
DOI: 10.1039/D5FB00493D

encapsulate both hydrophilic and lipophilic compounds, offering targeted delivery and improved stability.[137]

9.4. Biopolymers:

Biopolymers obtained from natural sources such as plants and animals are observed to be a desirable and eco-friendly substitute for synthetic polymers, which contribute to the sustainable management of non-degradable plastic waste.[138] For instance, carrot fibres (CF) and microcrystalline cellulose (MCC), when added to chitosan (CH) films at different concentrations (0-5%), the resulting films exhibited better tensile strength, optical properties and thermal stability with an increase in the number of fillers added, hence showcasing the potential of CF for the production of biopolymer-based packaging material [139]. Likewise, red carrot pomace (RCP), being a rich source of carotenoids and polyphenols, can be utilised for the development of edible biofilms offering both stability and functional benefits. In addition, RCP carotenoids aid in improving the thickness, water resistance and free radical scavenging activity, thereby serving as a natural and nutrient-rich packaging material.[140] Similarly, black carrot pomace enriched with anthocyanin and polyphenols can utilised for the formation of biodegradable edible film, acquiring better antioxidant, barrier and heat-resistant potential. Therefore, carrots and their waste products can be efficiently utilised for manufacturing eco-friendly food biofilms that can replace conventional harmful plastic packaging.[140]

Further, carrot extract used for the development of active and intelligent packaging systems. Active packaging involves the incorporation of bioactive compounds (e.g., antioxidants, antimicrobials) that interact with the food or its environment to extend shelf life. For example, carrot extract-enriched films have shown inhibitory effects against common foodborne pathogens such as *Escherichia coli* and *Staphylococcus aureus*, owing to the presence of phenolic compounds [141]. Intelligent packaging, on other application, utilizes indicators such as anthocyanins from black carrot to monitor changes in pH, temperature, or microbial activity.[142] Another emerging area is the use of nanotechnology in carrot-based biopolymers. Cellulose nanocrystals (CNCs) and nanofibers extracted from carrot waste have been incorporated into polymer matrices to form nanocomposite films with superior mechanical strength, reduced gas permeability, and enhanced thermal stability. These nanomaterials increase the surface area and interaction between polymer chains, leading to improved structural integrity. Additionally,

View Article Online
DOI: 10.1039/D5FB00493D

nanoencapsulation of carrot bioactives within biopolymer films allows for controlled release, enhancing the functional performance of packaging materials.[143]

Table 2: Extraction methods for isolation of essential compounds from carrots and their by-products and their key benefits.

CATEGORY	PROCESSING METHOD	PURPOSE	KEY BENEFITS	REFERENCES
Physical and Thermal Processing	• Microwave (MW) • Microwave vacuum (MWV) • Window drying Freeze-drying	Stabilisation and preservation of carrots and their by-products.	• Preserves functional properties. • Preserves phenolic compounds and carotenoids. Maintains the nutritional composition.	119,120
Green Extraction Techniques	• Ultrasound-Assisted Extraction (UAE) • Microwave-Assisted Extraction (MAE) Enzymatic-Assisted Extraction (EAE)	Efficient extraction of carotenoids and other essential phytochemicals from carrots and their waste products.	• Reduced extraction time. • Improves antioxidant activity. • Energy-saving extraction. Environment-friendly methods of extraction.	125,130,131
	• Ultrasound-Assisted Extraction (UAE)	Extraction of anthocyanin with maximum cytotoxicity	• Microwave-assisted extraction achieved	144

	• Microwave-Assisted Extraction (MAE) • Conventional Solvent Extraction		the highest number of anthocyanins. • Highest cytotoxicity was observed in alveolar adenocarcinoma (A-549), osteosarcoma (Saos-2), neuroblastoma (Neuro-2A), and breast cancer (MCF-7) cells	
	• Ultrasound-Assisted Extraction (UAE) • Microwave-Assisted Extraction (MAE) • Conventional Solvent Extraction	Efficient extraction of carotenoids from carrot	• MAE showed highest extraction efficiency compare to UAE and SE	128
Encapsulation	• Free dried encapsulation • Electrostatic extrusion	Protecting carotenoids and bioactive compounds	• Manufacturing of functional foods like yoghurt.	135,145,146

	Whey protein-based microencapsulation	exhibited by *Daucus carota* and their rejects.	• Preserves sensory attributes. • Improves shelf-life and antioxidant activity. Utilisation of anthocyanin as a natural colourant.	
	• Freeze and spray drying techniques	Optimization of wall material formulations (whey protein/maltodextrin/inulin) for the encapsulation of carrot waste extract by freeze drying (FD) and spray drying (SD)	• In FD, pure whey protein gave best carotenoid, antioxidant capacity, efficiency. • In SD, best performance was obtained with a 71 g/100 g whey protein – 29 g/100 g inulin mixture. • FD encapsulate had better hygroscopicity,	133

			oxidative stability, colour properties	
	• Encapsulation of black carrot extract using complex coacervates technique.	• Optimizing the encapsulation parameters of black carrot extract by Response Surface Method. • Maximizing the bioaccessibility and release kinetics in different food matrixes.	• Heat treatment had no significant effect on the in vitro bioaccessibility of BCPE-CCp in terms of total phenolic compound and antioxidant activity ($p < 0.05$), indicating its suitability for hot formulations. • The release of BCPE in a protein-rich environment was observed to be higher than in a carbohydrate-rich food matrix under	147

			both gastric and intestinal conditions	
	• β-carotene extracted with sunflower oil from juice carrot waste were encapsulated • Electrostatic extrusion technique and alginate as wall material were applied	• To examine feasibility of encapsulated β-carotene for the fortification of yoghurt	• The carrot waste-alginate beads provide sufficient protection for β-carotene over a complete storage period at 4 ◦ C. • The stability and microbiological profile of tested fortified yogurts did not change to the end of the examination period. • The application of carrot waste beads in yogurt provides bioactive potential and gives to a	146

			consumer an optional functional food for daily diet	
Biopolymers	•	Interaction of carrot bioactive and fibres with polymers such as cellulose and chitosan.	• Manufacturing of edible food biofilm. • Substitute for synthetic polymers. • Reduces environmental degradation.	[138,139,148]
	• To produce bio-nanocomposites for potential food packaging applications	• Nanocellulose (NC) was extracted from carrot pulp and different weight fractions of NC (5, 7, and 10 wt%) were incorporated into corn starch, either with or without thyme extract, using the solvent casting process	• The presence of NC in starch nanocomposites decreased oxygen gas permeability and water absorption capacity, followed by an increment in the crystallinity index	[149]

			of the nanocomposites. • The antibacterial activity against both gram-positive and gram-negative bacteria were observed after incorporating thyme extract into the nanocomposites	
	• Lyophilized RCP (Red carrot pomace) was subjected to carotenoid extraction at different concentrations (15, 25, 35, and 45% (w/v)) in 100 ml ethyl acetate followed by delivering the RCP carotenoids in	• The films formed with RCP carotenoid emulsion were compared to control films made from corn starch, HMC, and chitosan. • The enrichment of films with RCP carotenoid emulsion	• Films enriched with carotenoids demonstrated lower thermal stability (40.04–138.15 °C and 36.04–125.35 °C for control and RCP extract film) and enthalpy changes (TGA) (up	140

	lemongrass oil emulsions. • The RCP carotenoids emulsion was further used in the development of a ternary blended edible film	tended to result in better functional and barrier properties, along with the addition of phytochemicals, carotenoids, and antioxidant properties.	to 230 °C) compared to control films	

View Article Online
DOI: 10.1039/D5FB00493D

10. Economic And Environmental Benefits:

Carrots and their by-products are observed to be packed with numerous health-promising compounds such as carotenoids, polyphenols and vitamins, which safeguard from issues including anti-cancer, antioxidant, immune-boosting, improve vision and cardiovascular diseases.[2] The total carotenoid and phenols ranges ~96–301 mg/100 g DW; and ~27–86 mg GAE/g DW respectively. The addition of these components improves phytochemical content, along with taste, texture and carotenoids bioactivity in developed products[39]. Therefore, utilising these for the manufacturing of value-added commodities contributes to improving the phytochemical content, texture, taste and carotenoid activity of the resulting products [39], as depicted in **Figure 4**. Primarily, carrot waste after isolation of β-carotene can be employed for the production of biofuel by using techniques such as hydrothermal liquefaction, hence serving both financial and environmental benefits by reducing post-harvest waste contributed by carrot waste generation ~25–30% and calorific value ~16 MJ/k.[128] For instance, *D.carota* leaves (DCL) extract examined using NMR and MS spectroscopy is revealed to be a rich source of flavonoids including apigenin, luteolin, cymaroside and chrysoeriol. Together, these compounds block the synthesis of TNF-α and IL-2, thereby showcasing the natural therapeutic potential of carrot waste.[150] Likewise, red carrot pomace (RCP) is a natural treasure of polyphenols and carotenoids, which is utilised for making edible biofilm with improved functional and barrier properties. Additionally, they possess enhanced bioactive compounds, carotenoids and free radicals neutralising potential, thus contributing to environmental and monetary benefits.[140] Significantly, black carrot's anthocyanin-rich extracts have acquired a role as a natural dye in the textile industry for colouring cotton and linen fabric, hence demonstrating the eco-friendly benefits of black carrot.[151] Moreover, carrot waste including pomace and mash, is an organic source of dietary fibres, natural colours, antioxidants and other essential constituents that can be extracted via solvent extraction, supercritical fluid extraction, pressurised liquid extraction and ultrasound-assisted extraction i.e. extraction yield ~26–30% for UAE efficiency ~2-3 times higher than conventional. Further, these extracted compounds are utilised for the formulation of functional foods and food additives, thereby declining environmental and financial constraints.[6] For instance, black carrot pomace (BCP) incorporated into yoghurt improves both sensory and nutritional values of yoghurt, hence reducing the pollution caused by carrot waste.[152] Likewise, A2 milk fortified with whole carrot root powder exhibits a better carotenoid concentration, thereby aiding in combating vitamin A deficiency and possessing sustainable benefits.[153] Besides, fermented carrot waste material

View Article Online
DOI: 10.1039/D5FB00493D

(peels and unused carrots) serves as a cattle feed that enhances the hepatic function of blood and faecal good microflora, and decreases the risk of infection by improving immunoglobulin G (IgG) levels in fattening pigs. This effect might be attributed to the presence of crude fibre in fermented feed, thus reducing environmental and economic constraints.[154] Therefore, valorisation of carrot and their waste products aids in decreasing the carbon footprint generated by greenhouse gases, serves nutritional benefits and monetary profits for both producers and processors.[59]

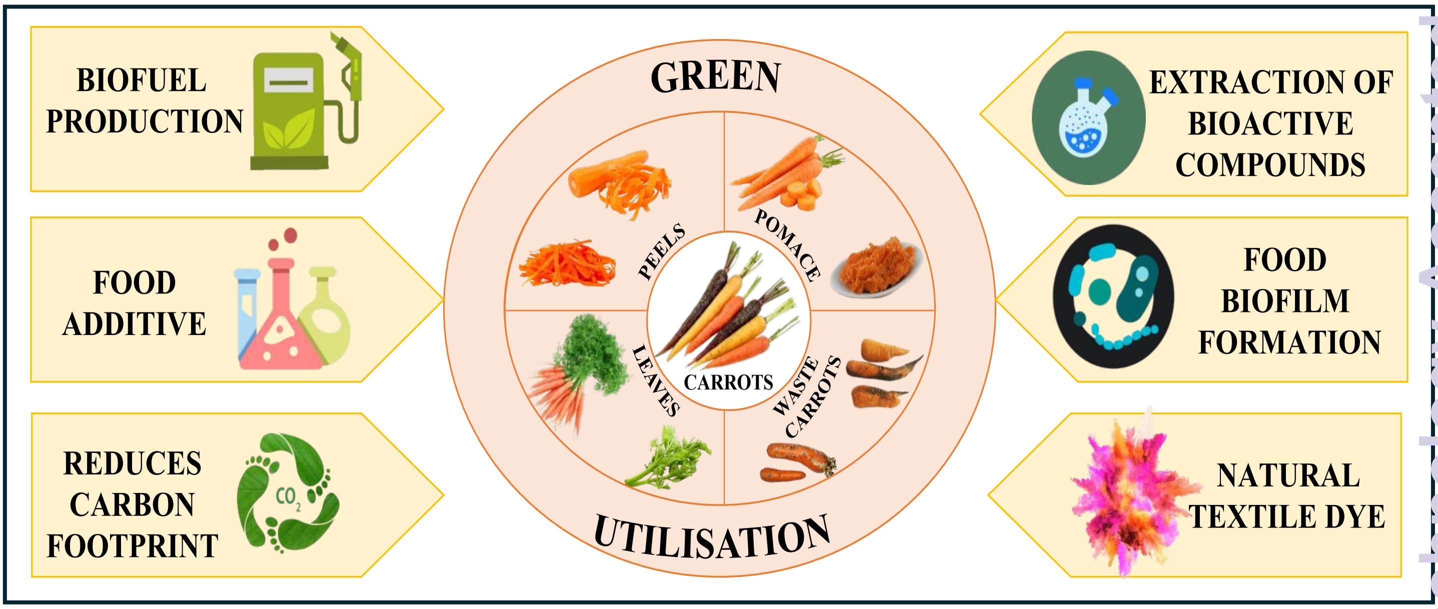


Figure 4: Valorisation of carrots and their by-products including peel, pomace, leaves, and unused carrots, has various applications such as extracting bioactive compounds, producing food additives, creating natural dyes, reducing carbon footprint, formulating biofuels, and developing food biofilms, which provide both economic and environmental benefits.

11. Limitations:

Carrots and their waste products are packed with both nutritional and bioactive compounds that impart various benefits including economic, monetary and therapeutic effects.[17] However, certain limitations like retailers' unwillingness to buy defective carrots even at low prices as a part of a bulk purchase sold by farmers, thus showcase the lack of coordination between farmers and retailers leading to huge economic losses.[155] Notably, the dumping of carrot rejects and waste (CRW) into landfills releases greenhouse gases such as methane and carbon dioxide, which contribute to environmental deterioration.[128] Moreover, studies have revealed that the presence of leaves and nitrogen fertilisation rate (240 kg ha^{-1}) adversely affect the phenolic

View Article Online
DOI: 10.1039/D5FB00493D

content and antioxidant properties of carrots. Particularly, leaves reduce weight and firmness, which directly impacts the quality of roots and the shelf-life of bunched carrots.[156] Besides, drying methods such as air-drying reduce the free radical neutralising activity of carrot waste powder, hence processing techniques should be opted wisely to preserve the antioxidant activity.[157] Likewise, with an increase in drying temperature uplifts the β-carotene degradation rate of carrot slices, thereby an optimal drying temperature (45-55°C) should be maintained.[158]

12. Conclusion and Future Perspectives:

It has emerged that carrot and its by-products -peel, pomace, pulp, seeds, roots and leaves-are rich sources of carotenoids and dietary fiber, hence value-added functional ingredients for food and industrial applications. Once considered agro-waste, these residues are valued in the formulation of fortified bakery, beverages and snack preparations, enhancing nutritional quality and antioxidant activity, with an extension of shelf life. Besides food applications, cosmetic emulsions and anti-aging formulas will also benefit from the antioxidant and skin-regenerative properties of extracts obtained from peels and seeds. Further research needs to be established regarding bioavailability, toxicological safety and LCA in order to establish scalability at an industrial level and ensure environmental benefits. Overall, valuations of carrot by-products represent the circular bioeconomy, where agricultural residues are transformed into value creation with positive impacts on human health and sustainability.

Funding: Not applicable.

Data availability: All the data related to the manuscript are included with the manuscript.

Competing interest: There are no financial and non-financial competing interests among all the authors.

Ethics Approval: Not applicable

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the reported work.

View Article Online
DOI: 10.1039/D5FB00493D

REFERENCES

1. Sáez-Escudero, L., Blanch, G. P., Morales, F. J., Mesías, M. & Del Castillo, M. L. R. Health-related compounds and Maillard reaction products in dry and steam roasted purple carrots (Daucus carota L.). *Food Chem.* **483**, 144296 (2025).

2. Ikram, A. *et al.* Exploring the health benefits and utility of carrots and carrot pomace: a systematic review. *Int. J. Food Prop.* **27**, 180–193 (2024).

3. Paparella, A. *et al.* Challenges and opportunities in the sustainable improvement of carrot production. *Plants* **13**, 2092 (2024).

4. Sharma, S., Abrol, G., Sharma, R. & Sharma, K. D. Carrot and Carrot Products: A Superb Functional Food. in *Functional Compounds and Foods of Plant Origin* 269–290 (Apple Academic Press, 2025).

5. Amin, S., Jung, S., Kang, I. & Duval, A. Valorization of baby carrot processing waste. *J. Culin. Sci. Technol.* **21**, 1–17 (2023).

6. Bhardwaj, S., Thakur, M., Rana, P. & Suthar, P. Carrot Waste: Chemistry, Processing and Utilization. in *Handbook of Vegetable Processing Waste* 215–238 (CRC Press, 2025).

7. Venkataramanan, R., Gunasekaran, S., Sreekumar, C., Anilkumar, R. & Iyue, M. Nutritional value and suitability of carrot whole top as green fodder. *Ind J Vet Anim Sci Res* **44**, 49–52 (2015).

8. Lopes, J., Medeiros, D. L. & Kiperstok, A. Combining cleaner production and life cycle assessment for reducing the environmental impacts of irrigated carrot production in Brazilian semi-arid region. *J. Clean. Prod.* **170**, 924–939 (2018).

9. Alhashim, R., Deepa, R. & Anandhi, A. Environmental impact assessment of agricultural production using LCA: a review. *Climate* **9**, 164 (2021).

10. Wang, Y. *et al.* Carrot 'antifreeze'protein has an irregular ice-binding site that confers weak freezing point depression but strong inhibition of ice recrystallization. *Biochem. J.* **477**, 2179–2192 (2020).

11. Šeregelj, V. *et al.* Natural bioactive compounds in carrot waste for food applications and health benefits. *Stud. Nat. Prod. Chem.* **67**, 307–344 (2020).

View Article Online
DOI: 10.1039/D5FB00493D

12. Ghadimi, N. S., Houshmand-Dalir, M., Jafarloo, H. R. & Ahmadi-Dastgerdi, A. Application of Carrot Pomace as Dietary Fiber in the Formulation of Bread. *J. Food Biochem.* **2025**, 6016591 (2025).

13. Suri, K., Singh, B., Kaur, A., Yadav, M. P. & Singh, N. Impact of infrared and dry air roasting on the oxidative stability, fatty acid composition, Maillard reaction products and other chemical properties of black cumin (Nigella sativa L.) seed oil. *Food Chem.* **295**, 537–547 (2019).

14. Üstün Argon, Z., Gümüş, Z. P., Doğu, S. & Akdağ, T. Bioactive Phytochemicals from Carrot (Daucus carota) By-Products. in *Bioactive Phytochemicals in By-products from Leaf, Stem, Root and Tuber Vegetables* 181–205 (Springer, 2025).

15. Boadi, N. O. *et al.* Nutritional composition and antioxidant properties of three varieties of carrot (Daucus carota). *Sci. African* **12**, e00801 (2021).

16. Sharma, K. D., Karki, S., Thakur, N. S. & Attri, S. Chemical composition, functional properties and processing of carrot—a review. *J. Food Sci. Technol.* **49**, 22–32 (2012).

17. Yusuf, E., Tkacz, K., Turkiewicz, I. P., Wojdyło, A. & Nowicka, P. Analysis of chemical compounds' content in different varieties of carrots, including qualification and quantification of sugars, organic acids, minerals, and bioactive compounds by UPLC. *Eur. Food Res. Technol.* **247**, 3053–3062 (2021).

18. Motegaonkar, S., Shankar, A., Tazeen, H., Gunjal, M. & Payyanad, S. A comprehensive review on carrot (Daucus carota L.): the effect of different drying methods on nutritional properties and its processing as value-added foods. *Sustain. Food Technol.* **2**, 667–688 (2024).

19. Audu, S. S. & Aremu, M. O. Effect of processing on chemical composition of red kidney bean (Phaseolus vulgaris L.) flour. *Pakistan J. Nutr.* **10**, 1069–1075 (2011).

20. Shyamala, B. N. & Jamuna, P. Nutritional Content and Antioxidant Properties of Pulp Waste from Daucus carota and Beta vulgaris. *Malays. J. Nutr.* **16**, (2010).

21. Mantiniotou, M., Athanasiadis, V., Kalompatsios, D. & Lalas, S. I. Optimization of carotenoids and other antioxidant compounds extraction from carrot peels using response surface methodology. *Biomass* **5**, 3 (2024).

22. Hamoudi-Belarbi, L. *et al.* Bioremediation of polluted soil sites with crude oil

View Article Online
DOI: 10.1039/D5FB00493D

hydrocarbons using carrot peel waste. *Environments* **5**, 124 (2018).

23. Surbhi, S., Verma, R. C., Deepak, R., Jain, H. K. & Yadav, K. K. A review: Food, chemical composition and utilization of carrot (Daucus carota L.) pomace. *Int. J. Chem. Stud.* **6**, 2921–2926 (2018).

24. Luca, M. I., Ungureanu-Iuga, M. & Mironeasa, S. Carrot pomace characterization for application in cereal-based products. *Appl. Sci.* **12**, 7989 (2022).

25. Bardakçi, M. S., Özçelik, A. & Karacabey, E. Does Daucus carota L. leaf provide a high potential as a source of bioactive constituents: A case study about the influences of process/storage conditions. *Food Sci. Nutr.* **12**, 5882–5889 (2024).

26. Siti, N. W. & Bidura, I. Effects of carrot leaves on digestibility of feed, and cholesterol and β-carotene content of egg yolks. *S. Afr. J. Anim. Sci.* **51**, 786–792 (2021).

27. Sodamade, A., Raimi, M., Owonikoko, A. D. & Adebimpe, A. T. nutritive evaluation, mineral composition and phytochemical analysis of leaf protein concentrates of Daucus carota. *Braz. J. Sci. Technol* **36**, 57–68 (2019).

28. Purewal, S. S. *et al.* A comparative study on proximate composition, mineral profile, bioactive compounds and antioxidant properties in diverse carrot (Daucus carota L.) flour. *Biocatal. Agric. Biotechnol.* **48**, 102640 (2023).

29. Mandrich, L., Esposito, A. V., Costa, S. & Caputo, E. Chemical composition, functional and anticancer properties of carrot. *Molecules* **28**, 7161 (2023).

30. Ismail, J. *et al.* The wild Carrot (Daucus carota): a phytochemical and pharmacological review. *Plants* **13**, 93 (2023).

31. Kultys, E. & Moczkowska-Wyrwisz, M. Effect of using carrot pomace and beetroot-apple pomace on physicochemical and sensory properties of pasta. *Lwt* **168**, 113858 (2022).

32. Stamatovska, V., Stojanovska, T., Delinikolova, E. & Ristevska, K. T. Application of carrot pomace in the food industry–A review. *KNOWLEDGE-International J.* **63**, 281–288 (2024).

33. Richards, J., Lammert, A., Madden, J., Kang, I. & Amin, S. Physical treatments modified the functionality of carrot pomace. *Foods* **13**, 2084 (2024).

View Article Online
DOI: 10.1039/D5FB00493D

34. Jayesree, N. *et al.* Valorisation of carrot peel waste by water-induced hydrocolloidal complexation for extraction of carotene and pectin. *Chemosphere* **272**, 129919 (2021).

35. Conversa, G., Bonasia, A., Natrella, G., Lazzizera, C. & Elia, A. Peeling affects the nutritional properties of carrot genotypes. *Foods* **11**, 45 (2021).

36. Giang, N. T., Hang, L. T. T., Loan, P. P. & Loan, L. T. T. Effect of drying temperature on the physico-chemical properties of carrot peel powder. *Pakistan J. Agric. Res.* **37**, 232–240 (2024).

37. Titcomb, T. J. *et al.* Carrot leaves maintain liver vitamin A concentrations in male Mongolian gerbils regardless of the ratio of α-to β-carotene when β-carotene equivalents are equalized. *J. Nutr.* **149**, 951–958 (2019).

38. Kim, J. S., Lim, J. H. & Cho, S. K. Effect of antioxidant and anti-inflammatory on bioactive components of carrot (Daucus carota L.) leaves from Jeju Island. *Appl. Biol. Chem.* **66**, 34 (2023).

39. Sharma, T. *et al.* Emerging innovative processing technologies for quality preservation of carrot and by-products: A review focused on therapeutic benefits and functional approach. *Food Bioprocess Technol.* **17**, 2943–2972 (2024).

40. Hammad, S., El-badawi, A., Suliman, A. & Al-Nemr, M. Chemical, nutritional, antioxidant and sensory properties of biscuit made from wheat, white bean and carrot composite flour. *Egypt. J. Chem.* **68**, 25–36 (2025).

41. Ukeyima, M. T., Dendegh, T. A. & Okeke, P. C. Effect of carrot powder addition on the quality attributes of cookies produced from wheat and soy flour blends. *Asian Food Sci. J.* **10**, 1–13 (2019).

42. Pandey, P., Grover, K., Dhillon, T. S., Chawla, N. & Kaur, A. Development and quality evaluation of polyphenols enriched black carrot (Daucus carota L.) powder incorporated bread. *Heliyon* **10**, (2024).

43. Mutie, E. C., José, A. E. & Júnior, A. A. M. Sensory acceptance of carrot bread. *Yeast (Saccharnomyces cerevisae)* **10**, 10 (2022).

44. Devi, M., Chintya Paramita, P., Nurjanah, N., Oktaviantry, D. A. & Din, N. Development of Traditional Indonesian Layer Cake From Pureed Yellow Pumpkin (Cucurbita moschata Durch) And Carrot (Daucus carrota L) as a Highly Nutritious as

View Article Online
DOI: 10.1039/D5FB00493D

an Additional Food For Toddlers. in *IOP Conference Series: Earth and Environmental Science* vol. 1446 12016 (IOP Publishing, 2025).

45. Prajapati, C., Kamaliya, K. & Dhingani, R. Optimizing the Process Parameters for Carrot Cake Development Using Response Surface Methodology. *Eur. J. Nutr. Food Saf.* **16**, 261–274 (2024).

46. Ciobanu, M.-M., Manoliu, D.-R., Ciobotaru, M. C., Flocea, E.-I. & Boișteanu, P.-C. Dietary fibres in processed meat: A review on nutritional enhancement, technological effects, sensory implications and consumer perception. *Foods* **14**, 1459 (2025).

47. Kaynakçı, E. The Effect of Purple Carrot Powder on the Microbiological and Physicochemical Properties of Vacuum-Packed Meatballs During Storage (4° C). (2025).

48. Khatun, M. M. *et al.* Formulation of value added chicken nuggets using carrot and ginger as a source of dietary fiber and natural antioxidant: Value addition of chicken nuggets. *SAARC J. Agric.* **20**, 185–196 (2022).

49. Chomanov, U. *et al.* Nutritive profile of canned goat meat food with added carrot. *Appl. Sci.* **12**, 9911 (2022).

50. Rocchetti, G. *et al.* Effect of partial replacement of meat by carrot on physicochemical properties and fatty acid profile of fresh turkey sausages: A chemometric approach. *J. Sci. Food Agric.* **100**, 4968–4977 (2020).

51. Bukya, A., Lawande, S. R. & Dawkhar, S. N. To Standardization, Formulation and Sensory Evaluation of Carrot Dessert with Rice Balls. (2019).

52. Arvind, P. C., Pandhi, S., Rai, D. C. & Paul, V. Process optimization for the production of ready-to-cook carrot halwa. *Indian J Dairy Sci* **73**, 285–291 (2020).

53. Labatjo, R. & Setiawan, D. I. Carcake as a healthy and nutritious dessert. *Food Res.* **7**, 21–26 (2023).

54. Prasoona, J., Kumari, B. A., Sarkar, S., Kiran, V. K. & Swamy, R. Development of Instant Chutney Powder with Incorporation of Blanched Carrot and Green Leafy Vegetable Powders. *Int. Res. J. Pure Appl. Chem.* **21**, 1–9 (2020).

55. Giri, N. A., Sakhale, B. K. & Nirmal, N. P. Functional beverages: an emerging trend in

View Article Online
DOI: 10.1039/D5FB00493D

beverage world. *Recent Front. Phytochem.* 123–142 (2023).

56. Aderinola, T. A. & Abaire, K. E. Quality acceptability, nutritional composition and antioxidant properties of carrot-cucumber juice. *Beverages* **5**, 15 (2019).

57. Saleem, M. *et al.* Nutritional, physicochemical, and antioxidant characterization of pomegranate, beetroot, and carrot concentrates supplemented functional whey beverages. *Food Chem. X* **25**, 102206 (2025).

58. Sharma, C., Sahota, P. P. & Kaur, S. Physicochemical and microbiological evaluation of antioxidant-rich traditional black carrot beverage: Kanji. *Bull. Natl. Res. Cent.* **45**, 143 (2021).

59. Kaur, P., Subramanian, J. & Singh, A. Green extraction of bioactive components from carrot industry waste and evaluation of spent residue as an energy source. *Sci. Rep.* **12**, 16607 (2022).

60. Bakers, G. & Fq, W. NOVEL METHODS SERVE UP FET Y SA d With you at every step . **24**, (2017).

61. Çoklar, H., Akbulut, M., Aygun, A. & Akbulut, M. T. Valorization of Dairy By-Products, Sweet Whey, and Acid Whey, in the Production of Fermented Black Carrot Juice: A Comparative Study of the Phytochemical, Physicochemical, Microbiological, and Sensorial Aspects. *Foods* **14**, 218 (2025).

62. Bredow, M. & Walker, V. K. Ice-binding proteins in plants. *Front. Plant Sci.* **8**, 325466 (2017).

63. Sharma, S. *et al.* Potential of carrot concentrated protein as a natural cryoprotectant in fish surimi during frozen storage. *J. Pharmacogn. Phytochem.* **7**, 917–923 (2018).

64. Ding, X. *et al.* Extraction of carrot (Daucus carota) antifreeze proteins and evaluation of their effects on frozen white salted noodles. *Food bioprocess Technol.* **7**, 842–852 (2014).

65. Liu, S., Zhu, W., Bai, X., You, T. & Yan, J. Effect of ultrasonic energy density on moisture transfer during ultrasound enhanced vacuum drying of honey. *J. Food Meas. Charact.* https://doi.org/10.1007/s11694-018-9969-z (2018) doi:10.1007/s11694-018-9969-z.

View Article Online
DOI: 10.1039/D5FB00493D

66. Liu, M. *et al.* Effects of recombinant carrot antifreeze protein from Pichia pastoris GS115 on the physicochemical properties of hydrated gluten during freeze-thawed cycles. *J. Cereal Sci.* **83**, 245–251 (2018).

67. Eliopoulos, C., Markou, G., Langousi, I. & Arapoglou, D. Reintegration of food industry by-products: Potential applications. *Foods* **11**, 3743 (2022).

68. Rahman, N., Uddin, M. B., Quader, M. F. Bin & Bakar, M. A. Optimization of mixed peels from banana, carrot and apple to develop high fiber biscuit. *Int. J. Nat. Soc. Sci.* **7**, 21–25 (2020).

69. Gokul, J. J., Thakur, S., Sharma, S. & Poduvachola, F. A. Studies on physicochemical and sensory characteristics of nutrient-rich biscuits prepared from blends of carrot and mango peel powder.

70. Haider, M. W. *et al.* Environmental and nutritional value of fruit and vegetable peels as animal feed: A comprehensive review. *Anim. Res. One Heal.* **3**, 149–164 (2025).

71. Mahmud, M. N., Ritu, F. Y., Ansary, A. A. & Haque, M. M. Exploring Protein-Based Fishmeal Alternatives for Aquaculture Feeds in Bangladesh. *Aquac. Nutr.* **2025**, 3198303 (2025).

72. Rauf, S. *et al.* Enhancement of color of platy fish (Xipophorus maculates) by using carrot peels as source of carotenoids. *J. Surv. Fish. Sci.* **11**, 1–3 (2024).

73. Ajay, A. *et al.* Chickpeas and gut microbiome: Functional food implications for health. *Heliyon* **10**, (2024).

74. Suraj, M., Abewaa, M., Mengistu, A., Bultosa, G. & Bussa, N. Influence of fermentation conditions, and the blends of sorghum and carrot pulp supplementation on the nutritional and sensory quality of tef injera. *Sci. Rep.* **14**, 12819 (2024).

75. de Oliveira, P. M. *et al.* Mango and carrot mixed juice: a new matrix for the vehicle of probiotic lactobacilli. *J. Food Sci. Technol.* **58**, 98–109 (2021).

76. Karaman, M., Firinci, F., Arıkan, Z. A., & Bahar, I. H. Effects of Imipenem, Tobramycin and Curcumin on biofilm formation of Pseudomonas aeruginosa strains. *Mikrobiyol. Bul.* **47**, 192–194 (2013).

77. Kaur, A., Singh, B., Kaur, A. & Singh, N. Chemical, thermal, rheological and FTIR

View Article Online
DOI: 10.1039/D5FB00493D

studies of vegetable oils and their effect on eggless muffin characteristics. *J. Food Process. Preserv.* **43**, e13978 (2019).

78. Akhter, M. J. *et al.* Effect of carrot pulp on the physicochemical, microbiological and sensory attributes of kulfi. *Food Res.* **8**, 1–9 (2024).

79. Hassan, M. F. Y. & Barakat, H. Effect of carrot and pumpkin pulps adding on chemical, rheological, nutritional and organoleptic properties of ice cream. *Food Nutr. Sci.* **9**, 969–982 (2018).

80. Ateteallah, H., Abd-Elkarim, N. & Hassan, N. A. Effect of adding beetroot juice and carrot pulps on rheological, chemical, nutritional and organoleptic properties of ice cream. *J. Food Dairy Sci.* **10**, 175–179 (2019).

81. Mohammed, A. R. M., Omar, M. M., El-Abbassy, M. M. & Khalifa, S. A. Manufacture of yoghurt drink supplemented with carrot and guava pulps. *Zagazig J. Agric. Res.* **46**, 1975–1984 (2019).

82. Senarathne, Y. S. M. & Wickramasinghe, I. Development of beta (β) carotene enriched drinking yoghurt by incorporating carrot (Daucus carota) pulp and orange (Citrus sinensis) juice. (2019).

83. Hanoğlu, A., Karaoğlu, M. M. & Bedir, Y. The effect of carob, orange and carrot pulps on physical, chemical and microbiological properties of Turkish delight. *Int. J. Gastron. Food Sci.* **32**, 100709 (2023).

84. Ullah, R., Nadeem, M. & Imran, M. Omega-3 fatty acids and oxidative stability of ice cream supplemented with olein fraction of chia (Salvia hispanica L.) oil. *Lipids Health Dis.* **16**, 1–8 (2017).

85. Lisiecka, K., Wójtowicz, A. & Gancarz, M. Characteristics of newly developed extruded products supplemented with plants in a form of microwave-expanded snacks. *Materials (Basel).* **14**, 2791 (2021).

86. Silva, P. C. D. *et al.* Compatibility study between lipoic acid with polymers used in controlled drug release systems. *J. Therm. Anal. Calorim.* **123**, 965–971 (2016).

87. Mahdi, N. S. & Shakir, K. A. Impact of green parts powder of locally cultivated carrot (Daucus carota L.) on qualitative and sensory properties of biscuits and cake. *Iraqi J. Agric. Sci.* **56**, 20–32 (2025).

View Article Online
DOI: 10.1039/D5FB00493D

88. Santos, G. dos, Nogueira, R. I. & Rosenthal, A. Powdered yoghurt produced by spray drying and freeze drying: a review. *Brazilian J. Food Technol.* **21**, (2018).

89. Conti, V. *et al.* Pasta enriched with carrot and olive leaf flour retains high levels of accessible bioactives after in vitro digestion. *Foods* **12**, 3540 (2023).

90. Boroski, M. *et al.* Enhancement of pasta antioxidant activity with oregano and carrot leaf. *Food Chem.* **125**, 696–700 (2011).

91. Zahorec, J. *et al.* Application of Plant Ingredients for Improving Sustainability of Fresh Pasta. *Sustainability* **16**, 209 (2023).

92. Joshi, N., Bains, K. & Kaur, H. Evaluation of antioxidant activity of developed instant soup mixes using vegetable leaf powders from unconventional greens. *Int J Curr Microbiol App Sci* **9**, 711–721 (2020).

93. Alkhatib, M. H., Alnahdi, N. S. & Backer, W. S. Antitumor activity, hematoxicity and hepatotoxicity of sorafenib formulated in a nanoemulsion based on the carrot seed oil. *Int. J. Life Sci. Biotechnol. Pharma Res* **8**, 50–57 (2018).

94. Singh, S., Lohani, A., Mishra, A. K. & Verma, A. Formulation and evaluation of carrot seed oil-based cosmetic emulsions. *J. Cosmet. Laser Ther.* **21**, 99–107 (2019).

95. Fernández-Varela-Gómez, F., Sandoval-García, A. & Cabrera-Rios, K. V. Signs of skin aging: a review. *Int. J. Res. Med. Sci.* **12**, 2674 (2024).

96. Kumari, M., Sadhu, P., Shah, N., Talele, C. & Aundhia, C. The science of skin ageing: From radicals to herbal remedies. *Ann. Phytomedicine* **13**, 108–117 (2024).

97. Siddique, B. M. *et al.* Physico-chemical properties of blends of palm olein with other vegetable oils. *Grasas y Aceites* **61**, 423–429 (2010).

98. Bajraktari, F. ENRICHMENT OF BAKERY PRODUCTS WITH BY-PRODUCTS FROM CARROTS AND BEETROOT-LITERATURE REVIEW. *KNOWLEDGE-International J.* **67**, 449–452 (2024).

99. Kamiloglu, S. *et al.* Black carrot pomace as a source of polyphenols for enhancing the nutritional value of cake: An in vitro digestion study with a standardized static model. *Lwt* **77**, 475–481 (2017).

100. Hryshchenko, A., Bilyk, O., Bondarenko, Y., Kovbasa, V. & Drobot, V. Use of dried

View Article Online
DOI: 10.1039/D5FB00493D

carrot pomace in the technology of wheat bread for elderly people. *Food Sci. Technol.* **13**, 98–105 (2019).

101. Ziobro, R., Ivanišová, E., Bojňanská, T. & Gumul, D. Retention of antioxidants from dried carrot pomace in wheat bread. *Appl. Sci.* **12**, 9735 (2022).

102. Sule, S., Oneh, A. J. & Agba, I. M. Effect of carrot powder incorporation on the quality of pasta. *MOJ Food Process Technol* **7**, 99–103 (2019).

103. Chepkosgei, T. M. & Orina, I. Quality and sensory properties of instant fried noodles made with soybean and carrot pomace flour. *African J. Food Sci.* **15**, 92–99 (2021).

104. Ozer, T. *et al.* Use of waste fermented black carrot powder dried by different methods as a substitute in noodle production. *J. Food Meas. Charact.* **18**, 6561–6573 (2024).

105. Gaur, S. S. & Kaur, N. Effect of carrot pomace and germinated chickpea soup mix on serum lipid profile in hyperlipidemic males. (2023).

106. Trilokia, M., Bandral, J. D., Sood, M., Gupta, N. & Dutta, U. Quality Evaluation of Gluten-Free Protein Enriched Pasta Prepared Using Basmati Rice Flour, Groundnut Meal and Carrot Pomace. *J. Agric. Sci. Technol.* **25**, (2023).

107. Nayi, P., Kumar, N. & Chen, H. Development of ready-to-reconstitute carrot pomace blended sweet corn porridge. *EFood* **4**, e78 (2023).

108. Santhi, D., Kalaikannan, A., Elango, A. & Natarajan, A. Functional Chicken Meatballs with Carrot Pomace Powder. *J. Meat Sci.* **17**, 31–36 (2022).

109. Yadav, S., Pathera, A. K., Islam, R. U., Malik, A. K. & Sharma, D. P. Effect of wheat bran and dried carrot pomace addition on quality characteristics of chicken sausage. *Asian-Australalasian J. Anim. Sci.* **31**, 729 (2017).

110. Noshad, M., Hojjati, M. & Goodarzi Shamsabadi, B. Impact of Carrot Pomace Powder (CPP) on the Physicochemical and Sensory Properties of Mayonnaise. *Innov. Food Technol.* **12**, 237–248 (2025).

111. El-Dardiry, A. I. Improving the properties of the functional frozen bio-yoghurt by using carrot pomace powder (daucus carota L.). *Egypt. J. Dairy Sci.* 1–10 (2022).

112. Rezvani, Z. & Goli, S. A. H. Production of milk-based drink enriched by dietary fiber using carrot pomace: Physicochemical and organoleptic properties during storage.

View Article Online
DOI: 10.1039/D5FB00493D

Food Hydrocoll. **151**, 109834 (2024).

113. Narwojsz, A., Sawicki, T., Piłat, B. & Tańska, M. Effect of heat treatment methods on color, bioactive compound content, and antioxidant capacity of carrot root. *Appl. Sci.* **15**, 254 (2024).

114. Andersson, J. *et al.* Comparison of steaming and boiling of root vegetables for enhancing carbohydrate content and sensory profile. *J. Food Eng.* **312**, 110754 (2022).

115. Razzak, A. *et al.* Effect of cooking methods on the nutritional quality of selected vegetables at Sylhet City. *Heliyon* **9**, (2023).

116. Bembem, K. & Sadana, B. Effect of different cooking methods on the antioxidant components of Carrot. *Biosci. Discov.* **5**, 112–116 (2014).

117. Thanuja, S., Sivakanthan, S. & Vasantharuba, S. The influence of various cooking methods on the antioxidant compounds of local carrot variety (Daucus carota) cultivated in Jaffna District. (2018).

118. Hernández-Santos, B. *et al.* Evaluation of physical and chemical properties of carrots dried by Refractance Window drying. *Dry. Technol.* **34**, 1414–1422 (2016).

119. de Mendonça, K. S. *et al.* Peruvian carrot chips obtained by microwave and microwave-vacuum drying. *Lwt* **187**, 115346 (2023).

120. Begum, R. *et al.* Efficacy of freeze-dried carrot pomace powder in improving the quality of wheat bread. *Food Res* **7**, 11–22 (2023).

121. James, M., Imathiu, S., Engelsen, S. B. & Owino, W. Impact of extraction techniques and processing conditions on pectin and antioxidant recovery from mango peels. *Discov. Food* **5**, 132 (2025).

122. Umair, M. *et al.* Ultrasound-assisted extraction of carotenoids from carrot pomace and their optimization through response surface methodology. *Molecules* **26**, 6763 (2021).

123. Vilkhu, K., Mawson, R., Simons, L. & Bates, D. Applications and opportunities for ultrasound assisted extraction in the food industry - A review. *Innov. Food Sci. Emerg. Technol.* **9**, 161–169 (2008).

124. Constantin, O. E. *et al.* Ultrasound-Assisted Extraction of Carotenoids from Carrot Pomace: Process Optimization and Application Potential. *Appl. Sci.* **16**, 1472 (2026).

View Article Online
DOI: 10.1039/D5FB00493D

125. Rédey, Á. *et al.* Recovery of valuable components from carrot peel as vegetable waste using microwave-assisted extraction. *Prog. Agric. Eng. Sci.* **21**, 269–286 (2025).

126. Routray, W. & Orsat, V. Microwave-assisted extraction of flavonoids: a review. *Food Bioprocess Technol.* **5**, 409–424 (2012).

127. Yara-Varón, E. *et al.* Vegetable oils as alternative solvents for green oleo-extraction, purification and formulation of food and natural products. *Molecules* **22**, 1474 (2017).

128. Kaur, G. J., Kumar, D., Orsat, V. & Singh, A. Assessment of carrot rejects and wastes for food product development and as a biofuel. *Biomass Convers. biorefinery* **12**, 757–768 (2022).

129. Ghosh, S., Kumar, R., Keshav, A. & Manivannan, R. Optimized microwave-assisted extraction of phytochemicals from carrot peels using neoteric eutectic solvents: A comparative study: S. Ghosh et al. *J. Food Meas. Charact.* **19**, 5988–6008 (2025).

130. Demir, Y. *et al.* Enzyme and Ultrasound Pretreatments to Improve Extraction of Carotenoids from Industrial Carrot Waste. *ACS Agric. Sci. Technol.* **5**, 1879–1888 (2025).

131. De Laet, E., Bernaerts, T., Morren, L., Vanmarcke, H. & Van Loey, A. M. The use of different Cell Wall degrading enzymes for pectin extraction from carrot pomace, in comparison to and in combination with an acid extraction. *Foods* **14**, 435 (2025).

132. Tuyen, C. K., Nguyen, M. H. & Roach, P. D. Effects of spray drying conditions on the physicochemical and antioxidant properties of the Gac (Momordica cochinchinensis) fruit aril powder. *J. Food Eng.* **98**, 385–392 (2010).

133. Šeregelj, V. *et al.* Encapsulation of carrot waste extract by freeze and spray drying techniques: An optimization study. *Lwt* **138**, 110696 (2021).

134. Bilek, S. E., Yılmaz, F. M. & Özkan, G. The effects of industrial production on black carrot concentrate quality and encapsulation of anthocyanins in whey protein hydrogels. *Food Bioprod. Process.* **102**, 72–80 (2017).

135. Ali, H. M., Eid, S. A., Eldeen, H. A. S. & Ebrahim, M. E. H. Oxidative degradation pathways of carrot carotenes and their protection via chitosan-TPP encapsulation. *Chem. Biol. Technol. Agric.* **12**, 130 (2025).

View Article Online
DOI: 10.1039/D5FB00493D

136. Mcclements, D. J. Nanoscale Nutrient Delivery Systems for Food Applications: Improving Bioactive Dispersibility, Stability, and Bioavailability. *J. Food Sci.* **80**, N1602–N1611 (2015).

137. Choudhary, P., Dutta, S., Moses, J. A. & Anandharamakrishnan, C. Nanoliposomal encapsulation of chia oil for sustained delivery of α-linolenic acid. *Int. J. Food Sci. Technol.* **56**, 4206–4214 (2021).

138. Kabir, E., Kaur, R., Lee, J., Kim, K.-H. & Kwon, E. E. Prospects of biopolymer technology as an alternative option for non-degradable plastics and sustainable management of plastic wastes. *J. Clean. Prod.* **258**, 120536 (2020).

139. Sogut, E. & Cakmak, H. Utilization of carrot (Daucus carota L.) fiber as a filler for chitosan based films. *Food Hydrocoll.* **106**, 105861 (2020).

140. Chhoden, T., Aggarwal, P., Singh, A., Kaur, S. & Grover, S. Application of red carrot pomace carotenoids for the development of biofunctional edible film: A sustainable approach. *Biomass Convers. Biorefinery* **15**, 27575–27592 (2025).

141. Al-Baarri, A. N., Legowo, A. M., Hayakawa, S. & Ogawa, M. Enhancement antimicrobial activity of hyphothiocyanite using carrot against Staphylococcus aureus and Escherichia coli. *Procedia Food Sci.* **3**, 473–478 (2015).

142. Kırca, A., Özkan, M. & Cemeroğlu, B. Effects of temperature, solid content and pH on the stability of black carrot anthocyanins. *Food Chem.* **101**, 212–218 (2007).

143. Amoroso, L. *et al.* Sustainable cellulose nanofiber films from carrot pomace as sprayable coatings for food packaging applications. *ACS Sustain. Chem. Eng.* **10**, 342–352 (2021).

144. Pala, C., Sevimli-Gur, C. & Yesil-Celiktas, O. Green extraction processes focusing on maximization of black carrot anthocyanins along with cytotoxic activities. *Food Anal. Methods* **10**, 529–538 (2017).

145. Ersus Bilek, S., Yılmaz, F. M. & Özkan, G. The effects of industrial production on black carrot concentrate quality and encapsulation of anthocyanins in whey protein hydrogels. *Food Bioprod. Process.* **102**, 72–80 (2017).

146. Šeregelj, V. *et al.* New concept of fortified yogurt formulation with encapsulated carrot waste extract. *Lwt* **138**, 110732 (2021).

View Article Online
DOI: 10.1039/D5FB00493D

147. Ayar-Sumer, E. N. *et al.* Optimizing encapsulation of black carrot extract using complex coacervation technique: Maximizing the bioaccessibility and release kinetics in different food matrixes. *Lwt* **198**, 115995 (2024).

148. Chhoden, T., Aggarwal, P., Singh, A. & Kaur, S. Valorization of black carrot pomace for the development of anthocyanin rich bio functional edible films: implications on structural, morphological and thermal properties for a sustainable approach. *J. Food Meas. Charact.* **18**, 5489–5506 (2024).

149. Hosseinvand, N., Eslahi, N. & Abbasian, A. Properties and characterization of carrot nanocellulose/starch biopolymer nanocomposites. *Polym. Compos.* **43**, 9158–9168 (2022).

150. Hwang, J. T., Kim, H. J., Ryuk, J. A., Jung, D. H. & Ko, B. S. Efficiency of the enzymatic conversion of flavone glycosides isolated from carrot leaves and anti-inflammatory effects of enzyme-treated carrot leaves. *Molecules* **28**, 4291 (2023).

151. Pars, A. & Karadag, R. Sustainable bio-dyeing of cellulosic-based fabrics with anthocyanins from black carrot (Daucus carota L.). *Fibres Text. East. Eur.* **32**, 50–56 (2024).

152. Stoica, F. *et al.* Application of pomace powder of black carrot as a natural food ingredient in yoghurt. *Foods* **13**, 1130 (2024).

153. Samilyk, M. *et al.* Devising a technique for improving the biological value of A2 milk by adding carrot powder. *Eastern-European J. Enterp. Technol.* **6**, 120 (2022).

154. Chu, G. M. & Park, B. K. Efficacy of fermented carrot by-product diets on blood profiles, immune responses, and faecal characteristics in fattening pigs. *Anim. Prod. Sci.* **63**, 773–781 (2023).

155. Pietrangeli, R. & Cicatiello, C. Lost vegetables, lost value: Assessment of carrot downgrading and losses at a large producer organisation. *J. Clean. Prod.* **478**, 143873 (2024).

156. Ierna, A., Mauro, R. P., Leonardi, C. & Giuffrida, F. Shelf-life of bunched carrots as affected by nitrogen fertilization and leaf presence. *Agronomy* **10**, 1982 (2020).

157. Bas-Bellver, C., Barrera, C., Betoret, N. & Seguí, L. Impact of fermentation pretreatment on drying behaviour and antioxidant attributes of broccoli waste

View Article Online
DOI: 10.1039/D5FB00493D

powdered ingredients. *Foods* **12**, 3526 (2023).

158. Demiray, E. & Tulek, Y. Degradation kinetics of β-carotene in carrot slices during convective drying. *Int. J. Food Prop.* **20**, 151–156 (2017).

View Article Online
DOI: 10.1039/D5FB00493D

Data availability: All the data related to the manuscript are included with the manuscript.