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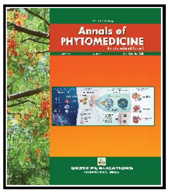

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Optimizing spray chilling encapsulation for prolonged shelf-life and retention of biochemical potential in black carrot (*Daucus carota* L.) juice

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Abstract

The preservation of black carrot juice, known for its high anthocyanin content and potent antioxidant properties, presents a significant challenge due to its susceptibility to degradation during storage. Spray chilling, a technique that involves atomizing the juice into fine droplets followed by rapid cooling to form a protective lipid-based coating, was investigated as a preservation strategy. Various parameters, including encapsulation material composition and spray chilling conditions, were optimized to assess their impact on juice stability. Analytical evaluations included total soluble solids (TSS), color change, anthocyanin content, antioxidant activity, and sensory attributes. The encapsulated juice demonstrated improved stability, retaining its nutritional and sensory qualities over extended storage periods. These findings highlight spray chilling encapsulation as an effective method not only for enhancing the shelf-life and marketability of black carrot juice but also for preserving its bioactive compounds, which are associated with antioxidant, anti-inflammatory, and cardioprotective health benefits. This research supports the development of functional beverages with prolonged efficacy and appeal, contributing to advancements in both food technology and human health.

1. Introduction

Black carrot (*Daucus carota* L.) is a biennial herbaceous species belonging to *Apiaceae* family (Kaur and Kapoor, 2001). The black variety of this root vegetable is distinguished by its deep color attributed to high levels of anthocyanins, a type of flavonoid with potent antioxidant properties (Cao and Prior, 1998). These compounds contribute to various health benefits, such as reducing oxidative stress, inflammation and a valuable addition to functional foods and dietary supplements (Lee and Nagy, 1996). Black carrot juice is commonly used for its potential health benefits, including improving cardiovascular health and supporting immune function. Its rich anthocyanin content also offers potential applications in natural colorants and nutraceuticals. The juice is incorporated into various products for its nutritional value and distinctive color, enhancing both the health benefits and visual appeal of food and beverage items (Akhtar *et al*., 2017). Despite these advantages, black carrot juice faces significant preservation challenges due to its susceptibility to oxidative degradation and microbial contamination during storage (Lee and Nagy, 1996). To address these challenges, advanced preservation techniques are essential, one such method is spray chilling encapsulation, which provides a protective barrier around the juice, reducing exposure to environmental factors such as oxygen and moisture, thereby enhancing its stability and extending shelf-life. This technique involves atomizing the juice into fine droplets and rapidly cooling them to form a coating that encapsulates the liquid within a protective matrix (Chou and Hsu, 2006). Black carrot juice and concentrates have been successfully incorporated into diverse food products from traditional fermented drinks such as Indian kanji and Turkish °algam, to functional dairy products including ice cream, yogurt, and buttermilk (up to 7.5% inclusion), which significantly enhance anthocyanin, mineral, and antioxidant content while maintaining sensory acceptability. Additionally, yogurts enriched with black carrot powder (1-2%) exhibit improved color and micronutrient content. The juice and powder have also been used in bakery items such as muffins, bread, cakes, and ready-to-drink beverages, and function as natural colorants (E163) in confectionery and baked goods.

The encapsulation process can mitigate oxidative and microbial degradation, which are critical factors in preserving the quality of sensitive liquid products. Previous studies have shown that spray chilling encapsulation can be effective in preserving various bioactive compounds in food products (Yoo and Cho, 2009). Additionally, encapsulated juice can be more easily handled and incorporated into various food products, enhancing its commercial viability (Kumar and Singh, 2011). Mazocatto *et al.* (2017) produced solid lipid microparticles (SLM) loaded with vitamin-B_{12} using the spray chilling technique and observed that encapsulation promoted better retention of vitamin-B_{12} until 120 days of storage period. Sa *et al.* (2023) evaluated the release, stability and antioxidant activity of Brazilian red propolis extract encapsulated by spray-drying, spray-chilling and using the combination of both techniques and combination of spray drying and spray chilling produced best results followed by spray-chilling encapsulation technique. As per the available literature, very few efforts have been made to use spray-chilling technique for

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encapsulating ascorbic acid (de Matos-Jr *et al*., 2017; Alvim *et al*., 2016 and Sartori *et al*., 2015), tucuma oil (de Freitas Santos *et al*., 2023) and galic acid (Consoli *et al*., 2016). The optimization of spray chilling parameters such as the choice of encapsulation materials and cooling conditions is crucial for maximizing the effectiveness of this technique in preserving sensitive bioactive compounds. However, a review of the available literature reveals a significant gap: no comprehensive efforts have been made to optimize the operating parameters of the spray chilling encapsulation process, particularly for fruit and vegetable juices rich in anthocyanins. Black carrot juice, known for its high anthocyanin content and antioxidant potential, is highly susceptible to degradation during processing and storage, limiting its commercial shelf-life.

There is a clear need for systematic research to develop optimized spray chilling conditions that can protect these sensitive compounds and improve product stability. This study aims to address that gap by optimizing key process parameters namely the percentage of encapsulation material, chilling temperature, and retention time to enhance the shelf-life and quality of encapsulated black carrot juice. The shelf-life analysis will involve evaluating critical quality attributes such as total soluble solids (TSS), color stability, anthocyanin content, antioxidant activity, and sensory properties (Sanchez-Moreno and Cano, 2003). By systematically investigating different encapsulation materials and process conditions, this research seeks to identify the optimal parameters that minimize degradation and maintain the juice's nutritional and sensory quality. The findings are expected to contribute to advancing food preservation technologies and support the development of more durable and high-quality juice products.

2. Materials and Methods

2.1 Plant materials

Freshly harvested black carrots (Variety: Punjab Black beauty with plant authentication number: IC-614611) having moisture content 85% to 90% (Holland *et al*., 1991; USDA, 2021) were procured during the Rabi season (December to March) from the Vegetable Farm of Punjab Agricultural University, Ludhiana, Punjab. Black carrots were stored at a refrigeration temperature of 4°C to preserve their freshness and prevent spoilage before the experiments (Kader, 1992). To ensure consistent treatment conditions, the carrots were equilibrated at room temperature before processing. This step was crucial for achieving uniform temperature throughout the samples and ensuring accurate experimental outcomes, as it allowed the carrots to stabilize at a temperature that closely resembled typical processing conditions (Kader and McLaughlin, 2000).

2.2 Sample and juice preparation

Black carrots (30-40 mm in diameter) were sorted and thoroughly washed with cold water at 5 ± 1°C. Stalks were partially removed before sanitation with sodium hypochlorite (100 mg/l) at 25°C for 2 min (Gorny *et al*., 2002). Subsequently, the carrots were immersed in a citric acid solution (3 g/l) at 25°C for 10 min to prevent browning (Gonzalez and Huber, 2004). Black carrots were cut into pieces and extracted using a commercial juice extractor (Model: Kalsi), maximizing yield and nutrient retention (Srinivasan, 2005). The juice was filtered through a fine mesh to ensure clarity (Lee *et al*., 2011) and stored in sterilized glass bottles at 4 ± 1°C to prevent contamination and maintain freshness (Kader, 1992).

2.3 Spray chilling encapsulation treatment

Black carrot juice was encapsulated using spray chilling process with maltodextrin concentrations of 30%, 35%, and 40%. The juice was atomized with these maltodextrin solutions and rapidly cooled to form protective coatings. This method aimed to assess the impact of maltodextrin concentration on encapsulation efficiency, stability and shelf-life of the juice. After encapsulation, black carrot juice underwent spray chilling process using experimental combinations designed through a 3-factor Box and Behnken design under response surface methodology (RSM) using the design expert DX 13.0.3 version. This approach enabled the systematic evaluation of the effects of key process parameters, including residence time, temperature and encapsulation material concentration, on the encapsulation efficiency and stability of the juice (Box and Behnken, 1960; Myers and Montgomery, 2002). Based on our preliminary treatments, the process parameters of spray chilling encapsulation process were, *i.e.,* residence time (10 to 30 min), temperature (-5 to 5°C) and percentage of encapsulation material (30 to 40%).

The five dependent variables were total soluble solids (TSS), colour change (CC), anthocyanin content (AC), antioxidant activity (AOX) and sensory attributes of the encapsulated juice. Each treatment was conducted in triplicate, and all laboratory analyses were performed in three independent replicates to ensure data accuracy and reproducibility.

2.4 Phytochemical analysis

2.4.1 Total soluble solids (TSS)

Total soluble solids in the black carrot juice was determined with the help of hand refractometer (Erma, Japan) using the method as recommended by the Cantwell *et al.* (2003). One or two drops of extracted juice were put onto the refractometer prism and readings were recorded by holding the refractometer against light. The point on the scale was noted where the boundary line of the shaded area intersects the unshaded area. The reading was noted according to blue colour indication on reading table. The results were expressed as ^{0}Brix. It had a scale ranging from 0^0 to 32^0 Brix. After each observation, the refractometer was cleaned with distilled water. This process was repeated three times and its average value was noted.

TSS (^{0}Brix) = Refractometer reading

2.4.2 Colour change (ΔE)

The colour of the treated spray chilling encapsulated black carrot juice was measured with the help of colour reader (CR-10, Konica Minolta Sensing Inc, Japan). For determination of colour, the juice was put in a glass beaker and positioned such that no light could pass through except for the illumination generated by the equipment during the measurement process. Colour measurements were taken in triplicate and average values were used. Total colour change was calculated using the following equation:

$$\Delta E = \sqrt{}(L - L_0)^2 + (a - a_0)^2 + (b - b_o)^2$$

where 'L_0', 'a_0', 'b_0' are the stimulus values of fresh black carrot juice respectively. In this colour space, 'L' represents lightness/whiteness or brightness/darkness, ranging from 0 (black) to 100 (white), 'a' represents the colour from greenness (-) to redness (+) and 'b' represents the colour from blueness (-) to yellowness (+) at any time, respectively.

2.4.3 Anthocyanin content (AC)

Anthocyanin content has been an indicator of major pigments in black carrot which was determined by using the UV-Visible spectrophotometer. The total anthocyanin content was determined in a UV-Visible spectrophotometer by the pH differential method (Wrolstad *et al*., 2005) using the two buffer systems – potassium chloride buffer, pH 1.0 with 0.025 M and sodium acetate buffer, pH 4.5 with 0.4 M. The pH was adjusted with HCl and then the samples were diluted in pH 1.0 and pH 4.5 buffers and absorbance measurements were taken at 510 and 700 nm using 1 cm path length cuvettes, respectively. The anthocyanin pigment content was calculated and expressed as mg/l using an extinction coefficient (e) of 26,900 l $cm^{-1}mol^{-1}$ and a molecular weight of 449.2 g mol^{-1}.

$$\text{Anthocyanin content, mg/l} = A \times MW \times DF \times 1000 / e \times 1$$

Absorbance was calculated by using the following formula:

$$\text{Absorbance (A)} = (A_{510nm} - A_{700nm})\ \text{pH 1.0} - (A_{510nm} - A_{700nm})\ \text{pH 4.5}$$

where,

A = Absorbance

MW = Molecular weight = 449.2 g mol^{-1}

DF= Dilution factor

e = Molar absorptivity = 26,900 l cm^{-1} mol^{-1}

2.4.4 Antioxidant activity (AOX)

The antioxidant activity in black carrots was primarily due to the presence of various phytochemicals, including anthocyanins, phenolic compounds, and carotenoids. Antioxidant activity in encapsulated black carrot juice was determined by following cupric reducing antioxidant capacity (CUPRAC) method, standardized by Apak *et al.* (2004). For determination of antioxidant activity 100 µl supernatant samples were mixed with 1 ml of 0.01 M copper chloride, 1 ml 7.5×10^{-3} M Neocuproine,1 ml ammonium acetate buffer (pH 7) and 1 ml distilled water in the test tubes**.** The final volume reached was 4.1 ml. The absorbance of the samples was taken at 450 nm after 30 minutes against a reagent blank in the UV spectrophotometer (Model: Rayleigh, UV-2601, Haidian, China). The calculation was done using the following equation:

$$\text{Antioxidant activity } (\mu \text{ mol Trolox/g}) = (A / {}^{\varepsilon}TR)\ (V_f / V_s)\ DF\ (V_t/m)$$

where,

A = Absorbance

$^{\varepsilon}TR$ = Molar absorptivity of Trolox (1.67×10^{4})

V_f = Final volume made (4.1 ml)

Vs = Sample volume taken from diluted extract (ml)

DF = Dilution factor

m= Weight of the sample (g)

The experimental data of spray chilling encapsulation system for black carrot juice as shown in Table 1 whereas ANOVA table for quality responses of spray chilling encapsulation system for black carrot juice as shown in Table 2, respectively.

Table 1: Experimental data of spray chilling encapsulation system for black carrot juice

Process parameters			Responses				
Retention time (min)	Temperature (°C) material (%)	Percentage of encapsulation	TSS (°Brix)	Colour change (ΔE)	Anthocyanin content (mg/100 g)	Antioxidant activity (µmol trolox/g)	Overall acceptability
30	0	40	7.56	12.77	141.22	66.26	8.2
20	0	35	7.36	12.23	153.45	82.4	8.4
20	-5	40	7.42	12.56	121.72	86.7	8.5
30	-5	35	7.44	12.71	138.93	89.4	8.6
20	0	35	7.36	12.14	152.37	83.7	8.5
10	-5	35	7.31	12.17	146.18	78.6	8.2
20	5	30	7.42	12.34	149.26	85.3	8.4
20	0	35	7.43	12.32	150.49	85.6	8.4
10	5	35	7.29	12.56	139.54	75.2	8.2
10	0	30	7.25	11.98	113.75	69.7	8.1
10	0	40	7.29	12.08	121.48	74.5	8.2
20	0	35	7.37	12.14	163.24	81.9	8.4
30	5	35	7.49	12.86	164.28	78.6	8.2
20	-5	30	7.37	12.49	118.58	84.6	8.5
20	5	40	7.45	12.56	159.27	87.6	8.6
20	0	35	7.39	12.16	149.89	86.3	8.3
30	0	30	7.52	12.65	143.08	79.2	8.4

2.4.5 Sensory evaluation

The sensory evaluation was done using Larmond's 9-point Hedonic scale (Larmond,1977).

2.5 Statistical analysis

The statistical analysis was performed independently for each response variable with the help of response surface methodology (RSM) by using a commercial statistical package (Design Expert DX 13.0.3). For 3 independent variables, a total number of 17 experiments were conducted according to the requirement of response surface methodology and the corresponding observations of the responses were recorded. An analysis of variance (ANOVA) was conducted with a 95% confidence level, in order to determine the accuracy of the model to represent the data. ANOVA include the statistical significance of process variables on each response, the model coefficient of determination (R^2), p value and the lack of fit.

Table 2: ANOVA table for quality responses of spray chilling encapsulation system for black carrot juice

	F – values (Responses)				
Source	**TSS (°Brix)**	**Colour change (ΔE)**	**Anthocyanin content (mg/100 g)**	**Antioxidant activity (μmol trolox/g)**	**Overall acceptability**
Model	8.70*	6.84*	4.65*	5.26*	4.87*
A-Retention time (min)	71.18*	35.89*	6.98	2.41*	8.17*
B-Temperature (°C)	1.14	1.13	11.91*	1.60	2.67
C-Percentage of encapsulation material (%)	2.41	1.93	0.57	0.1412	0.1667
AB	0.9215	0.8542	3.23	1.11	5.33
AC	0.0014	0.0059	0.2898	6.35	3.00
BC	0.0752	0.3337	0.1487	0.0008	1.33
A^2	0.0715	4.20	2.59	25.04	19.74
B^2	0.0873	15.27	0.0059	8.68	4.30
C^2	2.44	0.4458	15.37	3.02	0.0877
Lack of fit	2.23**	5.20**	4.97**	6.42**	2.17**
R^2	0.918	0.8978	0.8567	0.8711	0.8623
C.V. (%)	0.493	1.05	6.24	4.35	1.04

*Significant at 5% level, **Non-significant values

3. Results

3.1 Total soluble solids (TSS)

The total soluble solids (TSS) ranged from 7.25 °Brix to 7.56 °Brix. The minimum TSS value (7.25 °Brix) was obtained for a retention time of 10 min, temperature of 0^0C and percentage of encapsulation material of 30%, whereas maximum TSS value (7.56 °Brix) was obtained for a retention time of 30 min, temperature of 0^0C and percentage of encapsulation material of 40%.

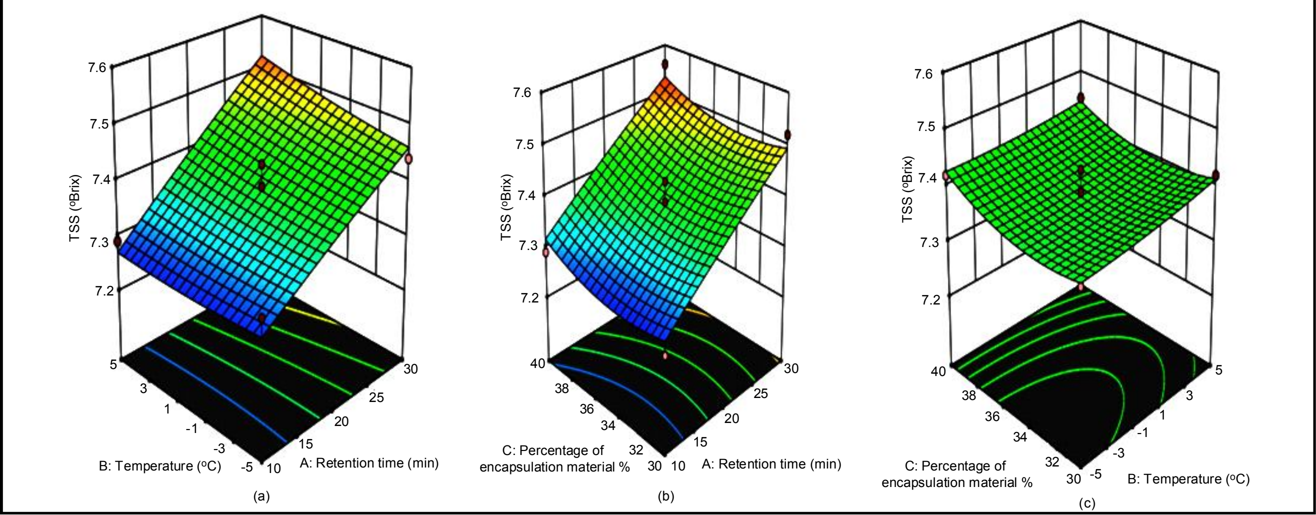

Figure 1: Response surface graphs of (a) retention time and temperature, (b) retention time and percentage of encapsulation material (c) percentage of encapsulation material and temperature on the TSS of spray chilling encapsulation of black carrot juice.

It can be clearly seen from the contour plots of the response surface graph (Figure 1) that with an increase in percentage of encapsulation material and retention time, higher TSS values was obtained. However, with increase in percentage of encapsulation material and temperature, slightly lower TSS values was observed. The percentage of encapsulation material improves the juice concentration and quality, with higher TSS values indicating a more concentrated and nutritious juice. Higher TSS values can inhibit the growth of microorganisms and thus improve the juice storage stability (Joshi *et al.*, 2017). Higher TSS values resulting in a thicker, more viscous juice that may require more force to pour (Schultz *et al.*, 2014). Juice sensory properties, such as taste and texture, with higher TSS values contributing to a sweeter and more viscous juice (Srivastava *et al.*, 2019). As TSS is related to the content of bioactive compounds like phenolics and flavonoids, it plays a crucial role in the juice nutritional value and health benefits (Kaur *et al.*, 2020). The model equation in coded factors, predicting TSS as influenced by retention time, temperature, and percentage of encapsulation material within the experimental range is given below:

TSS $= +7.382 + 0.1088 \times A + 0.0138 \times B + 0.02 \times C + 0.018 \times A \times B + 0.00 \times A \times C - 0.005 \times B \times C - 0.0047 \times A^2 + 0.0053 \times B^2 + 0.028 \times C^2$

where, TSS is total soluble solids, A is retention time (min), B is temperature (^{0}C) and C is percentage of encapsulation material (%).

3.2 Colour change (CC)

Retention time, temperature, and percentage of encapsulation material affected the colour change in black carrot juice. The colour change ranged from 11.98 to 12.86. The maximum colour change value (12.86) was obtained for a retention time of 30 min, temperature of 5^{0}C and percentage of encapsulation material of 35% and whereas minimum colour change value (11.98) was obtained for a retention time of 10 min, temperature of 0^{0}C and percentage of encapsulation material of 30%.

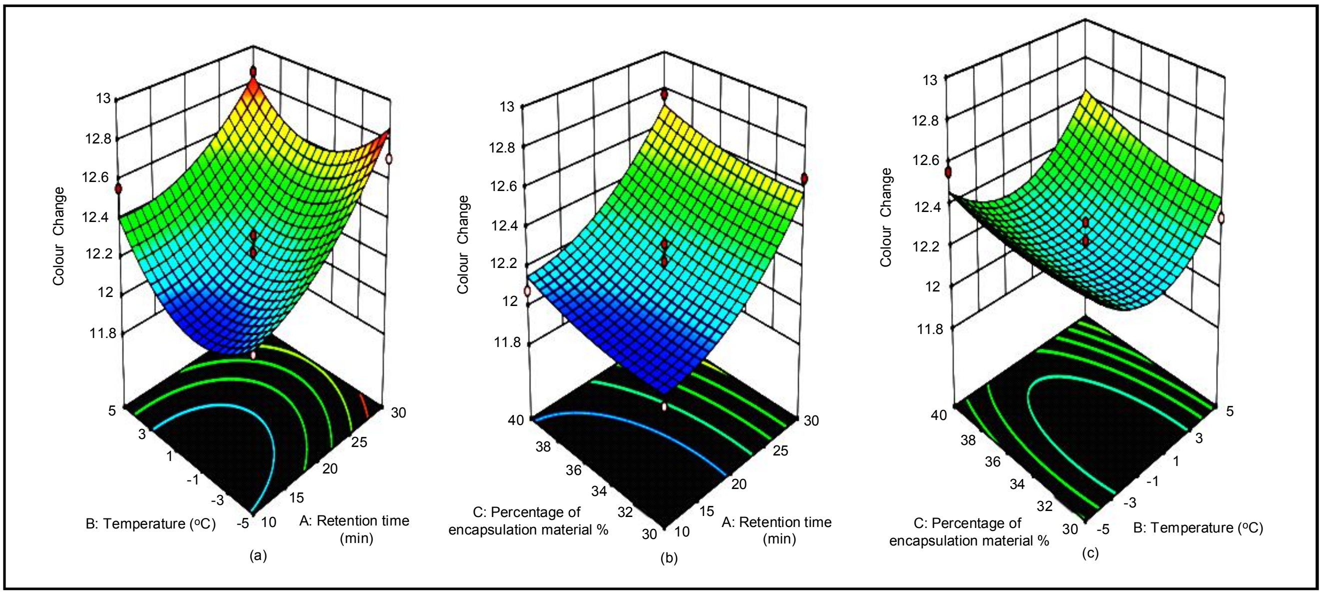

Figure 2: Response surface graphs of (a) retention time and temperature, (b) retention time and percentage of encapsulation material (c) percentage of encapsulation material and temperature on the colour change of spray chilling encapsulation of black carrot juice.

It can be clearly seen from the contour plots of the response surface graph (Figure 2) that with an increase in retention time with moderate percentage of encapsulation material, higher colour change values were obtained. However, with decrease in temperature, slightly lower colour change values were observed. The color of black carrot juice is related to its nutritional value, with darker colors indicating higher antioxidant activity (Kumar *et al.*, 2014). The vibrant color of black carrot juice can add visual appeal to food products, making them more attractive to consumers (Sharma *et al.*, 2019). Changes in color can indicate degradation or spoilage, making color an important quality control parameter (Srivastava *et al.,* 2019). Color can indicate the level of processing, with darker colors suggesting more intense processing (Turkyilmaz *et al.*, 2018). The color compounds in black carrot juice may have functional properties, such as anti-inflammatory effects (Kumar *et al.*, 2014).

The model equation in coded factors, predicting colour change as influenced by retention time, temperature, and percentage of encapsulation material within the experimental range is given below:

Colour change (ΔE) $= + 12.20 + 0.028 \times A + 0.049 \times B + 0.064 \times C - 0.06 \times A \times B + 0.005 \times A \times C + 0.038 \times B \times C + 0.13 \times A^2 + 0.25 \times B^2 + 0.04 \times C^2$

where A is retention time (min), B is temperature (^{0}C) and C is percentage of encapsulation material (%).

3.3 Anthocyanin content (AC)

Retention time, temperature, and percentage of encapsulation material were affected by the anthocyanin content in black carrot juice. The anthocyanin content ranged from 113.75 mg/100 g to 164.28 mg/100 g. The maximum anthocyanin content value (164.28 mg/100 g) was obtained for a retention time of 30 min, temperature of 5^{0}C and percentage of encapsulation material of 35%, whereas minimum anthocyanin content value (113.75 mg/100 g) was obtained for a retention time of 10 min, temperature of 0^{0}C and percentage of encapsulation material of 30%.

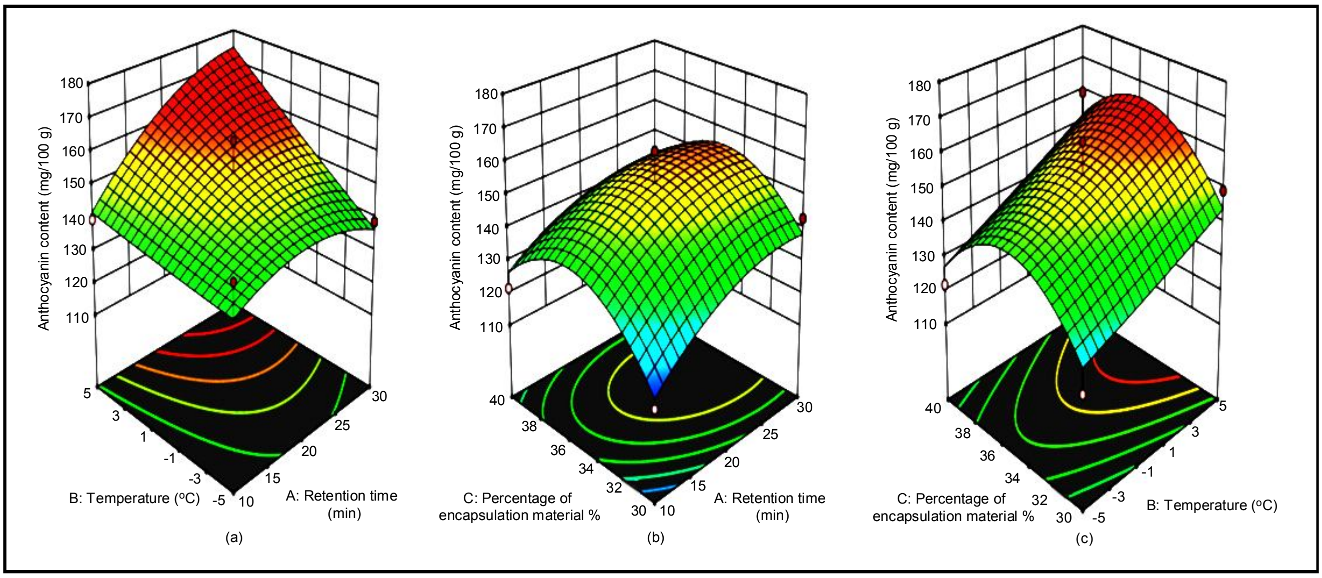

Figure 3: Response surface graphs of (a) retention time and temperature, (b) retention time and percentage of encapsulation material (c) percentage of encapsulation material and temperature on the anthocyanin content of spray chilling encapsulation of black carrot juice.

It can be clearly seen from the contour plots of the response surface graph (Figure 3) that with an increase in temperature with moderate retention time, higher anthocyanin content values were obtained. However, with decrease in percentage of encapsulation material and retention time, slightly lower anthocyanin content values were observed.

The model equation in coded factors, predicting anthocyanin content as influenced by retention time, temperature, and percentage of encapsulation material within the experimental range is given below:

Anthocyanin content (mg/100 g) $= + 153.89 + 8.32 \times A + 10.87 \times B + 2.38\ C + 8.00 \times A \times B - 2.4 \times A \times C + 1.72 \times B \times C - 6.99 \times A^2 + 0.3348 \times B^2 - 17.12 \times C^2$

where, A is retention time (min), B is temperature (°C) and C is percentage of encapsulation material (%).

3.4 Antioxidant activity (AOX)

Retention time, temperature, and percentage of encapsulation material were affected by the antioxidant activity in black carrot juice. The antioxidant activity ranged from 66.26 (µmol trolox/g) to 89.4 (µmol trolox/g). The maximum antioxidant activity value (89.4 µmol trolox/g) was obtained for a retention time of 30 min, temperature of -5°C and percentage of encapsulation material of 35% and whereas minimum antioxidant activity value (66.26 µmol trolox/g) was obtained for a retention time of 30 min, temperature of 0°C and percentage of encapsulation material of 40%.

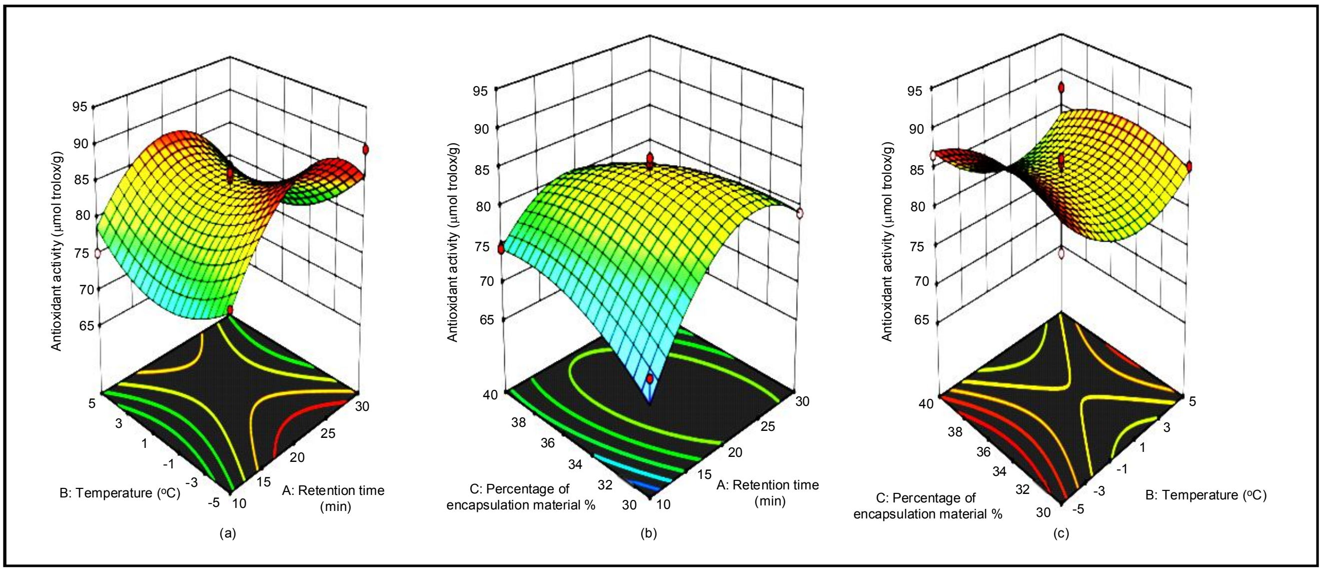

Figure 4: Response surface graphs of (a) retention time and temperature, (b) retention time and percentage of encapsulation material (c) percentage of encapsulation material and temperature on the antioxidant activity of spray chilling encapsulation of black carrot juice.

It can be clearly seen from the contour plots of the response surface graph (Figure 4) that with a decrease in temperature with retention time, higher antioxidant activity values were obtained. However, with an increase in percentage of encapsulation material and retention time, slightly lower antioxidant activity values were observed.

The model equation in coded factors, predicting antioxidant activity as influenced by retention time, temperature, and percentage of encapsulation material within the experimental range is given below:

Antioxidant activity (μmol trolox/g) $= + 83.98 + 1.93 \times A - 1.58 \times B - 0.4675\, C - 1.85 \times A \times B - 4.44 \times A \times C + 0.05 \times B \times C - 8.58 \times A^2 + 5.05 \times B^2 - 2.98 \times C^2$

where, A is retention time (min), B is temperature (^{0}C) and C is percentage of encapsulation material (%).

3.5 Overall acceptability

Retention time, temperature, and percentage of encapsulation material were affected by the total soluble solids in black carrot juice. The overall acceptability (OA) ranged from 8.1 to 8.6. The minimum value (8.1) was obtained for a retention time of 10 min, temperature of 0^0C and percentage of encapsulation material of 30% and whereas maximum value (8.6) was obtained for a retention time of 30 min, temperature of -5^0C and percentage of encapsulation material of 35%.

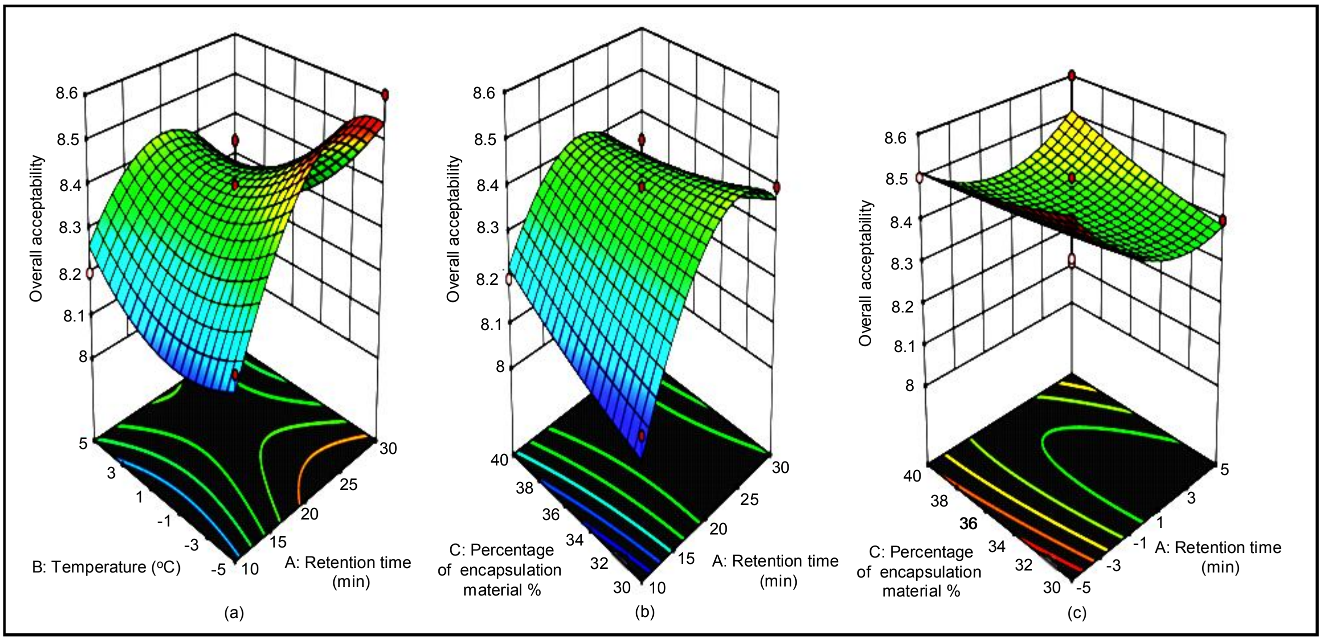

Figure 5: Response surface graphs of (a) retention time and temperature, (b) retention time and percentage of encapsulation material (c) percentage of encapsulation material and temperature on the overall acceptability of spray chilling encapsulation of black carrot juice.

It can be clearly seen from the contour plots of the response surface graph (Figure 5) that with a decrease in percentage of encapsulation material and temperature, higher overall acceptability values were obtained. However, with decrease in percentage of encapsulation material and retention time, slightly lower overall acceptability values were observed.

The model equation in coded factors, predicting overall acceptability as influenced by retention time, temperature, and percentage of encapsulation material within the experimental range is given below:

Overall acceptability $= + 8.40 + 0.0875 \times A - 0.05 \times B + 0.0125\, C - 0.01 \times A \times B - 0.075 \times A \times C + 0.05 \times B \times C - 0.1875 \times A^2 + 0.0875 \times B^2 + 0.0125 \times C^2$

where, A is retention time (min), B is temperature (^{0}C) and C is percentage of encapsulation material (%).

3.6 Optimization of spray chilling encapsulation process parameters for black carrot juice

The optimum values of process parameters and responses are presented in Table 3. The system variables for black carrot juice were optimized using numerical optimization technique. The main criteria for optimization of constraints were TSS, anthocyanin content (mg/100 g), antioxidant activity (μmol trolox/g) and overall acceptability were targeted to maximum, while the color change was targeted to minimum and the process parameters to be in range. The response surface graph and contour plots were generated for each response for interaction with system parameters.

In order to optimize the process conditions for spray chilling encapsulation using numerical optimization technique, equal importance of '3'was given to the three independent variables (*i.e.*, retention time in min, temperature in ^{0}C, and percentage of encapsulation material in %) and response parameters (*i.e.,* TSS, color change, anthocyanin content, antioxidant activity, and overall acceptability). The results optimized by response surface methodology (RSM) and their corresponding experiment values with variation are as presented in Table 3, along with the desirability value in Table 4. The results of the predicted and experimental values were compared statistically and desirability of the model was 0.713.

Table 3: Optimum and experimented values of spray chilling encapsulation process parameters and responses for black carrot juice

	Parameters	Optimized values	Experimented values	% Error
Independent variables	Retention time (min)	21.75	21.52	1.06
	Temperature (°C)	3.63	3.7	0.909
	Percentage of encapsulation material (%)	35.12	34.7	1.19
Response parameters	TSS (°Brix)	7.42	7.3	1.61
	Colour change (ΔE)	12.41	12.38	0.24
	Anthocyanin content (mg/100 g)	164.28	158.32	3.63
	Antioxidant activity (µmol trolox/g)	85.3	83.4	2.23
	Overall acceptability	8.4	8.5	0.11

Table 4: Optimum values of spray chilling encapsulation process parameters and responses for black carrot juice

Parameter	Goal	Lower limit	Upper limit	Importance	Optimized level	Desirability
Retention time (min)	In range	10	30	3	21.75	
Temperature (°C)	In range	-5	5	3	3.63	
Percentage of encapsulation material (%)	In range	30	40	3	35.12	
Responses				**Predicted values**		
TSS (°Brix)	Maximize	7.25	7.56	3	7.42	0.713
Colour change (ΔE)	Minimize	11.98	12.86	3	12.41	
Anthocyanin content (mg/100 g)	Maximize	113.75	164.28	3	164.28	
Antioxidant activity (µmol trolox/g)	Maximize	66.26	89.4	3	85.3	
Overall acceptability	Maximize	8.1	8.6	3	8.4	

The second order polynomial equation was fitted to the experimental data of each dependent variable. Maximum importance was given to the colour. Table 4 shows the desired goals for each independent variable and response. The software generating optimum values of independent variables were retention time of 21.75 min, temperature of 3.63°C and percentage of encapsulation material of 35.12%. Optimum conditions of responses corresponding to the values of independent process variables were TSS of 7.42 °Brix, CC of 12.41, AC of 164.28 mg/100 g, AOX of 85.3, OA of 8.4 with overall desirability of 0.713 (Table 4).

4. Discussion

Total soluble solids (TSS) in black carrot juice serve not only as a marker of juice concentration and quality (Kumar *et al*., 2014), but also play an important role in its nutritional density and consumer acceptability. Higher TSS values contribute to improved stability and shelf-life (Joshi *et al*., 2017), ensuring that bioactive compounds are retained for longer periods. Moreover, since TSS influences taste and texture (Srivastava *et al*., 2019), optimizing it enhances palatability, which is critical for encouraging regular consumption of nutrient-dense functional beverages. In this study, TSS was affected by retention time, temperature, and encapsulation material, indicating that process optimization directly impacts nutritional preservation and consumer adherence.

Color is a key sensory and biochemical trait in black carrot juice. The deep purple hue, derived from high anthocyanin content (Giust and Wrolstad, 2003), serves as an indicator of potent antioxidant capacity. Color not only influences consumer appeal (Teixeira *et al.,* 2015) but also reflects the presence of compounds that support cellular health and protect against oxidative stress. By maintaining color through spray chilling encapsulation, the bioavailability of these pigments can be preserved, enhancing their functional efficacy in the human body.

Anthocyanin content is central to the functional potential of black carrot juice. These natural pigments are associated with anti-inflammatory, cardioprotective, neuroprotective, and anti-cancer properties. Their ability to scavenge free radicals and reduce oxidative stress supports a range of therapeutic benefits, including protection against age-related diseases and chronic inflammatory conditions. By demonstrating a significant retention of anthocyanins under optimized spray chilling conditions, this study affirms the process as a means to preserve and deliver functional bio actives efficiently.

The antioxidant activity (AOX) of black carrot juice is closely tied to its content of phenolic compounds, particularly anthocyanins and carotenoids. These antioxidants help neutralize free radicals that contribute to cellular damage, ageing, and diseases such as cancer and Alzheimer's (Kumar *et al.,* 2014). Regular consumption of antioxidant-rich foods like black carrot juice has been associated with improvements in cardiovascular health, including lowering blood pressure and improving lipid profiles. The preservation of antioxidant activity through encapsulation confirms the technique's effectiveness in safeguarding bioactivity for long-term health benefits.

Sensory attributes including taste, aroma, texture, and overall acceptability play a critical role in consumer preference and sustained consumption (Sahin *et al.,* 2020). Sensory analysis not only helps align product development with consumer expectations (Dilmacunal *et al.,* 2019) but also acts as a quality control tool (Koca *et al.,* 2019), ensuring that no degradation occurs over time. Given that consumers are more likely to include health-promoting foods in their diets when those foods are also enjoyable, maintaining sensory quality through spray chilling supports both marketability and public health outcomes (Gunes *et al*., 2020).

In summary, the traits studied like TSS, color change, anthocyanin content, antioxidant activity, and sensory attributes are not only critical markers of product quality but also integral to the nutritional and therapeutic potential of black carrot juice. The spray chilling encapsulation process has shown to be effective in preserving these parameters, reinforcing its value in developing functional beverages that support human health and wellness. This approach can contribute to preventive healthcare strategies by enabling the delivery of bioactive-rich foods with extended shelf-life and high consumer acceptance.

5. Conclusion

The response surface methodology proved to be an effective tool for optimizing the spray chilling encapsulation process of black carrot juice. Optimal process conditions like 21.75 min retention time, 3.63°C temperature, and 35.12% encapsulation material yielded desirable quality attributes, including a TSS of 7.42 °Brix, color change (CC) of 12.41, anthocyanin content (AC) of 164.28 mg 100 g, antioxidant activity (AOX) of 85.3, and overall acceptability (OA) of 8.4. The encapsulation process notably preserved anthocyanin content and antioxidant activity, while also enhancing color stability and maintaining sensory quality. Beyond its technological success, this study underscores the potential of spray chilling encapsulation as a viable method to elevate the nutritional and functional value of black carrot juice. By enabling better retention of bioactive compounds, the technique supports the development of shelf-stable functional beverages rich in antioxidants and natural pigments. Moreover, leveraging underutilized crops like black carrot-known for its resilience and high phytonutrient content-can enhance agricultural sustainability and contribute to dietary diversification. The findings thus have broader implications: promoting the use of black carrot as a functional food ingredient can support rural economies, reduce post-harvest losses, and address public health concerns by providing accessible, antioxidant-rich products that support chronic disease prevention. These positions spray chilling encapsulation as a simple, cost-effective, and scalable solution with meaningful impact across the food supply chain and human health.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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