Stabilization of canthaxanthin produced by *Dietzia natronolimnaea* HS-1 with spray drying microencapsulation

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Abstract The strain bacterium *Dietzia natronolimnaea* has propounded as a source for biological production of canthaxanthin. Because of sensitivity of this pigment, examine on its stability is important. In this study, stability of encapsulated canthaxanthin from *D. natronolimnaea* HS-1 using soluble soybean polysaccharide (SSPS), gum acacia (GA), and maltodextrin (MD) as wall materials was investigated at 4, 25, and 45 °C in light and dark conditions during 4 months of storage. It was shown that the type of walls influenced the size of emulsion droplets; spray dried particles, microencapsulation efficiency (ME), and retention of canthaxanthin in microcapsules. SSPS and MD produced the smallest and the biggest emulsion droplets and spray dried particles, respectively. Microcapsules made with SSPS resulted in better ME and higher stability for canthaxanthin. Samples were degraded in all conditions, especially in light and 45 °C. Degradation of microencapsulated canthaxanthin with SSPS and GA proceeded more slowly than did with MD. Regardless of the type of wall materials, total canthaxanthin contents of the microencapsulated products decreased by an increase in time or temperature. Also, samples exposed to

light indicated less stability at 4 and 25 °C when compared to the storage at dark conditions. According to the results of this study, SSPS can be considered as potential wall material for the encapsulation of carotenoids.

Keywords Microencapsulation · Canthaxanthin · *Dietzia natronolimnaea* · Spray drying

Introduction

Canthaxanthin (4, 4'-diketo- β -carotene) is an orange-red xanthophylls (a subclass of carotenoids) with strong antioxidant activity (Bhosale and Bernstein 2005). canthaxanthin has widely used in the pharmaceutical, medical, cosmetic, fishery, poultry and food industries (Nasrabadi and Razavi 2010). Commercial demand for canthaxanthin is mainly satisfied by chemical synthesis. However, as the application of synthetic substances is restricted in food, cosmetic and pharmaceutical industrials, production of canthaxanthin from biological sources has been attended in recent years (Ausich 1997).

For the industrial production of carotenoids, microorganisms are preferred over other natural sources, such as vegetables and fruits, owing to problems of seasonal and geographic variability in production. In addition, there are economic advantages to microbial processes that use agricultural waste and industrial wastewater as substrates (Buzzini 2000).

However, most carotenoids, including canthaxanthin, are highly unsaturated molecules and therefore highly susceptible to environmental conditions such as, light, oxygen and water. Emulsification and microencapsulation are among the methods that can be applied for stabilizing such components in food industry (Higuera-Ciapara et al. 2004). Dehydration

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by spray drying is used extensively in food related industries for a wide range of products in dry particulate form as powders and agglomerates (Sagar and Suresh Kumar 2010). Spray drying is the most commonly used microencapsulation technique in food industry. Modified and hydrolyzed starch, maltodextrin (MD), and gum acacia (GA) are common wall materials for use in spray drying encapsulation of food ingredients (Desai and Park 2005). The shelf lives of α and β -carotene were reportedly increased by spray drying using MD with different dextrose equivalent values (Wagner and Warthesen 1995; Desobry et al. 1997). Loksuan (2007) used modified/native tapioca starch and MD to increase the stability of microencapsulated β -carotene. Also, chitosan was applied to encapsulate urucum, a natural pigment extracted from the seeds of *Bixa orellana* species (Parize et al. 2008). The light stability of bixin was improved by spray drying microencapsulation using MD and GA (Barbosa et al. 2005). Lycopene was spray dry microencapsulated by such wall materials as gelatin/sucrose (Shu et al. 2006) and β -cyclodextrin (Nunes and Mercadante 2007). Multiple emulsions containing carotenoid oleoresins from red chilies and marigold petals were encapsulated with gellan, mesquite gum, MD, and GA (Rodríguez-Huezo et al. 2004).

The canthaxanthin is an unstable compound and there are no reports in the literature on improve stability of this carotenoid. Therefore, the aim of this research was to microencapsulate (by spray drying) the canthaxanthin, extracted from a microbial source (*D. natronolimnae*), using soluble soybean polysaccharide (SSPS), GA, and MD as wall materials and study the storage stabilities of microcapsules at different temperatures in dark and light conditions.

SSPS is a water-soluble polysaccharide containing a protein fraction (extracted from soybean) with good emulsifying properties (Madea and Nakamura 2009). The bacterium *D. natronolimnae* is gram positive, catalase positive, and oxidase negative with high canthaxanthin production potential among the studied microbial sources (Khodaiyan et al. 2007).

Materials and methods

Materials The D-glucose, peptone, yeast extract, agar, and malt extract were all purchased from Sigma-Aldrich Chemical Company (St. Louis, MO). The canthaxanthin standard was supplied by Dr. Ehrenstorfer GmbH (Augsburg, Germany). Acetonitrile, dichloromethane, methanol (HPLC grade), and GA were obtained from Merck (Darmstadt, Germany). MD with 18–22 DE was procured from Dextroseiran Company (Tehran, Iran). SSPS was kindly donated by Fuji Oil Chemical Co., Ltd. (Osaka, Japan). Pure ethanol

(99.9 %, v/v) was purchased from Bidestan Company (Qazvin, Iran). Beet molasses were purchased from Qazvin Sugar Industry (Qazvin, Iran).

Production of natural canthaxanthin The strain of bacterium *D. natronolimnae* HS-1 (DSM 44860) used in this work was obtained from Bioprocess Engineering Laboratory, University of Tehran. *D. natronolimnae* HS-1 maintained on yeast/malt (YM) agar plates containing glucose, peptone, yeast extract, malt extract, and agar at 4 °C. Colonies were transferred into Erlenmeyer flasks containing beet root molasses and yeast extract and were incubated in an incubator (Stuart Orbital Incubator, Model S150, Staffordshire, UK) at 180 rpm and 28 ± 1 °C for 5 days to produce canthaxanthin.

Extraction and analysis of canthaxanthin After the production stage of canthaxanthin, aliquots of cultures were centrifuged and washed with a solution of NaCl and centrifuged to remove supernatant. Then, ethanol was added to the pellet and mixed by vortex and centrifuged to extract the pigment. This was repeated three times until pellets were colorless. Thereafter, the extracted pigments in ethanol were filtered through a 0.2 μ m hydrophobic fluorophore membrane (Sigma-Aldrich Co., St. Louis, MO) and pooled. Canthaxanthin concentration was determined according to a method previously published by Razavi et al. (2006). A Knauer HPLC system (Berlin, Germany) equipped with a UV-visible detector (K-2600, Knauer, Germany) and a pump (K-1001, Knauer, Germany) and a Nucleosil 100 C18 column (125 mm $\times$ 4.0 mm $\times$ 5.0 μ m). A pre-column (5.0 mm $\times$ 4.0 mm) of the same material was used as a guard column. The mobile phase was a mixture of acetonitrile, methanol and dichloromethane at 71:22:7 ratios (v/v/v). Flow rate was set at 1.0 mL.min⁻¹. The system was operated at room temperature. The injection volume was 100 μ L. Also, the detector was set at 480 nm to monitor canthaxanthin.

Preparation of emulsions and microencapsulated powders Solvent removal from canthaxanthin solution was carried out using a Heidolph Laboratory Digital 4010 rotary evaporator (Heidolph Instruments GmbH & Co., Schwabach, Germany) after the addition of some pure corn oil (Kristal Oil, Co., Izmir, Turkey). SSPS, GA, and MD were dissolved in distilled water at 10 % (w/v) with slight heating and after one night of stay at those conditions, canthaxanthin was added into polysaccharides solutions at 1:4 ratios. These mixtures were first coarsely emulsified by blending them using a laboratory mixer (Ultra Turrax T25, IKA, Werke GmbH & Co. KG, Staufen, Germany). To prepare fine emulsions, mixtures were further homogenized three times using a two-stage high pressure laboratory homogeniser (APV Homogenisers, Albertslund, Denmark) at 25 and

4 MPa in the first and second stages, respectively. The emulsions were then fed to a mini-spray-drier (model B-191, Buchi Laboratorioums-Technik, Flawil, Switzerland) containing a 0.5 mm atomizer, inside a chamber of 44 cm in height and 10.5 cm in diameter. The inlet and outlet air temperatures were maintained at 170 ± 2 °C and 90 ± 5 °C, respectively. The pressure of compressed air for the flow of the sprayed materials was set at 0.5 MPa and the feed rate was adjusted to $300 \text{ mL} \cdot \text{h}^{-1}$. The microencapsulated powders were collected at the drier's cyclone.

Size distribution of emulsion droplets and spray-dried particles The size distribution of the droplets in the emulsion was determined by the laser light scattering method using a Mastersizer 2000 (Malvern Instruments Ltd., Worcestershire, UK). The spray-dried powders were dispersed in 2-propanol and droplet size was analyzed (using the above method) by an analyzer equipped with a batch cell-unit (Mastersizer E, Malvern Instruments Ltd., Worcestershire, UK). $D(4,3)$ is the volume mean diameter of the drops or particles and all size results reported are based on volume distribution of diameter of the drops or particles.

Moisture and water activity To determine the moisture contents of the powders, samples were dried at 105 °C for 16 h inside an oven (Memmert, model ULM400, Memmert GmbH, Schwabach, Germany). The water activities of the samples were measured using an a_w -Sprint TH500 system (Novasina, Pfäffikon, Switzerland).

Scanning electron microscopy (SEM) The morphology of the microcapsules was studied by using a scanning electron microscope (SEM) (Cam Scan-MV 2300, Cambridge, UK) at an acceleration voltage of 25 kV. The particles were fixed to the SEM stubs and were coated with gold (20 nm) using the sputtering technique and a Sputter-Coater (E5200 automatic, Bio-Rad, Oxford, UK).

Storage stability of microencapsulated canthaxanthin To study the storage stabilities of microcapsules, powder samples were poured into 15 mL glass vials, placed in desiccators and stored in temperature-controlled incubators at 4, 25, and 45 °C under light and dark conditions for 16 weeks. The intensity of 2,000 lx was used with cool-white and fluorescent lamps (20 cm away from the samples) in light conditions. Samples for the zero-time were analyzed within 24 h after spray drying and analyzed over a period of 16 weeks for total retention of canthaxanthin. The retention percentage of microencapsulated canthaxanthin was defined as the ratio of the total amount of canthaxanthin in the spray-dried powders at a given time to the total amount of canthaxanthin at zero time in the same sample.

Carotenoids determination Total amounts of carotenoids in the sample powders were determined according to a method described by Desobry et al. (1997). Fifty mg of powder were dispersed in 2.5 mL water in a test tube, and then 25 mL hexane was added. Afterwards, the tube was shaken on IKA- Vibrax VXR (IKA-Werke, Staufen, Germany) at 500 rpm for 30 min. The fraction of yellow to orange color of the hexane layer was measured at 464 nm according to Sewram and Raynor (2000) with a BioQuest CE2502 spectrophotometer (Progen Scientific Ltd, London, UK). Surface carotenoids in the powders were determined according to Wagner and Warthesen (1995). Fifty mg of powder were weighed into a test tube and extracted with 25 mL hexane for 15 s (shaken at 100 rpm). The tubes were centrifuged at $1,000 \times g$ for 1 min and the carotenoids concentration in the supernatant was measured by above spectrophotometer at the same wave length.

Microencapsulation efficiency of the powders The microencapsulation efficiency (ME) was evaluated using the following expression (McNamee et al. 1998):

$$ME = \left(\frac{TC - SC}{TC} \right) \times 100 \quad (1)$$

Where TC and TS are total and surface carotenoids contents of the spray-dried powders, respectively.

Statistical analysis All experiments were performed in triplicate and mean values along with their standard deviations were reported. Analysis of the data was carried out using ANOVA from SPSS statistical software (version 11.5 for windows, SPSS, Chicago, IL). Comparison among the means was made using the Duncan's multiple-range analysis at probability value of 0.05.

Results and discussion

Canthaxanthin analysis The results of HPLC analysis of carotenoids produced by *D. natronolimnaea* HS-1 are shown in Fig. 1. Three peaks were clearly characterized on the chromatogram. The first peak on the chromatogram was astaxanthin (retention time: 2.40 min). Canthaxanthin was the major peak (retention time: 3.11 min) contributing to over 90 % of total carotenoid production (based on their relative area percents). β -carotene was identified at 4.73 min (the last peak). Similar to this study, others (Khodaiyan et al. 2007; Nasrabadi and Razavi 2010) reported that the amount of canthaxanthin produced by *D. natronolimnaea* HS-1 was at the highest possible when compared with other important wild canthaxanthin-producing strains.

Fig. 1 HPLC chromatogram of carotenoids produced by *D. natronolimnae* HS-1. column: Nucleosil C18 (125 mm×4.0 mm×5.0 μm), mobile phase: acetonitrile–methanol–dichloromethane (71:22:7 v/v/v), flow rate: 1.0 mL·min⁻¹, detection at 480 nm

Size distribution of emulsion droplets and spray-dried particles Median diameter, D(4,3), of the emulsion droplets and spray-dried microcapsules are listed in Table 1. As shown in Table 1, the sizes of emulsion droplets and microcapsules were significantly affected by the type of wall materials ($P<0.05$).

SSPS gave the smallest median diameter of emulsion droplets and microcapsules (0.78, 7.94 μm) followed by GA (0.84, 9.08 μm) and MD (1.035, 10.42 μm), respectively. SSPS and GA are polysaccharides with highly-branched structures having some proteineous residues rendering their emulsifying abilities in oil-in-water emulsions (Dickinson et al. 1988; Nakamura et al. 2004a, b). SSPS shows a better emulsifying ability due to its higher levels of proteineous residues compared to GA (Madea and Nakamura 2009). MD is a linear polysaccharide without any proteins and therefore does not provide a good emulsifying property (Loksuwan 2007). Results of the current study showed that among the three wall materials applied here, SSPS was the best in order to prepare the oil-in-water emulsions as well as the spray-dried powders with smaller sizes. This result is in accordance with that published by Liu et al. (2001), who applied SSPS and GA as emulsifiers for the microencapsulation of hydrophobic flavors by MD. They found that SSPS produced smaller particles and was a better emulsifier than GA to encapsulate flavors. Furthermore, Watanabe et al.

(2004) reported that the oil-in-water emulsions prepared with SSPS had the smallest size compared to GA and MD, and this polysaccharide was a good wall material for the encapsulation of 6-o-arachidonyl ascorbate.

Moisture contents and water activities of the powders

Amount of moisture contents and water activities of spray-dried powders are shown in Table 1. The moisture contents were at 0.75–0.77 % levels indicating that there were no significant differences ($P<0.05$) among the moisture contents of spray-dried microcapsules. Water activities of the powders did not change significantly and stayed within 0.080–0.091 limit only. In agreement with this study, it has been reported that the moisture contents and water activities of the spray-dried powders were affected only by the spray drying conditions and wall materials did not influence on them significantly (Dian et al. 1996; Soottitantawat et al. 2003).

Microencapsulation efficiency ME is the fraction of encapsulated canthaxanthin in the powder. Therefore, its quantity is also dependent on the surface (un-capsulated) canthaxanthin level in the powder. Both surface and total canthaxanthin contents of spray-dried microcapsules along with their corresponding ME values are shown in Table 2. Significant differences ($P<0.05$) were found among the surface canthaxanthin contents, total canthaxanthin contents and ME levels of the various samples of this study. The highest total canthaxanthin contents and the lowest surface canthaxanthin contents corresponding to the highest ME levels were shown in microcapsules prepared with SSPS as wall material. However, the microcapsules prepared with MD had the lowest total canthaxanthin contents and therefore ME levels. These data are in agreement with those reported by Minemoto et al. (2002), who encapsulated linoleic acid with SSPS, GA, or a mixture of them together with maltodextrin. This means that the surface and total canthaxanthin contents (or ME values) were correlated directly with the type of wall materials. It is known that the protein fraction of materials is adsorbed on the surface of the oil droplets in the oil-in-water emulsions and stabilizes such emulsions (Nakamura et al. 2004b). Therefore,

Table 1 Effect of wall composition on the moisture content, water activity (a_w), and size of emulsion droplets [D(4,3)] and of spray-dried microcapsules (Mean ± SD)

Type of wall	Moisture (%)	a_w	Emulsion size (μm)	Powder size (μm)
SSPS	0.77±0.05 ^{a1}	0.083±0.01 ^a	0.78±0.01 ^c	7.94±0.14 ^c
GA	0.75±0.09 ^a	0.091±0.05 ^a	0.840±0.01 ^b	9.08±0.07 ^b
MD	0.75±0.02 ^a	0.080±0.05 ^a	1.035±0.008 ^a	10.42±0.14 ^a

¹ In each column, means identified with the same letter are not significantly different ($P<0.05$). $n=3$. a_w Water activity, SSPS Soluble Soybean Polysaccharide, GA Gum Acacia, MD Maltodextrin

Table 2 Surface and total canthaxanthin contents and microencapsulation efficiencies of spray-dried microcapsules (Mean $\pm$ SD)

Type of wall	Surface canthaxanthin ($\mu\text{g}\cdot\text{mg}^{-1}$)	Total canthaxanthin ($\mu\text{g}\cdot\text{mg}^{-1}$)	Microencapsulation Efficiency (%)
SSPS	0.24 $\pm$ 0.02 ^{c1}	2.46 $\pm$ 0.02 ^a	90.3 $\pm$ 0.7 ^a
GA	0.30 $\pm$ 0.01 ^b	2.32 $\pm$ 0.07 ^b	86.9 $\pm$ 0.3 ^b
MD	0.54 $\pm$ 0.03 ^a	2.02 $\pm$ 0.06 ^c	73.5 $\pm$ 0.6 ^c

¹ In each column, means identified with the same letter are not significantly different ($P<0.05$). $n=3$. a_w Water activity, SSPS Soluble Soybean Polysaccharide, GA Gum Acacia, MD Maltodextrin

since both SSPS and GA contain proteinous residues, they could produce microcapsules with higher ME levels.

According to Tables 1 and 2, decrease of the size of emulsions and particles caused a significant increase in the ME. This was found that a small emulsion is stable and a large emulsion broke down during spray drying processing (Sootitawat et al. 2003). So, there were higher amounts of canthaxanthin on the surface of larger particles compared to smaller. Also, the works reported by others support the observation made in this study. Modified tapioca starch as wall gave smaller particles size, and had higher ME as compared to native starch and MD in encapsulation of β -carotene (Loksuwan 2007), and GA had smaller size and higher ME compared to MD and MD:GA mixed as wall materials in encapsulation of rosemary (Rosenberg et al. 1990). Therefore there were a reverse relation between the size of emulsions and particles, and ME.

Scanning electron microscopy of spray-dried microcapsules

The SEM images of surface structures of samples clearly showed that the all of microcapsules were spherical and the type of wall materials influenced only the sizes of the microcapsules (Fig. 2). The microcapsules prepared with SSPS and GA are almost similar shape (both spherical with some dents on the surfaces) and also consistent in their sizes. Microcapsules prepared with MD have smooth surfaces (with a little dented area) but they are inconsistent in their sizes. Figure 2c shows that small particles from MD were joined to each other and formed the larger agglomerated particles. The dented surfaces of the spray-dried samples were attributed to their shrinkage during the drying process (Janiszewska and Witrowa-Rajchert 2009).

Storage stability of microencapsulated canthaxanthin

Microencapsulated canthaxanthin were stored at 4, 25, and 45 °C in dark and light conditions for 16 weeks and their storage stabilities were determined by measuring their total canthaxanthin contents during the storage period on a weekly basis (Fig. 3). Total canthaxanthin contents (i.e., the retention values) were decreased when the storage temperature increased. Microcapsules prepared with SSPS and GA exhibited higher retention values when compared to those of MD. Therefore, MD was not an effective wall material for

preventing the oxidation of canthaxanthin. This is due to the lack of its emulsification ability and low film-forming capacity (Loksuwan 2007). SSPS, GA and maltodextrin have also been applied for the encapsulation of linoleic acid (Minemoto et al. 2002) and arachidonyl ascorbate (Watanabe et al. 2004). In agreement with the results of the current study, SSPS in the above studies were reported to be more effective wall material for the encapsulation and improvement of the stability of the lipophilic cores than were GA and maltodextrin. The hydrophobic peptides present in SSPS and GA are adsorbed on the surfaces of oil droplets and act as an anchor and consequently create a strong protective film around the oil droplets in the emulsion (Nakamura et al. 2004a). The findings from the current study showed that SSPS could protect canthaxanthin more than GA. SSPS contains higher hydrophobic peptide levels than do GA (Madea and Nakamura 2009).

It was observed that the temperature influenced retention of canthaxanthin in microcapsules during storage. Figure 3 shows the losses of canthaxanthin in samples at 45 °C in both dark and light conditions were greater than those at other temperatures. However, light did not show significant effect on the total canthaxanthin content in the microcapsules at 45 °C, which is in good agreement with the study of Wagner and Warthesen (1995), who investigated the stabilities of encapsulated α and β -carotenes with MD at the same conditions.

The retention percentage of canthaxanthin in the microencapsulated samples prepared with SSPS, GA and MD stored for 16 weeks at 25 °C were 75, 72, and 57, respectively, for dark conditions and 58, 53, and 26, respectively, for light conditions. It was observed that light influenced significantly ($P<0.05$) on the retention of canthaxanthin in stored samples at 25 °C. Barbosa et al. (2005) also observed the significant effect of light on encapsulated bixin at 21 °C. The result of present work was contradicted by Cinar (2004), who freeze-dried enzyme extracted carotenoid pigments from orange peel, sweet potato and carrot samples and stored at 25 °C for 45 days and showed the effect of the light on the all three freeze-dried pigments was not significant.

Figure 3 shows the storage of microcapsules at 4 °C provides the minimum loss of pigments. The retention

Fig. 2 SEM micrographs of spray-dried microencapsulated canthaxanthin particles prepared with soluble soybean polysaccharide (a), gum acacia (b), and maltodextrin (c)

percentage of canthaxanthin at this temperature for the samples prepared with SSPS, GA and MD over the 16 weeks of storage were 95, 93, and 84, respectively, for dark conditions and 88, 86, and 74, respectively, for light conditions.

Fig. 3 Changes in the retention of canthaxanthin in the spray-dried microcapsules prepared with SSPS, GA, and MD over 16 weeks of storage at different temperatures (4, 25, and 45 °C) in light (a) and dark (b) conditions. $n=3$

The light indicated significant effect ($P<0.05$) on the retention of canthaxanthin during the storage at 4 °C; similar results were also found by Pesek and Warthesen (1987) who reported the deterioration of α and β -carotene in a vegetable juice system was accelerated by exposure to light at 4 °C.

Conclusion

The canthaxanthin produced by *D. natronolimnae* HS-1 was stabilized by spray drying microencapsulation using SSPS, GA, and MD as wall materials. The type of wall materials did not influenced moisture content and shape of particles during process. The size of emulsion droplets and spray-dried powders were significantly affected by the type of wall materials. The emulsions and microcapsules prepared with SSPS showed the smaller size in emulsions and powders. The low

surface canthaxanthin contents were observed for SSPS which indicated better ME. SSPS provided good retention for canthaxanthin during the storage process. Due to its good emulsifying and film forming properties, SSPS was found to be a better wall material for microencapsulation of canthaxanthin as compared to GA and MD. According to the present work, light and high temperatures were drastic factors to the stability of microencapsulated samples due to the acceleration of degradation phenomena on the carotenoids. Further work is needed with other wall materials and encapsulation processes to find about the canthaxanthin maintenance.

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References

- Ausich RL (1997) Commercial opportunities for carotenoid production by biotechnology. *Pure Appl Chem* 69:2169–2173
- Barbosa MI, Borsarelli CD, Mercadante AZ (2005) Light stability of spray-dried bixin encapsulated with different edible polysaccharide preparations. *Food Res Int* 38:989–994
- Bhosale P, Bernstein PS (2005) Microbial xanthophylls. *Appl Microbiol Biotechnol* 68:445–455
- Buzzini P (2000) An optimization study of carotenoid production by *Rhodotorula glutinis* DBVPG 3853 from substrates containing concentrated rectified grape must as the sole carbohydrate source. *J Ind Microbiol Biotechnol* 24:41–45
- Cinar I (2004) Carotenoid pigment loss of freeze-dried plant samples under different storage conditions. *Food Sci Technol LEB* 37:363–367
- Desai K, Park J (2005) Recent developments in microencapsulation of food ingredients. *Dry Technol* 23:1361–1394
- Desobry SA, Netto FM, Labuza TB (1997) Comparison of spray-drying, drum drying and freeze-drying for β -carotene encapsulation and preservation. *J Food Sci* 62:1158–1162
- Dian NL, Sudian N, Yusoff MS (1996) Palm-based oil as affected by type of wall material. *J Sci Food Agric* 70:422–426
- Dickinson E, Murray BS, Stainsby G, Anderson DM (1988) Surface activity and emulsifying behaviour of some Acacia gums. *Food Hydrocoll* 2:477–490
- Higuera-Ciajara I, Felix-Valenzuela L, Goycoolea FM, Argüelles-Monal W (2004) Microencapsulation of astaxanthin in a chitosan matrix. *Carbohydr Polym* 56:41–45
- Janiszewska E, Witrowa-Rajchert D (2009) The influence of powder morphology on the effect of rosemary aroma microencapsulation during spray drying. *Int J Food Sci Technol* 44:2438–2444
- Khodaiyan F, Razavi SH, Emam-Djomeh Z, Mousavi SM, Hejazi MA (2007) Effect of culture conditions on canthaxanthin production by *Dietzia natronolimnaea* HS-1. *J Microbiol Biotechnol* 17:195–201
- Liu XD, Atarashi T, Furuta T, Yoshii H, Aishima S, Ohkawara M, Linko P (2001) Microencapsulation of emulsified hydrophobic flavors by spray drying. *Dry Technol* 19:1361–1374
- Loksuwan J (2007) Characteristics of microencapsulated β -carotene formed by spray drying with modified tapioca starch, native tapioca starch and MD. *Food Hydrocoll* 21:928–935
- Madea H, Nakamura A (2009) Soluble soybean polysaccharide. In: Phillips GO, Williams PA (eds) *Handbook of hydrocolloids*. CRC, Boca Raton, pp 693–706
- McNamee B, O'Riordan ED, O'Sullivan M (1998) Emulsification and microencapsulation properties of gum Arabic. *J Agric Food Chem* 46:4551–4555
- Minemoto Y, Fang X, Hakamata K, Watanabe Y, Adachi S, Kometani T, Matsuno R (2002) Oxidation of linoleic acid encapsulated with soluble soybean polysaccharide by spray drying. *Biosci Biotechnol Biochem* 66:1829–1834
- Nakamura A, Takahashi T, Yoshida R, Maeda H, Corredig M (2004a) Emulsifying properties of soybean soluble polysaccharide. *Food Hydrocoll* 18:795–803
- Nakamura A, Yoshida R, Maeda H, Furuta H, Corredig M (2004b) Study of the role of the carbohydrate and protein moieties of soy soluble polysaccharides in their emulsifying properties. *J Agric Food Chem* 52:5506–5512
- Nasrabadi MR, Razavi SH (2010) Use of response surface methodology in a fed-batch process for optimization of tricarboxylic acid cycle intermediates to achieve high levels of canthaxanthin from *Dietzia natronolimnaea* HS-1. *J Biosci Bioeng* 109:361–368
- Nunes IL, Mercadante AZ (2007) Encapsulation of lycopene using spray-drying and molecular inclusion processes. *Braz Arch Biol Technol* 50:893–900
- Parize AL, de Souza TCR, Brighente IMC, de Fávère V, Laranjeira MCM, Spinelli A, Longo E (2008) Microencapsulation of the natural urucum pigment with chitosan by spray drying in different solvents. *Afr J Biotechnol* 7:3107–3114
- Pesek CA, Warthesen JJ (1987) Photodegradation of carotenoids in a vegetable juice system. *J Food Sci* 53:744–746
- Razavi SH, Fabrice B, Marc I (2006) UV-HPLC/APCI-MS method for separation and identification of the carotenoids produced by *Sporobolomyces ruberrimus* H110. *Iran J Chem Chem Eng* 25:1–10
- Rodríguez-Huezo ME, Pedroza-Islas R, Prado-Barragán LA, Beristain CI, Vernon-Carter EJ (2004) Microencapsulation by spray drying of multiple emulsions containing carotenoids. *J Food Sci* 69:351–359
- Rosenberg M, Kopelman IJ, Talman Y (1990) Factors affecting retention in spray drying microencapsulation of volatile materials. *J Agric Food Chem* 38:1288–1294
- Sagar VR, Suresh Kumar P (2010) Recent advances in drying and dehydration of fruits and vegetables: a review. *J Food Sci Technol* 47(1):15–26
- Sewram V, Raynor MW (2000) Supercritical fluid chromatography of carotenoid pigments. In: Wilson ID, Adlard ER, Cooke M, Poole C (eds) *Encyclopedia of separation science*. Academic Press Ltd, London, pp 2245–2252
- Shu B, Yu W, Zhao Y, Liu X (2006) Study on microencapsulation of lycopene by spray-drying. *J Food Eng* 76:664–669
- Sootitawat A, Yoshii H, Furuta T, Ohkawara M, Linko P (2003) Microencapsulation by spray drying: influence of emulsion size on the retention of volatile compounds. *J Food Sci* 68:2256–2262
- Wagner LA, Warthesen JJ (1995) Stability of spray-dried encapsulated carrot carotenes. *J Food Sci* 60:1048–1053
- Watanabe Y, Fang X, Adachi S, Fukami H, Matsuno R (2004) Oxidation of 6- O-arachidonoyl l-ascorbate microencapsulated with a polysaccharide by spray-drying. *Food Sci Technol LEB* 37:395–400