Food Science of Animal Products

Research Article

Combination of entropy weighting and global stability index provides a potential strategy for monitoring the shelf-life of *Litopenaeus vannamei* during cold storage

Defeng Xu[1], Peifeng Cai[1], Luyun Cai[2], Jianmeng Liao[3], Hui Luo[1] ✉

[1] *School of Ocean and Tropical Medicine, Guangdong Medical University, Zhanjiang 524023, China*
[2] *College of Biosystems Engineering and Food Science, Zhejiang University, Hangzhou 310058, China*
[3] *Zhanjiang Institute for Food and Drug Control, Zhanjiang 524000, China*
✉Address correspondence to Hui Luo, luohui@gdmu.edu.cn

Received: March 11, 2024; Revised: March 20, 2024; Accepted: March 25, 2024

Abstract: Monitoring the quality degradation of shrimp during cold storage is a tough task due to the involvement of multi-biological process and the accurate kinetic model is extremely necessary to optimize the storage management. Here, the entropy weighting and global stability index (GSI) were combined to establish the model monitoring the shelf-life of *Litopenaeus vannamei* during storage at –23, –5, 0, 4 and 9 °C, respectively. The typically quality-related indicators including sensorial score, total aerobic count, total volatile base nitrogen, and activity of protease and polyphenol oxidase was selected to reflect the quality degradation. After systematical calculation, the weighting factors of these indicators were determined, respectively. Subsequently, the zero-order reaction model reflecting the overall quality degradation process was satisfactorily described based on GSI, in which the activation energy (E_a) and reaction rate constant (k_0) were calculated to be (64.78 ± 0.75) kJ/mol and (3.47 ± 0.54) × 10^{11}, respectively. As a consequence, the GSI model was established as following: GSI = 1 – 3.47 × $10^{11}t$ × exp (–64.78 × 10^3/RT), with the relative error of less than 15%. Therefore, the established GSI model could be applied to monitor the quality deterioration of *L. vannamei* during cold storage and is helpful for distributors and consumers to determine the storing time.

Keywords: *Litopenaeus vannamei*; cold storage; quality degradation; entropy weighting; global stability index

Citation: D. F. Xu, P. F. Cai, L. Y. Cai, et al., Combination of entropy weighting and global stability index provides a potential strategy for monitoring the shelf-life of *Litopenaeus vannamei* during cold storage, Food Sci. Anim. Prod. 2 (2024) 9240050. https://doi.org/10.26599/FSAP.2024.9240050.

1 Introduction

By virtue of high level of nutrients and special flavor, Pacific white shrimp (*Litopenaeus vannamei*) is widely consumed in the world[1–2]. However, owing to its high perishability, *L. vannamei* usually has a short shelf-life and the aggravation of quality deterioration is often observed after harvesting and during storing[3–4]. As a time period for any commercial products with market-acceptability and safety requirements, shelf-life is of significance to everyone in the food supply chain from producers to consumers[5]. Therefore, accurate prediction on the shelf-life of *L. vannamei* during storage could allow companies to optimize their storage management and minimize the economic losses[6]. Nevertheless, owing to the simultaneous activation of endogenous enzyme and microbial proliferation, the accurate evaluation on shelf-life of food matrix during storage is consequently an arduous task.

Moreover, the traditional quality evaluation involves amount of experimental determinations, which not only consumes numerous time and labor, but also relates to the high cost of experimentation. Comparatively, the kinetic modeling is a systematic way to describe the degradation process of food products with reduced experiments, and thus provides a powerful tool to predict the shelf-life of food product[7–9]. To date, many of kinetic models concerning quality change of aquatic products have been reported. For example, Yao et al.[10] established the kinetic models to predict freshness of *Carassius carassius* according to the electrical conductivity and freshness indices. Sánchez-Valencia et al.[11] developed models based on the changes of Kramer shear resistance and water holding capacity in hake muscle during storage at different temperatures. Tsironi et al.[12] modeled the dependence of color, total volatile base nitrogen (TVB-N) and trimethylamine (TMA) content of frozen shrimp on storing temperature and time. Nevertheless, these conventional models are mainly based on the individual quality indicator. When the food quality is defined by multiple attributes, the comprehensive changes in quality indices becomes fuzzy and the conventional models usually produce significant discrepancies[13]. Therefore, it is necessary to integrate the individual quality index into comprehensive quality evaluation.

Currently, some optimized models such as the multivariate accelerated shelf-life testing and global stability index (GSI) model have been reported[13–15]. However, these methods present the typical shortcomings in the comprehensive evaluation of food quality owing to the lack of objective judgment on weighting assignment. Therefore, the establishment of quantitative evaluation models through transferring the multiple indices into a comprehensive indicator is of great significance to desirably predict the shelf-life. Moreover, the linear weighted sum method is a common strategy

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to construct a single numerical index, and the reasonable allocation of weights plays a vital role in the effectiveness of this method. In terms of food matrix, they are thermodynamically unstable and gradually tending to the state with higher entropy and lower enthalpy[16]. As an originally thermodynamic concept, entropy has been introduced into information theory to quantitatively reflect the comprehensive alteration. Therefore, the changes in biochemical and quality indices of *L. vannamei* during storage can be reflected and evaluated by the information entropy.

Furthermore, according to the linear weighted sum method, the amount of information is regarded as the sole standard for judging the entropy and fully reflect the inherent law of the obtained data[17–18]. Therefore, the effectiveness of weighting determination depends on the acquired information from experimental data and the entropy weighting presents strong objectivity owing to eliminating the influence of subjective factors[19]. Although the entropy weighting has been successfully applied in the food industry[20], it has not been reported in the comprehensive evaluation of *L. vannamei* during storage at typical cold chain temperatures. Hence, this study aims to propose a novel method of shelf-life prediction based on the entropy and comprehensive kinetic evaluation. First, the entropy weighting method was used for weight allocation of multi-quality indices and then a comprehensive evaluation index GSI was calculated by the linear weighted sum method to reflect the overall quality change of *L. vannamei* during storage.

2 Materials and methods

2.1 Shrimp collection and refrigeration

About 500 of fresh *L. vannamei* with the length of (15.23 ± 1.58) cm and weight of (12.36 ± 1.64) g were purchased from a local aquatic products wholesale market in Zhanjiang City of China and were immediately transported to the laboratory in Guangdong Ocean University within 2 h. Upon arrival, the live shrimps with uniform size and color were sorted out for subsequent experiment. Next, the collected shrimps were rinsed with tap water and sacrificed on ice. Subsequently, the shrimps were randomly divided into 5 groups (about 80 samples in each group) and packed into the sterile zipper polyethylene bags (26.8 cm × 27.9 cm). The wrapped samples were stored at –23, –5, 0, 4 and 9 °C in the refrigerator of KG23F1830W (Siemens, China), respectively, with 70%–80% relative humidity and without exposure to light. Six shrimps were periodically taken out for quality analysis and all the experiments were performed in triplicate. Generally, the critical limit of shelf-life of shrimp is mainly determined by the number of microorganisms. Besides, considering the rapid development of melanosis of shrimp during storage, the sensory score of below 5 is regarded as the endpoint of shelf-life[20].

2.2 Analysis of quality indices

2.2.1 Sensory analysis

The sensory analysis was performed according to the reports by Alparslan et al.[21] and Khodanazary[22] with some modifications. Briefly, 6 shrimps were taken out from the refrigerated compartments for every 24 h interval and the quantitative descriptive analysis was conducted by 10 trained sensory panelists (5 men and 5 women from our laboratory staff, aged 20–35 years old). The sensory characteristics were described with the scores ranging from 1 to 10, in which the overall sensory score was assessed as following: 1 = dislike extremely, 2 = dislike very much, 3 = dislike moderately, 4 = dislike slightly, 5 = neither like nor dislike, 6 = like slightly, 7 = like moderately, 8 = like very much, 9 = like extremely, 10 = excellent, respectively. The panelists were asked to give a score of 1–10 for each shrimp based on the quality of appearance, color, odor and texture. The results were analyzed statistically and the sensory rejection time was consequently defined as the time when at least 50% of the panelists regarded the samples as below 5. For accuracy, 3 parallel experiments were conducted.

2.2.2 Determination of total aerobic count (TAC)

Briefly, 6 shrimps in each group were taken out on every 24 h interval and the whole shrimps were powdered in liquid nitrogen. Subsequently, 10 g of powder were aseptically homogenized with 90 mL 0.9 g/100 mL sterile physiological saline for 2 min. The homogenates were serially 10-fold diluted with 0.1 g/100 mL peptone in 0.9 g/100 mL sterile physiological saline. TAC analysis was performed according to the report by Zhao et al.[23]. Marine agar (BD-Difco, USA) was used for standard plate and each dilution (100 μL) plate of appropriate dilutions was incubated for 48 h at 30 °C and all counts were expressed as (lg (CFU/g)). For accuracy, 3 parallel experiments were conducted.

2.2.3 Determination of TVB-N content

The determination of TVB-N content was carried out according to the semi-micro-titration method as reported by Zhao et al.[24] with some modifications. About 5 g of shrimp flesh was homogenized with 15 mL of 4 g/100 mL trichloroacetic acid (TCA, analytical grades, Fuchen Co., Ltd., China) and then centrifuged at 8 000 × *g* and 4 °C for 5 min. Subsequently, 5 mL of supernatant was collected and mixed with 5 mL of 2 mol/L NaOH (analytical grades, Fuchen Co., Ltd., China), following by steam distillation in a semi-micro-distillation tube. The distillate was collected in a beaker containing 15 mL of 0.01 mol/L HCl (analytical grades, Fuchen Co., Ltd., China) standard solution in a final volume of 50 mL of 1% rosolic acid (analytical grades, Shanghai Yuanye Bio-Technology Co., Ltd., China) and titration was performed using 0.01 mol/L NaOH. The pale pink was regarded as the end point and the TVB-N content was calculated accordingly with the expression of mg N in 100 g of shrimp flesh sample (mg/100 g). For accuracy, 3 parallel experiments were conducted.

2.2.4 Preparation of enzyme extract and determination of polyphenol oxidase (PPO) and protease activitives

PPO and protease crude extract were prepared as described in our previous report[20]. Briefly, 6 whole shrimps were finely powdered in liquid nitrogen and 10 g of powder was mixed with two volumes of 0.01 mol/L sodium phosphate buffer (pH 7.6). The mixture was homogenized for 5 min using a homogenizer (IKA labortechnik, Selangor, Malaysia) at a speed of 10 000 × *g*. The homogenate was stirred for 30 min at 4 °C, following with centrifugation at 10 000 × *g* at 4 °C for 30 min using a refrigerated centrifuge (Beckman Coulter, Avanti J-E Centrifuge, Fullerton, CA, USA). Solid ammonium sulphate was added into the supernatant to obtain 40% saturation. The mixture was allowed to stand at 4 °C overnight and then centrifuged at 12 000 × *g* and 4 °C for 30 min. The collected pellet was dispersed in a minimum volume of 50 mmol/L sodium phosphate buffer (pH 7.2) and then dialyzed against 15 volumes of the same buffer at 4 °C overnight. After dialysis, the insoluble

materials were removed by centrifugation at 3 000 × *g* and 4 °C for 30 min, followed by the collection of crude enzymes in supernatant. Protease activity was determined using 2% casein as substrate according to the method of Manheem et al.[25] and PPO activity was assayed using levodopa as substrate according to the method of He et al.[26]. For accuracy, 3 parallel experiments were conducted.

2.3 Modelling

2.3.1 Calculation of weighting factors

The temporal changes in quality indices of shrimp samples stored at different temperatures were arranged in a matrix of $X = (x_{ij})_{m \times n}$, where m was the number of data points during shelf-life and n was the number of quality indices. In this study, 5 quality indices were analyzed and n was taken to be 5. More precisely, x_i was a vector representing the data of each quality index in a certain time, while x_j was a vector representing the changes in an analyzed quality index during storage. Due to the differences of index units, the standardization of matrix X was carried out and a non-dimensional index matrix $R = (r_{ij})_{m \times n}$ was obtained accordingly, in which the data of each index was confined to the range of [0, 1]. Subsequently, the entropy of the quality index was calculated as described in Eq. (1):

$$H_j = -\frac{1}{\ln m}\sum_{i=1}^{m} P_{ij}\ln P_{ij},\ j = 1, 2, \cdots, n \tag{1}$$

Where $P_{ij} = r_{ij}/\sum_{i=1}^{m} r_{ij}$, when $P_{ij} = 0$, $P_{ij}\ln P_{ij} = 0$.

The weight ω_j of each quality index was calculated according to the entropy and the formula was expressed as Eq. (2):

$$\omega_j = \frac{1 - H_j}{n - \sum_{j=1}^{n} H_j},\quad j = 1, 2, \cdots n \tag{2}$$

Where $0 \le \omega_j \le 1$ and $\sum_{j=1}^{n} \omega_j = 1$.

2.3.2 Determination of GSI

GSI was calculated with Eq. (3) as described by Achour[9]:

$$GSI_t = 1 - \sum_{j=1}^{n} \omega_j V_{jt} \tag{3}$$

Where t was the units of storage time; n was the number of quality indicators; j represented a certain indicator; V_{jt} was the variation of indicator j at time t; ω_j was the weighting factor that reflected the relative importance of indicator j in the product's total quality. The variation term V_{jt} was calculated by Eq. (4):

$$V_{jt} = \frac{C_{jt} - C_{j0}}{L_j - C_{j0}} \tag{4}$$

Where C_{jt} was the observed value of indicator j at time t; C_{j0} and L_j were the initial value and the threshold value of indicator j, respectively.

In this study, the threshold value of TAC at 7.0 (lg (CFU/g)) bacterial count was stipulated as the acceptable limit for frozen shrimp according to International Commission on Microbiological Specifications for Foods. Meanwhile, the TVB-N content at 30.0 mg/100 g was set as the threshold values according to the National Standard of China (GB 2733–2015). For sensory score, it was recognized as 5 since the shrimps were rejected by the sensory panel at that point. In addition, according to our previous study, the activities of protease at 90.0 U/mg and PPO at 80.0 U/mg were set as the threshold values. Therefore, GSI varied between 0 and 1. As GSI was close to 1, the food product was close to its initial quality. In contrast, the food product was being decayed and the shelf-life dramatically reduced when GSI approached 0.

The comprehensive evaluation index GSI was a variable over time, and it could be fitted in terms of a zero-order or first-order kinetics model. According to the fitting effect of kinetics model on data points, the order was calculated to obtain the reaction rate constant (k). The relationship between kinetic constant (k) and storage temperature (T) was expressed in the form of Arrhenius Eq. (5):

$$\ln k = \ln k_0 - \frac{E_a}{RT} \tag{5}$$

Where k_0 was the frequency factor, R was the universal gas constant, and E_a was the activation energy. Subsequently, E_a was calculated by regressing the value of $\ln|k|$ and the reciprocal of storage temperatures of −23 (250 K), −5 (268 K), 0 (273 K), 4 (277 K), and 9 °C (282 K), respectively, as reported by Bailón-Moreno et al.[27].

2.4 Validation of the models

The experimental data obtained from the shrimp samples stored at 5 temperatures were used to establish the quality predictive model and the values of GSI at 268 and 277 K were adopted to validate the effectiveness of established kinetic model. The relative error between the experimental and predicted shelf-life was served as the criteria to evaluate the prediction accuracy of the established models.

2.5 Statistical analysis

All statistical analyses were performed using SPSS 16.0 software. The fitting performance of different models was evaluated using the regression coefficient R^2. The calculation of entropy weighting was carried out using Microsoft Excel 2017.

3 Results and discussion

3.1 Changes in storing quality of *L. vannamei* at different temperatures

3.1.1 Deterioration of sensory quality

The deterioration of sensory quality is an imperative and sensitive indicator for food quality, leading to the substantial reduction of market value. As shown in Figure 1, the decreased tendency in sensory score was observed in shrimps during storing at different temperatures. However, the degradation rate substantially altered among the 5 temperatures. The sensory scores at initial stage were assessed to be about 10 among all samples. With the prolongation of storing time, the gradual decrease was observed at 250 and 268 K, whereas the significant reduction presented at 273 and 277 K. Obviously, the most prominent reduction was found at 282 K, with the substantial drop from 10 at initial stage to the values of 8.46 ± 0.26 on day 1, 6.54 ± 0.32 on day 2, and 4.12 ± 0.28 on day 3, respectively. On the contrary, the sensory score of shrimp samples at 250 K almost remained the initial level throughout the experiment. Besides, according to the limit acceptability of sensory score of 5, the shelf-life was determined about 2.5 days at 282 K, 4.2 days at 277 K, 14 days at 273 K, and more than 20 days at 268 and 250 K, respectively.

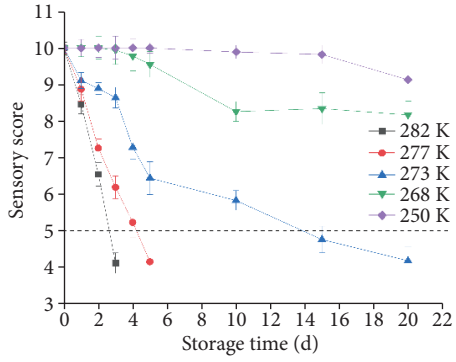

Figure 1 Changes in sensory score of *L. vannamei* stored at 5 temperatures. Data were shown as the mean ± standard deviation.

3.1.2 The growth characteristics of TAC

Figure 2 depicted the increase of TAC in all samples during storing at 5 temperatures. The value of TAC was (3.42 ± 0.25) (lg (CFU/g)), but remarkably increased above 7.0 (lg (CFU/g)) when the shrimps were stored at 282 and 277 K for 3 and 5 days, respectively. However, the values at 268 and 250 K were still below 5.0 (lg (CFU/g)) during the entire storage. As one of the important indices to classify the freshness of shrimp species, the upper-limit of acceptability for microbial population is stipulated by the national standard. According to the International Commission on Microbiological Specifications for Foods, 7.0 (lg (CFU/g)) was set as the acceptable limit for frozen shrimp[1]. In present study, the microbial population was less than 7.0 (lg (CFU/g)) within the storage of 14 days when the samples were stored at 273 K. However, the values dramatically increased to (7.81 ± 0.31) and (7.52 ± 0.35) (lg (CFU/g)) when the shrimps were stored at 277 and 282 K, respectively. In addition, although the microbial proliferation would inevitably exert detrimental effects on the sensory quality, especially when stored at high temperatures, the sensory attributes are more perceivable than the microbial proliferation. Therefore, the sensory and microbial attributes should be considered simultaneously to evaluate the quality status of *L. vannamei* during cold storage.

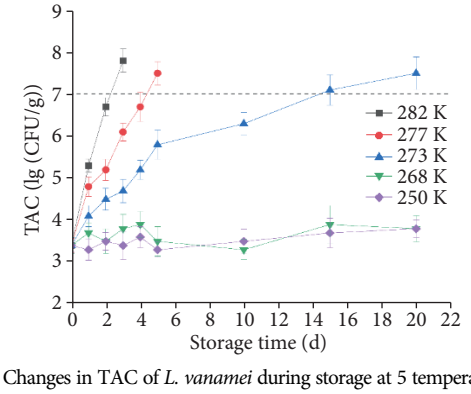

Figure 2 Changes in TAC of *L. vanamei* during storage at 5 temperatures. Data were shown as the mean ± standard deviation.

3.1.3 Changes in TVB-N content

Generally, TVB-N content reflects the degradation extent of proteins and non-protein nitrogenous compounds and the spoiled fishery products have a high content of TVB-N, indicating the degradation of quality properties of fishery products[1]. Figure 3 illustrated the changes of TVB-N contents in all samples at 5 temperatures. Specifically, the values of (34.06 ± 1.48), (33.67 ± 1.41), and (32.12 ± 1.28) mg/100 g were detected when the shrimps were stored at 282 K for 3 days, 277 K for 5 days, and 273 K for 10 days, respectively. Notably, the TVB-N content above 30 mg/100 g has been regarded as the upper acceptability limit for spoilage of shrimp species (GB 2733–2015). Obviously, in present study, the TVB-N content of *L. vannamei* were all beyond this boundary at the end of storage when they were stored above the temperature of 273 K. Comparatively, the samples stored at 268 and 250 K were below this limit and indicated the effectiveness of low temperature on suppression of microbial proliferation. Generally, the rise of TVB-N content results from the microbial multiplication and the temperature plays a vital role in microbial proliferation. As reported by Dabadé et al.[28], there was close association of TVB-N content increase with the microbial proliferation in naturally contaminated tropical brackish water shrimp (*Penaeus notialis*) during storage at 268, 277, and 273 K respectively, which was similar to our findings.

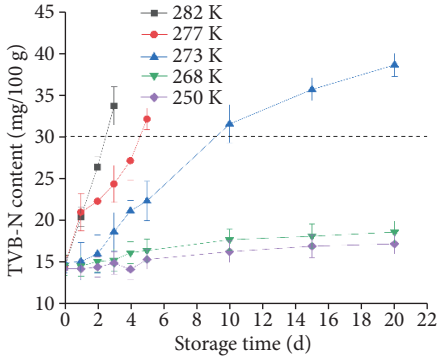

Figure 3 Changes in TVB-N content of *L. vanamei* during storage at 5 temperatures. Data are shown as the mean ± standard deviation.

3.1.4 Changes in the activity of protease

As for the protein-rich foods, protease plays a vital role in the spoiling process and the increase of protease activity means the acceleration of spoiling process. As presented in Figure 4, the protease activity increased with the prolongation of storage time but the increasing rate substantially differed among the different temperatures. The highest value was observed at temperature of 282 K, in which the initial protease activity was (44.57 ± 2.18) U/mg, and then rapidly increased to (71.45 ± 3.16), (99.32 ± 4.22), and (147.25 ± 5.28) U/mg on day 1, 2, and 3, respectively. However, the corresponding value of samples stored at temperature of 250 K on day 3 was just (45.18 ± 2.28) U/mg, significantly lower than those stored at 282 K. With respect to the samples stored at 273 K, protease activity gradually increased throughout the experiment and the value of (149.55 ± 3.39) U/mg on day 20 was determined, 2 times higher than that at initial stage.

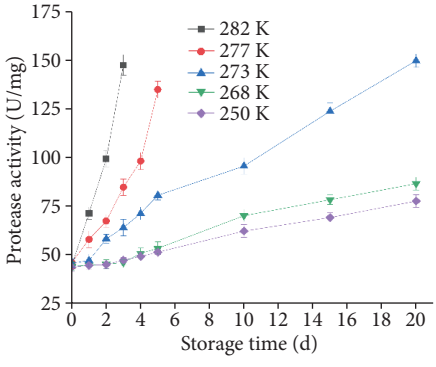

Figure 4 Changes in protease activity of *L. vanamei* during storage at 5 temperatures. Data were shown as the mean ± standard deviation.

3.1.5 *Changes in the activity of PPO*

The change of PPO activity is closely related with the sensory quality such as melanosis development. PPO activity of *L. vannamei* stored at typical cold chain temperatures was monitored and the result was shown in Figure 5. On the whole, the initial PPO activity in all samples were 50–55 U/mg and subsequently elevated with the increase of storing time. However, the increasing rates varied among different temperatures, in which the PPO activity of *L. vannamei* stored at 250 K was (54.26 ± 3.13) U/mg on day 3, while the corresponding value at 282 K was determined to be (136.89 ± 5.24) U/mg, approximately 3 times of that at 250 K. Besides, the PPO activities of *L. vannamei* stored at temperature of 273 K increased slowly before the first 3 days, but the remarkable increase was observed thereafter. As for the samples at 268 and 250 K, PPO activities remained below the level of 60 U/mg, indicating an effective suppression of low temperature on PPO activity and maintenance of desirable sensory appearance.

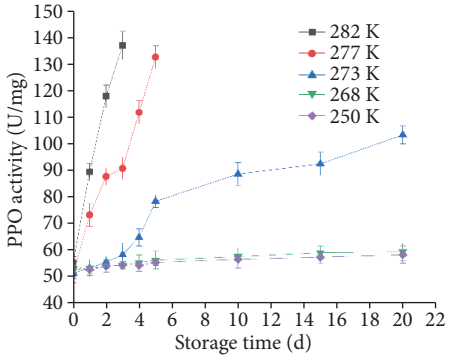

Figure 5 Changes in PPO activity of *L. vanamei* during storage at 5 temperatures. Data are shown as the mean ± standard deviation.

Notably, a correlation matrix showed good relationships among most of the parameters (Figure 6). Specially, a high positive correlation (with correlation coefficient of 0.73–0.99) between biochemical and microbial indicators, such as TVB-N content, protease activity, PPO activity and TAC, was observed. Besides, sensory score had a high and significant negative correlation with overall biochemical indicators. This finding confirmed that sensory evaluation was in well agreement with the instrumental determinations.

3.2 Assignment and distribution of entropy weight at different temperatures

The entropy weighting method was used to assign the weights for all indices at different storing temperatures and the results were presented in Figure 7. The weights of quality indices heavily depended on the storing temperatures. Exactly, the weight of each quality index was evenly distributed at the range of 0.19–0.23 when the shrimp samples were stored at 277 and 282 K, indicating the similar amount of information. Unlike to these situations at 277 and 282 K, the weights of quality indices significantly altered when the shrimp samples were stored at 268 and 250 K, among which the weights of quality indices TAC of 0.28, TVB-N content of 0.24, and PPO activity of 0.24 were observed, respectively. This result revealed that the quality indices TAC, TVB-N content and PPO activity contained more information and indicated a greater impact on the comprehensive evaluation than the other indices, when the shrimps were stored at relatively low temperatures.

Besides, the weights of TAC, TVB-N content and PPO activity at 5 different temperatures were always greater than 0.18 and this distribution suggested that the comprehensive evaluation of shrimp quality during shelf-life might depend heavily on TAC, TVB-N

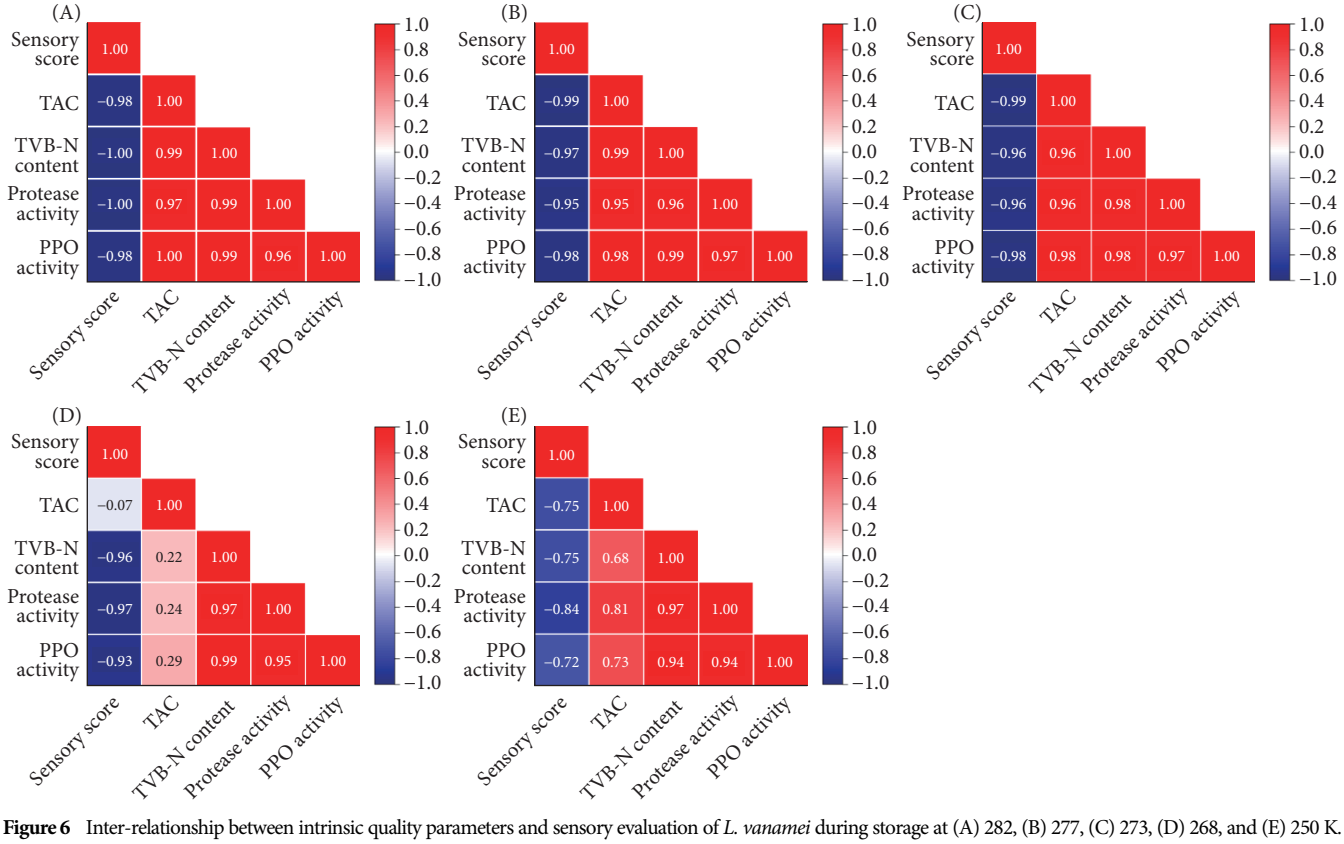

Figure 6 Inter-relationship between intrinsic quality parameters and sensory evaluation of *L. vanamei* during storage at (A) 282, (B) 277, (C) 273, (D) 268, and (E) 250 K.

content, and PPO activity. The possible reason for this result was that these indices were correlated to each other from a biological or physical perspective. Melanosis is the vital appearance quality attribute and the decrease of sensory score is primarily due to the melanosis development. There is a clear connection between the melanosis development and the increase of PPO activities. Therefore, elevation of protease and PPO activity is the primary reason for the increase of TVB-N content and reduction of sensory score. Our previous research has revealed that the loss of compartmentalization and integrity in hepatopancreas tissues of *L. vannamei* during cold storage consequently led to the breakdown of cellular membranes and the leakage of proteases and PPO, followed by the TVB-N production and melanosis development. Overall, the weighting assignment of each quality index is based on experimental data and the subjective interference from human factors can be avoided consequently. Moreover, all indices can be merged into a comprehensive evaluation index and the multiple attribute decisions are transformed into the single attribute decisions accordingly.

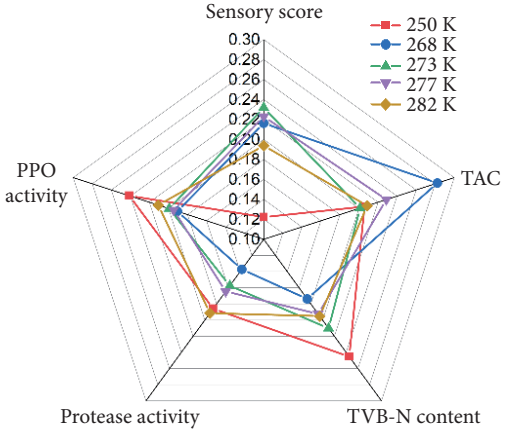

Figure 7 Alterations of the weights of all quality indices of shrimp *L. vannamei* stored at 5 temperatures.

3.3 Changes in GSI

Based on the weights of each quality index, the comprehensive evaluation index GSI at each storage temperature was calculated according to Eqs. (3) and (4). As shown in Figure 8, the initial values of GSI under each storing temperature were all kept 1.0 and then decreased consistently with the prolongation of storage period. Exactly, the significant difference was observed between the samples stored at different temperatures.

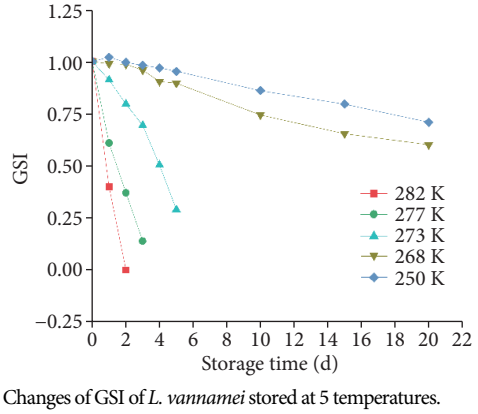

Figure 8 Changes of GSI of *L. vannamei* stored at 5 temperatures.

GSI decreased slowly when the samples were stored at 250 K, with two-folds higher as compared to the other groups stored at the temperatures of 273, 277 and 282 K. This relatively high value of GSI might be attributed to the reduction of bacterial population and the inhibition of enzyme activity in *L. vannamei* at low temperature. The values of GSI approached to 0 on day 2 at 282 K, day 4 at 277 K, and day 10 at 273 K, respectively.

3.4 Establishment of the GSI predictive model

The reaction order with the highest R^2 value at each temperature was chosen to determine the appropriate reaction rate constant (k). The GSI were well fit to the relationship in zero-order kinetics with the high values of regression coefficients ($R^2 > 0.90$). Generally, the zero-order kinetics model always resulted in a better fitting of the comprehensive evaluation index. For example, zero-order kinetics has been reported for color degradation of shrimp shell during frozen storage[12]. In the present study, the regression coefficients R^2 were greater than 0.90 under 5 storage temperatures.

Moreover, the reaction constant (k) estimated by the linear regression of the comprehensive evaluation index GSI was the result of contribution from all independent indices and was influenced by storing temperature and time. In this investigation, the temperature dependence of the rates of GSI changes was adequately described by Arrhenius kinetics ($R^2 > 0.90$) in the whole temperature range and the result was illustrated in Figure 9. Regression analysis indicated that the quality deterioration rate of *L. vannamei* increased with the increase of storing temperatures. The activation energy (E_a) and the reaction rate constant (k_0) were calculated by fitting the values of $\ln|k|$ and the reciprocal of storage temperature at 250, 268, 273, 282, and 288 K, respectively. The values of E_a and k_0 in GSI were (64.78 ± 0.75) kJ/mol and (3.47 ± 0.54) × 10^{11}, respectively. Generally, the activation energy of food-related chemical reactions commonly fell within 30–120 kJ/mol and the values of E_a calculated here might be considered justified. In addition, the value of E_a indicated the dependency of quality degradation on temperature, among which the lower value of E_a suggested the faster speed of quality degradation. As compared to the value of 85.61 kJ/mol in bighead carp heads stored at a constant temperature[6], the value of 64.78 kJ/mol in this research was significant reduced, and this finding implied that *L. vannamei* was more liable to suffering quality degradation than the bighead carp heads during cold storage. Based on the E_a and k_0, therefore, the predictive model of GSI was established as following: GSI = 1 − 3.47 × $10^{11}t$ × exp (−64.78 × 10^3/RT), in which t, R and T were the storage time of days, the gas constant of 8.314 J/(mol·K), and the thermodynamic temperature, respectively.

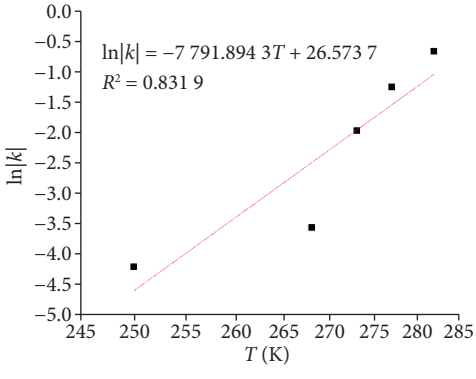

Figure 9 Arrhenius plots of rate constant for GSI change of *L. vannamei* during storage at different temperatures.

3.5 Validation of the established model

The effectiveness of the established GSI kinetic models was verified by comparing the predictive values with the experimental data. The relative percentage deviations between the experimental and predicted values for GSI were below 6% at 268 K and 12% at 277 K during the storage of 10 and 4 days, respectively. Hence, the experimental data had an acceptable fitness with the model and the application of this model could benefit the quality management of shrimp during storage. Additionally, another important application of this model was to estimate the shelf-life. Based on the acceptable traditional quality index criteria, GSI value of 0.5 was assigned as the upper-limit of shelf-life. Consequently, the storage temperatures of 250, 268, 273, 282 and 288 K were successively substituted into the established model and calculated the shelf-life. By following this procedure, 1.43, 2.36, 3.56, 6.05 and 49.11 days of storage time were obtained and these data were well accordance with the experimental values (relative errors < 12%).

4 Conclusion

With the entropy weight method, the present study objectively determined the weight of each quality-related index of *L. vannamei* during cold storage at 250, 268, 273, 282 and 288 K. In addition, the dynamic model GSI based on the entropy weighting method was established and was used to comprehensively evaluate the overall quality degradation status. Furthermore, the accelerated shelf-life testing proved its accuracy to predict the shelf life, which provided a useful tool to monitor the quality degradation of *L. vannamei* during cold storage.

Conflict of interest

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

Acknowledgements

This study was supported by the National Natural Science Foundation of China (No. 31772048) and Natural Science Foundation of Guangdong Province (No. 2023A1515010852).

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