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ORIGINAL ARTICLE

Shelf life and storage stability of spray-dried bovine colostrum powders under different storage conditions

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Abstract Spray dried bovine colostrum (SDBC) powders were packaged in aluminium-laminated polyethylene (ALPE) and polyethylene terephthalate (PET) pouches and then stored under different conditions (25 °C and 50 % relative humidity (RH), 4 °C and 40–70 % RH, 50 °C and 20–50 % RH). The shelf life of SDBC powder was evaluated as 425.5 and 86.5-days in ALPE and PET pouches under 25 °C and 50 % RH, respectively. The storage stability of SDBC powder in terms of quality parameters including thiobarbituric acid (TBA), hydroxymethyl furfural (HMF), colour change, moisture content and IgG concentration was studied in both packaging materials under different storage conditions. Results showed that ALPE pouches were more suitable for packaging SDBC powder than PET pouches and storage condition of 4 °C and 40–70 % RH was relative suitable for keeping quality of SDBC powder. The glass transition concept was helpful for evaluating the chemical stability of SDBC powder during storage.

Keywords Shelf life · Glass transition concept · Storage stability · Bovine colostrum powder · IgG · Spray drying

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Introduction

With the upsurge of seeking for more healthy food and lifestyle, consumers are becoming more aware of the relationships between diet and disease and greatly concerned about functional foods with health benefits. In the past decades, colostrum-based products have received much attention and become one of the most popular functional foods (Mehra et al. 2006). Bovine colostrum is the initial milk secreted by cow during the first 4 days after calving (Gopal and Gill 2000), which is rich in established nutrients such as fat, casein, lactose and salts and is also characterised by more bioactive components, including immunoglobulins (Igs), especially IgG, growth factors, as well as lactoferrin, lactoperoxidase and lysozyme (Elfstrand et al. 2002). The fortification of immunity against diseases by oral administration (passive immunization) of immunoglobulin preparations has been found to be effective in experiments with animals as well as in human clinical trials (Mietens et al. 1979). It also has been reported that Igs can lower cholesterol in those people with hypercholesterolaemia, which is a risk factor of cardiovascular disease (Earnest et al. 2005). Thus, it is extensively suggested that immunoglobulins be added into infant formula and other foods to fortify the immunity of young children (Facon et al. 1993). At present, colostrum-based products have been being industrially produced in Australia, New Zealand, USA and China, marketed as a health food supplement after standardizing their IgG content (Cao et al. 2007).

Current commercial colostrum-based products are commonly in the form of spray dried or freeze dried powders. Dehydration can facilitate subsequent processing and handling, prolong shelf life and reduce related cost (Chelack et al. 1993). Moreover, choosing the appropriate storage conditions and packaging materials is of great importance to keep after-drying food qualities and extend shelf life. In recent years, aluminium foil/plastic film laminates have been introduced as replacements for the traditional tinplate cans

(Tehrany and Sonneveld 2010). Flexible packages can reduce the volume of traditional packaging, cut down transport and packaging costs, require fewer materials, and thus minimize post-consumer waste (Twede and Goddard 1998). So it is valuable to investigate preservation effect of aluminium foil/plastic film laminates on quality attribute of food materials to obtain more suitable packaging materials.

Moreover, the shelf life of food powder is not only determined by the package materials, but also by external environmental factors such as temperature and relative humidity. During storage, the qualities of spray dried bovine colostrum (SDBC) powder including colour, flavour and bioactive components are affected by external factors and have received more concern by consumers and food manufactures. Common quality deterioration of such products as SDBC powder by inappropriate storage conditions are browning, development of an unpleasant stale flavour as a result of generation of insoluble compounds from the Maillard reaction (Kumar and Mishra 2004; Mistry and Pulgar 1996; Pereyra Gonzales et al. 2010) and lipid oxidation (Kumar and Mishra 2004; Nielsen et al. 1997; Stapelfeldt et al. 1997), loss of bioactive components because of protein denaturation, and lumpiness (Tehrany and Sonneveld 2010). For practical usage of immunoglobulins as supplements to foods, their stability under different food processing and storage conditions should be determined. Several reports have been published on stability of bovine immunoglobulins in fluid milk or bovine colostrum to homogenization, heat and ultrasonic treatments (Cao et al. 2007; Fukumoto et al. 1994; Li-Chan et al. 1995). However, little information has been reported about stability of Igs in SDBC powder during storage.

In many instances, the water activity concept combined with the glass transition concept has been recommended to employ in assessing process-ability, deterioration, food stability, and shelf-life predictions (Sablani et al. 2007a, b, 2011; Rahman 2006, 2009, 2010). The state diagram of SDBC powder has been constructed and the glass transition temperatures of SDBC powders at given moisture content can be evaluated from the state diagram. In addition, water adsorption isotherms of FDBC powders at different temperatures have been reported by Yu et al. (2013). Evaluating the storage stability of food materials using water activity or/and glass transition concepts has been validated by many researchers (Sablani et al. 2007a, b; Bell and White 2000; Chen et al. 1999).

The objectives of this paper were to predict the shelf life and evaluate physicochemical and biochemical stability of spray dried bovine colostrum (SDBC) powder packaged in aluminium-laminated polyethylene (ALPE) and polyethylene terephthalate (PET) pouches under storage condition of 25 °C (room temperature) and relative humidity (RH) of 50 %, in order to choose suitable packaging material, and then investigate physicochemical and biochemical stability of SDBC powder packaged in the more suitable packaging material (ALPE pouches) based on the glass transition concept or the water activity concept under different storage conditions (4 °C and 40–70 % RH, 25 °C and 50 % RH, 50 °C and 20–50 % RH) so as to obtain the optimum storage condition.

Materials and method

Preparation and handling of SDBC powders

Bovine colostrum powders used in the storage experiment were obtained by drying the fresh bovine colostrum provided by dairy farm of Bright Dairy & Food Co., Ltd (Shanghai, China) in a mini–scale spray dryer (Shandong Tianli Drying Equipment Inc., Jinan, Shandong province, China). Fresh bovine colostrums were employed with a constant total solids mass concentration of 11.13±0.01 %, containing fat 2.28±0.02 %, protein 4.93±0.01 %, lactose 2.96±0.01 %, and ash 0.956±0.002 %. The spray dryer with concurrent regime and a two-fluid nozzle atomizer was used for the spray drying process. The atomizer with an inside diameter of 0.47 mm employed compressed air with a flow rate that was controlled by a variable area flow meter. Feed was metered into the dryer by means of a peristaltic pump. Inlet drying air, after passing through an electrical heater, flowed concurrently with the spray through the main chamber. The main chamber was made of thick transparent glass. According to preliminary experiments (Yu et al. 2010) and working capacity of spray dryer, the low temperature spray-drying conditions were the atomizer pressure of (0.7±0.01) MPa, the feed temperature of (32±1)°C, the feed rate of (160±20)mL h^{-1}, air inlet temperature of (125±1)°C, drying air flow rate of (0.78±0.01)m^3 min^{-1} and compressed air flow rate of (300±10)L h^{-1}. The outlet air temperature was measured for 48.9±1.3 °C with a thermocouple. The SDBC powder obtained was stored in a desiccator with silica gel until used.

The SDBC powder samples (12±0.5 g) with initial moisture content of 3.83 g H_2O/100 g dry solids were placed in aluminium-laminated polyethylene (ALPE, 100 μm; PET, 12 μm; Al, 8 μm; PE, 80 μm) pouches (155 mm×135 mm) and polyethylene terephthalate (PET, 111 μm; PET, 12 μm; SiO_x, 9 μm; NY; 15 μm; R-CPP, 65 μm) pouches (130-mm×135 mm) and were closed by heat sealing, avoiding any air space but without vacuum application. The water vapour permeability, k (kg m^{-2} day^{-1} Pa^{-1}), of the packaging materials (ALPE and PET) was measured using a water vapour permeability analyser (Mocon Permatran-W, 3/61, Mocon Inc., Minneapolis, MN, U.S.A.). The glass transition temperature (T_g) of the samples with initial moisture content of 3.83 g H_2O/100 g dry solids was estimated for 40 °C based on the state diagram of SDBC powder. Therefore, the upper limit of storage temperatures was chosen as 50 °C (10 °C more than T_g) since the amorphous matrix at temperature 10 °C above T_g begins to become sticky (Labuza 1995).

Two different experiments were designed. In the first experiment, shelf life and storage stability of SDBC powder at different packaging materials (ALPE and PET) was evaluated. Every six samples of ALPE and PET pouches were placed in a Binder constant climate chamber (Constant climate chamber KBF series, Binder GmbH, Tuttlingen, Germany) setting the temperature at 25 °C (room temperature) and 50 % RH (storage condition 1). In the second experiment, storage stability of SDBC powder packaged in ALPE pouches under different storage conditions was evaluated. Every six samples of ALPE pouches were placed in a Binder constant climate chamber (Constant climate chamber KBF series, Binder GmbH, Tuttlingen, Germany) setting the temperature at 50 °C and 20–50 % RH (relative humidity of local environmental atmosphere in the chamber) (storage condition 2) and in a refrigerator (Haier BCD-196F refrigerator, Haier Group, Qingdao, China) setting the temperature at 4 °C and 40–70 % RH (relative humidity of local environmental atmosphere in the refrigerator) (storage condition 3), respectively. Storage procedure was carried out for 90 days. Every three samples of ALPE and PET pouches under different storage conditions were taken out from the chambers at the time of 15d, 30d, 45d, 60d, 75d, and 90d during 90 days' storage respectively and analysed for physicochemical and biochemical changes.

Prediction of shelf life

The shelf life was calculated using the following equation (Hernandez and Giacin 1997):

$$t = \frac{W}{A \cdot P(T) P_s} \int_{M_0}^{M_c} \frac{dM}{[a_w(e) - a_w(M,T)]} \tag{1}$$

Where t is the storage time, day; W is dry weight of SDBC powder, g; P(T) is permeability constant of the package at certain temperature, g m^{-2} day^{-1} Pa^{-1}; P_s is saturated vapour pressure of water at temperature; A, area of the package, m^2; M is the moisture content, % dry basis; M_0 is initial moisture content, % dry basis; M_c is the critical moisture content, % dry basis; $a_w(e)$ is water activity external to the package; $a_w(M,T)$ is internal water activity given as a function of temperature and moisture content of the product; T is temperature, K. The internal water activity, $a_w(M,T)$, can be obtained from the moisture adsorption isotherm.

Physicochemical and biochemical tests

Moisture content

The moisture contents of SDBC powders at different stages were determined using AOAC method 927.05 (AOAC 1990) and the results were expressed as % (dry basis).

Lipid oxidation

Lipid oxidation was evaluated spectrophotometrically using the thiobarbituric acid (TBA) test (Kumar and Mishra 2004) and the results were expressed as optical density measured at 532 nm.

Hydroxymethylfurfural (HMF)

The total HMF content was determined following the method (Mistry and Pulgar 1996) and the results were expressed as μmol of HMF per kg of powder (dry basis).

Colour change

The colour values of powder samples were measured as CIE parameters L, a, and b using a colour difference meter (Model WSC-S, Shanghai precision & scientific instrument co., Ltd, Shanghai, China). The L, a, and b values of the stored powder were measured and the net (total) colour difference (ΔE) was calculated using Eq. (2) using SDBC powder at the initial day of the storage period as a reference:

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \tag{2}$$

Single radial immunodiffusion (SRID) test

An aliquot (1±0.1) g samples of SDBC powder was assayed for IgG concentration by the SRID procedure (Fukumoto et al. 1994), and the results were expressed as % (dry basis). The samples were prepared by acid coagulation procedure (David et al. 2006).

Statistical analysis

Data for physicochemical and biochemical properties were expressed as means ± standard deviation of three replicates and subjected to the analysis of variance (ANOVA) using the SAS9.2 software program (SAS Institute Inc., NC, USA). The factors included in the models were packaging materials (ALPE and PET), storage conditions (25 °C and 50 % relative humidity (RH), 4 °C and 40–70 % RH, 50 °C and 20–50 % RH) and storage time (0, 15, 30, 45, 60, 75, and 90 days). The equation predicting shelf life of SDBC powder was analysed using the Mathematica 6.0 software program (Wolfram Research, Inc., IL, USA). $P<0.05$ was regarded as statistically significant.

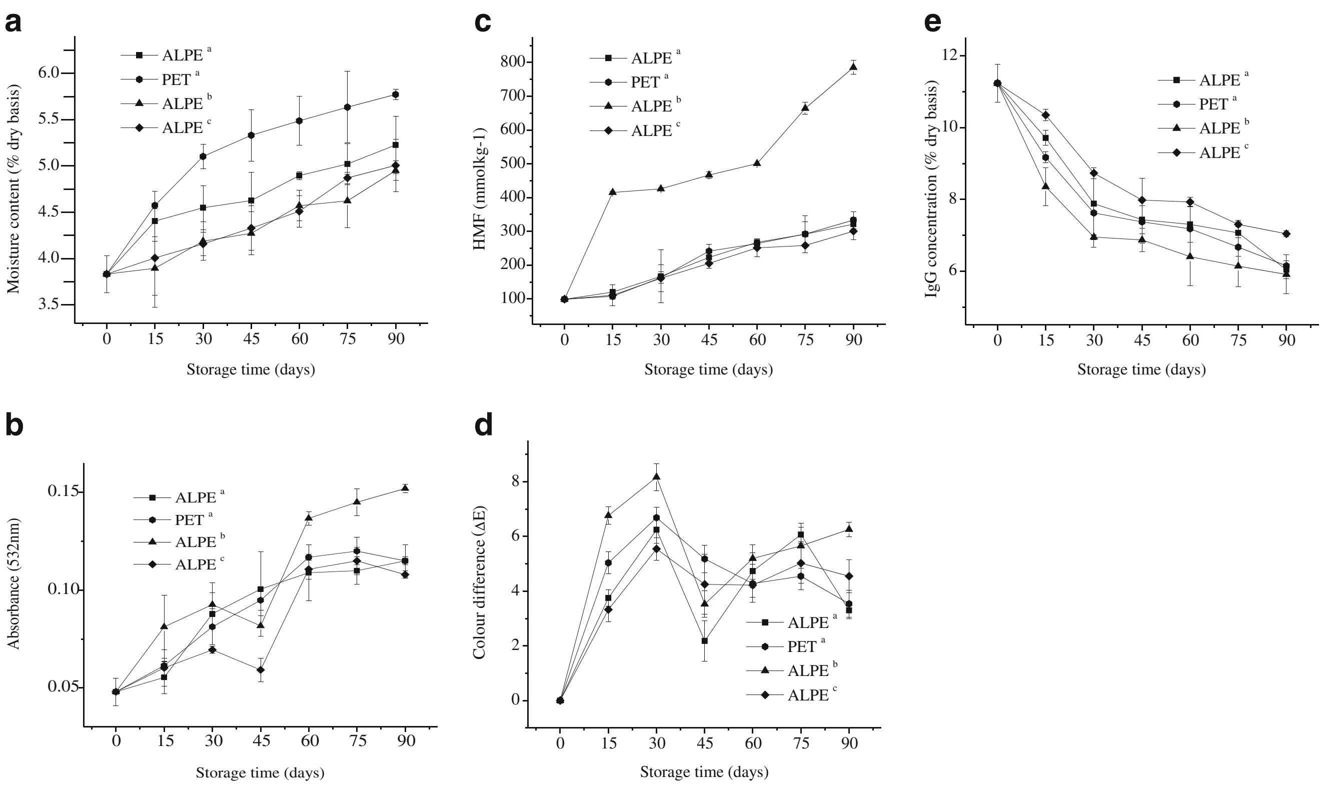

Fig. 1 Change in quality characteristics of SDBC powder packaged in ALPE and PET pouches under different storage conditions during storage (n=3), **a,** moisture content, **b**, TBA, **c**, HMF, **d**, colour difference (△E), **e**, IgG concentration. [a] mean 25 °C and 50%RH, [b] mean 50 °C and 20–50%RH, [c] mean 4 °C and 40–70%RH

Results and discussion

Shelf life of SDBC powder packaged in ALPE and PET pouches

Packaged SDBC powders at a certain storage period are subjected to moisture gain depending on a number of factors including the storage temperature and relative humidity, the sorption properties of the product, the water activity gradients relative to the storage atmosphere, and the water vapour permeability of the packaging materials (Hernandez and Giacin 1997). The final moisture content was decided based on the free flowability of the powder and its water activity. This moisture content was considered as critical moisture content and the corresponding water activity was calculated using the GAB parameters (Ramachandra and Rao 2011). According to the preliminary results, the estimated GAB parameters M_m, C and K at 25 °C were 3.983 % dry basis, 39.804 and 0.957, respectively. The integral part of equation was estimated between the limits of initial moisture content: 3.832 % (dry basis) and

Table 1 ANOVA for physicochemical and biochemical properties of SDBC powder packaged in ALPE and PET pouches (n=3)

Source of variation	df	MSS				
		Colour change	Moisture content	TBA	HMF	IgG concentration
Packaging material (PM)	1	0.64	0.72^a	5.8×10^{-5b}	7.07	0.12
Storage period (SP)	6	8.22^b	0.65^a	1.56×10^{-3}	15875.38^a	6.15^a
Error	6	1.01	3.44×10^{-2}	1.84×10^{-4}	55.05	2.66×10^{-2}

SDBC spray dried bovine colostrum; *ALPE* aluminium-laminated polyethylene; *PET* polyethylene terephthalate; *TBA* thiobarbituric acid; *HMF* hydroxymethyl furfural; *IgG* immunoglobulin G

[a] mean significant at P<0.01

[b] mean significant at P<0.05

critical moisture content: 5.707 % (dry basis). The area, A, of ALPE and PET pouches was 0.04185 and 0.0351 m^2, respectively. $A_w(e)$ in this experiment was 50 %, equal to the relative humidity in the climate chamber. The amount of dry solids, W, in the 12 g powder was 11.557 g. P_s at 25 °C is 3.169×10^3 Pa. Water vapour permeability, P(T), of the ALPE and PET pouches were experimentally determined as 1.58×10^{-8} and 9.49×10^{-8} kg m^{-2} day^{-1} Pa^{-1}, respectively. By putting the values of W, P(T), A, Ps, M_i, M_c in the equation, shelf life of SDBC powder were estimated as 425.5 and 86.5 days in ALPE and PET pouches under the storage condition 1, respectively, so it was obvious that the preservation effect of ALPE was much better than PET.

Storage stability of SDBC powder under different storage conditions

The variation in moisture content of SDBC powder packaged in ALPE and PET pouches under different storage conditions was shown in Fig. 1a. There was a progressive increase in moisture content of the samples in both packaging materials. The moisture gained by powders packaged in PET pouches was higher than that in ALPE pouches during the 90 days storage period, mainly due to the higher water vapour permeability of PET pouches, indicating that ALPE pouches provided better barrier to water vapour for SDBC powder. Similar results were reported by Mridula et al. (2010), who found the moisture gained by two sattu samples in laminated aluminium foil pouches was lower than those in low density polyethylene pouches. It can be also found that the moisture gained by SDBC powders packaged in the ALPE pouches under storage condition 1 was higher than that under other storage conditions, mainly contributed to higher levels of relative humidity of storage environment. Statistical analysis showed that moisture content of SDBC powder during the storage time was significantly affected by packaging materials, storage conditions and storage time (Table 1). which was consistent with the results obtained by Kumar and Mishra (2004), Ramachandra and Rao (2011) and Agrahar-Murugkar and Jha (2011).

The variation of water activity and the $T-T_g$ (the difference between storage temperature and T_g) of SDBC powders as a function of storage time was predicted by using water adsorption isotherms and the state diagram, respectively, and presented in Fig. 2. Lipid oxidation during processing and storage of milk-based products with fat is unexpected, makes the products off-flavour, lowers the product quality and reduces the shelf life. The rate of oxidation during storage is mostly affected by composition of fatty acids, degree of unsaturated fatty acids, presence of antioxidants, and process and storage conditions such as temperature, relative humidity, and light exposure (Tehrany and Sonneveld 2010). The TBA value has been used as a measurement of the formation of secondary lipid oxidation products by some authors (Koç et al. 2010), e.g. carbonyls, which are responsible for the sensory impact of lipid oxidation. As shown in Fig. 1b, TBA values of SDBC powder packaged in ALPE and PET pouches showed an increase trend with time increasing. Although there was a significant difference ($p<0.05$) in the water activities of SDBC powders in two pouches (Fig. 2-a), the difference between them was not significant at the same storage time ($p>0.05$), probably indicating that reaction rate of lipid oxidation was not significantly affected by variation of water activity at 25 °C when a_w was lower than 0.24. In addition, the $T-T_g$ of SDBC powders in ALPE and PET pouches was higher than −10 °C, meaning that SDBC powders in both pouches was in the glassy state, and at this state, the rate of chemical reaction was relative low, which was the possible reason of no significant difference between TBA values of SDBC powders in ALPE and PET pouches. The results were also explained by the reason that the encapsulated oil was released and then underwent rapid oxidation as a consequence of the crystallization of amorphous lactose occurring above glass transition of SDBC powders (Rahman 2007). Moreover, TBA values of SDBC powder packaged in ALPE pouches under storage condition 2 were generally higher than those of packaged powders under storage conditions 1 and 3 during the whole storage period, which was attributed to higher reaction rate when the powders occurred at the rubbery state under storage condition 2 (Fig. 2b). TBA values of SDBC powder packaged in ALPE pouches under storage conditions 1 and 3 became steady up to 60 days, which was in agreement with the results obtained by Stapelfeldt et al. (1997), who reported that TBA increased steadily in milk powder stored at 45 °C for 60 days.

The Maillard reaction is one of the most undesirable reactions that can occur during processing and storage of milk powder, because it can result in the loss of nutritional quality and the decrease of appearance. HMF is the compound formed during an early stage of Maillard degradation and has been recognised as a classical index of the browning process in milk products (Kuo-Hui and Fennema 1989). Maillard reaction rate is affected by water content, storage temperature, system composition, and pH. As shown in Fig. 1c, the HMF contents of SDBC powder packaged in PET and ALPE pouches increased from 98.7 μ mol kg^{-1} to 333.2 and 300.5 μ mol kg^{-1}, respectively, after 90 days of storage under storage condition 1, which were lower than those of whey protein concentrate with high lactose content obtained by Kuo-Hui and Fennema (1989). Production of HMF was partly related to the amount to lactose present in the dairy powder such as non-fat dry milk and whey protein concentrate (Mistry and Pulgar 1996). Statistical analysis showed that packaging material had no significant effect on HMF content. The HMF contents of SDBC powder packaged in ALPE pouches under three storage conditions showed a steady increase as storage time increased, and increased with temperature increasing as expected. The HMF contents of SDBC powder under condition 2 were higher than those under conditions 1 and 3, which was possibly attributed to the rubbery

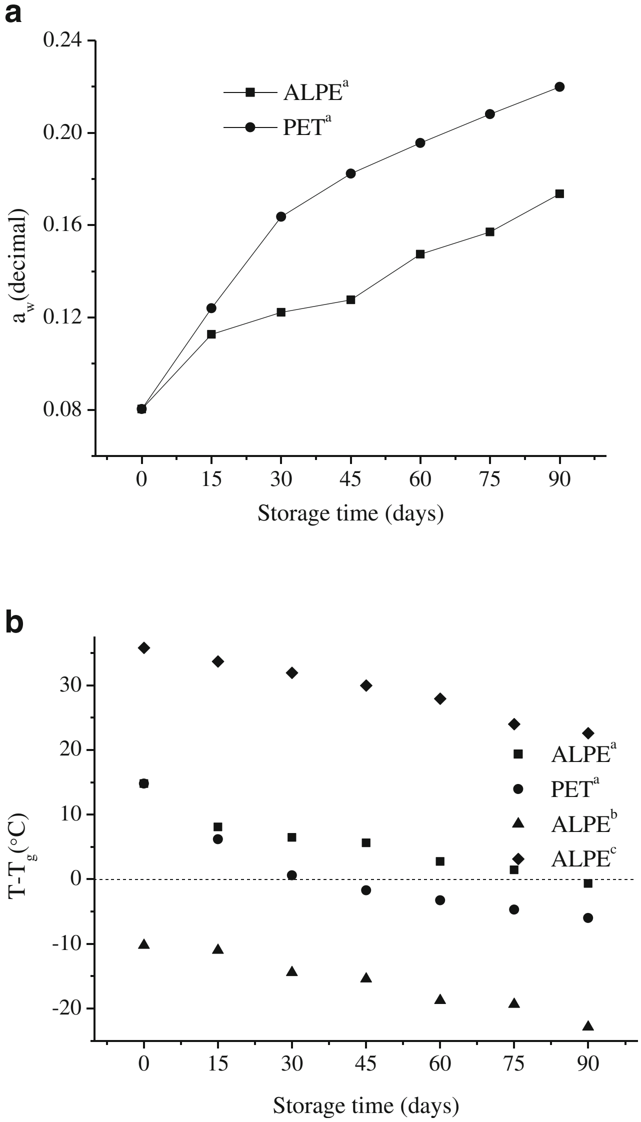

Fig. 2 Variation of water activity (**a**) and the difference (T-T_g) between storage temperature and glass transition temperature (**b**) with different storage time

state of the powders under condition 2 (Fig. 2b). In the literature, it was verified that the rate of the reaction was low at temperatures below glass temperature and increased with increase in T-T_g (Rahman 2007). In addition, the increase in water activity due to the increase of water content during storage of SDBC powders may favour the development of the non-enzymatic browning reactions (Rossini et al. 2011). The HMF contents were significantly affected by both storage conditions and storage period (Table 2), which was similar to the finding by Mistry and Pulgar (1996).

Changes of colour difference ($\triangle E$) of SDBC powder showed an increase trend as storage time increased during the storage period (Fig. 1d) at all storage conditions investigated in this experiment. There was no difference in $\triangle E$ between packaging materials ($p>0.05$) and storage time had significant effects on $\triangle E$ ($p<0.01$). Changes of $\triangle E$ under storage condition 2 were generally the highest during almost all storage period, mainly due to that fat oxidation and Maillard reaction can be accelerated by higher temperature. Moreover, Changes of $\triangle E$ under storage condition 1 were close to those under storage condition 3, indicating that choosing room temperature or refrigerator temperature for storing SDBC powder showed an equivalent effect for inhibiting colour changes. Statistical analysis showed that $\triangle E$ was significantly affected by storage condition. Nielsen et al. (1997) and Koç et al. (2010) also reported that the powdered milk gradually turned darker and yellower with increasing storage time.

The predominant immunoglobulin type present in bovine colostrum and milk was IgG, and thermal stability and bioactivity of IgG determined the quality and shelf life of SDBC powder. IgG concentration changes of SDBC powder packaged in ALPE and PET pouches under different storage conditions were illustrated in Fig. 1e and showed a progressive decrease with storage time. It can be seen that IgG concentration in PET pouches decreased faster than that in ALPE pouches, but the difference in IgG concentration between SDBC powder in ALPE and PET pouches was not

Table 2 ANOVA for physicochemical and biochemical properties of SDBC powder packaged in ALPE pouches under different storage conditions ($n=3$)

Source of variation	df	MSS				
		Colour change	Moisture content	TBA	HMF	IgG concentration
Storage temperature (ST)	2	3.85[b]	0.20[a]	1.03×10^{-3}[b]	175670.68[a]	2.72[a]
Storage period(SP)	6	13.52[a]	0.55[a]	2.81×10^{-3}[a]	45571.23[a]	8.87[a]
Error	12	0.89	9.64×10^{-3}	1.49×10^{-4}	7298.81	0.13

SDBC spray dried bovine colostrum; *ALPE* mean aluminium-laminated polyethylene; *PET* polyethylene terephthalate; *TBA* thiobarbituric acid; HMF hydroxymethyl furfural; *IgG* immunoglobulin G

[a] mean significant at $P<0.01$

[b] mean significant at $P<0.05$

Table 3 Non-linear regression analysis of IgG concentration changes from zero and first order reaction kinetics of SDBC powder packaged in ALPE and PET pouches under different storage conditions

Conditions	Zero order			First order			
	C_0	K_0	R	C_1	K_1	R	D value (days)
ALPE25[a]	10.39	−0.051	0.92	10.49	−0.0061	0.94	366.1
ALPE4[b]	10.74	−0.046	0.94	10.80	−0.0052	0.96	435.3
ALPE50[c]	9.65	−0.050	0.83	9.58	−0.0063	0.88	340.2
PET25[d]	10.13	−0.049	0.9	10.07	−0.0060	0.93	365.6

SDBC spray dried bovine colostrum; *ALPE* mean aluminium-laminated polyethylene; *PET* polyethylene terephthalate; *IgG* immunoglobulin G

[a] mean ALPE pouches under storage condition 1

[b] mean ALPE pouches under storage condition 3

[c] mean ALPE pouches under storage condition 2

[d] mean PET pouches under storage condition 1

significant ($p>0.05$). As expected, IgG concentration of SDBC powder packaged in ALPE pouches showed a decrease as temperature increased, due to higher protein denaturation at higher temperature. Changes of IgG concentrations were significantly affected by both storage temperature and storage time (Table 2). In contrast, Husu et al. (1993) reported that Ig molecules seemed to retain their specific activity well in milk powder, irrespective of the storage temperature; the storage of freeze-dried anti-Campylobacter jejuni Igs at 4, 20 and 37 °C had little effect on the immune specificity for up to 12 months of storage. Difference in changes of IgG concentration was possibly contributed to higher temperature that SDBC powders were subjected to during drying than freeze dried powder.

Kinetics of IgG concentration change in SDBC powder during storage

Thermal destruction of IgG was calculated using the thermal death time method described by Ramaswamy et al. (1989). Kinetic modelling is necessary to derive basic kinetic information for a system in order to describe the reaction rate as a function of experimental variables and, hence, to predict changes in a particular food during processing and storage (Van Boekel 1996). The majority of chemical reactions report zero-order (Eq. (3)) or first-order (Eq. (4)) degradation reaction kinetics.

$$C = C_0 \pm kt, \quad (3)$$

$$C = C_0 \exp(\pm kt), \quad (4)$$

Where (+) and (−) indicate formation and degradation of any quality parameter, respectively. In order to determine the reaction rate of IgG denaturation, the kinetics of these parameters were investigated. The constants of kinetics models were presented in Table 3. It can be found on the basis of correlation coefficients (R) that decrease of IgG concentration fitted better with first-order kinetics model than zero-order kinetics model. The same results were reported by Fukumoto et al. (1994) and Li-Chan et al. (1995) for IgG thermal denaturation in fluid milk or colostrum. Neglecting effects of the change of moisture content, D values at temperatures, representing the time for 90 % IgG denaturation at certain temperatures, were calculated with the assumption that decrease of IgG concentrations followed first-order kinetics and listed in Table 3. It can be seen that value k_1 of IgG concentration, representing the reaction rate, increased with temperature increasing, and was the lowest under storage condition 3, indicating that low temperature was more suitable for storing SDBC powder.

Conclusions

The results of this investigation demonstrated that the predicted shelf life of SDBC powder packaged in ALPE and PET pouches was estimated as 425.5 and 86.5 days under storage conditions of 25 °C and 50 % RH, respectively. Moisture content and HMF of SDBC powders under all the storage conditions investigated in this experiment progressively increased with storage time increasing, and TBA and colour change showed an increase trend as storage time increased. In contrast, IgG concentration showed a decrease with storage time increasing. Change of IgG concentration of SDBC powder during storage followed first-order kinetics. Comprehensively considering storage stability of SDBC powders, ALPE pouches were recommended to be more suitable for packaging SDBC powder and storage condition of 4 °C and 40–70 % RH was more suitable for storing SDBC powder. In addition, the glass transition concept was helpful for evaluating the chemical stability of SDBC powder.

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