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Anthocyanin extraction from black carrot: Health promoting properties and potential applications

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ABSTRACT

Anthocyanins are natural flavonoids found abundantly in black carrots posses natural colour to raw material beside renowned multiple biological activities possessing positive effects on health for preventing cardiovascular diseases, inflammation, cancer, etc., have gained considerable attention for their diverse applications in food which are reviewed critically in this study. The review commences with an in-depth comparison of novel anthocyanin extraction techniques such as ultrasound (US), high-pressure processing (HPP), microwave-assisted extraction (MAE), and supercritical fluid extraction (SCFE) from black carrots. The impact of novel extraction techniques with optimized parameters like temperature, vacuum pressure, air velocity with drying time is discussed in detail providing insights into achieving superior anthocyanin preservation compare to traditional solvent extraction and degradation of anthocyanins by traditional drying method. Furthermore study also highlights the impact of various pretreatments with traditional and novel drying techniques such as freeze, microwave, convective and vacuum drying on retention of anthocyanin in black carrot extracts and powders. Beside this role of natural deep eutectic solvents are also highlighted with novel extraction techniques with potential health benefits of black carrot as source of natural pigment possessing various biological activities. So this review offers a systematic scientific basis for holistic understanding of recent advancement in anthocyanin extraction from black carrot with health enhancing properties highlighting the potential industrial applications of anthocyanin rich powders in the food.

1. Introduction

Black carrots (*Daucus carota L.*) are attractive purple-coloured vegetables belonging to the genus *Daucus* and classified under the family Apiaceae. Turkey, Afghanistan, Egypt, Pakistan, and India have traditionally produced this purple-rooted vegetable native to Afghanistan's Himalayan ranges and Hindu Kush mountains [1,2]. According to FAO (FAOSTAT, 2021), the output of carrots (including black ones) increased at a 10.3 % annual growth rate from 40.2 million tonnes in 2015 to 44.8 million tonnes in 2019 [3,4]. This crop is available seasonally [5] in the winter and early spring (October to June) are small to medium, slender with a conical shape of 15–20 cm long and purple with tapering towards the pointed non-steam end.

Black carrots have a high moisture content of 88 % and include 1 % protein, 0.14 % fat, and 2.5 % fibre, besides several essential micro elements such as magnesium (9 mg), calcium (34 mg), potassium (240 mg), phosphorus (25 mg), zinc (0.2 mg) and copper (0.02 mg) per 100 g [6]. Additionally, carrot also contain a significant amount of vitamins including riboflavin (0.02 mg), thiamine (0.04 mg), niacin (0.2 mg) and a notable amount of carotene (5.33 mg) per 100 g [7,8]. Further it has been found to include various bioactive substances such as phenolic components, flavonoids, including phenolic acid and anthocyanins (delphinidin, cyanidin, peonidin, petunidin, pelargonidin and malvidin) [9,10]. The predominant phenolic acid is hydroxycinnamic, an aromatic compound with three carbon side chains and also contains a good amount of chlorogenic acid (from 57 to 72.5 %) [11]. Black carrots

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contain significant amount of water soluble anthocyanins which provide appealing bluish-purple colour and used as a natural food colouring in food and beverages but face various challenges during extraction due to rapid degradation and having less stability owing to their high sensitivity towards heat, pH, and light conditions [2]. Anthocyanins may undergo the degradation process easily when exposed continuously to light conditions and thermal degradation occurs when exposed to high temperature conditions during drying and in traditional extraction process. But acylated anthocyanins which are 6 times higher in black carrot are seems to be highly resistant to hydration owing to more stability at different pH ranges with wider bioavailability [12]. Additionally, compared to non-acylated anthocyanins, acylated anthocyanins have a shorter half-life for gastrointestinal absorption, which offers important information on the kinetics of individual anthocyanins in humans [13]. As a flavonoids in black carrot, the five primary anthocyanin derivatives, cyanidin-3-(2″-xylose-6-glucose-galactoside), cyanidin-3-(2″-xylose-6″-sinapoyl-glucose galactoside), cyanidin-3-(2″-xylose-galactose), cyanidin-3-(2″xylose-6″-(4-coumaroyl)glucose-galactoside), and cyanidin-3-(2″-xylose-6″-feruloyl-glucose-galactoside) have been shown to offer protection against diseases like oxidative stress, cardiovascular disease, certain cancers, and diabetes [12,14]. Anthocyanins as water soluble pigments also possess antioxidant properties, antimicrobial and anti-inflammatory properties to the product. Anthocyanins are developed through the phenylpropane pathway in the cytoplasm and accumulate in vacuoles of plant cells. However the synthesis is largely depend on the environmental factors such as temperature, light, ultraviolet radiation and drought. Black carrots contains higher anthocyanin content up to 350 mg/100 g FW [9,12] which is higher as compared to red cabbage (24 %) and purple carrot extracts (44 %) beside showing a greater degree of COX-2 inhibition [12].

Extraction is a method that involves the separation of bioactive compounds of plant tissue from inactive and undesirable components by using selective solvents and novel extraction techniques. Several extraction techniques, including UAE (ultrasound assisted extraction), SFE (supercritical fluid extraction), HPP (High-pressure processing), and MAE (microwave-assisted extraction), are thoroughly investigated in this review [15–17]. These methods are chosen to optimize efficiency, decrease solvent consumption reduce extraction time, and increase yield using selective solvents. This comprehensive review addresses challenges occurred during extraction of anthocyanin and explore alternative way for extraction and preserving bioactive compounds from black carrots using novel extraction techniques correlating with various health benefits owing to their anthocyanin richness. The primary objective is to delve into innovative extraction techniques for anthocyanin, aiming to overcome the limitation of anthocyanin degradation beside increasing extraction efficiency by utilizing green solvents. The focus of this study is on the development of a shelf-stable anthocyanin powder derived from black carrot extracts for utilization in food and beverage industry. This approach allows for the continuous utilization of black carrot anthocyanins, offering a solution for utilization in wide variety of products and maintaining elevated anthocyanin levels. Additionally, the study investigates the impact of various drying techniques, including freeze drying (FD), microwave drying (MD), spray drying (SD), hot air convective drying (HACD), vacuum convective drying (VCD), and conductive hydro drying (CHD) [4]. The drying technique is crucial in preserving and enhancing black carrot unique properties as source of anthocyanin rich powder for exploration in many food products like bakery, confectionery, beverages, snacks, and dairy [12]. By improving the extraction and drying procedures, the ultimate objective is to close current research gaps and explore the use of black carrot anthocyanins in a wider range of food products, such as dairy, beverages, snacks, and baked goods [12,18].

There is a significant lack of thorough comparisons across various extraction methods taking all in consideration as solvent extraction, enzyme-assisted extraction, and microwave-assisted extraction, in terms of their effectiveness, yield, and sustainability. The health advantages of black carrot anthocyanins have been proven, but there is a little knowledge on their bioavailability in humans following consumption, including the factors that influence absorption, metabolism, and distribution in tissues. More investigation is required for understanding the precise processes by which black carrot anthocyanins contribute to their health-enhancing effects, including their antioxidant activity, anti-inflammatory capabilities, and potential influence on metabolic pathways. Based on this the objective of the review is to provide a thorough analysis of the existing knowledge on black carrot anthocyanins, with a focus on their health advantages, innovative extraction methods, and prospective applications in industry.

2. Health benefits of black carrot

Black carrots containing bioactive substances like anthocyanins have been studied for their potential to prevent or treat metabolic syndrome. Studies have shown that anthocyanins possess antioxidant and anti-inflammatory properties, which can be beneficial. These compounds may also reduce blood pressure and improve insulin sensitivity, both critical factors in the risk of metabolic syndrome. The bioactive components found in purple carrots offer protection against various diseases, including cancer, CVD (cardiovascular disease), diabetes, and obesity [12]. Carrots, as a whole, play a vital role in supplying essential fiber and nutrients to the body, contributing to proper digestion [19]. Anthocyanins with phenolic acids have been proven to reduce animal metabolic changes and inflammation by reducing inflammatory markers. Additionally, plant extracts can produce polyacetylenes, which have shown anti-cancer and anti-inflammatory effects *in vitro* tests. They also exhibit similar anti-fungal, anti-inflammatory, and anticoagulant activities. The various health benefits of black carrot are presented in Fig. 1.

2.1. Anti-cancer

Anthocyanins in black carrots have been found to possess anti-cancer properties, leading to cancer cell death and inhibiting tumor development and spread in animal tests. Moreover, the antioxidant properties of black carrots could have a preventive impact on certain cancers, such as breast and colon cancer [20]. The lyophilized aqueous black carrot anthocyanins powder, administered at doses ranged from 0.0 to 2.0 mg/mL, demonstrated a dose-dependent inhibition of HT-29 and HL-60 cancer cells. Notably, it achieved an 80 % inhibition at the highest concentration of 2.0 mg/ml [12,13,21]. Similarly, ethanol extracts of anthocyanins were assessed for their effectiveness against various human cancer cell lines, including breast adenocarcinomas (SK-BR-3, MCF-7, MDA-MB-231), prostate adenocarcinoma (PC-3), colon adenocarcinoma (HT-29), musculus neuroblastoma (Neuro A), and MDA-MB-231 (breast adenocarcinomas) [20]. Purple carrot compounds, particularly cyanidin 3-xylosyl galactosidase, have demonstrated successful inhibition of key enzymes involved in glucose metabolism, such as α-glucosidase, α-amylase, and dipeptidyl peptidase [22]. Additionally, acylated anthocyanins in black carrots exhibited a more pronounced inhibitory effect than anthocyanin-3-glycosides, emphasizing their potential impact on glucose regulation.

The consumption of phenolic compounds has been linked to positive health effects, partly because of their antioxidant activity and consequent anti-ageing, anti-inflammatory, and antiproliferative properties [22]. For instance, a crude phenolic extract derived from black carrot concentrate exhibited robust radical scavenging activity, measuring over 125 μM Trolox Eq/g DW, surpassing or equalling the antioxidant activity of selected fresh fruits like cherries (55 μM Trolox Eq/g DW) or polyphenol-rich berries like strawberries, raspberries, and blueberries (85–120 μM Trolox Eq/g DW), which are known for their health-promoting properties [23]. The scientific literature reveals that phenolic compounds, including cyanidin-3-glucoside, cyanidin-3-galactoside, and cyanidin-3-arabinoside, possess significant potential to hinder the growth of colorectal carcinoma (Caco-2) cells [19]. This

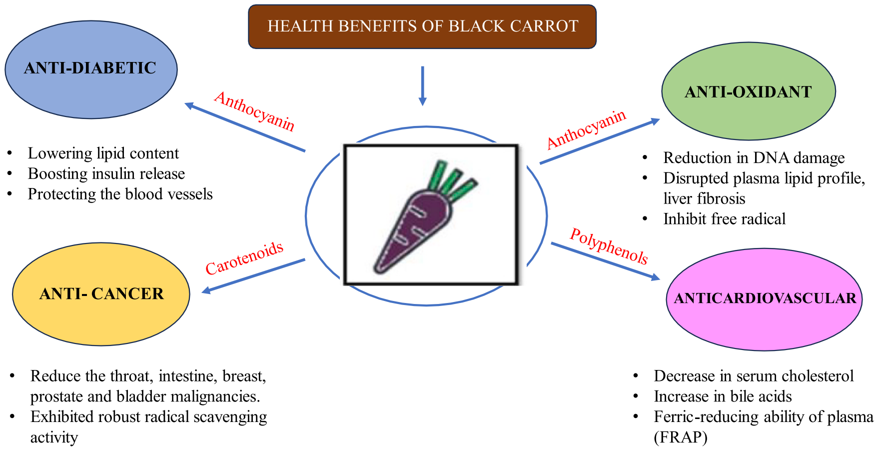

Fig. 1. Health benefits of black carrot due to presence of anthocyanins, carotenoids, polyphenols and bioactive compounds.

inhibitory impact is directly linked to compound concentration, emphasizing their dose-dependent anti-proliferative qualities in colorectal cancer research. These discoveries promise to advance therapeutic strategies in addressing this malignancy [12].

2.2. Anti-cardiovascular

Cardiovascular diseases are becoming more prevalent in both developed and developing countries, with estimates predicting that by 2030, roughly 23.6 million people will pass away from them. Black carrots are a possible source of fibre as well as polyphenols, and because of their bioactive components, which can bind molecules like cholesterol and glucose and reduce their availability in the body, eating black carrots has been associated with a lowered risk of CVD (cardiovascular illnesses) [24]. Additionally, dietary fibre lowers blood levels of low-density lipoprotein (LDL), and short-chain fatty acids intestinal bacteria make. Through the suppression of 3-hydroxy-3-methylglutaryl-coenzyme A (HMG-CoA) reductase, fibre ingestion has also been associated with decreased liver cholesterol production. Other characteristics of black carrot bioactive chemicals that help prevent CVD include activation of lymphocytes, inhibition of cell proliferation, anti-inflammatory activities, lowering body mass index, and lowering blood pressure and lipid levels. Black carrots, containing anthocyanins, phenolic acids, and carotenoids, exhibit potential in combating metabolic syndromes and reducing cardiovascular disease risk. Additionally, a black carrot diet is associated with increased levels of vitamin E, faecal steroids, and ferric-reducing ability of plasma (FRAP) [12]. Additionally, black carrot polyphenols have shown promise in addressing various metabolic syndromes like hypertension and cardiac dysfunction [12]. By lowering blood cholesterol and glucose levels, the bioactive components in black carrots have also been shown to reduce the risk of cardiovascular disease. In addition, by inhibiting 3-hydroxy-3-methylglutaryl--coenzyme, cholesterol formation in the liver is lowered [22]. In numerous studies, it has been noted that polyphenol-rich black carrot extracts, including those from its peel and pomace, efficiently attenuate the secretion of pro-inflammatory markers such as monocyte chemoattractant protein-1 (MCP-1), interleukin-8 (IL-8), intercellular adhesion molecule-1 (ICAM-1), and vascular endothelial growth factor (VEGF). These observations highlight their potential to alleviate inflammation under both normal conditions and in TNF-α-induced inflammatory situations, suggesting their value as natural anti-inflammatory agents [12].

2.3. Antioxidant

Anthocyanin in black carrots has been demonstrated to have a greater antioxidant capacity than traditional antioxidants, such as BHA (butylated hydroxyl anisole), BHT (butylated hydroxyl toluene), and alpha-tocopherol. It was suggested that these pigments might prevent lipid per-oxidation and auto-oxidation in biological systems [25]. The potent antioxidant properties found in the anthocyanin pigment of black carrots offer protective benefits against a range of physiological challenges in humans. Acylated anthocyanins in black carrots play a role in reducing LDL levels and elevating HDL levels. Likewise, these components have demonstrated antioxidative and rejuvenating effects in counteracting issues like impaired glucose tolerance, disrupted plasma lipid profile, liver fibrosis, and heightened plasma liver enzymes in rats subjected to high carbohydrate and fat diets [12]. This indicates the therapeutic potential of black carrot polyphenols in addressing cardiovascular disease [12]. A reduction in DNA damage caused by oxidative stress in colon mucosa cells treated with digested purple carrot extract suggests that colonic cells are protected from oxidative stress by anthocyanin rich extract from purple carrots [26]. Purple carrots showed significant antioxidant activity and decreased inflammation.

2.4. Anti-diabetic

Insulin resistance pertains to a process wherein the pancreatic β-cells face impediments in generating sufficient insulin to counterbalance peripheral insulin resistance. This condition predominantly denotes a state where insulin fails to stimulate glucose transportation in skeletal muscles and adipose tissue adequately. Likewise, it indicates an insufficient ability of insulin to suppress hepatic glucose production effectively. This phenomenon underscores a pivotal aspect in developing metabolic disorders, particularly those associated with glucose metabolism. It underscores a crucial interplay between insulin secretion and its responsiveness in target tissues. Essentially, insulin resistance results in a diminished capacity of cells to effectively utilize glucose, leading to elevated blood glucose levels. This intricately woven mechanism is pivotal in understanding the pathophysiology of conditions like type 2 diabetes and provides a basis for therapeutic interventions targeting insulin sensitivity. Anthocyanins, such as cyanidin, delphinidin, and petunidin, show promise in improving chronic metabolic conditions. This is due to their unique structure in ring B, which triggers apoptosis. It is reviewed that increased oxidative stress is a critical factor in high post-meal blood sugar in diabetes, as well as in vascular complications. Anthocyanins are believed to play a role in preventing diabetes by lowering lipids, boosting insulin release, and protecting blood vessels. Carrot-derived anthocyanin and anthocyanidin-derived compounds efficiently inhibit COX-2 enzymes and stimulate insulin release from pancreatic cells. They also inhibit alpha-glucosidase, reducing post-meal blood sugar. This research highlights the potential of anthocyanins in managing metabolic disorders and diabetes [12]. Cy3G demonstrates the capacity to effectively decrease blood glucose levels and enhance insulin sensitivity in live subjects by mitigating inflammation at both cellular and biochemical levels. This includes the reduction of inflammatory cytokines and an increase in adiponectin production in both white adipose tissue and the bloodstream of diabetic mice. These outcomes are associated with the inhibition of the JNK/FoxO1 pathway. Interestingly, Cy3G treatment also results in the upregulation of genes like C/EBPα and GLUT4 and the expression of insulin receptor proteins, which are critical elements in facilitating insulin-mediated glucose uptake [27].

3. Novel extraction techniques of anthocyanin

The Nutritional content of fresh black carrot roots is presented in Table 1 which reveals the higher content of anthocyanin. Extraction is one of the important step used to separate the anthocyanins from black carrot [28] which will be dependent on factors like the extraction method used, raw material, temperature, type and polarity of solvent used. Traditional extraction techniques like heat reflux, maceration, and soxhlet are proven ways to extract bioactive substances from materials with large quantity of solvent at high temperature conditions which is usually carrying drawback for extraction of heat sensitive component like anthocyanins. So achieving optimal extraction of anthocyanins from plant tissues necessitates a method that balances product quality, process efficiency, cost-effectiveness, and environmental considerations [29]. HPP, UAE, and SF are among the novel extraction techniques the food industry is investigating aligning with the increasing need for eco-friendly substitutes that do not use harmful chemicals [30]. These emerging technologies enhance extractability, resulting in higher extraction rates, reduced impurities, preservation of thermo-sensitive compounds, lower energy consumption, and utilization of different ecofriendly solvents [29]. In contrast to non-enzymatic approaches, previous research on enzyme-assisted extraction (EAE) demonstrated superior recovery, accelerated extraction, decreased energy consumption, and minimized solvent usage. The micellar composition of cell walls and membranes, predominantly macromolecules like proteins and polysaccharides, was vital in optimizing EAE efficiency. Addressing challenges related to protein denaturation and coagulation at elevated temperatures was a crucial focus in refining the extraction of natural products [31]. This review studies various extraction techniques for anthocyanin extraction from black carrots.

Various optimization strategies have been employed to enhance the extraction efficiency of bioactive compounds, particularly anthocyanins, from black carrots. Usman et al. [38] investigated the use of PEF (pulsed electric field) pre-treatment for improved anthocyanin recovery from black carrot pomace. They found that PEF conditions of 20 kV/cm for 100 μs, with a specific energy input of 10 kJ/kg, significantly enhanced the extraction efficiency by disrupting cell membranes and facilitating mass transfer. Additionally, enzyme-assisted extraction has shown promise, with Lee et al. [39] demonstrating that a combination of cellulase and pectinase enzymes resulted in the highest anthocyanin yield due to the synergistic breakdown of cellulosic and pectin structures. Sun et al. [9] (2016) investigated enzyme-assisted extraction using pectinase and cellulase, reporting improved yields with a synergistic effect of the two enzymes. Roohinejad et al. [40] explored PEF (pulsed electric field) pre-treatment, demonstrating enhanced extraction efficiency with PEF conditions of 25 kV/cm for 100 μs. Zhu et al. [41] combined PEF and ultrasound, achieving improved yields compared to individual treatments. Tena et al. [42] optimized pressurized liquid extraction, identifying optimal conditions of 60 % ethanol, 150 °C, and 10 min extraction time. The nutritional content of fresh black carrot

Table 1
Nutritional composition of black carrot root.

Parameters	Components	Concentration	References
Energy (Kcal/100 g)	–	43	[1,32,33,34]
Moisture content (%)	–	88.20	
	–	16.40–92.0	
Carbohydrate (g/100 g)	Glucose	0.69–1.85	
	Fructose	0.14–0.58	
	Sucrose	4.11	
Fibre (%)	Total dietary	2.61	
	Water insoluble	1.65	
	Water soluble	0.97	
	Fibre	2.50	
Protein (%)	–	1.00–1.14	
Fat (%)	–	0.14–0.94	
Vitamin B (mg/100 g)	Thiamine	0.032–0.04	
	Riboflavin	0.02–0.035	
	Niacin	0.20–1.308	
	Vitamin B_6	0.079	
Minerals (mg/100 g)	Iron	0.40–0.28	
	Phosphorus	25.0–38.0	
	Calcium	34–60.45	
	Magnesium	9.0–18.0	
	Potassium	240–421.2	
	Sodium	40.0–86.0	
	Zinc	0.2–0.17	
	Copper	0.02	
Ash (%)	–	0.92–12.40	
Total soluble solids (°Brix)	–	8.6–9.46	[1]
Reducing sugar (%)	–	0.96–3.09	
Total sugar (%)	–	0.48–5.28	
Carotenoids	α-carotene (μg/100 g)	21.87–8725	[7,10,35,34,36]
	β-carotene (μg/100 g)	60.38–16130	
	Lutein (μg/g dry weight (DW)	57.58	
	Carotenoids (mg/100 g)	0.66–19.5	
	Total Carotenoids (μg/g) (DW)	139.83	
Volatile compound (ppm)	α-pinene	0.017	[34]
	Cis-ocimene	0.013	
	Camphene	0.002	
	Sabinene	0.001	
	β-pinene	0.043	
	Myrcene	0.494	
	α-phellandrene	0.066	
	α-terpinene	0.002	
	p-cymene	0.017	
	Limonene	0.066	
	Trans-ocimene	0.001	
	Gamma-terpinene	0.056	
	Terpinolene	0.810	
	2,5-dimethyl styrene	0.012	
	Undecane	0.004	
	β –caryophyllene	1.025	
	Trans- α –bergamotene	0.010	
	α –humulene	0.052	
	Cis-β-farnesene	0.008	
	β –bisabolene	0.007	
	Gamma-bisabolene	0.245	
Ascorbic acid (mg/100 g)	–	2.8–4.5	[1]
Anthocyanins (*m/z*)	(mg/kg FW)	175	[1,4,7,12,37]
	(mg/100 g FW)	1.5–350	
	Cyanidin 3-xylosyl glucosyl galactoside	743	
	Cyanidin 3-xylosyl glucoside	581	
	Sinapic acid derivative of Cyanidin3-xylosyl glucosyl galactoside	949	
	Ferulic acid derivative of Cyanidin 3-xylosyl glucosyl galactoside	919	

(*continued on next page*)

Table 1 (*continued*)

Parameters	Components	Concentration	References
	Coumaric acid derivative of Cyanidin 3-xylosyl glucosyl galactoside	889	
	Peonidin 3-xylosyl glucosyl galactoside	757	
	Ferulic acid derivative of pelargonidin 3-xylosyl glucosyl galactoside	903	
	Ferulic acid derivative of peonidin 3-xylosyl glucosyl galactoside	933	
	Cyanidin 3-xylosyl (glucosyl) galactoside (mg K Eq/g DW)	0.97	
	Cyaniding 3-xylosyl galactoside (mg K Eq/g DW)	3.28	
	Sinapic acid derivative of cyanidin 3-xylosyl (glucosyl) galactoside (mg K Eq/g DW)	0.37	
	Ferulic acid derivative of cyanidin 3-xylosyl (glucosyl) galactoside (mg K Eq/g DW)	7.69	
	Coumaric acid derivative of cyanidin 3-xylosyl (glucosyl) galactoside (mg K Eq/g DW)	1.52	
	Cyanidin 3-O-103 glucoside equivalent per g of dry material (mg/g DW)	1543	
Total phenolics compounds (mg/100 g)	3′-caffeoylquinic acid	0.88	[1,7,35,36,37]
	cis-3′-caffeoylquinic acid	1.94	
	5′-caffeoylquinic acid	54.08	
	caffeic acid	2.42	
	3′-p-coumaroylquinic acid	0.91	
	3′-feruloyl quinic acid	7.30	
	3′,4′-dicaffeoylquinic acid	2.78	
	5′-feruloyl quinic acid	0.96	
	cis-5′-caffeoylquinic acid	0.49	
	5′-p-coumaroylquinic acid	0.74	
	3′,5′-dicaffeoylquinic acid	0.44	
	3′,4′-diferuloylquinic acid	0.53	
	3′,5′-diferuloylquinic acid	1.17	
	(mg/100 g)	102	
	(mg GAE/100 g FW)	268.1	
	Polyphenols (mg/g DW)	16.6	
	Total flavonoids (mg CE/100 g FW)	118.9	
Chlorogenic acid	(%)	72.5	[1,7,10,12,34]
	(mg/100 g)	54.1	
	(mg/kg)	657	
Antioxidant activities	(μM TE/100 g FW)	17.6–240	[1,7,35,36,37]
	FRAP activity (μmol TE/g FW)	43.98	
	CUPRAC activity (μmol TE/g FW)	66.30	
	ABTS activity (μmol TE/g FW)	55.86	

roots is presented in Fig. 2.

3.1. Ultrasound-assisted extraction

Ultrasound, denoting sound waves beyond the audible range for humans (above 20 kHz), finds diverse applications in food science. Its utilization, known as ultrasonication, is recognized as an environmentally sustainable and green unique technology due to its positive impact on industries. It uses the movement of particles in the medium to propagate sound waves which operates between 20 and 100 kHz in frequency and between 10 and 1000 W/cm^2 in power density [43,44]. The mechanism of ultrasonic-assisted extraction of black carrot presented in Fig. 3. This vibrational energy is applicable to liquids, dispersions, solids, and gaseous media and is produced by ultrasonic transducers. In comparison to traditional approaches, ultrasound-assisted extraction produces higher yields by combining ultrasonic power with solvents to extract specific bioactive compounds from plant biomass. The mechanism behind this extraction lies in acoustic cavitation, where ultrasonic waves dislodge molecules, creating cavitation bubbles that collapse during the compression phase, forming hot spots. Ultrasound's impact on temperature, noise, and material contact influences output data in instrumentation [43].

In a study, three extraction methods CSLE (conventional solid–liquid extraction), UAE, and MAE—were evaluated. The findings indicated that UAE at a solvent–liquid ratio of 1:30 proved to be the most efficient technique for extracting anthocyanin from black carrots, yielding higher amounts compared to both CSLE and MAE [45]. In their study, three replicates of a 10 g sample of black carrot were extracted using different solvents: 10-ml MeOH(methanol 95 %), 10 ml EtOH(ethanol 98 %), 10-ml acetone (70 % in water), and 10-ml distilled water. Lastly, the total anthocyanin content in the extract was determined by the pH method, and the extraction they obtained was 18.27 (WA) and 383.05 (EtOH) [46,47]. In another study utilizing an ultrasound technique, the process involved creating a granulated black carrot, mixing it with ethanol, and placing it directly into an ultrasound device. This ultrasound device was equipped with power adjustment, a temperature controller, and a digital timer [48]. Finally, after the extraction process, the extract was centrifuged at 4000 rpm for 5 min, similar to the previous step, and stored at 4 °C. The resulting extracted anthocyanin yield was 91.64 mg/L, achieved at 40 °C for 20 min [48]. In another study, the authors used ultrasound-assisted extraction in which the 200 mg fresh and nitrogen-ground black carrot was mixed with a solvent water and formic acid (95/5 v/v), methanol and formic acid (95/5, v/v). They probe-sonication for the 20 s at 75 % amplitude using ultrasound homogenizer sonopuls UW 3100 armed with microtip MS72 [49]. Next, they centrifugated ($3112\times g$ for 4 min) after extraction. The supernatant was separated, and the resulting extract was consolidated before being filtered through a cellulose membrane with a pore size of 0.45 μm. Later, they separated anthocyanin by UHPLC-PDA method, and they found that in the fresh variety, total anthocyanin content was 19.86 g/kg, and in nitrogen ground black carrot, entire anthocyanin content was 11.45 g/kg. In one of the studies, the researchers used thermo-sonication extraction techniques to extract anthocyanin from the black carrot pomace. The extraction processing conditions used were temperature (50 °C), energy density 183.10 J/g, power 102.4 W at frequency 24 kHz, and the amount of anthocyanin extracted was 34.20 mg/L. Jha and Sit [29] optimized the UAE extraction of anthocyanins using RSM (response surface methodology), identifying optimal conditions of 40 % ethanol, 60 °C temperature, and 30 min sonication time. They reported a 2.3 fold increase in anthocyanin yield compared to conventional solvent extraction. Pala et al. [48] optimized ultrasound-assisted extraction, finding that 50 % ethanol, 60 °C, and 30 min sonication time yielded the highest anthocyanin content. Mehta et al. [43] employed RSM (response surface methodology) to optimize ultrasound-assisted extraction of anthocyanins, identifying optimal conditions of 70 % ethanol, 60 °C, and 5 min extraction time.

3.2. Microwave-assisted extraction (MAE)

MAE harnesses microwave energy to increase the solvent temperature, facilitating the efficient extraction of target compounds from plant matrices [50]. This method leverages non-ionizing electromagnetic waves within a specific frequency range, commonly employing 2450 MHz in domestic microwave ovens. The mechanism of microwave-assisted extraction of black carrot presented in Fig. 4. MAE's application involves breaking down cell walls through molecular dipole rotation, enhancing the extraction process. Microwave energy is applied directly to materials by interacting with the electromagnetic field. Electromagnetic waves penetrate the material, engaging with molecules and converting the energy into heat [9]. This interaction attenuates the

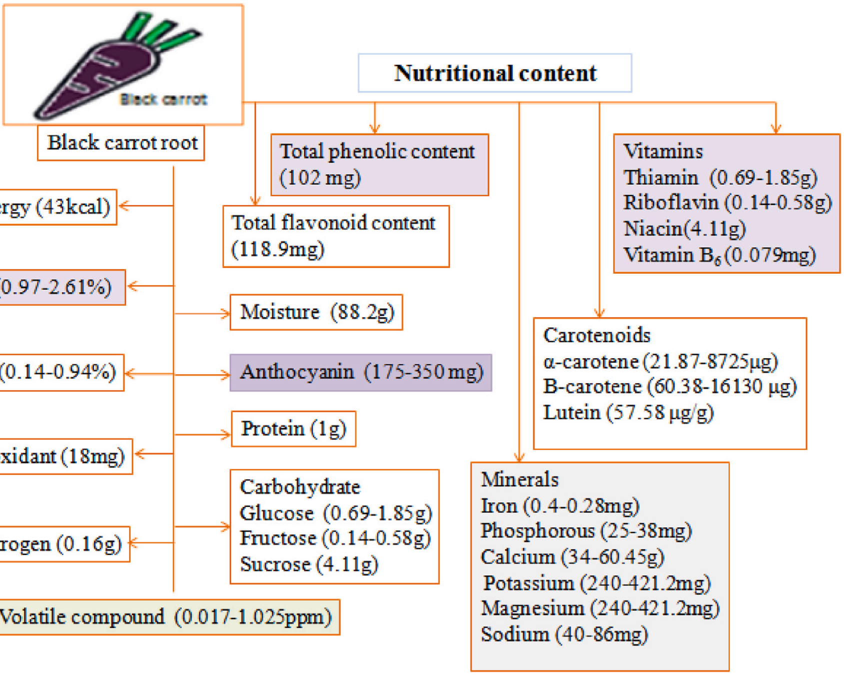

Fig. 2. Nutritional composition, bioactive compounds, vitamins and minerals present in black carrot.

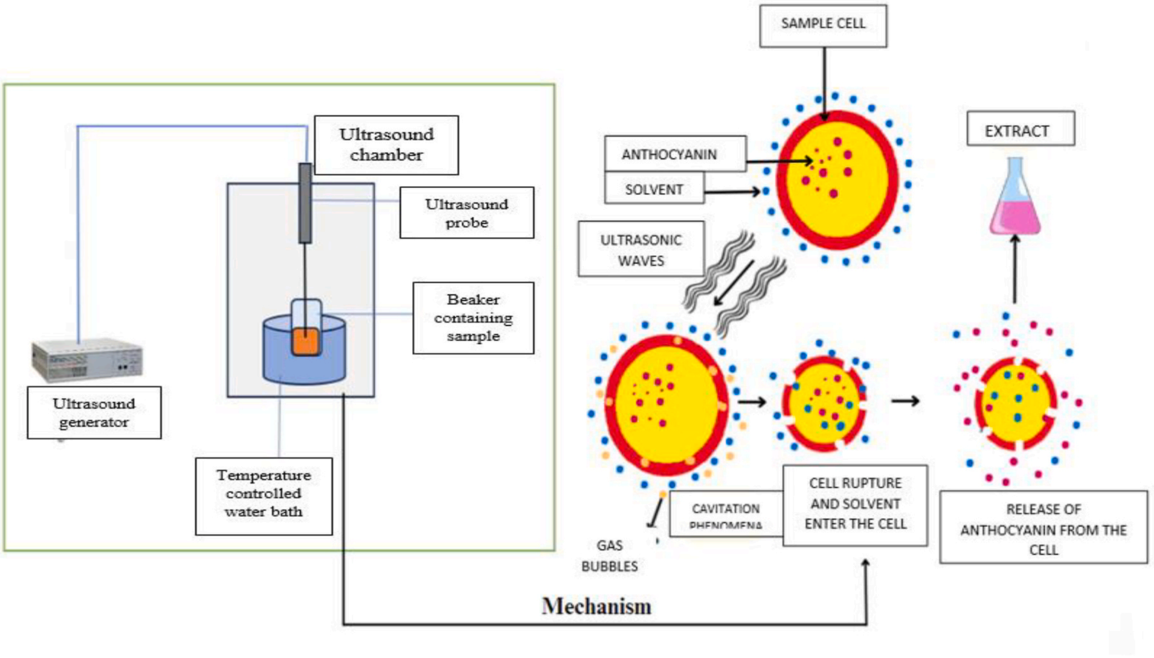

Fig. 3. Mechanism of ultrasonic-assisted extraction of black carrot.

microwave field amplitude as distance increases from the material's surface. The primary mechanisms for converting microwave energy into heat in dielectric materials involve dipolar rotation and ionic conduction. Dielectric properties quantify the absorption and transmission of microwave energy in materials, providing insights into their response and heating rates in microwave electric fields. Understanding these properties is crucial for predicting material behaviour and designing practical microwave reactors [51].

In one of the studies, they first weighed the sample, mixed it with ethanol before microwave treatment, and centrifuged the sample at 4000 rpm. The power of the microwave used was 500 W, and lastly, the extraction of anthocyanin was maintained at a temperature of 4 °C, and they got a yield of 95.81 mg/L obtained at 60 °C for 9 min [48,52]. Kumar et al. [53] extracted the anthocyann content from black carrot using microwave assisted extraction for maximum recovery of anthocyanins with 348.07 W microwave power, 9.8 min extraction time, 19.3 mL/g of solvent–solid ratio with ethanol concentration of 19.80 % and reported the maximum recovery of total anthocyanin content at optimized condition as 753.40 ± 31.6 mg/L.

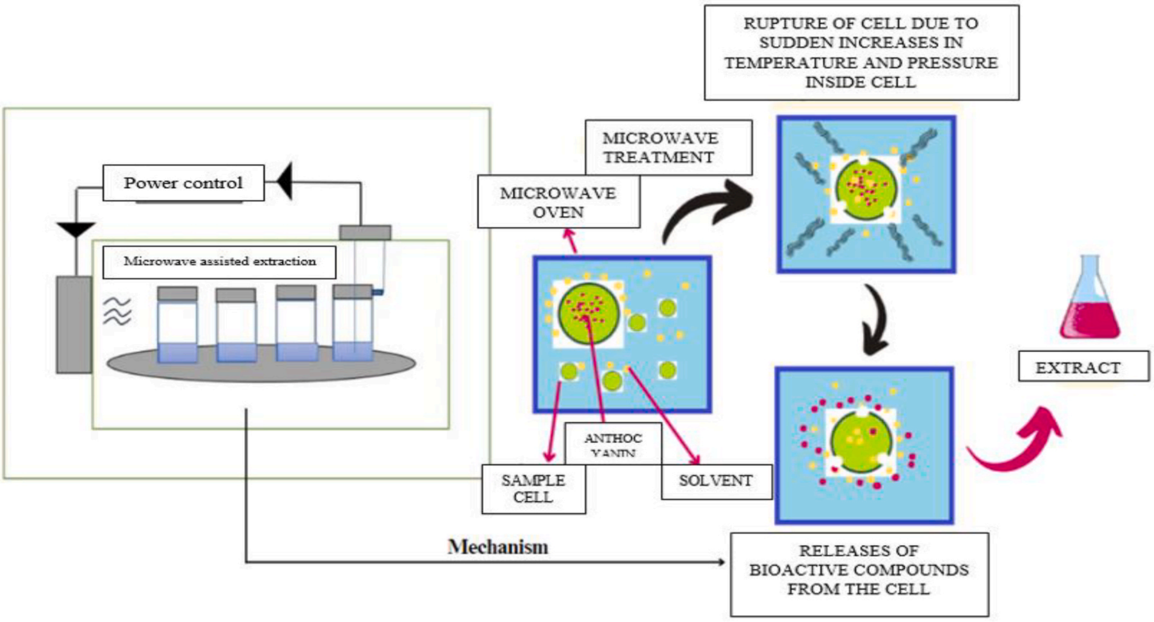

Fig. 4. Microwave-assisted extraction mechanism of black carrot.

3.3. *High pressure processing*

HPP (High-pressure processing) is utilized to preserve food where traditional heat pasteurization may compromise product quality. The application involves inducing pressure-induced changes in molecular configuration and chemical reactions, reducing volume. This volume decrease is accentuated by the uniformly applied isostatic pressure within the pressure vessel system, preventing food from getting squashed. A pressure vessel, pressure-vessel fluid, a pressure-handling system, and auxiliary equipment like heating with cooling components are the main parts of an HPP system. A pressure-transmitting media is placed within the pressure vessel and sealed after loading. Automatic deaeration valves eliminate air from the boat using a low-pressure fast-fill and drain pump [40]. Finally, direct or indirect compression of the pressure medium or heating of the pressure medium produces tremendous hydrostatic pressure [54]. The mechanism of high-pressure extraction of black carrot presented in Fig. 5.

In one of the studies, the extraction of anthocyanin with other bioactive compounds of black carrot took place by using high-pressure processing in which a temperature of 78.3 °C was applied at a pressure of 266.6 MPa for 13.6 min. They extracted total monomeric anthocyanin at 105.7 mg/L, with bioactive compounds up to 41.90 per cent [55]. In another study, the researchers used the high pressure assisted extraction for the recovery of anthocyanins from black carrot pomace. They used 600 MPa for 15 min and they resulted about 28.74 mg/g anthocyanin [55]. Zhu et al. [41] also used the high pressure processing at 600 MPa for 10 min and extracted 97.60 mg/100 g of anthocyanin from the extracted black carrot juice from fresh black

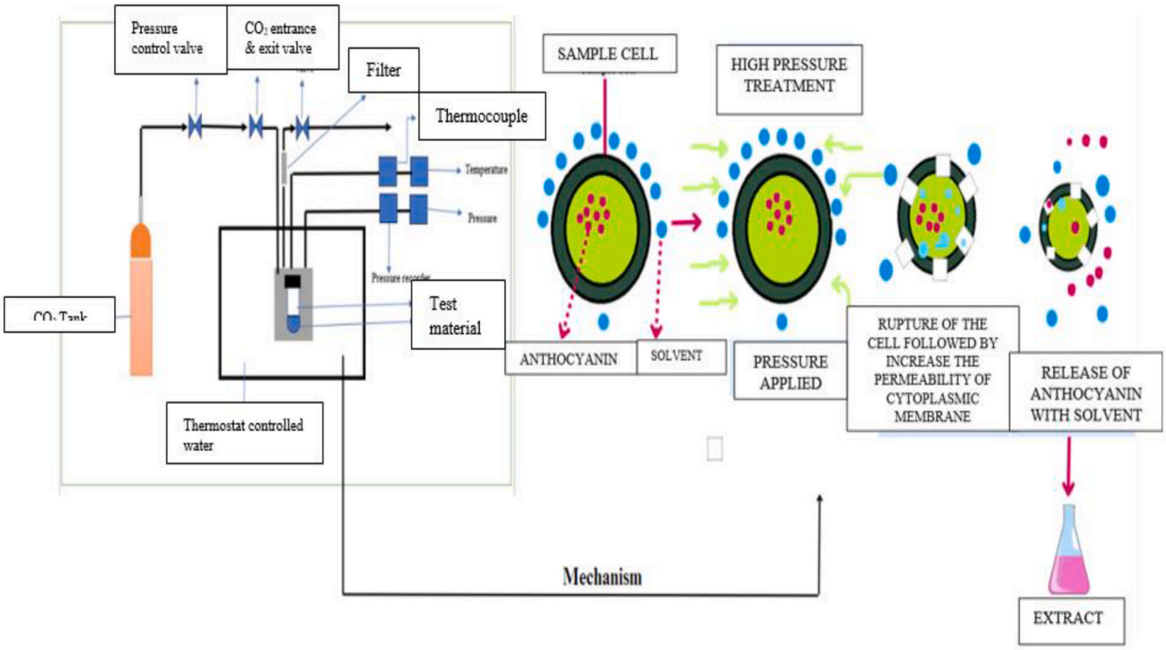

Fig. 5. Mechanism of High-pressure processing extraction of black carrot.

carrot root.

3.4. Supercritical fluid extraction technique

Supercritical Fluid Extraction (SFE) has gained widespread use due to its reputation as an environmentally friendly technology. Employing supercritical CO_2 as the solvent, SFE benefits from its non-toxic nature, cost-effectiveness, resistance to atmospheric oxidation, and moderate critical temperature (CT) of 31.3 °C and critical pressure (CP) of 72.9 atm. The non-polar nature of CO_2 is addressed by incorporating co-solvents, such as methanolor ethanol, in concentrations ranging from 1 % to 15 %, especially for extracting polar compounds like anthocyanins. SFE and Pressurized Liquid Extraction (PLE) commonly operate at medium-to-high pressures. However, SFE utilizes SF properties to extract the target compound [56]. The process comprises two key stages: initial extraction by the supercritical fluid followed by rapid fluid removal through pressure and temperature changes. The extraction involves static and dynamic periods, ensuring continuous contact between the solvent and the solid matrix [15]. The mechanism of supercritical fluid extraction of black carrot presented in Fig. 6.

In one of the studies, they used solvent fluid extraction techniques in which the solvent apparatus contained the ethanol and set it with the determined time. Lastly, a similar procedure was followed for centrifugation. At last, they analyzed the anthocyanin content in the extract by using the UPLC technique, and in the solvent extraction technique, the highest yield (92.14 mg/L) was obtained at 40 °C for 2 min [48]. In another study, the researchers used SFE with supercritical CO_2 at 45 °C with 35 MPa pressure and 10 % ethanol as a co-solvent with optimized extraction time of 120 min. The optimized SFE conditions resulted in an anthocyanin yield of 8.92 mg cyanidin-3-glucoside equivalents per gram of dry weight (mg C3GE/g DW) [57]. Nayak et al. [58] used SFE with supercritical CO2 at 50 °C, 30 MPa, and 5 % ethanol as a co-solvent. The extraction time was set at 90 min. The optimized SFE conditions yielded 11.6 mg cyanidin-3-glucoside equivalents per gram of dry weight (mg C3GE/g DW) of anthocyanins. Ribeiro et al. [59] reported enhanced anthocyanin recovery using supercritical fluid extraction with optimized parameters of 40 °C, 300 bar, and 20 % ethanol as a co-solvent.

3.5. Deep eutectic solvents for extraction

In recent years, DES (deep eutectic solvents) are emerging as promising green alternatives to conventional organic solvents for the extraction of specific bioactive components from natural sources, including black carrots. Ribeiro et al. [59] explored the potential of various DES systems, such as choline chloride-based and betaine-based solvents, for the extraction of anthocyanins from black carrot pomace. Their findings revealed that the DES composed of choline chloride and lactic acid exhibited the highest extraction efficiency, yielding an anthocyanin content of 15.20 mg cyanidin-3-glucoside equivalents (mg C3GE/g DW). The authors attributed this superior performance to the DES's ability to disrupt the plant cell wall and facilitate the mass transfer of anthocyanins. Additionally, Martins et al. [60] investigated the use of DES in combination with UAE for the recovery of anthocyanins from black carrots. They reported that the DES consisting of choline chloride and glycerol, coupled with ultrasonic treatment, resulted in an anthocyanin yield of 18.60 mg C3GE/g DW, demonstrating the synergistic effect of DES and ultrasound in enhancing the extraction efficiency. Furthermore, Araya-Quintanilla et al. [61] explored the application of NADES (natural deep eutectic solvents) for the extraction of anthocyanins from black carrot peels. They identified a NADES system composed of glucose and fructose as an effective solvent, yielding an anthocyanin content of 12.80 mg C3GE/g DW.

4. Factors influencing extraction efficiency

Several factors play a critical role in influencing the extraction efficiency of anthocyanins from black carrots. Optimization of the extraction process parameters efficiently maximizes the amount of anthocyanins recovery from black carrot for industrial applications in food and beverages which over time also highlighted in many studies using different extraction methods. Recent studies have highlighted the importance of optimizing process parameters to maximize the yield and quality of extracted anthocyanins. Various studies collectively highlight the importance of carefully selecting and optimizing extraction parameters, such as pressure, temperature, co-solvent concentration and type, extraction time, and the choice of extraction technique, to achieve maximum anthocyanin yield and quality without degradation from black carrot. For instance, Yıldız and Bozkurt [57] demonstrated that temperature (30–40 °C), pressure (200–400 bars), and the presence of a co-solvent (50 % ethanol:50 % water) significantly influenced the anthocyanin yield during supercritical CO_2 extraction. Similarly, Nayak et al. [58] observed that the co-solvent concentration and extraction

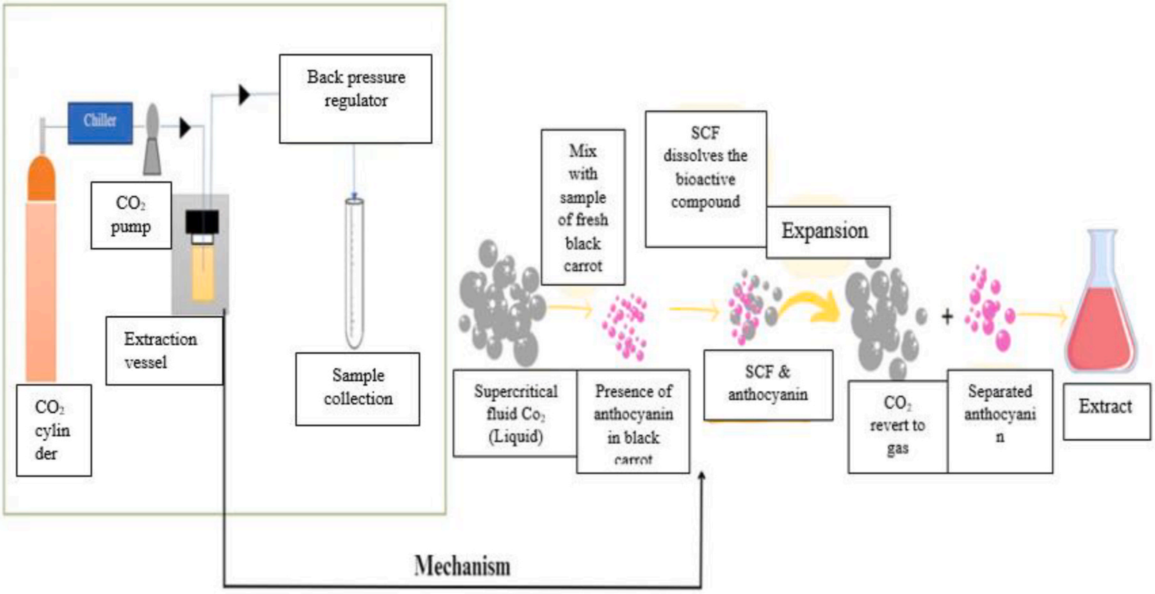

Fig. 6. Mechanism of supercritical fluid extraction technique in black carrot.

time were critical parameters affecting the anthocyanin recovery from black carrots using supercritical fluid extraction. Furthermore, Gomez-Garcia et al. [61] reported that the extraction yield was highly dependent on the temperature and pressure conditions, as well as the duration of the extraction process. Additionally, the choice of extraction technique itself has a substantial impact on the efficiency of anthocyanin recovery. For example, Coman et al. [55] demonstrated that high-pressure assisted extraction (HPAE) yielded significantly higher anthocyanin content compared to conventional solvent extraction methods. Likewise, Park et al. [62] found that high-pressure homogenization (HPH) enhanced the extraction of anthocyanins from black carrots by disrupting the plant cell walls and facilitating mass transfer.

4.1. Influence of solvent type and polarity

The selection of an appropriate solvent system plays a crucial role in the efficient extraction of anthocyanins from black carrots. Recent studies have demonstrated that the solvent's polarity significantly impacts the extraction yield and stability of these valuable pigments. As during extraction of anthocyanin mostly solvent like ethanol, water, methanol incombination with acids are being used widely in most studies to maximize the yield of Anthocyanins in extract. Zhu et al. [41] investigated the influence of various solvent systems, including water, ethanol, and their mixtures, on the extraction of anthocyanins from black carrots. They reported that the binary solvent system comprising 60 % ethanol and 40 % water resulted in the highest anthocyanin yield, attributing this to the optimal polarity for facilitating the mass transfer of these compounds. Similarly, Park et al. [62] examined the effect of different solvent polarities on the extraction of anthocyanins from black carrots using high-pressure homogenization (HPH). Their findings revealed that a moderately polar solvent mixture of ethanol and water (50:50 v/v) outperformed highly polar or non-polar solvents, likely due to the ability of these solvents to effectively solubilize and stabilize the extracted anthocyanins. Furthermore, Gomez-Garcia et al. [61] demonstrated that the addition of a polar co-solvent, such as ethanol, during supercritical CO_2 extraction significantly enhanced the recovery of anthocyanins from black carrot pomace, highlighting the importance of solvent polarity in overcoming the limitations of non-polar supercritical fluids. Furthermore the possible disadvantage of using highly polar solvent likes water alone is lower selectivity towards desirable compound of interest resulting co extraction of other undesirable compounds like sugar or other phenolic components. Thus combination and addition of medium polarity solvent with acid directly affect the rate of extraction of anthocyanins from plant based matrix.

4.2. Impact of pre-treatment methods on extraction efficiency

Black carrots have gained significant attention due to their high content of bioactive compounds, particularly anthocyanins, and several studies have investigated the impact of different pre-treatment methods on the extraction efficiency of these valuable compounds. PashaeiKamali et al. [63] found that UAE extraction significantly improved the extraction efficiency compared to conventional methods, with optimized conditions including a temperature of 40 °C, a solvent concentration of 60 % ethanol, and a sonication time of 30 min. The extraction process is based on acoustic cavitation, in which molecules are moved by ultrasonic waves, resulting in cavitation bubbles that burst during the compression stage and create hot areas. Grajek et al. [64] demonstrated that PEF pre-treatment enhanced the extraction efficiency by disrupting cell membranes, with optimal PEF conditions being 20 kV/cm for 100 μs and a specific energy input of 10 kJ/kg. This can be based upon the mechanism involving exploration of eukaryotic cell membranes to external electric fields, which cause electroporation and increases solute transport. Lee et al. [65] reported that the combined use of cellulase and pectinase resulted in the highest extraction yield due to the synergistic effect of breaking down cellulosic and pectin structures, with optimal conditions involving a pre-treatment with 0.5 % (w/v) cellulase and 0.3 % (w/v) pectinase at 50 °C for 2 h thus facilitating the extraction of anthocyanins. Xu et al. [66] investigated microwave-assisted extraction (MAE) and found that it significantly reduced the extraction time compared to conventional methods, following second-order kinetics and suggesting an endothermic and spontaneous process.

5. Application of black carrot in the food processing

Bioactive substances with potential medical benefits, including volatile chemicals, phenolic compounds, carotenoids, anthocyanins, and chlorogenic acid, are abundant in black carrots [12]. Extraction, drying, and microencapsulation are the novel processing techniques used to preserve and increase the shelf life of black carrot powder. Developing and marketing diverse black carrot products, considering their health benefits, is essential for addressing public nutrient requirements. This is especially important because black carrots are a cheap way to get vitamin A [67]. Black carrots can be made into various fortified and value-added foods to increase their convenience and absorption [24]. This addresses seasonality and perishability challenges and enhances black carrot economic value and market prospects [68]. The various value-added products of black carrot powder and its nutritional quality is presented in Table 2.

5.1. Bakery and confectionary

Bakery and confectionery products remain popular among consumers, offering various traditional favourites and innovative formulations [32]. A study found that incorporating black carrot flour into sponge cake, replacing 6 % wheat flour, yielded the best results with minimal baking losses. The cake's brightness, redness, and yellowness values decreased as the proportion of black carrot flour increased, with 6 % replacement emerging as the optimal percentage level for sensory, antioxidant, and rheological qualities [24,75]. Another research investigation revealed that enhancing cake flour with black carrot pomace powder led to heightened antioxidant activity and elevated levels of phenolic acids, anthocyanins and total phenols [76]. Furthermore, Singh et al. (2016) observed that muffins fortified with black carrot dietary fiber garnered significant approval, attributed to enhanced batter visco-elasticity and paste viscosity stemming from the fiber water-retaining characteristics. Consequently, this reduced water activity, specific volume, firmness, and increased total dietary fiber content. Fortified flatbread with black carrot fiber enhances antioxidant content and visual appeal. These studies underscore the potential of black carrot derivatives in enhancing nutritional and sensory aspects across various bakery products [69]. Black carrot-based jams and marmalades hold promise as abundant reservoirs of polyphenolic compounds. Nonetheless, the processing of these products resulted in a reduction in antioxidant capacity, phenolic acids, and total phenolics. This decrease was linked to the disruption of cell structure during processing, which left carrots vulnerable to non-enzymatic oxidation [76].

5.2. Dairy products

Dairy products are widely consumed by most of the age group population. Fortification of yoghurt and cream buttermilk with bioactive compounds such as polyphenolic compounds and fibre, which can further provide health benefits besides its nutritional value [8,70]. Studies consistently show that incorporating 7.5 per cent black carrot concentrate into dairy products like buttermilk, yoghurt, and ice cream enhances sensory acceptance and boosts their polyphenolic, antioxidant, and mineral content. This results in a significant increase in flavonoid and anthocyanin content, improving the nutraceutical properties of these products [8]. Similar positive effects on antioxidant activity, total phenolics and anthocyanins were observed in yoghurt with added black carrot concentrate, improving colour properties [24,70].

Table 2
Value added products of black carrot powder and its nutritional quality.

Product	Items	Ingredients	Equipment and conditions applied	Product quality/nutritional quality	References
Bakery and confectionary	Black carrot pomace powder flour cake	Eggs, sugar, sunflower oil, yoghurt, Black carrot pomace powder, cake flour, baking powder.	Blender for 3 min, Baking in oven at 180 °C for 30min, grinder.	Anthocyanin-72-267 μg/g DW Total phenolics -54-202 mg GAE/100 g DW Total antioxidant-153- 478 mg TE/100gDW Phenolic acids -49-148 μg/g	[32]
	Eggless gluten-free rice muffins	Rice flour, milk powder, sugar, soya protein isolates, salt, baking powder, refined sunflower oil, glycerol, monostearate, deionised water and xathan gum, black carrot dietary fibre concentrate	Juicer, Cabinet drier at 60 °C for 2 h, pin mixer for 1 min, Baking oven at 170 °C for 22 min.	Sensory property- muffins with the highest sensory scores could be prepared using 6 % Black carrot fibre and 0.5 g Xanthan gum. Muffins were crusts and crumbs in texture, Greyish-purplish colour, specific −1.77 mL/g, height-33.1 mm, Water activity-0.88, Firmness-1.1N, Cohesiveness-0.45, springiness −0.76, gumminess- 0.51,	[11]
	Black carrot fibre-fortified flatbread	Wheat flour, salt, yeast, black carrots	glass blender forced air oven for 24 h at 35 °C, Mill	Total phenolic-788.86–793.12 mg GAE/100 Antioxidant activity-75.26%–76.22 % Sensory characteristic- flavour (5.2), odour (6.5), appearance (6.6)and overall acceptability (6.8), Diameter-152.3 mm, thickness-21.3 mm, spread ratio −7.15 T	[69]
Dairy products	Black carrot concentrateIcecream	Fresh whole milk, whipped cream, sugar, skim milk powder, cornflour and black carrot concentrate	Freezer	Appearance- 8.50 Colour- 8.45 Texture-8.30 Flavour - 8.01 Taste −8.20 Overall acceptability- 8.25	[8]
	Black carrot concentrate yoghurt	Milk, skim milk powder, starter culture (L. delbrukiisubspbulgaricus and S. Thermophile)	Homogenizer, pasteurizer used at 90 °C for 30 min, agitator	Appearance-8, colour-7.80,Consistency-8, Flavour-7.80, taste-7.85 overall acceptability-7.80	[8]
	Black carrot anthocyanin yoghurt	Milk, yoghurt culture (NCDC263), Black carrot concentrate, synthetic colourant erythrosine	Homogenizer at 2000psi, Refrigerator	Total phenolic - 253.26 mg/GAE/kg Total antioxidant - 39.81 Acidity (%LA)- 0.886 pH - 4.52 Brightness-63.54 Redness - 10.33 Yellowness - 2.69 Chroma value-10.67 Hue angle (rad) −0.25 Sensory parameter – Flavour - 40, Body and texture - 26.50, acidity-7.75, Colour and appearance - 7.33, overall acceptability- 86.25	[70]
	Black carrot concentrate buttermilk	Double-toned milk, Bacterial culture NCDC 144 (L. Delbrukiisubspbulgaricus and S. Thermophiles)	Incubaterat 42 °C for 7 h, agitator at 10,000 rpm for 90s, homogeniser	Appearance-8.25, colour −8.35,Consistency-8.35, Flavour-8.20, taste −8.50, overall acceptability- 8.40	[8]
	Black carrot fibre -enriched functional yoghurt	Black carrot pulp, Milk, and mix culture (S. thermophilus, L. delbrueckii subsp. bulgaricus, L. acidophilus and B.animalis subsp. lactis	Pasteurizer at 85–90 for 10 min, freezer at −18 °C	Total anthocyanin-63.66 mg\kg Total phenolic −55.90 mg GAE\100 g Total antioxidantactivity- 45.23 mg Trolox\100 g Total solids- 11.97 % Ash-1.12 % Titrable acidity −1.01 % pH- 4.45 Reduced sugar-4.20 % Brightness −61.59 Redness-11.12 Yellowness −2.95 Firmness-739.86 g Consistency-6902.09 gs cohesiveness-99.40	[71]
Snack products	Potato chips	Fresh potato chips and fresh black carrot	Enzyme viscozyme, Manual slicer, Centrifuge	Anthocyanin - 39.73 mg\kg Total Phenolic −220mg\100 g Antioxidant-3.88 μmolITE\100 g Ascorbic acid - 4.58 mg\100 g Brightness- 18.03 Redness-7.96 Yellowness −0.48	[72]
	Apple chips	Apples, black carrot anthocyanin extract	Spray dryer, Hot air oven, Vacuum drying,	Total anthocyanin −947 %	[73]
Beverage product	Kanji	Black carrot, Common salt, rye, lukewarm water	Fermenter, Autoclave	Phenols-37.07 mg\ml Flavonoids-34.04 mg\ml pH-3.78 Antioxidant-72.78 % Ascorbic acid-80mg\100 ml Total soluble solid-3.2°Brix Total acidity −1.06 % Total sugar-38.84 mg\ml Reducing sugar −26mg\ml	[74]
	Shalgam juice	Shalgam, black carrot, culture	Centrifuge, Fermenter	Soluble solid-3.4 % pH-3.43 Total acidity - 6.38 g Total carbohydrate-0.29 g\L Fructose-0.006 g\L Sucrose-0.01 g\L	[19]

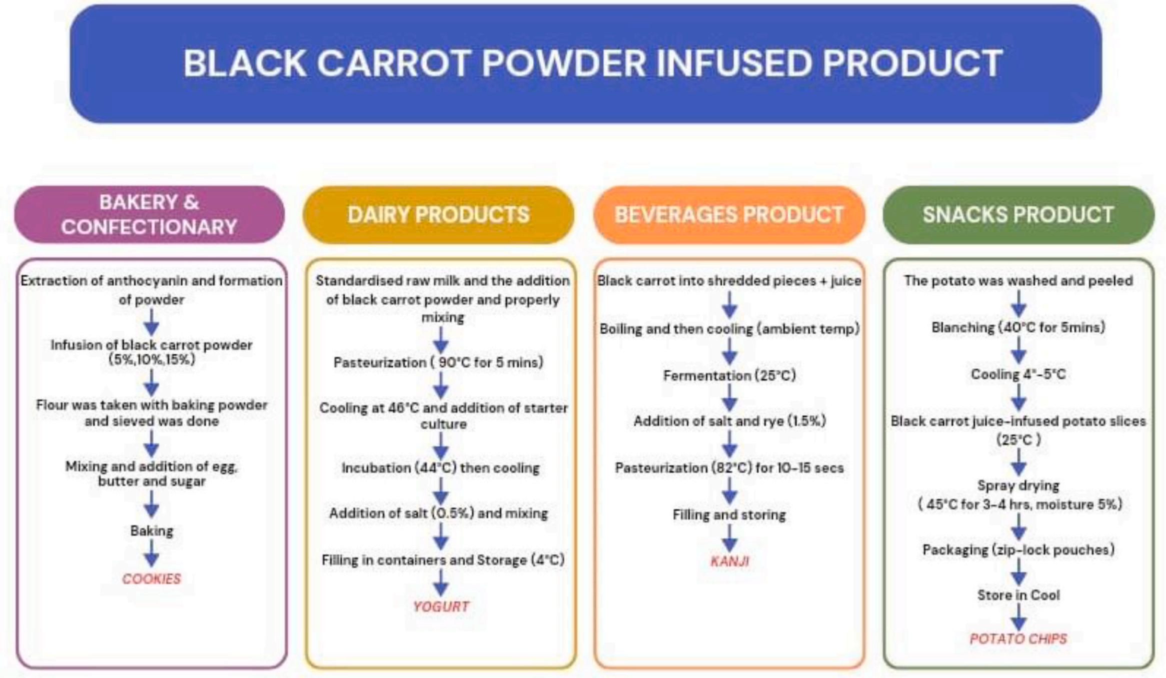

Fig. 7. Value added bakery, dairy, beverages, and snacks products of black carrot.

Moreover, the incorporation of black carrot fiber into probiotic yogurts resulted in enhanced textural characteristics, elevated phenolic content, and heightened antioxidant activity by improving water retention capacity [71]. Additionally, the effective fortification of Ayran with black carrot powder showcased a notable increase in antioxidant activity, rising from 4.7 % to 22 % [77].

5.3. *Snack products*

Snack products stand at the forefront of the modern food industry, offering consumers a quick and satisfying solution for on-the-go cravings. Noodles, apple chips, and potato chips are a few items that contain black carrot extract. By addition of black carrot extract, potato chips were made more bioactive, with their anthocyanin concentration rising from 22 to 40 mg/kg. Additionally, it enhanced colour qualities by raising the brightness, redness, and yellowness values. The antibacterial properties of the anthocyanin-rich extract also prevented the growth of *Salmonella* spp. and *Shigella* spp. in the potato chip samples [72]. In a related investigation, apple chips were enhanced with black carrot extract, leading to better colour characteristics, higher anthocyanin concentration, and higher antioxidant activity [24,73]. Furthermore 10 per cent of black carrot powder was added to the noodles formulation, which resulted in improved anthocyanins (15 mg/100 g), flavonoid content (30 mg/100 g), and antioxidant activity (35 % inhibition) [24]. Additionally, the inclusion of black carrot powder resulted in an improvement in the water absorption capability, a beneficial effect added to the fiber found within the powder, as outlined in the research conducted by Singh et al., [35]. These results highlight the promising use of black carrot powder as a functional component to enhance the nutritional content and texture of noodle products.

5.4. *Beverage products*

Beverages encompass a vast and dynamic category, reflecting a spectrum of flavours, formulations, and consumer preferences. The beverage industry constantly changes to accommodate consumers shifting tastes and health-conscious needs, from old favourites to cutting-edge creations. Kanji and Shalgam are examples of traditional fermented drinks made from black carrots; Kanji is a Pakistani and Indian culinary tradition, while Shalgam is primarily made in Turkey's Mediterranean region [24,78,79]. These drinks provide a unique look into the various ways that black carrots are used in traditional cuisines, highlighting both their regional variances and cultural significance. Shalgam juice demonstrated a more significant suppression of Caco-2 cell proliferation in comparison to black carrot juice [19]. According to Tanguler et al. [80], the phenolic composition and anthocyanin concentration of shalgam were influenced by the size of black carrots. Smaller cuts increased the surface area and allowed for a better bioactive extraction. Lactic acid was shown to be the main acid in black carrots, and LC/MS/MS analysis verified the presence of anthocyanins, such as cyanidin-3-arabinoside, cyanidin-3-galactoside, and cyanidin-3-glucoside [19]. These insights provide a valuable understanding of the intricacies influencing the chemical makeup and bioactivity of beverages derived from black carrots. An in-depth look into the endogenous yeast recovered from black carrots, discovering and describing strains appropriate for the synthesis of shalgam. Due to their prominent involvement in fermentation, they suggested *Pichia kudriavzevii* 3-3Y1, 3-3S9, and 3-3S2 as the best starter cultures. The author studied microbial elements crucial for shaping the characteristics and quality of shalgam, offering valuable guidance for improving the fermentation process in the production of this traditional beverage [81]. In Kanji production, *Pediococcus acidilactici* emerged as the bacterial strain with the highest growth potential, as highlighted in research by Sharma et al., [74]. This probiotic beverage showed noteworthy levels of flavonoids (38.14 mg/mL), ascorbic acid (110 mg/100 mL), phenolic content (40.80 mg/mL), and antioxidant activity (79.96 %). Furthermore, Kanji's purported capacity to manage *Salmonella enterica* and *Shigella boydii* highlights its distinct functional characteristics [24]. Another study showed inventive approaches to enhance the production processes of this traditional drink, effectively producing a Kanji mixture by combining a freeze-dried lactic acid bacterial culture with black carrot powder that had been reflectance window-dried [5]. The flow chart for making various value-added products of black carrot were presented in Fig. 7.

Incorporating black carrot powder into food products improves their aesthetic appeal and increases their nutritional and bioactive content.

Bakery and confectionery goods like cakes, muffins, biscuits, bread, pastries, jam, and marmalade can be made with black carrot powder highlighting improved phytochemical properties [24]. Dairy products such as ice cream, yoghurt, and buttermilk beside snack products such as potato, apple chips and traditional fermented beverages as shalgam and kanji can be prepared using black carrot [8].

6. Conclusion

Black carrots are rich in anthocyanins that give them their characteristic dark purple color, are a nutritionally valuable and culturally significant vegetable offering essential nutrients and bioactive compounds. The high anthocyanin exhibits antioxidant properties with possible role in reducing the risk of CHD (coronary heart disease), stroke, and cancer which makes it a valuable natural food colourant source with broad applications across various industries. But due to challenges like seasonal availability and degradation of anthocyanin during traditional extraction by heat restrict its wide applicability in food industry which can be overcome by use of novel extraction methods. Traditional extraction methods have limitations, including degradation of anthocyanin, however, novel approaches such as ultrasound, microwave-assisted, high hydrostatic pressure, and their combination offers efficient alternatives for increasing anthocyanin yield with less degradation. These methods reduce the time for extraction with solvent consumption beside increased yield. So this offers opportunity for integrating black carrot anthocyanins into diverse food products, including bakery items, dairy products, snacks, and traditional beverages, showcases their versatility aligning with improving health and market potential. The elevated level of anthocyanins in these products may offer protection against diseases like oxidative stress, cardiovascular disease, cancer etc. So, adoption of novel extraction technique in combination with green solvents in future can lead to the sustainable recovery of anthocyanin without degradation beside focusing on metabolic absorption pathways. These applications and advancements in extraction technologies highlight black carrots anthocyanins as health-enhancing ingredients in the modern food industry, bridging traditional culinary practices with contemporary nutritional demands.

CRediT authorship contribution statement

Akansha Saini: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis. **Hamid:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rafeeya Shams:** Writing – review & editing, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Kshirod Kumar Dash:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ayaz Mukarram Shaikh:** Visualization, Validation, Software, Resources, Funding acquisition. **Béla Kovács:** Visualization, Validation, Software, Resources, Project administration, Funding acquisition.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Ethics approval consent

Not applicable.

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Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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