

Original paper

Microencapsulation of Sodium Bicarbonate Based on Glycerol Monostearate and Konjac Glucomannan Wall Systems by Phase Separation

Baomiao DING^{1,2*}, Quanhui ZHENG¹, Xiangzhou YI¹, Minhsiung PAN², Yishiou CHIOU², Fengwei YAN¹ and Zhenshun LI¹

¹College of Life Science, Yangtze University, Jingzhou Hubei 434025, P.R. China

²Institute of Food Sciences and Technology, National Taiwan University, Taipei 10617, R.O.C.

Received May 11, 2017 ; Accepted December 20, 2017

Sodium bicarbonate microcapsules (SBCM) were prepared by phase separation method using glycerol monostearate (GMS) and konjac glucomannan (KGM) as wall materials. Microscope micrographs clearly showed that SBCM microcapsules were spherical shapes, and the microcapsule morphology could not be changed at 40°C, while it could be destroyed at temperature above 60°C. DSC thermograms implied that SBCM wall materials could be melted at temperature about 59°C. Size distribution indicated that the particle size of SBCM was mainly distributed in the range of 50 µm to 300 µm. SBCM stability was evaluated using the percentage of SBC (sodium bicarbonate) retention, i.e. retention ratio. SBC retention ratio showed that SBCM was highly stable in the temperature range 40–80°C. Furthermore, carbon dioxide (CO₂) release efficiency of SBCM was investigated by pairing the microcapsules with monopotassium phosphate. The CO₂ release ratio of SBCM was very low at temperature below 60°C. However, the release ratio was sharply increased at temperature above 60°C, and CO₂ was almost completely released at 60°C for 10 min. According to the results, the CO₂ release of SBC could be effectively controlled by encapsulating into microcapsules based on GMS/KGM wall materials.

Keywords: leavening agent, differential scanning calorimetry, size distribution, release ratio, temperature-dependent release

Introduction

Sodium bicarbonate (SBC) is a well-known basic leavening agent, and it has been widely applied in baking industry because SBC can decompose and release carbon dioxide (CO₂) during baking processing (Miller, 2016). However, the interaction between SBC and food components (e.g. organic acids, fruit pieces) could result in partial release of CO₂ from the chemical leavening agent during storage. Moreover, SBC as a leavening agent usually releases less than half of theoretically available CO₂ in the batter and dough (Miller, 2016). Furthermore, the residue, sodium

carbonate, could lead to astringent taste, yellowish crumb and surface coloration of products (De Leyn *et al.*, 2014). In order to enhance the leavening ability of SBC and to improve the quality of baking products, leavening acids are generally utilized to neutralize the basic leavening agent, to release CO₂ thoroughly and to remove sodium carbonate (Book and Waniska, 2015). Nevertheless, the coexistence of a basic and an acidic leavener without restriction would lead to rapid and uncontrolled double decomposition reaction, and it would cause SBC loss and CO₂ formation in dough during storage and/or at an inappropriate time, and producing

Abbreviations: SBC: Sodium Bicarbonate; SBCM: Sodium Bicarbonate Microcapsule; GMS: Glycerol Monostearate; KGM: Konjac Glucomannan; CO₂: Carbon Dioxide; MPP: Monopotassium Phosphate; ADI: Acceptable Daily Intake; DSC: Differential Scanning Calorimetry

*To whom correspondence should be addressed.

E-mail: bmding@yangtzeu.edu.cn

baking products with poor quality (Vetter, 2003).

Microcapsules are a controlled-release form of active ingredients which could be dispersed into a few microns to several hundred microns via physical and/or chemical methods (Dordevic *et al.*, 2015). Microencapsulation technology has been extensively researched and applied in many fields, such as pharmaceutical, cosmetic, and food industries (Bakry *et al.*, 2017; Dong *et al.*, 2015). The technology also has been employed to control CO₂ release of leavening agents and to reduce its addition (Lakkis, 2007; Vitaglione *et al.*, 2015). The leavening agents encapsulated in microcapsules could be protected from the external condition, and the stability of core materials could be greatly enhanced. Wall materials used to encapsulate leavening agents could be fat, wax, gum, protein, cellulose and so on (Desai and Park, 2005). Furthermore, the release of core materials could be controlled by adopting appropriate coating materials, which could melt or crumble at baking temperature (Janovsky, 1993). A number of methods have been proposed to prepare microcapsules, and phase separation method of which is commonly employed to effectively encapsulate water-soluble core materials (Jyothi *et al.*, 2010; Madan, 1978). The method was flexible, low-cost, and easy scale-up, when compared with other microencapsulation techniques.

Wall materials play a vital part in microcapsule properties. Glycerol monostearate (GMS) is an important food additive with an unlimited ADI (acceptable daily intake) used as an emulsifying, thickening, preservative agent (FDA, 2016). The food additive is largely applied in the baking industry to add 'body' to the products, and it is occasionally utilized as an antistaling agent for bakery products (Gray and Bemiller, 2003; Orthoefer, 2008). Furthermore, GMS has been adopted to encapsulate water-soluble ingredients as a wall material in food industry due to its good film-forming property (Wang *et al.*, 2016). Konjac glucomannan (KGM), a high-molecular weight water-soluble polysaccharide, is isolated from tubers of *Amorphophallus Konjac* plant. The polysaccharide has very good film-forming ability and the film formed is very stable (Huang *et al.*, 2015). Furthermore, the polysaccharide could be easily complexed with other ingredients to form mixture films. A series of blend films have been prepared based on KGM complexes, such as KGM/chitosan, KGM/gelatin, and KGM/starch (Du *et al.*, 2013). Due to the characteristics, KGM as a wall material has been employed to encapsulate enzymes, cells, and biological agent.

The aims of the present study were to prepare SBC microcapsules (SBCM) by phase separation method using GMS and KGM as wall materials, and to characterize the morphology, thermogram and size distribution, and to evaluate the CO₂ release of SBCM.

Materials and Methods

Materials SBC, GMS, MPP and anhydrous ethanol were obtained from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China). KGM was obtained from Shanghai Yuanye Biological

Science and Technology Co., Ltd (Shanghai, China)

Preparation of SBC microcapsules (SBCM) SBCM was prepared by a nonaqueous phase separation method with minor modification (Zheng *et al.*, 2011). Briefly, GMS 1 g was thoroughly dissolved in 30 mL of anhydrous ethanol at 60°C. KGM 0.2 g and SBC 1 g were added to the GMS ethanol solution, and the mixture was stirred to form a suspension at 500 rpm (IKA RW20 Digital, IKA® Works Guangzhou, China) at 60°C for 2 min. The ethanol suspension was then cooled down to room temperature at 500 rpm, and the mixture of GMS, KGM and SBC was precipitated from the suspension and was separated by decantation. Ten mL of SBC saturated aqueous solution was added to the precipitate and incubation at 30°C and 500 rpm for 10 min. Anhydrous ethanol 100 mL was then added to the aqueous phase, and the suspension was stirred at 30°C and 500 rpm for 10 min, and SBCM was formed. The microcapsules were filtered out and rinsed to remove free SBC by distilled water, and dried using an electric heating air-blowing drier at 30°C.

The amounts of GMS and KGM in the dried SBCM as final products were determined using the periodic acid method (GB/T, 2008) and 3, 5-DNS colorimetric assay (Chua *et al.*, 2012), respectively. The percent recovery of GMS and KGM was $96.28 \pm 3.61\%$ and $98.31 \pm 1.22\%$, respectively. Water content (wt%) of SBCM measured by reduced pressure drying method (GB, 2016) was $1.43 \pm 0.27\%$.

Characterizations of SBCM

Morphology observation of SBCM A SBCM suspension (0.5%) was prepared with 30% (v/w) glycerol. A drop of the suspension was flattened on a microscope slide, and covered with a coverslip. SBCM shapes were observed and photographed using Olympus IX71 inverted microscope equipped with CellSens software.

Analysis of differential scanning calorimetry (DSC) SBCM was thermally scanned on a differential scanning calorimeter (TA instruments DSC Q2000). Each sample of 15 mg was weighed into an aluminum DSC pan and was scanned from 20°C to 80°C at a heating rate of 5°C/min.

Measurement of size distribution The particle sizes of SBCM were measured by laser diffraction technology using a particle size analyzer (Mastersizer 2000, Malvern Instruments Ltd.) at 25°C. The concentration of microcapsules was diluted to 0.1% using distilled water.

Determination of SBC amount in microcapsules The amount of SBC in microcapsules was determined by acid-base titration (GB, 2015). Briefly, SBCM (0.2 g) was added to twenty mL of chloroform (40°C), and the mixture was stirred at 2000 rpm for 3 min using a vortex mixer (XH-J vortex mixer, Jiangsu Jinyi automation instrumentation Co., Ltd., China). SBC was then extracted using distilled water from the mixture for three times (10 mL per time), and the aqueous phase was collected. Methyl orange was used as an indicator, and hydrochloric acid solution

was used sequentially to titrate the aqueous phase until the colour turned from yellow to pink. The SBC amount, encapsulation yield and SBC retention ratio of SBCM were calculated using the following equations, respectively.

$$W_{SBC} = c_{HCl} V_{HCl} \times 84 \quad \cdots \cdots \text{Eq. 1}$$

$$EY_{SBCM} (\%) = W_{SBC} / W_{A_{SBC}} \times 100 \quad \cdots \cdots \text{Eq. 2}$$

$$\text{Retention ratio} (\%) = W_{SBC(A)} / W_{SBC(N)} \times 100 \quad \cdots \cdots \text{Eq. 3}$$

Where, W_{SBC} was the amount of encapsulated SBC; c_{HCl} was the concentration of hydrochloric acid; V_{HCl} was the titrimetric volume of hydrochloric acid solution; 84 was the SBC molar mass; EY_{SBCM} was the SBCM encapsulation yield; $W_{A_{SBC}}$ was the amount of SBC used in the preparation process; $W_{SBC(A)}$ was the SBC amount in microcapsules after incubation in release medium; $W_{SBC(N)}$ was the SBC amount in original SBCM.

Determination of the stability of SBCM Ten samples of SBCM were obtained, and each sample was transferred to a flask. Each sample was incubated in a water bath at a designated temperature (40, 50, 60, 70, and 80°C) for a designated period of time (5 and 10 min), respectively. Then SBCM was washed to remove the release SBC using distilled water, and the SBC retention ratio in microcapsules was determined using acid-base titration (the method as shown above).

Similarly, six samples of SBCM were obtained, and each sample was transferred to a flask. Each sample was placed in a water bath at 60°C and incubated for a designated period of time (5, 10, 15, 20, 25, and 30 min), respectively. And then the SBC retention ratio in microcapsules was determined using acid-base titration (the method as shown above).

Determination of CO₂ release efficiency from SBCM Ten samples were obtained, and each sample containing SBCM (encapsulating SBC 0.5 g) and MPP (0.41 g) was placed into a flask. Each flask was sealed with a rubber stopper, and the flask was connected via a glass tube to a 500-mL flask preloaded NaOH aqueous solution (0.4 M) 100 mL. Each flask was then placed in a water bath at a designated temperature (40, 50, 60, 70, and 80°C) and incubation for a designated period of time (5 and 10 min), respectively. Once the release experiment was finished, NaOH aqueous solution was removed from the 500-mL flask, and 5 mL of BaCl₂ saturated solution was added into the solution. The sample was titrated by oxalic acid solution, and phenolphthalein was used as an indicator. The release ratio of CO₂ was calculated using the following equation.

$$\text{Release ratio of CO}_2 (\%) = \frac{(c_{NaOH} V_{NaOH} - c_{H_2C_2O_4} V_{H_2C_2O_4}) / 2}{W_{SBC} / 84} \times 100 \quad \cdots \cdots \text{Eq. 4}$$

Where, c_{NaOH} was the concentration of NaOH solution; V_{NaOH} was the volume of NaOH solution; $c_{H_2C_2O_4}$ was the concentration of oxalic acid solution; $V_{H_2C_2O_4}$ was the titrimetric volume of oxalic acid solution; W_{SBC} was the SBC amount of microcapsules; 2 was

the Na number in sodium carbonate; 84 was the SBC molar mass.

Statistical analysis Statistical analysis of the data obtained was performed with the Matlab (Version 7.11.0.584 (R2010b), The MathWorks, Inc., Natick, Massachusetts, USA). P values less than 0.05 were considered to be significantly different between two groups. Variance within treatment groups was expressed as standard deviation (SD).

Results and Discussion

Morphology of SBCM Photomicrographs of SBCM taken from the Olympus IX71 inverted microscope were shown in Fig. 1.

As could be observed, inverted microscope examination of SBCM revealed that the original microcapsules showed smooth surfaces and spherical shapes with a homogenous size distribution (Fig. 1A). Moreover, microcapsule sizes less than 100 μm were predominant. Fig. 1B depicted that there were no significant difference in the particle shapes and size distribution between original microcapsules and SBCM after incubation at 40°C. SBC leaked out from SBCM was not visibly observed. It indicated that SBCM was very stable, and the microcapsules could not be markedly destroyed at such temperature. It could be ascribed to the fact that KGM film-forming ability greatly contributed to the toughness of SBCM shell. However, it could be seen from Fig. 1C that the particle shapes of microcapsules had been severely deformed and destroyed after incubation at 60°C. Though the shapes of SBCM have not been thoroughly ruined, the surfaces of SBCM became irregular and unsmooth. Fig. 1D showed that SBCM had been completely damaged at 80°C, and the particle shapes were destructed. It could be mainly attributed to the GMS melt because the temperature was above the melting point of the wall material ingredient (Lauridsen, 1976). Core material also could be found in the outside of microcapsules because of wall material melting.

Differential scanning calorimetry The thermograms of SBCM and their wall constituents were illustrated in Fig. 2. The endothermic peak of the DSC curve of GMS was observed around 58°C, which could be the melting point of GMS. The result was in good accordance with the reported values of GMS melting endothermic peaks between 56.5°C and 62.5°C (Dewan *et al.*, 2011). However, no peak was observed in the DSC curve of KGM in the temperature scan range. Xu *et al.* (2007) found that the DSC curve of KGM showed an exothermic peak around 326°C, attributing to the greatest thermal degradation of KGM.

Two peaks were observed in the DSC curve of SBCM at about 59°C and about 65°C, respectively. It suggested that the greatest endothermic peak of the DSC curve of GMS/KGM complex was slightly shifted to high temperature compared to that of GMS, which may infer that a certain degree of interaction between the two ingredients existed (Lin *et al.*, 1995). It possibly explained the phenomenon that the particle shapes of SBCM were not obviously altered at 40°C, while the microcapsules could be apparently

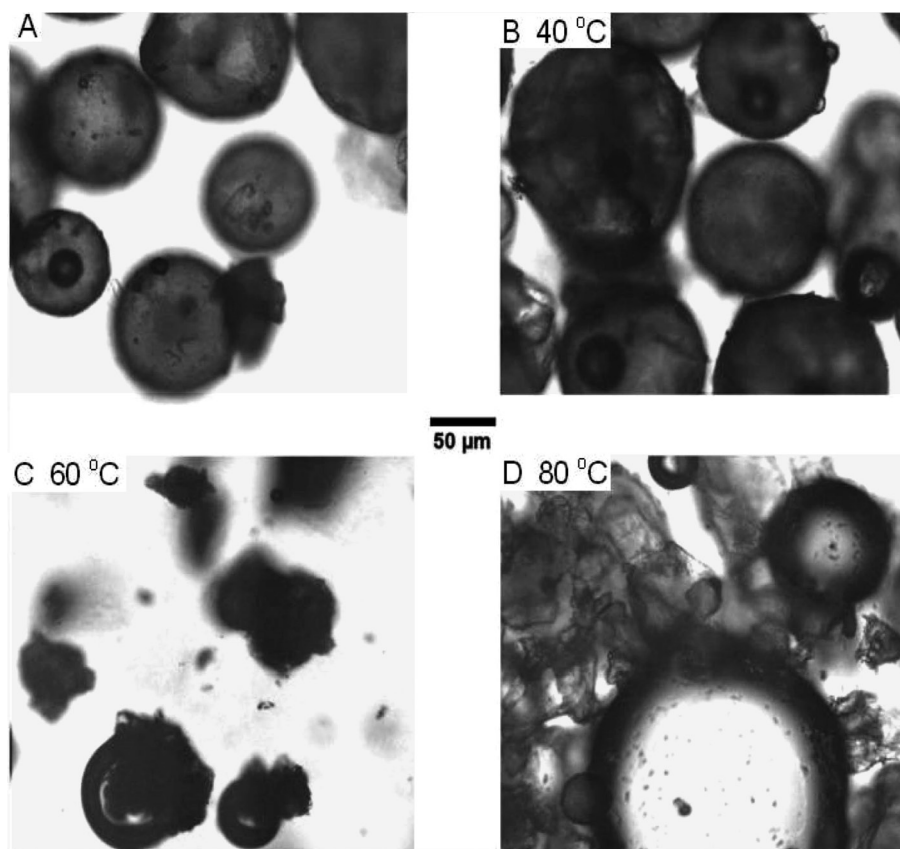


Fig. 1. The inverted microscope micrographs of the microcapsules of original SBCM (A) and SBCM after incubation in distilled water at different temperature for 5 min (B, C and D)

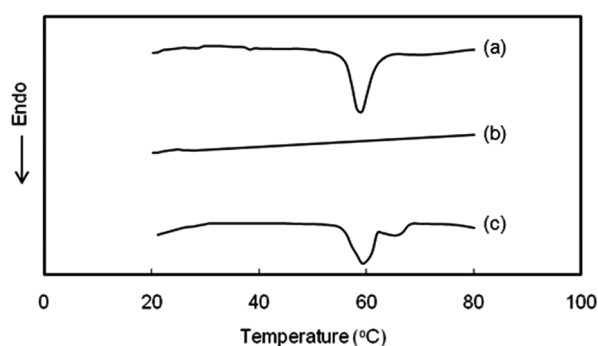


Fig. 2. DSC thermograms of (a) GMS, (b) KGM and (c) SBCM

damaged at 60 °C and 80 °C. According to Kawai *et al.* (2012), the higher peak temperature indicated that the complex helical length was longer, and its physical stability was greater. The emulsifier chain length played a crucial role in both the formation and the characteristics of the complex. Emulsifiers with long carbon chains (e.g. GMS) usually provide greater thermostability to V-type complexes (Putseys *et al.*, 2009).

Size distribution Size distribution is commonly utilized as an important tool to estimate the quality of microcapsules, and particle size is a relevant characteristic regarding both the encapsulation efficiency and release ratio. The encapsulation yield of SBCM was $94.72 \pm 3.14\%$ in the study. As shown in Fig. 3, the particle sizes of SBCM were mainly varied in the range from 50 μm to 300 μm . The volume weighted mean diameter was about 126 μm and

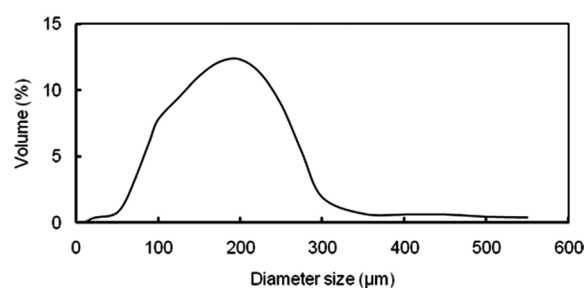


Fig. 3. SBCM size distribution

maximum frequency occurred around 91 μm .

Microcapsule size distribution is usually affected by processing parameters, such as core-to-wall material ratio, wall material ratio, and agitation energy. Generally speaking, an intensive mechanical energy could lead to the breakdown of microcapsules and the reduction of particle diameters (Hong *et al.*, 2009). The phase separation velocity could be another important factor for influencing the size distribution of microcapsules. Faster velocity of phase separation could result in smaller particle size, while slower velocity of phase separation could cause bigger particle size (Madras and McCoy, 2003). Moreover, the size distribution of SBCM also could be greatly influenced by the relative water affinity of wall materials and the overall balance of molecular interactions, i.e. the minimization of the total free energy of the system (Dickinson, 1992). The lower relative water affinity of wall material usually leads to the greater the aggregation number, and

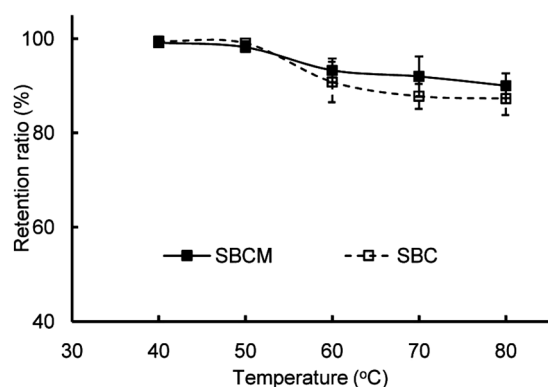


Fig. 4. Effect of temperature on SBCM retention ratio

the particle size becomes greater (Wokadala *et al.*, 2012).

SBCM stability

Effects of temperature on SBCM retention ratio SBCM was incubated under different temperature for 10 min based on the baking time in food industry. The effects of temperature on SBCM retention ratio were depicted in Fig. 4.

It could be found that the retention ratio profile of SBCM was in agreement with that of SBC. Both of them were very stable at 40°C and 50°C. The SBC from SBCM could be more stable than free SBC at temperature above 60°C, but the stability both of them decreased with further increasing temperature, and the transition temperature was coincident with GMS melting point. The loss both of SBCM and free SBC could be attributed to thermal decomposition, while the decomposition of SBC from SBCM could be partly inhibited by microcapsule shell, so the SBC retention ratio of SBCM was slightly higher than that of free SBC.

The CO₂ from leavening agent should be released to increase the volume of baking products before dough solidifying (Brodie and Godber, 2000). If the CO₂ derived from leavening agents was formed too early and too much, the gas could not be efficiently held in dough. While CO₂ was released too late, dough could have solidified, and the dough bulk could not be effectively expanded yet. It is a well-known fact that dough usually begins to gelatinize and solidify at about 60–70°C. Leavening agents could be encapsulated into appropriate coating materials to control CO₂ release at a specified temperature (Augustin *et al.*, 2010). The CO₂ release from SBCM could be chiefly controlled by the thermal behavior of GMS/KGM wall materials. GMS/KGM blend films could be partly/entirely destroyed at temperature above GMS melting point because of GMS fusion.

Effects of heating time on SBCM retention ratio SBCM was stored at 60°C based on the temperature of dough commonly starting to gelatinize and solidify. The retention ratio of SBCM at 60°C and different heating time was presented in Fig. 5.

As can be seen from Fig. 5, the retention ratios both of SBCM and SBC tended to decrease with increasing heating time. There was no significant difference between the retention ratios of SBCM and SBC in the first 20 min ($P > 0.05$). However, the retention ratio of SBCM was obviously higher than that of SBC after 20 min

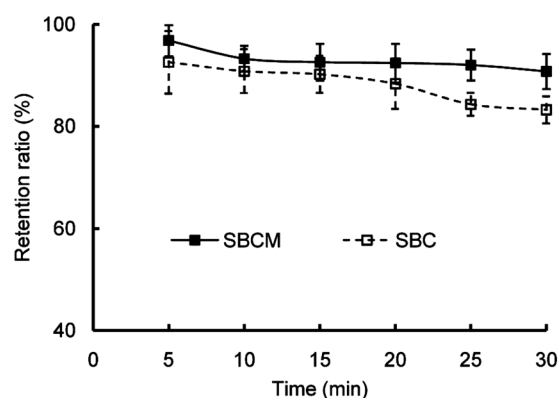


Fig. 5. Effects of heating time on SBCM retention ratio at 60°C

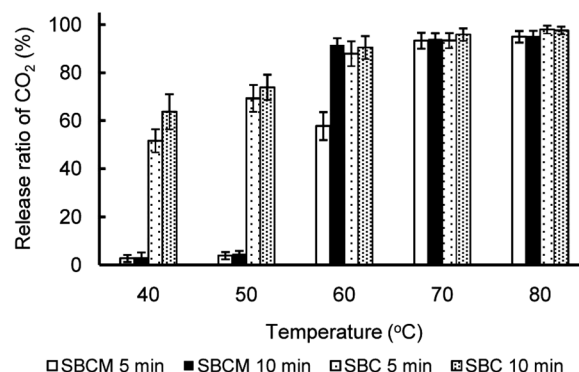


Fig. 6. Effect of temperature on CO₂ release of SBC and SBCM paired with MPP

($P < 0.05$). It indicated that the thermostability of SBC could be enhanced by encapsulating into microcapsules. The stability increase could be attributed to the protection of GMS/KGM blend films, and the blend films strengthened the heat resistance of SBC due to the wall material melting point near to the heating temperature (Fig. 2).

Effect of temperature on CO₂ release of SBCM paired with MPP The CO₂ from SBC is usually released by thermal decomposition during baking, so the gas release efficiency of the basic leavening agent mainly depends on the heating temperature. However, the leavening agent could not thoroughly release CO₂ via thermal decomposition (De Leyn *et al.*, 2014; Heda *et al.*, 1995). Furthermore, sodium carbonate, the residue of SBC thermal decomposition, could result in bitterness and puckery taste of baking products. CO₂ could be completely released by the double decomposition reaction of the complex of basic/acidic leavening agents, and sodium carbonate could be eliminated to improve the quality of baking products (Cepeda *et al.*, 2000; Liu *et al.*, 2016). In the study, MPP as an acidic leavening agent was chosen to pair with SBC and SBCM, respectively. Effects of temperature on CO₂ release of the two complex leavening agents, SBC/MPP and SBCM/MPP, were illustrated in Fig. 6.

As shown in Fig. 6, CO₂ releases of the two complex leavening agents were temperature-dependent, and the gas release increased with increasing temperature. For example, about 51.7%, 69.3% and 87.9% of CO₂ were released from SBC/MPP complex at 40°C,

50°C and 60°C for 5 min, respectively. The CO₂ release could be ascribed to the double decomposition reaction between SBC and MPP because the basic and acidic leavening agents coexisted directly. Compared with that of SBC, the CO₂ release profile of SBCM/MPP complex was apparently triphasic release processes. In the first stage, a slow release of CO₂ was observed at 40°C and 50°C, where about 2.7% and 3.9% of CO₂ were released for 5 min, respectively. In the second stage, CO₂ was rapidly released at temperature up to 60°C, in which about 57.8% and 91.6% of CO₂ were released for 5 min and 10 min, respectively. In the third stage, CO₂ was almost entirely released at 70°C and 80°C for 5 min.

The CO₂ release characteristic of SBCM/MPP complex could be attributed to the SBC microencapsulation, and the reaction between SBC and MPP could be controlled by coating materials. SBC hardly interacted with MPP at low temperature because the two leavening agents were separated from each other by GMS/KGM shell. However, the wall materials could be melted by increasing temperature up to GMS melting point, and the integrity of SBCM shell could be disrupted, and the basic leavening agent was leaked out. Then the SBC released from microcapsules reacted with MPP to produce CO₂. The results were accordant with inverted microscope micrographs (Fig. 1) and DSC thermograms (Fig. 2).

Several ingredients and methods for manufacturing chemically-leavened shelf stable bakery products have been documented and claimed in some patent literature in the last few decades. However, most of these inventions were straight to a specific bakery application, providing the effectiveness of encapsulation in delaying CO₂ release under the optimum baking conditions (Dorko and Penfield, 1993; Lakkis, 2007). The SBCM prepared in the study could be used in common baking products.

Conclusion

In this study, SBCM was prepared successfully to enhance SBC stability and to control CO₂ release using GMS/KGM complex as wall material. SBCM stability characteristics showed that SBC stability from SBCM was increased under different conditions. CO₂ release of the complex leavening agent of SBCM/MPP was mainly depended on temperature, and the mixture of SBCM/MPP was stable enough at temperature below 60°C. However, CO₂ could be effectively released from the complex leavening agent at temperature above 60°C. The results indicated that SBC-loaded GMS/KGM microcapsules could be employed to control CO₂ release. The leavening effectiveness of SBC may be improved by encapsulating into GMS/KGM coating material. It is very possible that some shortcomings of SBC could be overcome by microencapsulation in the baking industry. This study further demonstrated that GMS/KGM matrix has the potential to carry chemical leavening agents for preparing bakery food. Further work is needed to verify SBCM leavening effectiveness in practical baking.

Acknowledgements The research was supported by the National Natural Science Foundation of China (31401477, 31501453).

References

- Augustin, M. A., Sanguansri, L., and Oliver, C. M. (2010). Functional properties of milk constituents: Application for microencapsulation of oils in spray-dried emulsions—A minireview. *Dairy Sci. Technol.*, **90**, 137–146.
- Bakry, A. M., Fang, Z., Khan, M. A., Chen, Y., Chen, Y. Q., and Liang, L. (2017). Tuna oil and Mentha piperita oil emulsions and microcapsules stabilised by whey protein isolate and inulin: Characterisation and stability. *Int. J. Food Sci. Tech.*, **52**, 494–503.
- Book, S. L. and Waniska, R. D. (2015). Leavening in flour tortillas. In “Tortillas,” ed. by S. O. Serna-Saldivar. AACC International Press, pp. 159–183.
- Brodie, J. and Godber, J. (2000). “Bakery processes, chemical leavening agents.” John Wiley & Sons, Chichester.
- Cepeda, M., Waniska, R. D., Rooney, L. W., and Bejosano, F. P. (2000). Effects of leavening acids and dough temperature in wheat flour tortillas. *Cereal Chem. J.*, **77**, 489–494.
- Chua, M., Chan, K., Hocking, T. J., Williams, P. A., Perry, C. J., and Baldwin, T. C. (2012). Methodologies for the extraction and analysis of konjac glucomannan from corms of *Amorphophallus konjac* K. Koch. *Carbohydr. Polym.*, **87**, 2202–2210.
- Desai, K. G. H. and Park, H. J. (2005). Recent developments in microencapsulation of food ingredients. *Dry. Technol.*, **23**, 1361–1394.
- De Leyn, I. (2014). Other leavening agents. In “Bakery Products Science and Technology (Second Edition),” ed by W. B. Zhou, Y. H. Hui, I. De Leyn, M. A. Pagani, C. M. Rosell, J. D. Selman and N. Therdthai, John Wiley & Sons, pp. 175–181.
- Dewan, I., Shahriar, M., and Islam, S. M. A. (2011) Study of differential scanning calorimetry of atorvastatin in solid solution. *Bangladesh Pharm. J.*, **14**, 141–146.
- Dickinson, E. (1992). Structure and composition of adsorbed protein layers and the relationship to emulsion stability. *J. Chem. Soc.: Faraday Trans.*, **88**, 2973–2983.
- Dong, D., Qi, Z., Hua, Y., Chen, Y., Kong, X., and Zhang, C. (2015). Microencapsulation of flaxseed oil by soya proteins–gum arabic complex coacervation. *Int. J. Food Sci. Technol.*, **50**, 1785–1791.
- Dordevic, V., Balanc, B., Belcak-Cvitanovic, A., Levic, S., Trifkovic, K., Kalusevic, A., Kostic, I., Komes, D., Bugarski, B., and Nedovic, V. (2015). Trends in encapsulation technologies for delivery of food bioactive compounds. *Food Eng. Rev.*, **7**, 452–490.
- Dorko, C. L. and Penfield M P. (1993). Melt point of encapsulated sodium bicarbonates: Effect on refrigerated batter and muffins baked in conventional and microwave ovens. *J. Food Sci.*, **58**, 574–578.
- Du, X., Yang, L., Ye, X., and Li, B. (2013). Antibacterial activity of konjac glucomannan/chitosan blend films and their irradiation-modified counterparts. *Carbohydr. Polym.*, **92**, 1302–1307.
- Estevinho, B. N., Rocha, F., Santos, L., and Alves, A. (2013). Microencapsulation with chitosan by spray drying for industry applications: A review. *Trends*

- Food Sci. Tech.*, **31**, 138–155.
- FDA. (2016). Title 21—Food and drugs, CITE: 21CFR184.1324, *Code of Federal Regulations*, April 1, 2016.
- GB. (2015). GB 1886.2-2015: Food Additive-Sodium bicarbonate. National Standard of the People's Republic of China. (in Chinese)
- GB. (2016). GB 5009.3-2016: Determination of the water content of foods. National Standard of the People's Republic of China. (in Chinese)
- GB/T. (2008). GB/T 22328-2008: Animal and vegetable fats and oils- Determination of 1-monoglycerides and free glycerol contents. National Standard of the People's Republic of China. (in Chinese)
- Gray, J. A. and Bemiller, J. N. (2003). Bread staling: molecular basis and control. *Compr Rev Food Sci F*, **2**, 1–21.
- Heda, P. K., Dollimore, D., Alexander, K. S., Chen, D., Law, E., and Bicknell, P. (1995). A method of assessing solid state reactivity illustrated by thermal decomposition experiments on sodium bicarbonate. *Thermochim. Acta*, **255**, 255–272.
- Hong, Y. J., Lee, H. Y., and Kim, J. C. (2009). Preparations and temperature-dependent release properties of Pluronic F127-containing microcapsules prepared by a double emulsion technique. *J. Ind. Eng. Chem.*, **15**, 758–762.
- Huang, Y. C., Chu, H. W., Huang, C. C., Wu, W. C., and Tsai, J. S. (2015). Alkali-treated konjac glucomannan film as a novel wound dressing. *Carbohydr. Polym.*, **117**, 778–787.
- Janovsky, C. (1993). Encapsulated ingredients for the baking industry. *Cereal Food. World*, **38**, 85–87.
- Jyothi, N. V. N., Prasanna, P. M., Sakarkar, S. N., Prabha, K. S., Ramaiah, P. S., and Srawan, G. Y. (2010). Microencapsulation techniques, factors influencing encapsulation efficiency. *J. Microencapsul.*, **27**, 187–197.
- Kawai, K., Takato, S., Sasaki, T., and Kajiwara, K. (2012) Complex formation, thermal properties, and in-vitro digestibility of gelatinized potato starch–fatty acid mixtures. *Food Hydrocolloid.*, **27**, 228–234.
- Lakkis, J. M. (2007). Encapsulation and controlled release in bakery applications. In “Encapsulation and Controlled Release Technologies in Food Systems,” ed by J. M. Lakkis. Blackwell Publishing, pp. 113–133.
- Lauridsen, J. B. (1976). Food emulsifiers: Surface activity, edibility, manufacture, composition, and application. *J. Am. Oil Chem. Soc.*, **53**, 400–407.
- Lin, C., Lin, S. Y., and Hwang, L. S. (1995). Microencapsulation of squid oil with hydrophilic macromolecules for oxidative and thermal stabilization. *J. Food Sci.*, **60**, 36–39.
- Liu, T., Hou, G. G., Book, S. L., and Marquart, L. (2016). Effects of chemical leavening system and processing conditions on the opacity and other quality characteristics of whole-wheat flour tortillas. *LWT - Food Sci. Technol.*, **73**, 123–130.
- Madan, P. L. (1978). Microencapsulation I. Phase separation or coacervation. *Drug Dev. Ind. Pharm.*, **4**, 95–116.
- Madras, G. and McCoy, B. J. (2003). Temperature effects for crystal growth: A distribution kinetics approach. *Acta Mater.*, **51**, 2031–2040.
- Miller, R. (2016). Leavening agents. In “Encyclopedia of Food and Health,” ed by B. Caballero, P. M. Finglas and F. Toldra. Academic Press, Oxford, pp. 523–528.
- Orthoefer, F. (2008). Applications of emulsifiers in baked foods. In “Food Emulsifiers and Their Applications (2ed),” ed by G. L. Hasenhuettl and R. W. Hartel, Springer New York, pp. 263–284.
- Putseys, J. A., Derde, L. J., Lamberts, L., Ostman, E., Bjorck, I. M., and Delcour, J. A. (2009). Functionality of short chain amylose– lipid complexes in starch– water systems and their impact on in vitro starch degradation. *J. Agric. Food Chem.*, **58**, 1939–1945.
- Vetter, J. L. (2003). Leavening agents. In “Encyclopedia of Food Sciences and Nutrition (Second Edition),” ed by B. Caballero, L. Trugo and P. M. Finglas. Academic Press, Oxford, pp. 3485–3490.
- Vitaglione, P., Troise, A. D., De Prisco, A. C., Mauriello, G. L., Gokmen, V., and Fogliano, V. (2015). Use of microencapsulated ingredients in bakery products: Technological and nutritional aspects. In “Microencapsulation and Microspheres for Food Applications,” ed by L. M. C. Sagis. Academic Press, San Diego, pp. 301–311.
- Wang, F. C., Challacombe, C., and Marangoni, A. G. (2016). Effect of the addition of palm stearin and storage temperatures on the thermal properties of glycerol monostearate-structured emulsions. *Food Res. Int.*, **79**, 29–32.
- Wokadala, O. C., Ray, S. S., and Emmambux, M. N. (2012). Occurrence of amylose–lipid complexes in teff and maize starch biphasic pastes. *Carbohydr Polym.*, **90**, 616–622.
- Xu, X., Li, B., Kennedy, J. F., Xie, B. J., and Huang, M. (2007). Characterization of konjac glucomannan–gellan gum blend films and their suitability for release of nisin incorporated therein. *Carbohydr. Polym.*, **70**, 192–197.
- Zheng, L., Ding, Z., Zhang, M., and Sun, J. (2011). Microencapsulation of bayberry polyphenols by ethyl cellulose: Preparation and characterization. *J. Food Eng.*, **104**, 89–95.