Sustainable Food Technology

REVIEW

Cite this: *Sustainable Food Technol.*, 2024, 2, 667

A comprehensive review on carrot (*Daucus carota* L.): the effect of different drying methods on nutritional properties and its processing as value-added foods†

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Received 13th September 2023
Accepted 9th March 2024

DOI: 10.1039/d3fb00162h

rsc.li/susfoodtech

Carrot (*Daucus carota* L.) is one of the major root crops, abundantly grown throughout the world. Carrots are perishable and difficult to preserve in fresh form. They are widely utilized due to rich bioactive compounds and nutrients, including carotenoids, anthocyanins, dietary fiber, and vitamins. The adoption of processing techniques becomes imperative with conventional and modern dehydration or drying methods as pivotal technologies for extending the shelf life of products. This review systematically explores the effect of diverse drying processing technologies on carrots, encompassing both conventional and modern processing methods, including solar drying, tray drying, freeze drying, microwave drying, spray drying, hot air oven drying, infrared drying, and conductive hydro drying. Through an in-depth study, the effect of these technologies on the physical characteristics and biochemical parameters (ascorbic acid, carotenoids, flavonoids, phenolic acids, total phenolics, and antioxidant activity) of carrots is elucidated. The significance of dried and fresh carrots is their use as an ingredient in various food products, such as beverages, soups, sauces, ready meals, and healthy snacks. Apart from providing an overview of current research, this review suggests possible directions for further studies on carrots. This review contributes to the holistic understanding of sustainable approaches to carrot processing and sets the stage for future developments in this area.

Sustainability spotlight

Carrot (*Daucus carota* L.) is one of the unique root vegetable crops among all vegetable families owing to the presence of different types of nutrients and bioactive compounds, which provide numerous health benefits. However, it contains high levels of moisture content and low shelf life; thus, it is necessary to develop a sustainable drying technology for carrots to enhance their storage shelf life and achieve maximum retention of bioactive compounds present in them. In recent years, convectional and modern processing methods have gained popularity because of their numerous benefits, such as simple unit operation and low energy consumption. Therefore, the selection between modern and conventional drying technologies for carrots should be made with the careful consideration of sustainability goals. In this review article, all the recent scientific findings address the above-mentioned problems for promoting sustainable carrot drying practices.

1. Introduction

Vegetables are an important part of agriculture for achieving food and nutritional security. Increasing the availability, affordability, and consumption of nutritious vegetables is one way to prevent malnutrition problems. Vegetable-planted areas are steadily increasing day by day due to an increase in production, a shortened maturation cycle, and increased value addition, leading to improved livelihoods, and its production is setting new records every year, making it the most popular product for farmers.[1] Carrot (*Daucus carota* L.), a biennial herbaceous species, stands as a versatile and nutrient-rich vegetable renowned for its vibrant color, distinct flavor, and numerous health benefits.[2] It is the most significant crop belonging to the Plantae kingdom, Apiaceae family, *Daucus*

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† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d3fb00162h

genus, and *Daucus carota* species.[3] Carrots are native to Europe, Asia, Northern Africa, and North and South America.[4] According to the AgriExchange APEDA[5] report, in India, Haryana is the largest producer state of carrots, with about 386.39 tons of production, followed by West Bengal, Punjab, Uttar Pradesh, and Madhya Pradesh. There are more than 60 species of carrot, among which only a few are cultivated in India. Depending on its origin and color characteristics, carrot may be classified into basic Western/carotene type and Eastern/Asiatic. The Western carrot is an orange, yellow, or white-colored tap root that was derived from the Asiatic types either by mutation or by selection in yellow-type hybrid progenies. The Asiatic carrot is either of black-purple/anthocyanin type or a red-colored root that is primarily grown in Egypt and Asian countries, including India.[6] The variation of color in carrots is due to the presence of different pigments, *viz.* carotenoid (yellow and orange) and anthocyanins (purple); however, white carrots have no color pigments.[7]

Carrot is a good source of various bioactive compounds, *viz.* carotenoids, flavonoids, phenolic compounds, vitamins (B_1, B_2, B_6), and minerals, which help to provide biological and medicinal properties such as improving digestion, regulating blood circulation, and improving eye vision.[8] It is a good source of higher antioxidant compounds that show anti-carcinogenic and immune enhancing properties. Also, it helps to control diabetes, cholesterol, and cardiac disease and has antihypertensive, hepatoprotective, and wound healing properties.[8,9]

Carrots are the most common food in the human diet and they can be eaten fresh and cooked into a variety of dishes or processed into puree, juices, or dehydrated products.[10,11] However, carrots are a seasonal product and their quality can be largely degraded by the decrease of their bioactive compounds after being harvested. In addition, during their storage, moisture content, sweetness, firmness, color, and taste are also changed, sometimes forming an unpleasant smell, which affects the consumers' acceptance of the product.[12] Fresh carrots can be converted into dehydrated form by drying, and the dried carrots can be commercially used as a natural ingredient for the formulation and development of functional products such as dietary supplements, nutraceuticals, and cosmetics.[1]

Different kinds of drying methods are used for drying carrots such as freeze drying, vacuum drying, osmotic dehydration, cabinet or tray drying, fluidized bed drying, ohmic and microwave heating, spray drying, conductive hydro drying, and supercritical drying. These methods help to improve shelf-life, product diversity, and volume reduction.[13] The present review examines and compares the effect of various modern and conventional drying methods on carrots (slices, strips, cubes, puree, juice), and their structural, physico-chemical, bioactive

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compounds parameters, and quality parameters are discussed. Additionally, it highlights the nutrient and bioactive compounds profiles and the associated health benefits of carrots. Furthermore, it explores opportunities for utilizing carrots in the creation of different kinds of functional food products, aiming to improve the storability, production efficiency, product quality and shelf-life of carrots for sustainable practices. Thus, we conducted searches for relevant articles across various research engines such as Google Scholar, ResearchGate, ScienceDirect, and PubMed. Synonyms and alternative words were identified and used to obtain the current literature. The major search terms and keywords used were carrot, carrot bioactive compounds, nutritional value, health benefits of carrot, carrot drying, drying methods, carrot processing, and carrot products.

2. Nutritional composition and health benefits of carrot

Carrots are rich sources of various bioactive compounds, mostly carotene and ascorbic acid, known as vitaminized food, with an average moisture content of 86–89 g/100 g, protein 0.9–1.09 g/100 g, fat 0.24 g/100 g, carbohydrates 9.58 g/100 g, and total sugars 4.74 g/100 g. The nutritional composition of fresh carrots is presented in ESI Table 1.† Carrots are a good source of minerals such as Ca (34 mg/100 g), Fe (0.4 mg/100 g), P (25 mg/100 g), Na (40 mg/100 g), K (240 mg/100 g), Mg (9 mg/100 g), Cu (0.02 mg/100 g), and Zn (0.2 mg/100 g).[1,14] Carrot roots contain various water-insoluble polysaccharides including cellulose 71.7%, hemicellulose 13.0%, and lignin 15.2%. According to literature, four different types of carrots showed cellulose contents that ranged from 35 to 48%. Fresh carrot has an average nitrate and nitrite concentration of 40 and 0.41 mg/100 g, respectively.[16] The flavouring profile of carrots is mostly due to the presence of glutamic acid and the buffering effects of free amino acids. There have also been reports of traces of succinic acid, α-ketoglutaric acid, lactic acid, and glycolic acid. The main phenolic acid in carrots is caffeic acid. Black carrots have a higher anthocyanin level of about 1750 mg kg^{-1}, while pink cultivars have trace quantities. The major anthocyanins that have been reported in carrots are cyanidin 3-(2-xylosylgalactoside), cyanidin 3-xylosylglucosylgalactoside, and cyanidin 3-ferulylxyloglucosyl galactoside.[1]

Carrots possess remarkable health benefits because they contain various nutrients and bioactive compounds such as carotenoids, polyphenols, and vitamins. They show good antioxidative, anticarcinogenic, mutagenetic, and immune enhancing properties.[17–19] They contain antioxidants that have the ability to lower free radicals in the body, and various dietary carotenoids have been shown to have anti-cancer effects.[20] Saleem *et al.*[21] showed that carrot extracts contain bioactive compounds that exhibited inhibition against MCF-7 cells in a dose-dependent effect against microbes and breast cancer proliferation. Varshney and Mishra[8] reported that carrot is a rich source of vitamin C and vitamin A, which help to keep human skin healthy and prevent wrinkles, discoloration, and uneven skin-related problems. Black carrots contain a good amount of anthocyanin, which is used for the treatment of brain cancer.[22] In another study, the impact of carrot fraction consisting of pentane/diethyl ether (50 : 50) on the motility and invasion of cancer cells from the lung, breast, glioblastoma, and skin was studied. From this treatment, a notable reduction was

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observed in cell motility across all four cell lines, accompanied by a reduction in cancer cell invasion and an elevation in adhesion.[23] Black carrot contains a good amount of anthocyanin compounds are more effective for reducing different types of cancer. The growth of cancer cells (HT-29 and HL-60) was 80% inhibited by lyophilized black carrot powder (20 μg mL^{-1}) extracted from aqueous extract. The ethanol-based extract obtained from black carrot is helpful for the treatment of breast, human colon, and prostate cancers and demonstrated antioxidant and anti-proliferative activities against diverse cancer cell lines.[9] Various studies showed that carrots (leaves, flowers, petals, and fruits) show good anti-microbial activity against different types of microbial species including *Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Listeria monocytogenes*, *Salmonella typhimurium*, *Streptococcus pyogenes*, *Haemopilus influenzae*, and *Campylobacter jejuni*.[24,25]

The antifungal properties of carrot subspecies (*carota*, *gummifer*, *halophilus*, *hispanicus*, and *maximus*) were studied against different microbes, namely, *Fulvia fulvum*, *Trichoderma viride*, *Aspergillus ochraceus*, *Candida albicans*, *Penicillium expansum*, *Cryptococcus neoformans*, and *Aspergillus flavus*, which were found to show good anti-fungal activities.[24–26] In a regular diet, consuming carrot-containing bioactive compounds (beta-carotene, lutein, and alpha-carotene) is associated with cardioprotective benefits. These effects encompass the activation of the lymphocyte, inhibition of cell proliferation, anti-oxidative properties, anti-inflammatory effects, reduction of body-mass index, lowered blood pressure and triglyceride, and modulation of relevant enzyme activities.[8,27]

3. Modern and conventional drying processing technologies

In general, drying is the process or technology that protects the qualities of raw and processed foods including color, flavor, nutrients, rehydration, appearance, and uniformity during the drying process.[28] Carrots have drawn a lot of attention among the various fruits and vegetables that need to be dried because it has been reported that they contain a variety of bioactive compounds that are said to have numerous health benefits, including antioxidant activity.[29] Efficient and energy-saving drying methods including solar drying, heat pump drying, freeze drying, superheated steam drying, and a combination of these methods help to reduce drying time and protect the quality of carrots.[28] There are different emerging new technologies used for drying that are used in carrot processing such as infrared, radio frequency, and microwave drying.[13]

Carrots show higher water activity, more susceptibility to mechanical damage, rapid microbial spoilage, lower shelf life, and environmental factors. Thus, the storage of carrot for long periods is challenging. These factors affect their quality attributes.[30] One of the major components present in carrots is water, which showed an impact on their quality parameters such as taste and texture of dried food items, microbiological growth, and fat oxidation. Food material when exposed to the environment either gains or loses water to maintain an appropriate moisture content in a state of equilibrium with the relative humidity of the environment.[31] One of the most popular and common methods is drying, which helps to increase food storage stability, reduce water activity, inhibit microbial growth, and reduce the physicochemical changes of food products.[32] Based on the technique used to remove the water, these processes can be broadly categorized as thermal drying, osmotic drying, and mechanical dewatering.[33] The effects of different drying processing methods on the physical and nutritional properties of carrot samples are presented in (Table 1 and Fig. 1).

3.1. Solar and sun drying

Fruits and vegetables are frequently dried using solar and sun drying methods because it is a natural and affordable drying method than other methods of drying. One of the oldest techniques for utilizing sun energy to dry is solar radiation. Since the dawn of the world, it has primarily been used to preserve food, though it is also used to dry other materials like clothes and construction items.[71] However, this method has problems such as contamination, infections, and microbial spoilage. Also, it depends on weather conditions. Additionally, the time required for drying is more, particularly for grapes into raisins.[72]

Apples and carrots were dried in a solar cabinet in a variety of shapes and sizes (slices and cubes). The results showed that air humidity and temperature inside the chamber showed a significant negative correlation, and weather conditions had an impact on the drying process as it takes more time to dry.[73] Carrot slices are dried using solar drying method with blanching treatment (55, 65, and 75 °C for 45 min) and soaked in salt solution of different concentrations (5, 10, and 15% for 5 h). The optimum nutrient retentions observed were protein 5.25%, fat 2.17%, fiber 2.17%, and beta-carotene 71.94 ppm on dry weight for carrot samples treated at 55 °C, whereas the 5% salt solution shows fat 2.88%, fiber 2.46%, and beta-carotene 73.89 ppm on a dry weight basis.[74] The different ranges of carrot thickness 0.3, 0.5, and 1.0 cm show significant effects on the drying of carrot slice samples.[34] The slices with thickness of 1–2 mm were placed in solar drying, and the overall shrinkage ratio and drying ratio of carrot slices observed were 11 : 1 and 8.8 : 1, respectively. From the solar method, the yield of the dried carrot sample was 9.09%. In the solar-dried carrot sample, retention of protein of 97.22%, starch 91.32%, total sugar 90.04%, reducing sugar 89.34%, fat 94.56%, ascorbic acid 58.00%, β-carotene 72.15%, and energy value 92.00% was observed.[15] The sun-dried sample had poor quality compared to the solar drying process, while in this drying process, a specific size of the sample was used for drying. The difficulties with the solar drying process include moisture condensation inside the dryer and the resulting increase in humidity percentage. Direct and indirect solar drying are two different methods of solar drying used for drying carrot samples.[35,37,38]

3.2. Tray drying

The most popular drying method among all drying methods is tray drying because of its simple and economical design. To

Table 1 Effect of different drying technologies on the quality parameters of carrots

Drying methods	Product form	Processing parameters	Physical parameters	Physico-chemical parameters	Biochemical parameters	References
Solar drying	Slices	Slice dimension: thickness 1–2 mm Drying time: 15–16 h	The overall shrinkage ratio and drying ratio of carrot slices are 11 : 1 and 8.8 : 1 Yield solar dried carrot was 9.09% The sensory attributes such as flavour, texture, and taste are acceptable for upto 6 months	The retention of protein 97.22%, starch 91.32%, total sugar 90.04%, reducing sugar 89.34%, fat 94.56%, and energy value 92.00%	The retention of β-carotene 72.15% and ascorbic acid 58.00%	15
Sun drying	Slices	Slice dimension: thickness 0.3, 0.5, and 1.0 cm Drying temperature: 31 °C Drying time: 8 days	The thickness of carrot slices impacts the weight loss value in all samples	NA	NA	34
Indirect solar drying	Strips	Strips dimension: thickness 0.2 cm and width 2 cm Solar irradiance: 7.2 kW h m^2 per day Airflow velocity: 1 m s^{-1}	The color difference (ΔE) 14.11 ± 0.14 between the carrots in the dry and fresh conditions ratio of redness over yellowness increased from 0.75 to 0.89, the browning index decreased from 209.82 ± 0.62 to 148.38 ± 0.26 and whiteness index increased from 24.5 ± 0.11 to 31.8 ± 0.17	NA	NA	35
Solar cabinet drying	Slices	Carrot varieties: Pusa Kesar Slice dimension: thickness 3 mm Blanching: 100 °C for 6 min Airflow velocity: 0.0082 m s^{-1} Drying temperature: 55 °C for 16 h	Drying rate variation A lower rehydration ratio of 4.70 after 120 days 3.84 were observed	NA	β-Carotene content 93 mg/100 g degradation	36
Solar drying	Slices	Slices dimension: thickness 2 mm and length 2.5 cm Blanching: 94 °C for 3 min	NA	Moisture content 91.42 ± 0.21 to 10.51 ± 0.31	Iron content was from 3.91 ± 0.37 to 5.03 ± 0.22 mg/100 g increased, zinc content was from 0.41 ± 0.05 to 0.88 ± 0.05 mg/100 g increased, and β-carotene reduced from 6.72 ± 0.28 mg/100 g to 3.53 ± 0.41 mg/100 g (0.53 folds decrease)	37
Solar drying	Slices	Slices dimension: thickness 3 mm and width 5 mm Drying temperature: 27 to 50 °C	Dehydration rates of 3.3 ± 0.30% and water activity 0.56 ± 0.011 to 0.63 ± 0.003 were observed	NA	A drying load of 715 g m^{-2} contained the highest β-carotene of 17.4%, vitamin A activity of 362 IU g^{-1}	39
Solar drying	Slices	Carrot varieties: PC-34, Sel-21, Ambala local' and Nantes Slices dimensions: 3, 4.5, 5, 7, and 10 mm	The 3 mm thick slices after 12 h of drying maximum total solids, dehydration ratio, and non-	NA	NA	16

Table 1 (*Contd.*)

Drying methods	Product form	Processing parameters	Physical parameters	Physico-chemical parameters	Biochemical parameters	References
		Blanching: hot water (95 °C), steam, and microwave blanching Chemical pre-treatment: ascorbic acid, brine, potassium sorbate, and potassium metabisulphite (KMS) Drying temperature: 50, 60, 70, 80 and 90 °C	enzymatic browning after drying at 60 °C observed			
Cabinet hot air dryer	Slices	Slice thickness: 3 and 6 mm thickness Airflow velocity: 0.6 m s^{-1} Drying temperature: 50, 60, and 70 °C	The temperature of 59.8 °C and the slice 3.5 mm thickness the La^*b^*; ΔE of 62.18 ± 5.12, 22.46 ± 1.98, 40.35 ± 6.64, 6.31 ± 4.74 and rehydration ratio of 0.48 ± 0.07 observed	NA	The highest retention of total carotenoids final product was 66.2% at 60 °C followed by 51.1% and 42.2% at 70 and 50 °C	39
Tray drying	Slices	Carrot varieties: Pusa Kesar Slices dimension: thickness 3 mm thickness and diameter 3 cm Drying temperature: 60, 65 70, 75, and 80 °C	NA	NA	Increased temperature reduction in ascorbic acid from 32.60 to 13.53 mg/100 g and β-carotene from 55.25 to 9.39 mg/100 g	40
Hot air drying	Cubes	Carrot varieties: Kazan, Maxima, Nandor, Nektarina, Simba, and Tito Cube size: 10 mm Airflow velocity: 2.0 m s^{-1} Drying temperature: 70 °C	The Kazan and Nektarina showed highest and lowest moisture diffusivity of 7.52×10^{-9} and 3.31×10^{-9} m^2 s^{-1} Lower drying time is required for the Kazan variety Lower color degradation was observed in the Tito variety Nandor and Tito varieties show more water absorption about 560 g/100 g	NA	NA	41
Hot air drying	Slices	Carrot varieties: Nantes Airflow velocity: 3.8 ± 0.3 m s^{-1} During temperature: 40, 50, 60, 70, and 80 °C Relative humidity: 48.5%	Different temperature ranges does not show significant differences in solid shrinkage The Weibull model satisfactorily simulates the degradation kinetics of carotenoids 2.8 ± 1.2%, phenolic content 5.7 ± 1.0%, and antioxidant activity 3.6 ± 1.8% Air temperature ranged between 52.6 and 57.7 °C, low effect on carotenoids, and phenolic and	NA	The Weibull model satisfactorily simulates the degradation kinetics of carotenoids 2.8 ± 1.2%, phenolic content 5.7 ± 1.0%, and antioxidant activity 3.6 ± 1.8% Air temperature ranged between 52.6 and 57.7 °C, low effect on carotenoids, and phenolic and antioxidant content retention of 2.2%	42

Table 1 (*Contd.*)

Drying methods	Product form	Processing parameters	Physical parameters	Physico-chemical parameters	Biochemical parameters	References
			antioxidant content retention of 2.2%			
Hot air drying	Slices	Carrot varieties: Karotka Slices dimension: thickness 5 mm and diameter 35 mm Drying temperature: 70 °C	A drop in lightness (L) was observed	NA	Retention of β-carotene is about 61–68%	43
Fluidized bed drying	Slices	Carrot varieties: Pusa Kesar Slice dimension: thickness 3 mm Blanching: 100 °C for 6 min Airflow velocity: 0.049 m s^{-1} Drying temperature: 50, 60, and 70 °C	The fall rate period was very slow Rehydration ratio 70 °C highest 6.03 Retention in color parameters Overall sensory acceptability	NA	Maximum β-carotene content was retained at 50 °C	36
Microwave oven drying	Slices	Carrot varieties: Pusa Kesar Slice thickness: 3 mm Blanching: 100 °C for 6 min Power: 650 W	The fall rate period was very slow Low retention of color parameters Lower overall sensory acceptability	NA	Low retention of β-carotene content	36
Microwave oven drying	Slices	Carrot varieties: Nanco Blanching: 90 °C for 7 min and unblanched Airflow velocity: 1.5 m s^{-1} Drying temperature: 60 °C Relative humidity: 6–10% Tray load: 3.0–3.4 kg m^{-2}	Variations in color A420 values for unblanched samples at 27, 37, 47, and 57 °C were 0.018, 0.058, 0.197, and 0.138; while blanched samples were found as 0.014, 0.033, 0.149 and 0.093	NA	Degradation of β-carotene in blanched 69% and unbleached 86%	44
Microwave oven drying	Slices	Slices thickness: 3, 4, and 6 mm Power: 90 W, 100 W, and 120 W	Fourier model gave better results coefficient of determination (R^2) 0.9991–1.000, error sum of squares (SSE) ranging from 0.000121 to 0.001034, and root mean square error (RMSE) from 3.32×10^{-3} to 0.02274. Effective moisture diffusivity (De) ranged from 9.7422×10^{-10} to 1.9962×10^{-9} m^2 s^{-1} while the drying constant (k) ranged from 5.7×10^{-5} to 0.00022 s^{-1}	NA	NA	45

Table 1 (*Contd.*)

Drying methods	Product form	Processing parameters	Physical parameters	Physico-chemical parameters	Biochemical parameters	References
Microwave oven drying	—	Carrot varieties: Nantes Power: 150, 200, 250, 300, 350, 400, and 450 W Power value: 0.50, 0.67, 0.83, 1.00, 1.17, 1.33 and 1.50 W g^{-1}	The highest value of ΔE was found for carrots dried at lower MW power (150 W) application and L^* and a^* values, the values of ΔE decreased as power increased	NA	The phenolic content of the carrot samples at microwave power levels of 150 and 200 W (0.50 and 0.67 W g^{-1}) was found Maximum terpenes compound were found in powdered samples dried with power levels (150 and 200 W)	46
Fluidized bed drying	Cubes	Carrot varieties: Macon F1 Cube dimension: 1 cm^3 Drying temperature: 60, 70, 80, and 90 °C	The intensity of heat and mass transfer during drying depends on the drying temperature Moisture content and the rehydration ratio at 60 °C were higher than at other drying temperature temperatures	NA	NA	47
Fluidized bed drying	Slices	Slices dimension: thickness 8–12.5 mm Air flow rate: 500–660 min^{-1} Inlet air temperature: 40–70 °C	The volume, diameter, and length ratio are correlated to shrinkage properties Air velocity, temperature, and presence of inerts did not show significant effects on shrinkage properties	NA	NA	48
Fluidized bed drying	Cubes	Cubes dimensions: 4, 7, and 10 mm^3 Drying temperatures: 50, 60, and 70 °C Bed depths: 30, 60, and 90 mm	The drying temperature and cube size affect energy efficiency	NA	NA	49
Spray drying	Puree	Carrot: black carrot Inlet temperature: 150, 175, 200, and 225 °C Outlet temperature: 76, 86, 98, and 112 °C Aspirator air flow rate: 50 m^3 h^{-1} Feed flow rate: 2.5 mL min^{-1}	Lower degradation of color parameters	The best results obtained at 150 °C for water solubility index and encapsulation efficiency	The retention of anthocyanin content, and antioxidant activity at 150 °C	50
Spray drying	Puree	Carrot: black carrot Inlet temperature: 160, 180, and 200 °C Outlet temperature: 107, 118, and 131 °C Feed flow rate: 5 mL min^{-1}	The maximum quality attributes at temperature 160 °C of L^*, a^*, b^*, C^* and H values, dry matter content and hygroscopicity properties	NA	Higher retention of anthocyanin content and antioxidant capacity at temperature 160 °C were observed	51
Spray drying	Juice	Carrot milk powder Inlet temperature: 165, 170, and 175 °C Outlet temperature: 60 °C Feed flow rate: 0.2, 0.25, and 0.3 kg h^{-1} Air pressure: 2 kg cm^{-2}	The physical properties of carrot milk powder were a loose density was 0.535 ± 0.008 g cm^{-3}, packed density was 0.606 ± 0.003 g cm^{-3}, insoluble index of 2.280 ± 0.073 mL, and 0.378 ± 0.003 for water activity observed	The protein, fat, and fiber were 28.54 ± 0.278, 3.90 ± 0.068, and 1.73 ± 0.027 g/100 g, respectively	β-carotene content was 2.038 mg/100 g observed	52

Table 1 (*Contd.*)

Drying methods	Product form	Processing parameters	Physical parameters	Physico-chemical parameters	Biochemical parameters	References
Spray drying	Juice	Inlet temperature: 150, 160, and 170 °C	Higher inlet air temperature showed an increase in solubility, and hygroscopicity, and a decrease in moisture content, color value, bulk density, and product recovery	NA	NA	53
		Outlet temperature: 75 °C Feed flow rate: 80, 120, and 160 mL h^{-1}	Higher feed flow rate showed an increase in moisture content, color value, bulk density, product recovery, and a decrease in solubility and hygroscopicity			
		Air pressure: 2 kg cm^{-2}	The best quality carrot powder was achieved at an inlet air temperature of 160 °C and a feed flow rate of 120 mL h^{-1}			
Freeze drying	Slices	Slices dimension: diameter 8 mm and length 10 mm Drying temperature: −28, −80, −150, and −196 °C Time – incremented temperature step: −30 °C up to 25 °C Pressure: 0.4 mbar Drying time: 27 h	Rehydration-dried samples of PFG NMR and MRI show that cellular compartments were not restored and instead, a porous network with permeable barriers is formed	NA	NA	54
Freeze drying	Slices	Slices dimensions: length 4.5 cm, width 1.5 cm, thickness 1.5 cm Drying temperature: −21 °C Pressure: 85–90 Pa	Retention of color, odor, and appearance characteristics Less effect on textural parameters, color measurements, and rehydration ratio of dried sample	NA	NA	55
Freeze drying	Slices	Carrot varieties: Heitianwucun Slices dimension: diameter 4.5 cm and thickness 7 mm Blanching: steam blanching 110 °C for 3 min Drying temperature: −65 °C for 8, 16, 32, and 64 h Vacuum pressure: 0.12 mbar	Retention of volume shrinkage below 30% and low effect on color parameters	NA	Carotenoids and lutein content degreed up to fresh and blanching freeze-dried sample was 41.56% and 47.14%	56
Microwave freeze drying	Slices	Slices dimensions: length 8 mm, width 8 mm, and thickness 8 mm	Higher energy consumption required	NA	Better retention of β-carotene and vitamin C content	57

Table 1 (*Contd.*)

Drying methods	Product form	Processing parameters	Physical parameters	Physico-chemical parameters	Biochemical parameters	References
		Microwave power: 2 W g^{-1} Vacuum pressure: 100 Pa Drying temperature: −40 °C	Higher sensory acceptability			
Microwave vacuum drying	Slices	Slices dimension: thickness 4 mm Blanching: 90 °C for 4 min Vacuum pressure: 40 mbar Rotation speed: 5 rpm Drying time: 24 to 42 min	High rehydration capacity Radial shrinkage values ranged from 36.2 ± 5.0 to 46.1 ± 4.6%	NA	Reduction in carotenoid content	58
Infrared drying	Slices	Carrot varieties: Nantes Blanching: 98 °C for 3 min Drying temperature and time: 95 °C for 40 min, 100 °C for 30 min, and 105 °C for 15 min	Shows good shrinkage, color, rehydration ratio, and density properties without affecting quality parameters	NA	NA	59
Infrared drying	Slices	Slices dimension: thickness 6 mm and diameter 29.5 mm Power: 300, 400, and 500 W Air velocities: 1.0, 1.5, and 2.0 m s^{-1}	The drying rate increased with increasing infrared power The process parameters are effects on shrinkage, rehydration ratio, and color parameters	NA	NA	60
Infrared drying	Slices	Slices dimension: thickness 1–2 mm Drying temperature: 50, 60, 70, and 80 °C	The drying rate almost doubled when the drying temperature was increased The model derived from the Midilli model gives the best result Effective diffusion coefficient in the temperature range 50–80 °C was determined as, 7.295×10^{-11}, 9.309×10^{-11}, 1.140×10^{-10}, 1.501×10^{-10} m^2 s^{-1} The activation energy was determined as 22.43 kJ mol^{-1}	NA	NA	61
Infrared drying	Slices	Slices dimension: thickness 5 mm and diameter 30.5 mm Power: 400, 600, and 800 W Air velocities: 1.0 m s^{-1} Drying time: 10 h	Effect on the dried carrots water condition dramatically changing Significant increases in the amount of immobilized water in the cytoplasm and extracellular space corresponded with significant decreases in the amount of free water in vacuoles, and the amount of immobilized water steadily decreased over time	NA	NA	62

Table 1 (*Contd.*)

Drying methods	Product form	Processing parameters	Physical parameters	Physico-chemical parameters	Biochemical parameters	References
Infrared drying	Slices	Slices dimension: thickness 5 mm Power: 62 to 125 W	Infrared power affected the drying and quality characteristics such as rehydration and color parameters The Midilli model showed the best results Moisture diffusivity which varied between 2.45×10^{-9} and 7.38×10^{-9} m^2 s^{-1} The activation energy was estimated by a modified Arrhenius-type equation as 4.247 kW kg^{-1}	NA	NA	63
Infrared drying	Slices	Slices dimension: thickness 5 mm Blanching: 95 °C for 5 min Power: 7.875 kW m^{-2} Air velocities: 1.2 m s^{-1}	NA	NA	The anthocyanin pigments as cyanidin-3-glucoside contents 211.4 and 870.3 mg/100 g, phenolic content 1448 and 3754 mg/100 g, and antioxidant activity 78.1 and 250 µmol Trolox/100 g were observed	64
Vacuum drying	Slices	Slices dimension: thickness 5 mm and diameter 25 mm PEF treatment: electric field strength (0.6 kV cm^{-1}), number of trains (10 pulses and time 100 µs) Drying temperature: 25, 50, 75, and 90 °C Pressure: 0.3 bar	NA	NA	Preserved β-carotene and color properties of dried sample	12
Vacuum drying	Slabs	Slab dimensions: thickness 5 mm, length 40 mm, and width 20 mm Blanching: 90 °C for 5 min Drying temperature: 50 to 70 °C Pressure: 5, 15, and 25 kPa	The pressure, temperature, and pre-treatments all improve the effective diffusivity of moisture transport	NA	NA	65
Vacuum drying	Cubes	Cube dimension: 1 cm^3 Pressure: 7 kPa Drying temperature: 60, 70, 80 °C	NA	NA	Low degradation of β-carotene content	66
Vacuum drying	Slices	Slices dimension: thickness 4 mm and diameter 2–3 mm Ultrasound treatment: ultrasonic mode 10 s on and 5 s off for time 20 min Pressure: 0.02 and 0.03 MPa Drying temperature: 65 and 75 °C	Ultrasound-treated samples reduce drying time by 41–53% Combination ultrasound treatment with a vacuum drying	NA	Combination ultrasound treatment with a vacuum drying process retains the β-carotene and ascorbic acid content	18

Table 1 (*Contd.*)

Drying methods	Product form	Processing parameters	Physical parameters	Physico-chemical parameters	Biochemical parameters	References
			process retains the rehydration potential and textural properties			
Conductive hydro drying	Pomace	Pomace parameters: homogeneous dough (80 g) and baking paper (8 pores per cm^2; 1.4 mm pore size) with a 0.4 cm thickness, 10 cm width, and 15 cm length	Less drying time 150 min	NA	Retention of anthocyanin content and phenolic compounds	67
		Drying parameters: 50 µm BOPET corona-treated film, the water level was constant, and water temperature (95 °C)	Retained the color characteristics			
Conductive hydro drying	Slices	Slices dimensions: thickness 0.2 and 0.4 cm and diameter 3 mm	Less drying time of 26–51%	NA	Retention of phenolic compounds	68
		Drying parameters: plastic film 0.017 cm thick, the water level was constant, and water temperature (74 and 94 °C)	Retention of color and texture characteristics		Reduction in antioxidant activity of 25.84%	
Conductive hydro drying	Puree	Drying parameters: temperature (70, 80, and 90 °C) and NaOH solution concentration (0, 1, and 2% v/v)	Retention of color parameters at the untreated sample for 70 °C	NA	Higher retention of anthocyanins 86.5 mg/100 g at 70 °C 2% NaOH solution and 90 °C retained total flavonoid content	69
Supercritical drying	Slices	Slices dimensions: length 2.5 cm and diameter 0.4 cm	Retention of shape, less shrinkage, and color characteristics	NA	Low degradation of β-carotene content	70
		Drying parameters: temperature 50 °C, pressure 20 MPa for 2.30 h	Reduction of moisture content with increased temperature			

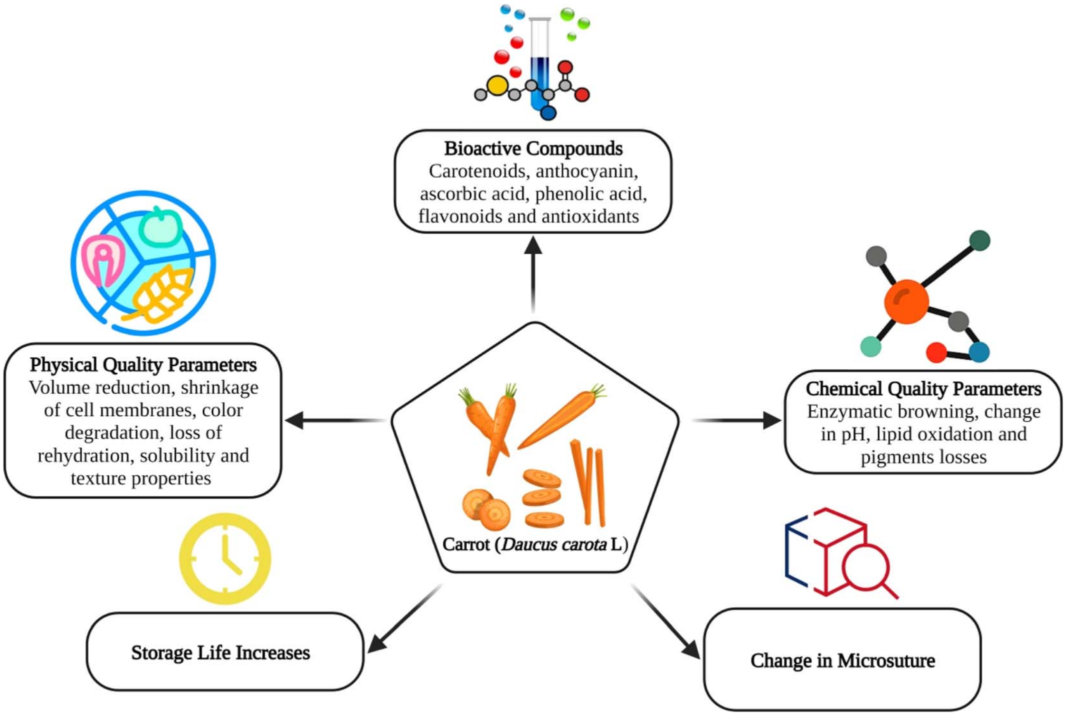

Fig. 1 Effect of different drying processes on carrots.

achieve uniform drying of the product, the product is spread over different trays at an appropriate thickness. The trays may be heated by a passage of hot air passing over them, through convection from the heated trays, or *via* radiation from heated surfaces. Trays are organized at various levels in a tray dryer and it is a batch process of drying where at one time, more products can be loaded. The uniform spread of airflow over the plates is essential to the tray dryer's efficient functioning. Any traditional drier that utilizes fossil fuels or electricity, including solar dryers, can use the tray dryer.[75]

Carrot pomace was dried using various drying processes such as convective drying (55 and 65 °C), sun drying, and solar drying. The convective drying process required minimum drying time with higher retention of fiber, total carotenoids, β-carotene content, and minimum change observed in dried carrot color parameters.[76] Aghbashlo *et al.*[77] studied the energy and exergy analysis of the drying process in a semi-industrial continuous band dryer for the drying of carrot slices with thickness of 5 mm, and they were subjected to different drying temperatures such as 50, 60, and 70 °C, airflow rates of 0.61, 1.22, and 1.83 kg s^{-1}, and feeding rates of 2.98×10^4, 3.48×10^4 and 4.16×10^4 kg s^{-1}. The energy utilization and energy utilization ratio were varied in the range of 3.78–25.57 kJ s^{-1} and 0.1554–0.3752, and the exergy loss and exergy efficiency were found to be in the range of 0.6677–14.1577 kJ s^{-1} and 0.5527–0.9329, respectively. In another study, carrot slices were subjected to two different drying methods including tray drying and infrared drying at temperatures of 65, 70, 75, and 80 °C. The infrared drying method had a low moisture content compared to the tray drying method and also required more time for drying the carrot slices.[78] The retention of β-carotene content increased from 9.86 to 11.57 mg/100 g while the ascorbic acid content retention dropped from 22.95 to 13.53 mg/100 g when the drying temperatures were raised from 60 to 75 °C. Based on the retention of β-carotene and ascorbic acid, the optimal drying temperature was found to be 65 °C for the drying of carrots.[40]

3.3. Microwave drying

Microwave drying is one of the alternative drying methods where electrical energy in the frequency form between 300 MHz and 300 GHz is used, and 2450 MHz is the most popular frequency. By stepping up the alternating current from household power lines at a frequency of 60 Hz up to 2450 MHz, microwaves are produced inside the chamber. This device is known as a magnetron.[79] In the food industry, microwave drying has become a popular alternative drying technique. The microwave drying of fruits and vegetables has shown several benefits, including a rapid drying process that can preserve nutritional quality in the dried product and also a greater retention of bioactive compounds.[80] However, concerns about uneven heat distribution, resulting in charring due to high microwave power and extended exposure time, have positioned it as a pre-treatment method. This approach facilitates the rapid removal of surface moisture, contributing to enhancing the process efficiency in a drying process.[81]

The carrot slices were dried using a microwave, halogen lamp–microwave combination, and hot-air drying method. A high-quality dried product was produced and the drying time was decreased by 98% when compared to traditional hot-air

Table 2 The comparison between different drying technologies used for carrot drying processing as a sustainable approach

Drying methods	Sample size (kg)	Initial moisture (%)	Final moisture (%)	Pre-processing cost (₹)	Water intake (kg)	Energy input per kg water removed (MJ kg^{-1})	Drying rate (kg min^{-1})	Remarks
Tray drying	1	85	5	0.5–1.5	0.7	600–1200	0.005–0.01	Method type: artificial Drying speed: moderate Temperature: low Processing cost: low
Fluidized bed drying	1	85	5	1.0–2.0	0.7	400–800	0.01–0.02	Method type: artificial Drying speed: moderate Temperature: low Processing cost: low
Freeze drying	1	85	5	3.0–5.0	0.7	1200–1800	0.001–0.005	Method type: artificial Drying speed: rapid Temperature: low Processing cost: high
Infrared drying	1	85	5	1.0–2.0	0.7	600–1000	0.01–0.03	Method type: artificial Drying speed: rapid Temperature: moderate Processing cost: moderate
Microwave drying	1	85	5	2.0–3.0	0.7	800–1400	0.02–0.04	Method type: artificial Drying speed: rapid Temperature: moderate Processing cost: moderate
Conductive hydro drying	1	85	5	1.5–2.5	0.7	400–800	0.02–0.04	Method type: artificial Drying speed: rapid Temperature: low Processing cost: moderate
Spray drying	1 L	95	5–10	3.0–4.0	0.9	400–500	0.04–0.06	Method type: artificial Drying speed: rapid Temperature: moderate Processing cost: high
Rotary drying	1 L	95	5–10	2.0–3.0	0.9	500–800	0.03–0.05	Method type: artificial Drying speed: low Temperature: low Processing cost: moderate

drying using microwaves at their highest power and a halogen lamp–microwave combination drying process. Also, a very low amount of color degradation was observed in the microwave drying process.[81] In carrot pomace powder, the maximum retention of bioactive compounds including β-carotene, epicatechin, gallic, and ferulic acids was higher than in the hot-air drying process.[68] In another study, carrots (cubes, discs, and sticks) were subjected to a microwave and a vacuum microwave. Both the drying processes were shown to impact the quality of dried carrots. The use of microwave vacuum drying shows an impact on the carrot's physical characteristics. The primary difference was that the samples dried in a vacuum microwave experienced less shrinking than samples dried in the microwave.[82] The different ranges of microwave power levels affect the phenolic content of fresh carrots. The best range for drying to retain the phenolic content was reported to be between 150 and 200 W (0.50 and 0.67 W g^{-1}).[46] The effect of microwave vacuum drying, either standalone method or in combination with either hot air drying or vacuum drying on the carotenoid content in carrot slices was studied. The microwave drying method showed a better retention of carotenoid content compared with other drying methods.[83] Nwajinka and Konjo[45] used different models for studying the drying behavior of carrot slices in microwave oven drying. This study reported that the Fourier model gave the better coefficient of determination (R^2) 0.9991–1.000, error sum of squares (SSE) ranging from 0.000121 to 0.001034, and root mean square error (RMSE) from 3.32×10^{-3} to 0.02274.

3.4. Freeze drying

A traditional method of food preservation by freeze-drying prevents food substance shrinkage. Various types of fruits and vegetables and their processed products can be dried using the freeze-drying method. It works on the principle of sublimating frozen goods, due to which all biochemical and microbiological processes are stopped at a low temperature, resulting in maintaining a high-quality product.[84]

Rai and Jain[85] investigated the freeze-drying of carrots and other popular vegetables. The ability to reconstitute, color appearance, taste, and storing stability of freeze-dried foods were evaluated. Vegetable pulao was found to have a higher acceptability score rating and could be kept in tightly sealed receptacles under nitrogen at room temperature. The benefits of freeze-drying include minimizing the loss of bioactive chemicals, increasing the stability of carrot pomace, homogenizing the components of the dried pomace, and facilitating quick and simple reconstitution. However, this drying method exhibits higher energy consumption and long processing is required. Voda *et al.*[54] (2012) studied the effect of freeze-drying, blanching, and freezing rate pre-treatments on the microstructure and rehydration properties of carrots. Rapid freezing using blanching pre-treatment created a less connected and more anisotropic porous network, suggesting that more of the natural cell wall morphology is retained. The application of ultrasound pre-treatments at different power levels was shown to have a significant effect on freeze-dried carrot slices. The combination of ultrasound and freeze-drying significantly reduced the drying time from 698 min to 593 min.[86] Rajkumar *et al.*[55] compared the effect of hot air and freeze-drying methods on the physical parameters and aromatic profile of carrot. The physical parameters such as water activity, shrinking, hardness, cohesiveness, springiness, chewiness, rehydration ratio, and color are significantly affected in the convective drying of carrots. The study shows that the freeze-drying method has more retention of aromatic compounds than the hot-air drying process and the shrinkage of freeze-dried carrot rate (20.83%) is lower than the that of hot-air drying (35.53%) observed. In another study, black carrot juice was subjected to freeze drying at a constant temperature of −53 °C and a vacuum of 0.22–0.11 mbar with the constant feed mixture. The product that had the highest anthocyanin concentration, antioxidant activity, water solubility index, encapsulation effectiveness, and change in color was determined to be the best choice.[50] In another study, probiotic carrot juice powder was prepared, and freeze-dried probiotic formulation was shown to have good storage stability up to one month (6–7 log CFU per g) compared to the spray-dried formulation.[87] Keskin *et al.*[88] studied the influence of three drying methods (freeze-drying, intermittent microwave drying, and hot air convective drying) on the amounts and types of volatile and phenolic compounds of black carrot powders. From this study, it was reported that the freeze-drying method conserved the number of aromas to a greater extent, and its overall acceptability was higher than the others based on the sensory analysis parameters.

3.5. Vacuum drying

The use of vacuum drying technology in the chemical, pharmaceutical, food, and biotechnology sectors plays a crucial role in the drying of heat-sensitive materials. Vacuum drying techniques can be described in terms of the physical setups utilized to generate heat and reduce the vapors of water. At low pressures, water evaporates more quickly, and heat is indirectly supplied through radiation or contact with a metal surface. Certain materials that might deteriorate or break down at higher temperatures can also be used at low temperatures under a vacuum.[12,13,89]

Carrot slices were dried using the application of ultrasonic vacuum (USV) drying and vacuum drying at 65 and 75 °C. The vacuum drying process showed a significant effect on the rehydration potential, nutritional value (retention of β-carotene and ascorbic acid), color, and textural properties of carrot compared to USV-dried carrot slices.[18] The combination of vacuum drying with the hot-air drying method retains the carotenoid content of the carrot well within a short drying time.[90] The degradation of beta-carotene content is less observed in the vacuum drying process as compared to the conventional air drying method.[66] Using a combination of Pulsed Electric Fields (PEF) along with the vacuum drying process, the activation energy was 13.4 kJ mol^{-1} and the drying time was also reduced. The final dried product retains β-carotene and the color properties of the carrot sample.[12] The pressure, temperature, and pre-treatments help to improve the effective diffusivity of moisture transport and drying time for a sample.[18,65]

3.6. Spray drying

Spray drying is another process of drying in which liquid food materials are converted into powder form by controlled temperature conditions, and it is a single-step process.[91] The obtained powder product from this process presents a low moisture content of 2.5% and low water activity ranging from 0.2 to 0.6; it is also more stable compared with other products.[92,93] The liquid feed material is atomized in the drying chamber using this straightforward technique, and when the liquid droplets come into contact with hot air, water evaporates from them. The dry components are then separated through exit air and collected. The time between hot air and liquid materials is much less (a few seconds). The drying temperature inlet chamber ranges from 150 to 200 °C, and the outlet temperature level used is 70 to 90 °C in the conventional spray drying process.[50,51,93] During spray drying, the juices from fruits or vegetables encounter various problems such as stickiness, wall deposition, and limited production. Fruits and vegetables are rich in sugars (fructose, glucose, sucrose) and organic acids (malic acid, citric acid, and tartaric acid), which have low molecular weights and low glass transition temperatures. To resolve this problem, different carrier agents are used during spray drying. The most common carrier agents used include methylcellulose, pectin, starches, gelatin, gum arabic, alginates, tricalcium phosphate, and their combinations.[53,94]

Carrot juice powder's physical parameters including moisture content, solubility, hygroscopicity, bulk density, color, and product recovery depend on the spray drying process parameters.[53] The process parameters used for spray drying including drying temperature (inlet and outlet), feed flow rate, atomizer speed, type of carrier, and carrier concentration have also shown significant effect on quality parameters.[13] Quality carrot powder is obtained at 150–160 °C with maximum retention of bioactive compounds and antioxidant activity as well as water solubility index, encapsulation efficiency, and color change of the final product.[50,51] The carrot milk powder prepared using the spray drying method's physical properties had a loose density of 0.535 ± 0.008 g cm^{-3}, packed density of 0.606 ± 0.003 g cm^{-3}, insoluble index of 2.280 ± 0.073 mL and 0.378 ± 0.003 water activity. The following contents were observed: protein 28.54 ± 0.278 g/100 g, fat 3.90 ± 0.068 g/100 g, and fiber 1.73 ± 0.027 g/100 g and β-carotene content was 2.038 mg/100 g.[52] In another study, carrot and celery juice powder in the ratio (2 : 1; w/w) was prepared using a spray drying method optimized by Response Surface Methodology (RSM). This study showed that maltodextrin concentration, inlet temperature, and feed flow rate had significant effects on moisture content, water activity, hygroscopicity, β-carotene, and bulk density of the carrot–celery powder. The optimum temperature (130 °C), feed flow rate (36 mL min^{-1}), and maltodextrin (0.87; w/w) retained the quality of the obtained powder.[95] The spray-dried carrot powder obtained using carrier agents maltodextrin demonstrated better anthocyanin and antioxidant activity retention as well as higher encapsulation efficiency and solubility when compared to gum arabic and tapioca starch. Apart from these, when maltodextrin was used in the preparation of carrot juice, the shelf-life was increased by 70–220 times.[50]

3.7. Infrared drying

In food processing sectors, infrared processing technology is used for various types of unit operations including peeling, blanching, pasteurization, roasting, and most importantly, the drying of food materials.[96] For the thermal processing of food products such as heating, drying, and pasteurization, infrared radiation is the portion of the electromagnetic spectrum with wavelengths between 0.78 and 1000 μm. The near-infrared (NIR, 0.78–1.4 μm), medium infrared (MIR, 1.4–3 μm), and far infrared (FIR, 3–1000 μm) are three zones of infrared wavelength.[97] It is used to dry foods with high moisture content as the energy only penetrates the materials a short distance before turning into heat. The advantages of this drying method over conventional drying methods are great energy efficiency, less drying times, uniform heating of food products, simple temperature controlling process, finished product quality, and low energy consumption and costs.[60,98]

Carrot slices were dried at different temperatures of 95, 100, and 105 °C for 15 to 40 min. The quality parameters such as shrinkage, color, rehydration ratio, and density properties were well maintained.[59] When the infrared power increased, the drying rate of the carrot sample was increased but the processing parameters were affected, such as shrinkage, rehydration ratio, and color parameters.[60,61,63] Xu *et al.*[62] studied the effect of far-infrared drying of carrot slice samples (thickness 5 mm and diameter 30.5 mm) on the water state and glass transition temperature. The outcomes of this work showed significantly increased amount of immobilized water in the cytoplasm and extracellular space corresponding with significant decreases in the amount of free water in vacuoles, and the amount of immobilized water steadily decreased over time.

3.8. Conductive hydro drying

Conductive hydro drying or refractance window drying is a modern technology that was first invented by MCD Technologies Inc. (Tacoma, Washington, USA). In this drying method, different parts including a stainless-steel hood, plastic conveyor belt, exhaust, hot water pump, water tank, and heating unit are employed.[99] The thermal energy is transferred through three different modes such as convection, radiation, and convection. This modern drying technology is mostly used for heat-sensitive materials such as liquids and purees into powders, cakes, or sheets.[69]

The conductive hydro drying method with drying parameters such as 50 μm BOPET corona-treated film and water temperature (95 °C) was used for the drying of black carrot pomace, which showed that for the drying process, 150 min time is required as compared to other drying methods. The end products showed similar color quality and yielded better preservation of color and phenolic compounds.[67,68] Kaur *et al.*[69] showed that from the study, the physical (color properties) and chemical parameters (anthocyanins and total phenolic content) were retained in dried carrot compared to other drying methods.

3.9. Supercritical drying

Supercritical drying is a modern drying method that can remove moisture from food materials at temperatures higher than the critical point of the solvent used, all the while maintaining the structural properties of the food product. The supercritical drying method helps to improve the microbiological, enzymatic, and shelf stability and is also helpful in maintaining the physicochemical stability of the final product.[70,100] Supercritical drying requires a short processing time, and operational costs are notably lower in comparison to other drying methods such as spray drying, vacuum drying, and freeze-drying. As a result, supercritical drying has several benefits over conventional drying techniques. Consequently, supercritical drying offers a multitude of advantages over traditional drying approaches. The different kinds of food items, including carrots, apples, coriander, red bell peppers, and chicken breast, have undergone successful drying using this drying method.[13] Brown *et al.*[70] used the supercritical drying method for drying carrot pieces (length 2.5 cm and diameter 0.4 cm) at 20 MPa pressure and studied the effects of temperature and co-solvent (ethanol). This study work shows that the supercritical dried carrot pieces show better results (microstructural characteristics, shapes, and rehydrated textural properties) than the air-drying method. However, very few scientific studies were done on carrots using supercritical drying; thus, further studies are needed for the process optimization of this drying technology and their comparison with other drying methods to improve the texture and retention of bioactive compounds in more depth.

4. Sustainability of different drying technologies in carrot processing

Three criteria are used to evaluate a process or product's sustainability: environmental, social, and economic. The food system faces sustainability issues at every point from production to processing, distribution, retailing to consumption and waste disposal of the products.[101] The above-mentioned different drying technologies are energy-intensive unit operations in engineering and reduce moisture content in carrots under safe storage conditions. In addition, they also prevent microbial growth and improve the product quality. The drying process removes the water content by inducing phase changes *via* heat, mass, and momentum transfer, coupled with physical, chemical, and structural transformations. The drying temperature range varies with drying methods such as freeze-drying (−30 to −80 °C) and other drying methods (air drying and spray drying temperature range 45 to 80 °C and 125 to 225 °C, respectively), which results in irreversible damage primarily because of the changes in cell structure, chemical structure, and nutritive value.[102] Nowadays, the assessment of drying process sustainability has been evaluated through the 4E-system analysis, including energy, exergy, environmental, and economic factors. This intricate multi-dimensional analysis is challenging due to the interconnections among these sustainability aspects. For instance, the utilization of diverse energy sources in drying may have adverse environmental impacts. Moreover, some of the drying methods (spray drying and freeze drying) require skilled labor, which is linked to training and employment considerations. Additionally, drying serves as a prevalent post-harvest technology for food preservation, ensuring food security and, consequently, upholding a fundamental human right. Lastly, like any industrial process, each drying procedure aims to enhance the product value, emphasizing the need for a comprehensive cost–benefit analysis of drying technology.[103,106]

The drying process is one of the most energy-intensive processes, and the precise percentage of energy used for drying depends on the source. In different types of food industries with high energy demand for drying or dehydration, even a one percent improvement in energy efficiency can yield up to a ten percent increase in profit. In food processing sectors, any small amount of improvement in the energy efficiency of the processing steps will contribute to sustainable global energy development. Different types of indices have been used to evaluate how much energy drying equipment uses. The first law of thermodynamics is followed in energy analysis, which emphasizes the idea of energy conservation. One way to understand the word "energy efficiency" is as the ratio of the net energy used for drying (moisture evaporation) to the total energy input that the drying air provides.[103,104] The analysis is based on exergy and its subsequent optimization in drying processes is gaining attention among researchers. Exergy represents the maximum work attainable from a substance, heat, or workstream when the substance reaches thermodynamic equilibrium with the surroundings through reversible processes. It measures the potential of a stream to induce change due to its instability relative to the reference environment.[105] The exergetic performance assessments not only identify the magnitudes, locations, and causes of irreversibility in plants but also facilitate the determination of waste emissions and internal losses. The primary goal of exergy analysis in drying systems is to offer a comprehensive understanding of the process, quantify inefficiencies, assess energy consumption quality, choose optimal drying conditions, and minimize the environmental impact. Exergy analysis is increasingly applied to various products, and recent studies integrate both energy and exergy calculations for a more comprehensive analysis and sustainability evaluation of the drying process.[104,105]

In the context of drying processes, it is imperative to conduct an environmental analysis, particularly regarding the environmental impact of diverse energy sources employed. The following emission figures for CO_2/kg of evaporated water are relevant for typical fossil fuels utilized in air heaters, natural gases (0.074 kg CO_2/kg water), heavy fuel oil (0.11 kg CO_2/kg water), and anthracite coal (0.13 kg CO_2/kg water). When electricity serves as the primary energy source for drying, it becomes essential to factor in CO_2 emissions at the generation site. The quantity of CO_2 generated per kilowatt-hour of electric energy at the generation site is contingent on the method of electrical energy generation.[103] Evaluating the economic elements of drying, such as the cost *vs.* potential economic benefits, is necessary for the systematic approach towards sustainability analysis.[103,107] Drying costs typically fall into two categories: fixed costs, representing long-term investments unaffected by the production process, encompassing initial capital outlay, equipment, and building depreciation, interest on investment capital, insurance, fixed portions of taxes and rents, maintenance costs, and executive salaries. The second category is variable costs or operational expenses, linked to production levels and covering expenses like raw materials, energy, labor, bank interest on working capital, royalties, daily maintenance, and other direct costs.[103,107,108]

The comparisons between different drying technologies are used for carrot drying processing based on different key performance indicators of sustainability. The comparisons between different drying technologies for the case of carrot (1 kg) drying are based on power consumption (1 kW), drying efficiency (75%), and cost of electricity (0.13 kW h × 10₹/kW h = 1.30₹), shown in Table 2. Table 2 shows the highest energy input required to remove water for microwave and tray drying, while the lowest is for spray drying. However, significant investments in microwave drying and high risks of product overheating limit the adoption of this technology by the industry. Fluidized bed drying, conductive hydro drying, and rotary drying have approximately the same economic cost. However, freeze-drying requires more capital investment and a longer payback period. The choice of a drying method for sustainability depends on pre-processing cost, energy efficiency, drying rate, processing cost, and overall economic viability. Drying methods such as tray drying, fluidized bed drying, infrared drying, and conductive hydro drying exhibit favor sustainability aspects in this comparison.

5. Utilization of carrots into value-added foods

Carrots are consumed either raw or in the processed form in different ways into value-added food products such as canned carrots, chips, candy, kheer, halva, powder, juice, and beverages.[10] According to Lingappa and Naik,[11] carrots were used as blending agents in different types of food products, *viz.*, soups, drinks, wine, stews, curries, pies, and jam preparation. Fig. 2 below shows the different products prepared from carrots.

For the preservation of carrots slices, diced and whole carrots are blanched with water or steam, which helps in the prevention of browning and quality deterioration of processed carrots and allow for high-temperature condition or low-temperature conditions.[109] Blanching treatment at 87.5 °C for a short duration of time leads to low quality and degradation of color, but treatment at 71 °C for 3–6 min helps to retain the quality of the product.[110] Blanching treatments cause the thermal degradation of beta-carotene bioactive compounds.[111] Negi and Roy[112] found that after drying, blanched carrots had greater levels of retentions of beta-carotene and negligible effects on ascorbic acid content than untreated carrots sample, whereas blanching had no impact on non-enzymatic browning. Several studies show that steam blanching increases the level of total carotenoid content. The steam blanching process requires less time for a cut and small size of products.[113] Apart from these methods, different thermal blanching treatments are also

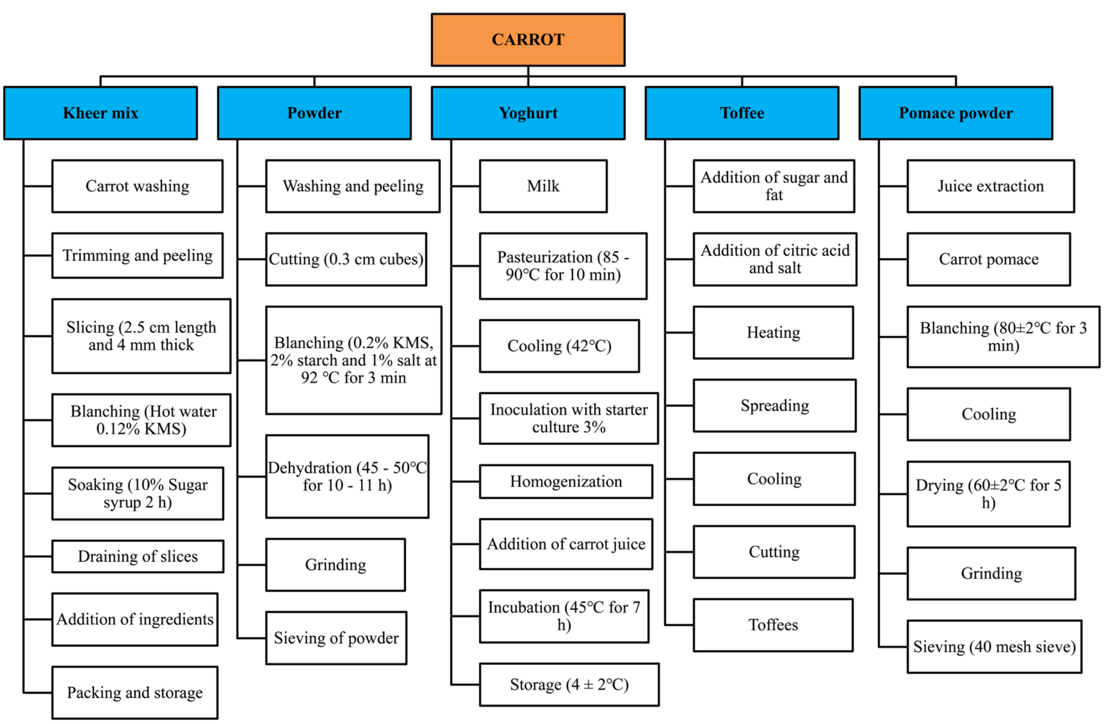

Fig. 2 Utilization of carrots in different value-added food products.

used for carrots such as microwave blanching, ohmic blanching, and infra-red blanching.[114]

The beta-carotene content in carrots is about 50%; thus, it should be incorporated into different kinds of products including biscuits, cake, bread, and other functional food products. The preparation of bakery products such as biscuits, buns, cookies, crackers, cakes, and muffins incorporates fruits and vegetable-based raw and processed ingredients to help enhance the quality characteristics and storage shelf life of the prepared products. The addition of carrot pomace tends to improve the color, physicochemical and bioactive, and sensory properties of cookies, biscuits, wheat rolls, buns, and cake bakery products.[115]

Carrot powder, shreds, and chops dried are used in the manufacturing of curry, halva, and biscuits. Non-alcoholic beverages have been prepared from carrot and their consumption has increased day by day due to the presence of high amounts of α and β-carotene and their health benefits.[1] Various studies have suggested that the incorporation or blending of carrot juice with other fruits and vegetables can increase the nutritional value and acceptability of the prepared final product.[116,117] In another study, a fermented non-dairy beverage was prepared from carrot, resulting in a distinctive flavor and aroma along with ensured microbiological safety and enhanced commercial value.[69]

Carrot pickle is prepared by lactic acid fermentation. The addition of potassium metabisulfite into the carrot pickle led to its preservation in excellent condition for 6 months at room temperature even in a non-air-tight container.[118] Another way for the preservation of carrots by preserving candy by immersing it into sugar syrup has been developed so that the TSS content increases to 70–75 °Brix.[119]

Various types of sweet products are prepared from carrots.[120] In Northern India, carrot halva is one of the famous products and it is prepared using heat treatment (cooking) with sugar and oil or milk fat and milk powder using the frying method.[121] A honey-based carrot candy with different formulations was prepared by Durrani *et al.*[122] In another study, carrot candy was prepared using sugar, coconut powder, and jaggery. In the prepared final product, the beta-carotene content was 11.2–13.2 mg/100 g.[123] Carrot dessert mix was prepared from dried carrot with the addition of other ingredients such as milk powder, coconut powder, powdered sugar, and a small number of dry fruits, which is available in the market as "Kanwal Carrot Dessert" and prepared by mixing with three times water to fully rehydrate the product, following by the addition of clarified butter.[124] The incorporation of carrots (fresh, juices, powder, puree, and extract) serves as a beneficial resource for the enrichment of different types of dairy products including cheeses, ice creams, and yogurts. This supplementation contributes to improving the rheological characteristics, physicochemical and color parameters, and sensorial and quality properties of the final product. Moreover, they are considered potential dairy product stabilizing agents due to their desirable functional properties, such as water binding and holding, gelling, and thickening ability.[125,126] Saldana *et al.*[127] have prepared a carrot-based ready-to-serve beverage by adding carrot juice with other fruit juices or skim milk. In yogurt preparation, the addition of 5–20% carrot juice before the fermentation process enhances the nutritional value and acceptability of the prepared yogurt.[128–130] The fortification of these products with carrots increases the market share due to the high demand for goods for an improved diet, rich in compounds with antioxidant activity and biological properties.[131]

6. Conclusion

In recent years, the demands for dried food products in the market have increased due to their nutritional value and ease of use. Various commercial scale drying techniques are used to process carrots; these drying techniques can all be grouped into distinct groups. Internationally-developed drying techniques include solar drying, tray drying, freeze drying, microwave drying, spray drying, hoover drying, infrared drying, and oven drying. These techniques are faster and more energy-efficient than conventional drying techniques (sun and open air). This current review article represents the initial step in quantitatively assessing the sustainability of different drying technologies. Moreover, various aspects of drying in order to enhance the quality of carrot after the harvesting have been briefly discussed. The drying techniques mentioned above are typically utilized and accepted for processing carrots. However, several important elements that have an impact on the drying of carrots such as product quality, reduction in drying time, energy efficiency, and overall cost-effectiveness, must be taken into consideration. Recent research on carrot drying, employing spray drying and conductive hydro drying methods, indicates that the most favorable approach is drying. Although, this method is costly, it is a time-saving approach. This method achieves high quality while minimizing energy consumption. The selection of a drying method for carrot processing mostly depends on factors such as pre-processing cost, energy efficiency, drying rate, and overall economic viability. However, further studies are needed to optimize these novel drying techniques and their combinations to improve the texture, retention of valuable bioactive compounds, health-promoting properties, and value-added carrot product quality parameters.

Conflicts of interest

The authors declare no competing interests.

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