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Carrot and its by-products in the circular economy: a review of valorisation pathways

Anmol Kaur,[a] Ravindra Kumar Tiwari,[b] Supriya Singh Gaur *[a] and Pintu Choudhary *[c]

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Carrots are one of the most widely consumed vegetables worldwide owing to their nutritional benefits. They offer a wide range of potential uses due to the utilization of all components of the plant. The carrot root, peel, pomace, and leaves are valuable resources that contribute to product development in diverse applications: food processing, pharmaceutical, cosmetic, and bioenergy industries. 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 compounds converted to powder materials that can be extracted, and hence, they are suitable for application as functional foods and dietary supplements. More significantly, the integration of carrots and their by-products provides an avenue to reduce environmental waste amidst emerging consumers' demand for clean-label and functional products. This review discusses the potential benefits as a way of mitigating waste accumulation and enhancing sustainable practices across industries. It 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 the value of plant-based products derived from carrots and points to the valorisation of whole-carrot biomass as one of the strategies to reduce waste and enhance environmental sustainability.

Sustainability spotlight

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.

1. Introduction

Carrot (*Daucus carota* L.) is widely consumed globally in both fresh and processed forms, thus providing essential nutrients for 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 fibres, vitamins and minerals.[2] Fig. 1 illustrates the carrot along with its primary by-products in detail. The total production of carrots amounted to about 42 million tonnes worldwide in 2022, where China remained the dominant producer, followed by Russia and the USA, among the 125 nations.[3,4] Parallelly, processing industry data estimate that commercial carrot processors generate as much as 175 000 tonnes of carrot waste yearly, which is considered a valuable source of dietary fibre and bioactive substances.[5] Additionally,

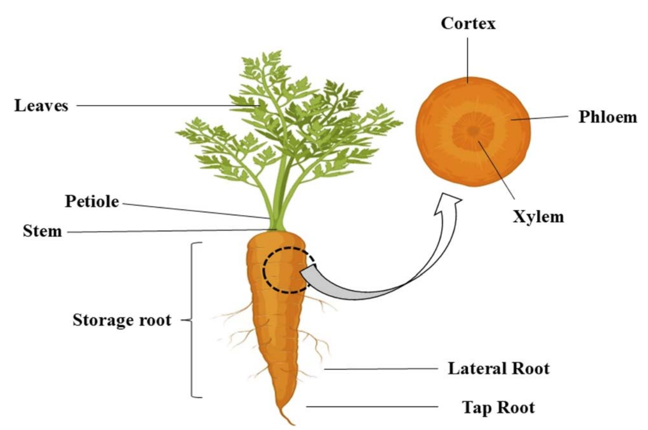

Fig. 1 Illustration of a carrot and its primary by-products.

[a]Department of Food Technology and Nutrition, Lovely Professional University, Phagwara, Jalandhar, Punjab, 144411, India. E-mail: supriya.27320@lpu.co.in
[b]Department of Post Harvest Technology, College of Horticulture and Forestry, Rani Laxmibai Central Agricultural University, Jhansi, U.P., India
[c]Department of Food Technology, College of Agricultural Engineering and Technology, Dr Rajendra Prasad Central Agricultural University, Pusa, Samastipur - 848 125, India. E-mail: choudharypintu14@gmail.com

recent work has 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, and pomace remain rather sparse in the literature, notably at the 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 its valorisation potential. A study concerning the nutritional value of whole carrot tops for fodder indicated that the tops can have high crude protein content ($\sim$144 g kg^{-1}) and relevant mineral content, indicating their valorisation potential.[7]

From the sustainability perspective, life cycle assessment (LCA) for carrot cultivation and processing opens the system boundary to include cultivation, harvest, processing, waste disposal and re-use.[8] Integrating LCA with by-product valorisation pathways would allow the quantification of 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 for carrot by-products, an emerging area is the presence of ice-binding proteins (IBP) or antifreeze-type proteins in carrots. However, IBP present in carrot possesses week freezing point depression potential, similar results were observed in grass proteins but but demonstrates high efficacy at nanomolar concentrations in inhibiting ice recrystallization.[10] In all, the scale 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 fibres, 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, there 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, and ready-to-eat foods 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 compositions of carrot and its by-products

Carrot and its by-products, such as seed oil, carrot peels, pulp, pomace, and 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]

2.1. Carrot

Carrot is one of the major root vegetables, rich in numerous bioactive compounds like dietary fibers and carotenoids that exert significant health-promoting effects. The edible portion of the carrot contains soluble carbohydrates ranging from 6.6 to 7.7 g/100 g.[16] Studies have revealed that the three varieties of carrot, *i.e.,* Pamella, Kuroda and Americano, exhibit high moisture (69.06% to 75.30%) and protein content and low carbohydrate level.[15] Moreover, carrots are packed with protein (0.6% to 2.0%), fat (0.2% to 0.7%), sugars (5.4% to 7.5%), fibers (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, the carrot is a great source of various minerals and vitamins, predominately calcium (34 to 80 mg/100 g), iron (0.4 to 2.2 mg/100 g), phosphorous (25 to 53 mg/100 g), magnesium (9 mg/100 g), thiamine

Table 1 Nutritional composition of a carrot and its by-products

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/100 g)	0.4–20,900	—	3050	16.25
β-carotene (mg/100 g)	1.50–54.8	13.74–20.45	0.607–11.83	—
Calcium (mg/100 g)	23.7–80	32.06	110–300	49.3
Phosphorous (mg/100 g)	25–2130	25.10	180	40.1
Potassium (mg/100 g)	6.6–240	—	1860	9.72
References	15–19	2 and 20–22	23 and 24	25–27

(B1) (0.04 mg/100 g), riboflavin (0.02 mg/100 g) and β-carotene.[28] Besides, the bioactive compounds present in the carrot are carotenoids (carotene, lutein, β-carotene, lycopene, and zeaxanthin), phenolic acids (*p*-hydroxybenzoic, chlorogenic and caffeic acid), and flavonoids (anthocyanins) that exert various pharmacological properties, comprising hypolipidemic, antifungal, gastro- and hepato-protective, antibacterial, antipyretic, antioxidant and analgesic properties.[29,30]

2.2. Carrot pomace

Being a valuable source of significant nutrients, carrot pomace has been 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%), proteins (4%), fats (1.30%), crude fibers (20.90%), cellulose (51.6%), pectin (3.88%), lignin (32.1%), hemicellulose (12.3%), reducing sugar (9%), calcium (3.00 mg g^{-1}), iron (30.50 mg g^{-1}), zinc (24.40 mg g^{-1}), phosphorous (1.80 mg g^{-1}), copper (4.00 mg g^{-1}) and potassium (18.60 mg g^{-1}).[32] Parallelly, pomace is also rich in vitamins, such as vitamin A, vitamins B complexes, vitamin C and vitamin K. The phytoconstituents present in the carrot pomace are polyphenols, carotenoids and antioxidants.[33] Thus, the utilization of carrot pomace provides an insight for the development of functional ingredients for the food industry and reduces the food waste.[34]

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 phenolic contents (54.1%).[16] Interestingly, carrot peel contains a significant amount of β-carotene (204.5 μg g^{-1}) as compared with carrot pulp waste (39.2 μg g^{-1}) and carrot pomace (19.81 μg g^{-1}).[35] Moreover, the peel has abundant amounts of cations (+92%), carotenoids (+42%), phenolic acids (seven times) and organic acids (+103%) compared to root flesh.[36] Besides, carrot peel powder conserved increased contents of beta-carotene, total carotenoids, lycopene and lutein and promotes their significant health benefits.[37]

Parallelly, carrot leaves are a remarkable source of macronutrients, like proteins (18.71%), fibres (15.69%), oils (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.[38] Studies have demonstrated that the carrot leaves have anti-inflammatory, antioxidant, antimicrobial and anticancer effects due to the presence of polysaturated fatty acids, α-pinene, germacrene, sabinene and luteolin.[39]

3. From farm to function: utilization of carrots

Carrots are progressively being utilized for the development of a wide spectrum of value-added products that not only enhance the nutritional and functional appeal of carrots but also contribute to its increased shelf life as well as consumer convenience.[40] This section outlines different carrot-based value-added products that offer enhanced shelf life and convenience, as illustrated in Fig. 2.

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 carrots into bakery products such as biscuits, cookies, cakes and breads has

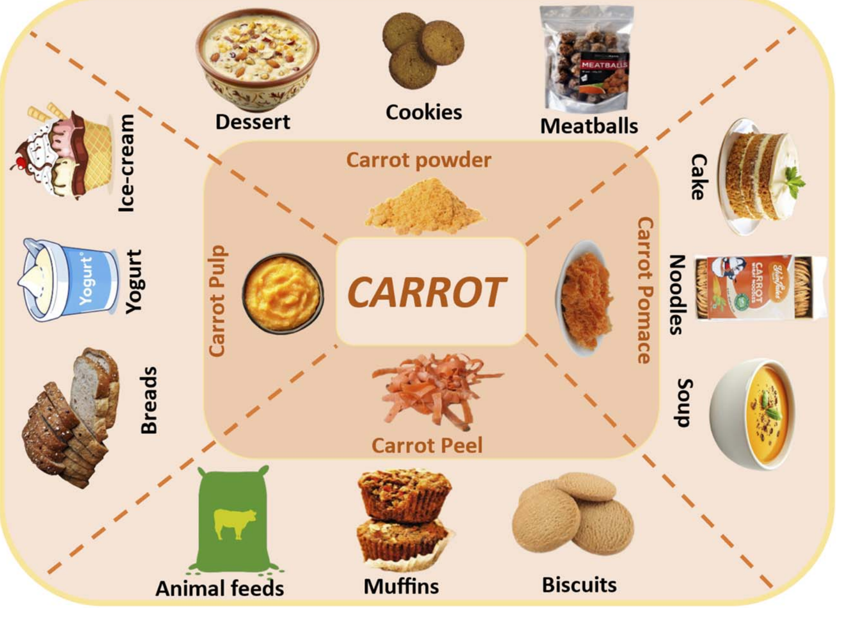

Fig. 2 Utilization of a carrot and its by-products in various industries.

a promising impact on both the 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).[41] 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.[42] Besides this, the addition of black carrot powder in breads with the level of 2.5, 5.0 and 7.5 percent preserved the moisture, protein and fat contents 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.[43] Thus, it indicates that the amount of carrot in breads may vary according to the form of carrot used and its processing.[44] Moreover, layer cakes prepared by a 40 percent mixture of carrot and pumpkin puree showed a significant enhancement in nutritional content, with the protein content reaching 8.89 percent, fat content rising to 18.31 percent, beta carotene increasing to 54.41 g and moisture content at 48.18 percent.[45] Similarly, Prajapati *et al.*[46] prepared a cake using carrots, which imparted unique flavour, colour and taste to the product. Moreover, the antioxidant activity, springiness and volume of the cake were excellent compared to the normal cake.

3.2. Meat-based products

Carrot, a natural additive, has lately exhibited immense potential for enhancing the nutritional quality and oxidative stability in meat-based product production. The components derived from carrot used in various meat products have therefore shown good prospects to act like natural additives to enhance the nutritional value, stability of oxidation and quality of the ultimate product.[47] According to a report by Kaynakç,[48] the purple carrot powder extract that was applied effectively reduced the 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, the flavour and juiciness had slightly declined during extended storage at −20 °C, highlighting the need for improved storage stability.[49] Additionally, a study evaluated the impact of incorporating carrot in canned goat meat and its biological value, where the increase in carrot content led to a significant increase in the content of fibres, β-carotene, select amino acids (histidine and lysine), vitamins (A, B5, B6, and B9), and minerals (potassium, magnesium, and phosphorus) and a reduction in the content of fats.[50] 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.[51]

3.3. Traditional food products

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 sandesh, rasgulla, chamcham, and rasmadhuri.[52] 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.[53] 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.[54] 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.[52] Significantly, the incorporation of carrots 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 showed an increase in micronutrients and bioactive molecules, thereby providing solutions to the problem of micronutrient deficiency.[55]

3.4. Functional beverages

As a rich source of antioxidants, dietary fibres, vitamins and minerals, functional drinks have become popular among health-conscious consumers.[56] 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.[57] Likewise, the incorporation of pomegranate, beetroot and carrot concentrates in whey-based beverage resulted in enhanced nutritional, antioxidant, physicochemical and sensory properties. The beverage with carrot concentrates exhibited the highest beta-carotene and anthocyanin content.[58] In addition, the bioactive profile of Kanji prepared from black carrot juice was excellent; the pH decreased from 6.0 to 3.47, the lactic acid content 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 flavonoid and phenolic contents.[59] 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 an antioxidant activity of 86.90% and a flavonoid content of 43.91 mg/100 mL, either comparable to or slightly higher than those of conventional Kanji, and consumer acceptability was also comparable.[60]

3.5. Dairy products

Various carrot extracts have been used for the fortification dairy products. In a study, Baker *et al.*[61] 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 per g) during storage, against typical changes in pH and acidity and carrots could be highlighted as a functional dairy additive. Similarly, the utilization of black carrot juice to develop a whey drink initially increased the acidity and decreased the anthocyanin content, though the resting period resulted in its enhanced phenolic content and colour. Inclusively, black carrot juice was highlighted not only as a source of vibrant pigments and phenolic compounds but also as a viable base for fermented functional drinks with probiotic potential.[62]

3.6. Carrot ice-binding proteins

Ice-binding proteins (IBPs) or anti-freeze proteins (AFPs) are specialized low-temperature-responsive proteins, which not only reduce the freezing damage but also control the growth of ice-crystals.[63] Notably, carrot (*Daucus carota*) antifreeze protein (*Dc* AFP) is considered as a leucine-rich repeat protein with a molecular weight of 36.8 kDa. This protein demonstrates significant anti-crystallization ability, thermal hysteresis and softer texture with pleasant aroma.[64] Besides, the carrot antifreeze protein has a strong influence on the textural properties of white salted noodles by increasing cooking absorption, reducing dry material loss, and protecting the gluten network from the freezing temperature and fluctuation of temperature.[65] Likewise, the protein reduces the depolymerization of glutenin macropolymers (GMP) and weakens the destruction of disulfide bonds, microstructures and secondary structures of hydrated gluten.[66] Studies have proven the fact that the carrot antifreeze protein improves the textural properties and fermentation capacity of dough during frozen storage. However, their production is generally limited due low yield and extensive purification process.[67]

4. Carrot peel utilization: a sustainable approach

Carrot peels have gained significant attention in the recent years for their potential application in development of value-added products in different sectors.[68] As they are high in bioactive compounds and fibers, they are being progressively used in bakery and 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 contents of fibres, fats, ash and essential minerals, thus giving fortified biscuits a better nutritional profile.[69] 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.[70]

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 these, 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.[71] In addition, vegetable wastes like carrot peel used as protein-based fishmeal alternatives in aquaculture show promising results.[72] In a study, Rauf *et al.*[73] used carrot peel as a carotenoid source in aqua feed for platy fish. It is known that the 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 with the passage of time. Moreover, including carrot peels in cattle feed will increase the content of nutrients such as omega-3 fatty acids and vitamins in the milk.[71]

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 and antioxidant potential, thereby offering cost-effective and sustainable formulations.

5.1. Probiotic fermented products

The nutritional potentiality of fermented food products significantly depends on the probiotic strain present in it.[74] However, the matrix used can improve the probiotic count as well as the nutritional composition of the product. A study conducted by Suraj *et al.*[75] 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, proteins, sensory properties and optimum microbial content. Besides, a probiotic drink developed using carrot and mango pulp showed excellent probiotic viability along with optimum pH, colour, soluble solids and sensory acceptance. Among the multiple probiotic strains used, *Lactobacillus plantarum* showed the highest survival under gastrointestinal conditions, highlighting the positive role of carrot-mango pulp as matrix.[76] Similarly, functional yoghurt developed using black carrot pulp and arabic gum demonstrated excellent phenolic content, antioxidant activity, and texture. Moreover, the incorporation of carrot pulp improved probiotic viability and sensory properties with storage.[77] Carrot pulp fortified with Lassi – a traditional fermented beverage – had improved viscosity, acidity, and total soluble solids with decreased fat content. Moreover, the probiotic count increased from 8.50 to 8.68 log CFU per ml with the increase in the concentration of carrot pulp in the product.[78]

5.2. Dairy-based products

Carrot pulp has been widely explored in dairy and frozen dessert formulations due to its potential to enhance the nutritional composition, functional properties and consumer appeal. A modified version of kulfi developed using carrot pulp exhibited excellent fibre content and optimum pH and the melting rate decreased with the addition of carrot pulp.[79] Likewise, the addition of pumpkin and carrot pulp into traditional ice cream resulted in a product enriched with pulp that demonstrated enhanced melting resistance and better sensory performance and increased antioxidant activity, especially at the 15 percent inclusion level.[80] Similarly, ice cream developed using carrot pulp and beetroot juice had higher levels of carotenoids, crude fibres, and total phenolic compounds and improved antioxidant activity, natural colour and flavour, indicating strong consumer acceptance.[81] In the case of yoghurt drink, the incorporation of carrot and guava pulp at varying levels reported significant increases in fiber, phenolic compounds ascorbic acid and antioxidant activity. Although acidity and syneresis increased over storage, carrot pulp addition enhanced the nutritional value and product acceptability.[82] 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 the microbial stability was maintained throughout the 35 day storage period.[83]

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.*[84] 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 and showed negligible changes in all sensory attributes, and all physicochemical properties remained comparable for a period of 90 days.[85] Additionally, vegetable-based extruded pellets and snacks can be developed by incorporating carrot pulps into them and such addition of pulps will limit energy and water requirement during processing[86] Carrot pulp can be used to prepare breads using cereal flours as the base material, which will have increased dietary fibres and vitamins and improved sensory properties compared to the regular bread.[44]

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 biscuits at different concentrations 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 indicating that carrot by-products can serve as the main component in maintaining the textural characteristics of the developed biscuits.[87] Besides, researchers evaluated carrot leaves as a cheap source of abundant nutrients, and hence, their addition in bakery products could be beneficial for below-poverty-line consumers, highlighting the potential of carrot waste valorisation in food security.[88] Moreover, carrot leaf powder assessed as a fortifying ingredient in sponge cake exhibited high contents of antioxidants, thereby enhancing the nutritional property, sensory quality, and functional properties of the product.[89]

6.2. Instant products

The incorporation of carrot with olive leaves showed great potential in the instant food industry for the development of nutrient-rich pasta. This exhibited significant potential by enhancing the functional and nutritional characteristics of the food product by increasing the content of polyphenol and antioxidant activity in it.[90] Similarly, carrot leaves and oregano show potential to be used as functional food ingredients for formulating pasta, thereby enhancing the bioactive compounds and nutritional composition of the product.[91,92] Besides, Joshi *et al.*[93] developed an instant soup mix using vegetable leaves including carrot leaves in their study. The antioxidant characteristics of the soup mix were maintained even after 60 days of 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.[78] 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 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 $\pm$ 2.39 nm for drug-free nano emulsion and 68.92 $\pm$ 10.6 nm for the sorafenib-loaded one). Additionally, the antitumor activity along with the reduction in hepatotoxicity and hematotoxicity was improved with the use of this nano-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.[94] 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.[95]

7.2. In cosmetics

Aging comprises several biological factors with physiological, psychological, and environmental influences. However, it is an inevitable and irreversible process. Moreover, 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.[96] 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.[97] A comparative study investigated the photoprotective potential of carrot seed oil and raspberry seed oil added to an SPF 30 sunscreen formulation. The 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.[98]

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 a 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 in Fig. 3.

8.1. Bakery products

Carrot pomace is being incorporated in different bakery products such as bread, muffins, cakes, cookies, biscuits, and crackers. The usage of carrot pomace flour in bakery products is an effective sustainable approach.[99] Black carrot pomace at different concentrations in cakes showed enhanced total phenolics, antioxidant activities and anthocyanins.[100] Additionally, the incorporation of 5 percent carrot pomace in 100 g of bread enhanced the content of cellulose (0.37 mg) and β-carotene (5.44 mg). Notably, consumption of 277 g carrot pomace-enriched breads on a daily basis fulfils 100 percent of carotene and 4.1 percent of daily dietary fibre.[101] Likewise, the addition of 15 percent carrot pomace not only affected the characteristics of the dough but also led to an increase in lipid content and antioxidant activities.[102]

8.2. Instant/ready to eat products

The addition of carrot waste to durum wheat pasta significantly enhanced its fat, protein, and ash content, as well as organoleptic properties of the product. It was reported that the addition of 25 percent pomace of carrots not only improved the

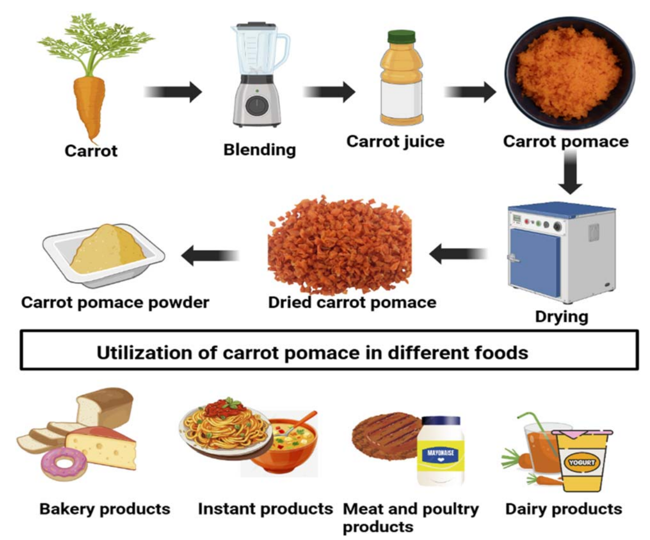

Fig. 3 Processing of the carrot pomace and its utilization in various food products.

dietary fibre and β-carotene content of the pasta, but also bridged the vitamin A deficiency.[103] In addition, the incorporation of the carrot pomace powder with wheat flour in instant fried noodles at different concentrations 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.[104] Similarly, the higher proportion of carrot pomace also affected the texture of noodles during thermal treatment.[105] Similarly, scientists demonstrated the nutritional improvement of soup mix from carrot pomace blended with other food items, which led to an increase in β-carotene, ascorbic acid, phenol, dietary fiber and mineral contents.[106] Alike, freeze-dried carrot pomace in combination with groundnut meal improved the colour, water absorption and swelling capacity of the pasta, thereby reducing its cooking time.[107] Additionally, the natural sweetness of carrot and corn minimized the requirement of artificial sweetener in the cooking of sweet corn and carrot pomace-enriched porridge.[108]

8.3. Meat and poultry

Carrot pomace powder incorporated with the emulsion-based low-fat chicken meatballs at concentration levels 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.[109] Besides, addition of 6 percent dried carrot pomace into the chicken sausages supplied 1/7 of the daily requirements of dietary fibers.[110] Additionally, the incorporation of dried carrot pomace into beef patties provided extra benefits such as enhancing the water holding capacity by 12 percent and reducing the cooking time by 5–15 percent. However, the texture of beef patties remained unchanged, making carrot pomace a valuable by-product to enhance the quality of the product. Moreover, beef patties supplemented with 1 percent carrot pomace received the highest overall acceptability compared to those prepared with 3 percent of carrot pomace.[34] Furthermore, its incorporation into mayonnaise at varying concentrations was systematically investigated to assess the developments in functional attributes and nutritional quality. The sample containing 4 percent carrot pomace showed the highest total phenolic content, firmness, and adhesiveness.[111]

8.4. Milk products

Carrot pomace is highly valued as an excellent source of carotene, ascorbic acid, dietary fibres and some essential minerals such as calcium, phosphorus, magnesium, iron, and copper, all of which are beneficial to 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 the 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 its classification as a nutrient-dense food.[112] 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.[113] The 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, and 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 reported the effect of thermal processing techniques, such as boiling, baking, steaming and microwave cooking on the carotenoid composition, antioxidant properties, nutritional composition, phenolic content and sensory attributes, including texture, flavour and colour.[131] Studies have demonstrated that the thermal processing technique facilitates the cell separation of vegetable tissues due to the pectin depolymerisation in the middle lamella through β-elimination.[132] The cell wall 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 contents compared to the uncooked carrot.[133] Similarly, it has been reported that compared to hot water cooking, steam cooking, and pressure cooking, microwave showed the highest increase in phenolic compounds.[134] However, Thanuja *et al.* (2018)[135] reported that hot water cooking of carrot have no significant effect on phenolic compound contents, while stir-frying and microwave cooking significantly reduced phenolic compounds with microwave showing a higher reduction of phenolic compounds compared 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.[136] Moreover, the combination of microwave (MW) and microwave vacuum (MWV) technologies improved the quality of the carrot chips by reducing shrinkage characteristics and hardness and preserving phenolic compounds, color changes and β-carotene with acceptable nutritional and physical quality.[114] In addition to this, the incorporation of freeze-dried carrot pomace powder in the wheat bread enhances the nutritional value of the product with acceptable flavor and taste.[115] Overall, the mild and controlled thermal processing enhances phenolic compounds; however, harsh thermal processing reduces the

Table 2 Extraction methods for the isolation of essential compounds from carrots and their by-products and 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	114 and 115
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	116, 117 and 118
	• Ultrasound-assisted extraction (UAE) • Microwave-assisted extraction (MAE) • Conventional solvent extraction	Extraction of anthocyanin with maximum cytotoxicity	• Microwave-assisted extraction achieved 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	119
	• Ultrasound-assisted extraction (UAE) • Microwave-assisted extraction (MAE) • Conventional solvent extraction	Efficient extraction of carotenoids from a carrot	• MAE showed highest extraction efficiency compared to UAE and SE	120
Encapsulation	• Free dried encapsulation • Electrostatic extrusion Whey protein-based microencapsulation	Protecting carotenoids and bioactive compounds exhibited by *Daucus carota* and their rejects	• Manufacturing of functional foods such as yoghurt • Preserves sensory attributes • Improves shelf-life and antioxidant activity Utilisation of anthocyanin as a natural colourant	121, 122 and 123
	• Freeze and spray drying techniques	Optimization of wall material formulations (whey protein/maltodextrin/inulin) for the encapsulation of the 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, oxidative stability, colour properties	124
	• Encapsulation of the black carrot extract using a complex coacervates technique	• Optimizing the encapsulation parameters of the black carrot extract by the 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 both gastric and intestinal conditions	125
				123

Table 2 (*Contd.*)

Category	Processing method	Purpose	Key benefits	References
	• 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 provides consumers with an optional functional food for daily diet				
Biopolymers	To produce edible biofilm with enhances stability	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	126, 127 and 128
	• To produce bio-nanocomposites for potential food packaging applications	• Nanocellulose (NC) was extracted from the carrot pulp and different weight fractions of NC (5, 7, and 10 wt%) were incorporated into corn starch, either with or without the 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 of the nanocomposites • The antibacterial activity against both gram-positive and gram-negative bacteria were observed after incorporating the thyme extract into the nanocomposites	129
	• 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 lemongrass oil emulsions	• The films formed with RCP carotenoid emulsion were compared to control films made from corn starch, HMC, and chitosan	• 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 to 230 °C) compared to control films	130
	• The RCP carotenoids emulsion was further used in the development of a ternary blended edible film	• The enrichment of films with RCP carotenoid emulsion tended to result in better functional and barrier properties, along with the addition of phytochemicals, carotenoids, and antioxidant properties		

phenolic compounds and additionally various other factors impact 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.[137] 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.[138]

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 UAE significantly reduces extraction time (by up to 50–70%) and solvent usage while maintaining high antioxidant activity of the extracted compounds.[138,139] Additionally, UAE is particularly advantageous for heat-sensitive compounds due to its relatively low operating temperature.

Recently, Constantin *et al.*[140] have 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 per g dry weight) along with strong antioxidant activity (≈1522 µmol TE per g), confirming that UAE not only improves the extraction yield but also retains the functional properties of bioactive compounds. However, the authors have mentioned that ultrasound parameters are very important in extraction, and excessive ultrasonication treatment may generate free radicals that will be responsible for the degradation of 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 the 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, the 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.[116] 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.[141,142]

In addition, MAE involves GRAS and food-grade solvents with high dielectric constants including ethanol, acetone and ethyl acetate, which boosts the antioxidant activity, highlighting MAE as a sustainable, energy-saving and high-performance extraction method having strong potential applications in food, medicine and nutraceutical industries.[120,143] Notably, enzyme-assisted extraction (EAE) is reported to enhance the total flavonoid and free radical scavenging properties by 2-fold, while β-carotene and phenolic concentrations improved by 5-fold as compared to the conventional methods used for the extraction of phytochemicals from carrot waste.[117] 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.[118]

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, the 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.[144] The choice of wall material plays a critical role in determining the 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 temperatures and pressures, minimizing the 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 effects and fulfilled β-carotene requirements, hence demonstrating the effectiveness of encapsulation for the production of value-added products from carrot waste.[124] Likewise, the encapsulation of anthocyanin-rich black carrot concentrates by employing whey protein-based microcapsules for the production of hydrogels show 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 natural food colourants.[145] 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.[121]

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.[146] Similarly, liposomal encapsulation involves phospholipid bilayers that can encapsulate both hydrophilic and lipophilic compounds, offering targeted delivery and improved stability.[147]

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.[126] For instance, carrot fibres (CFs) and microcrystalline cellulose (MCC), when added to chitosan (CH) films at different concentrations (0–5%), resulted in films exhibiting better tensile strength, optical properties and thermal stability with the increase in the number of fillers added, hence showcasing the potential of CFs for the production of biopolymer-based packaging materials.[127] Likewise, red carrot pomace (RCP), 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 natural and nutrient-rich packaging materials.[130] Similarly, black carrot pomace enriched with anthocyanin and polyphenols can be 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.[130]

Further, the carrot extract is used for the development of active and intelligent packaging systems. Active packaging involves the incorporation of bioactive compounds (*e.g.*, antioxidants and antimicrobials) that interact with the food or its environment to extend the 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.[148] Intelligent packaging, on other application, utilizes indicators such as anthocyanins from black carrot to monitor changes in pH, temperature, or microbial activity.[149] 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, the nanoencapsulation of carrot bioactives within biopolymer films allows for controlled release, enhancing the functional performance of packaging materials.[150]

10. Economic and environmental benefits

Carrots and their by-products are rich in numerous health-promoting compounds such as carotenoids, polyphenols and vitamins, which provide benefits including anti-cancer, antioxidant, immune-boosting, vision-improving and cardiovascular protective effects.[2] The total carotenoid and phenol ranges are ∼96–301 mg/100 g DW and ∼27–86 mg GAE/g DW, respectively. The addition of these components increases the phytochemical content, along with taste, texture and carotenoid bioactivity in developed products.[40] 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,[40] as depicted in Fig. 4. Primarily, carrot waste after the 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 of ∼25–30% and a calorific value of ∼16 MJ k^{-1}.[120] 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.[151] 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 radical-neutralising potential, thus contributing to environmental and monetary benefits.[130] Significantly, black carrot's anthocyanin-rich extracts have acquired a role as natural dyes in

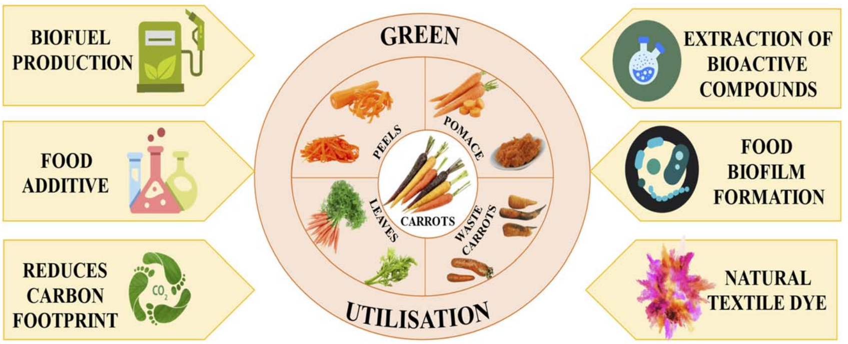

Fig. 4 Valorisation of carrots and their by-products, including peel, pomace, leaves, and unused carrots, has various applications such as extracting bioactive compounds, producing food additives, creating natural dyes, reducing carbon footprint, formulating biofuels, and developing food biofilms, which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

the textile industry for colouring cotton and linen fabrics, hence demonstrating the eco-friendly benefits of black carrot.[152] Moreover, carrot wastes, including pomace and mash, are 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.* the extraction yield is ∼26–30% for UAE, which is ∼2–3 times higher than that of the conventional method. 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.[153] 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.[154] Besides, fermented carrot waste material (peels and unused carrots) serves as cattle feed that enhances the hepatic function of blood and faecal good microflora, and decreases the risk of infection by improving the immunoglobulin G (IgG) levels in fattening pigs. This effect might be attributed to the presence of crude fibres in fermented feed, thus reducing environmental and economic constraints.[155] Therefore, the valorisation of carrots and their waste products aids in decreasing the carbon footprint generated by greenhouse gases and provides nutritional benefits and monetary profits for both producers and processors.[60]

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.[156] 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.[120] Moreover, studies have revealed that the presence of leaves and nitrogen fertilisation rate (240 kg ha^{-1}) adversely affects the phenolic 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.[157] 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.[158] Likewise, the increase in drying temperature uplifts the β-carotene degradation rate of carrot slices, and hence, an optimal drying temperature (45–55 °C) should be maintained.[159]

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 fibers, 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 the extension of shelf life. Besides food applications, cosmetic emulsions and anti-aging formulas will 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, the valorisation of carrot by-products represents the circular bioeconomy, where agricultural residues are transformed into value-added products with positive impacts on human health and sustainability.

Conflicts of interest

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

Data availability

All the data related to this study are included in the manuscript.

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