Study of golden pompano (*Trachinotus ovatus*) freshness forecasting method by utilising Vis/NIR spectroscopy combined with electronic nose

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**ABSTRACT**

Golden pompano (*Trachinotus ovatus*) quality forecasting method utilising Vis/NIR spectroscopy combined with electronic nose (EN) was investigated in this article. Responses of Vis/NIR spectroscopy and EN to pompanos stored at 4°C were measured for 6 days. Physical/chemical indexes including texture, total volatile basic nitrogen, pH, total viable counts, and human sensory evaluation were synchronously examined as quality references. Chemometric methods including principal component analysis (PCA) and stochastic resonance (SR) were employed for spectroscopic and EN data analysis. Physicochemical examination demonstrated that fish quality decreased rapidly during storage. PCA qualitatively classified freshness degree of pompano samples, while SR signal-to-noise ratio (SNR) spectrum using SNR maximum quantitatively characterised quality for all samples. Golden pompano quality predictive models were developed based on spectroscopy, EN, and spectroscopy combined with EN, respectively. Results demonstrated that the model developed based on spectroscopy combined with EN presented a forecasting accuracy of 93.3%.

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**Introduction**

Golden pompano (*Trachinotus ovatus*) is an economically important marine fish species and favoured by most consumers, due to its good taste and rich nutrients (e.g. proteins, fats, unsaturated amino acids, and minerals).\(^{[1-3]}\) However, pompanos have limited shelf life, and deteriorate easily after post-mortem due to biochemical reactions and microbial pollution.\(^{[1]}\) Therefore, investigation on golden pompano freshness rapid analysis method is of great importance.

Nowadays, there are many protocols available for marine fish quality analysis, such as total viable counts (TVC)\(^{[4]}\) and total volatile basic nitrogen (TVB-N).\(^{[5]}\) But these protocols often rely on microbiological/chemical examination, which is rather time-consuming. To address this issue, many instrumental analysing methods such as gas chromatography, gas chromatography coupled with mass spectrometry, and HPLC have been applied for fish quality analysis.\(^{[6-8]}\) Although the use of instrumental analysis realises computerised control and saves time, only well-trained operators can perform these experiments. Also, the high cost for these instruments limits their wide application.

Recently, great attention has been paid on food quality analysis by Vis/NIR spectroscopy. Vis/NIR spectroscopy has shown potential usage in various agricultural and food products for freshness...
discrimination due to its non-destruction, no pollution, easy operation, capability of on-line analysis,\textsuperscript{9} variety classification,\textsuperscript{10} bruise identification,\textsuperscript{11} and adulteration analysis.\textsuperscript{12} Also, this method has been reported for aquatic products quality analysis. For instance, Sivertsen et al. proposed a Vis/NIR spectroscopy-based method for differentiation between fresh and frozen-thawed cod fillets.\textsuperscript{13}

Electronic nose (EN) is an intelligent detecting device that consists of several chemical sensors with specific sensing types. Since the detecting objectives of EN are volatile compounds, it provides an access for food quality analysis in a non-destructive way. After one sampling, a characteristic signal can be obtained. Then, this unknown pattern can be identified through a proper pattern recogniser.\textsuperscript{14,15} EN measurement can achieve better stability and reproducibility, compared with human sensory evaluation (HSE). A large number of researches have demonstrated the application of EN coupled with pattern recognition methods in diverse fields, particularly in food quality analysis, including fruits,\textsuperscript{16,17} oils,\textsuperscript{18,19} grains,\textsuperscript{20,21} meat,\textsuperscript{22,23} and fish.\textsuperscript{6,24} However, there is little information on investigating the usage of EN combined with Vis/NIR spectroscopy for golden pompano freshness prediction.

In this work, golden pompano quality prediction by utilising Vis/NIR spectroscopy combined with EN was explored. Spectroscopic and EN responses of pompanos stored at 4°C were examined for 6 days. Physicochemical indexes including texture, TVB-N, pH, TVC, and HSE were examined to provide quality references for instrument analysis. Principal component analysis (PCA) and stochastic resonance (SR) were utilised for spectroscopic and EN data analysis, respectively. Pompano quality predictive models were developed based on Vis/NIR spectroscopy, EN, and Vis/NIR spectroscopy combined with EN, respectively. Validating experiments were also performed to evaluate the forecasting accuracy of the developed models.

Materials and methods

Raw materials

Fresh golden pompanos with an average weight of 500 ± 100 g were bought from an aquatic market, Hangzhou, China. After transporting to the laboratory within half an hour in a foam box with ice, pompanos were decapitated, eviscerated, and washed with cold water. Then, the fish were cut into small pieces, each containing 10 g ± 1 g (30 × 20 × 10 mm). The total number of samples was displayed in the online supplementary information (SI) Table S1. Afterwards, samples were packaged with sealing membrane and stored at 4°C for 6 days. Each day, some pompano samples were randomly taken out for physicochemical, spectroscopic, and EN measurements. Each test was repeated by five replications.

Chemicals

The main chemicals utilised for the experiments including magnesium oxide (Tianjin Bodi Chemical Co., Ltd. Tianjin, China), hydrochloric acid (Hangzhou Chemical Reagent Co., Ltd. Hangzhou, China), boric acid (Wuxi Jingke Chemical Co., Ltd. Jiangsu, China), sodium hydroxide (Sinopharm Chemical Reagent Co., Ltd. Shanghai, China), methyl red (Shanghai SSS Reagent Co., Ltd. Shanghai, China), and methylene blue (Shanghai SSS Reagent Co., Ltd. Shanghai, China) were of analytical pure grade. Deionised water was utilised in the experiments.

Physicochemical examination

Texture

TA.XT2i Texture Analyser (Stable Micro Systems, UK) was used for pompano texture analysis. Flat cylindrical probe p/5 (5 mm in diameter) was set and TPA mode was adopted. Speed in pre-measurement and after-measurement was 3 mm/s. Measurement speed was 1 mm/s. Compression
degree was 50%. Residence time interval was 5 s. Load probe type was Auto-0.2 g. Data collection range was 200.

**Total volatile basic-nitrogen**

TVB-N content in golden pompanos was determined by a micro Kjeldahl apparatus (Hongji Instruments Company, Shanghai, China), according to China standard protocols (GB/T 5009.44–2003). Briefly, 10 g of sample was mixed with 100 ml distilled water in a heating flask. After 30 min, the mixture was filtered and the filtrate was kept in a refrigerator before being analysed. Then, 5 ml filtrate and 5 ml magnesium oxide suspension (10 g/l) were mixed, followed by distilling for 5 min. The absorption solution (containing 10 ml boric acid (20 g/l) and 5–6 drops of mixed indicator) was titrated with 0.010 mol/l hydrochloric acid. The TVB-N of pompanos was calculated as follows:

$$X = \frac{(V_2 - V_1) \times c \times 14}{m \times 5/100} \times 100$$

where

- $X$ is the TVB-N content of pompanos in mg N/100 g
- $V_2$ is the volume of hydrochloric acid consumed for sample titration in ml
- $V_1$ is the volume of hydrochloric acid consumed for control titration in ml
- $c$ is the concentration of hydrochloric acid in mol/l
- $m$ is the weight of sample in g

**pH**

For pH measurement, the minced sample was homogenised with 90 ml deionised water after cooling down. After attaining equilibrium at room temperature for 30 min, the filtrate was taken out and measured with a PHS-3C pH meter (Hangzhou Leici Analytical Instruments Company, China).

**Total viable counts**

Pompano sample was aseptically weighted and homogenised with 225 ml sterile 0.1% physiological saline for 1 min. The homogenised sample was serially diluted using 9 ml sterile saline for bacteriological analysis. TVC was determined in plate count agar by the spread plate method (AOAC, Official methods of analysis (17th edit) 2002).

**Sensory evaluation**

According to the previously reported method by Gao et al[2], the sensory of pompano samples was evaluated by six experienced panellists (two males and four females). Table 1 displays the sensory evaluation details. Voting number is set at $k$, $k \in (1,10)$. The quality of pompano is divided into $m$ levels, and the score of a specific level is set at $h_j$, $j \in (1,m)$. Pompano attributes are divided into $n$ elements, and a specific element is set at $u_i$, $i \in (1,n)$. The contributory weight is determined by pairwise comparison of contribution weight of attributes set at $x_i$ ($\Sigma x_i = 1$). If there is a specific relationship between two objects of $h_j$ and $u_i$, the relation set (matrix) of $f$ is calculated as follows:

$$F = \begin{bmatrix}
    f_{11}/k & f_{12}/k & \cdots & f_{1m}/k \\
    f_{21}/k & f_{22}/k & \cdots & f_{2m}/k \\
    \vdots & \vdots & \ddots & \vdots \\
    f_{n1}/k & f_{n2}/k & \cdots & f_{nm}/k
\end{bmatrix}$$

Thus, the overall acceptability of pompano is calculated by the weight grade method as follows:

$$Z = \sum_{i=1}^{n} x_i \cdot \sum_{m=1}^{m} \frac{f_{ij}}{k} h_j$$
Vis/NIR spectroscopy schematic diagram is displayed in Fig. S1 (SI). The system mainly consists of three functional parts including sampling device (light controller, sampling pedestal, optical fibre, and special halogen lamp), detection device (S3000 Vis/NIR spectrometer, USB 2000+, America Ocean Photology Company), and data acquisition system (Spectrapro software, American Ocean Photology Company).

Spectroscopy measurement was performed at room temperature. The determined sample was fixed in the sampling pedestal and contacted with the optical fibre with a dip angle of 75°. The optical fibre was connected to the detecting device and the special halogen lamp. The sampling pool was a sealable and opaque cube.

Electronic nose

EN system has three basic parts: data acquisition, modulating and transmitting unit (U1); sensor array and chamber unit (U2); power and gas supply unit (U3) (Fig. 1a). The pump is FML201 (Xinweicheng Technology Co., Ltd, Chengdu, China). The valve is WTA-2K (Takasago Electrical Co., Ltd, Tokyo, Japan). The data acquisition unit is developed by our lab. The EN sensor array consists of eight metal oxide semiconductor (MOS) gas sensors with different sensitive species (Fig. 1b). The selectivity towards volatile compound classes of MOS sensors is indicated by the supplier: S1 (TGS-825, hydrogen sulphide), S2 (TGS-821, hydrogen), S3 (TGS-826, ammonia), S4 (TGS-822, ethanol, methylbenzene, xylene gas), S5 (TGS-842, hydrocarbon component gas), S6 (TGS-813, methane, propane, and butane), S7 (TGS-2610, propane, butane), and S8 (TGS-2201, nitrogen oxides) (Fig. 1c). Each sensor is installed in independent chamber to avoid cross-influence of gas flow. Special high temperature resistant material is utilised to fabricate gas sensor chamber. The detecting mechanism is displayed in Fig. 1d, where \(V_H\) is the heating voltage, \(V_C\) is the supplying voltage, and \(V_{RL}\) is the sampling voltage. The sensing membrane is heated by the resistance wire. EN response is recorded as sampling voltage (V).

Before EN measurement, pompanos were placed into 50 ml air-tight vials, and sealed with sealing membrane. The vials were equilibrated at room temperature for 30 min. After turning on the EN power, washing pump and valve-2 were started. Sampling pump and valve-1 remained off. Sensor array was recovered by zero gas, which was obtained by filtering air through active carbon. When sensors’ responses returned to the baseline, washing pump and valve-2 were shut off. Sampling pump and valve-1 were turned on. Gases existing in the headspace were inhaled into gas sensor chambers by sampling pump at a flux speed of 400 ml/min for 45 s. EN measurement interval was 0.05 s. EN real-time responses to pompanos were recorded. When measurement was over, gas sensors were recovered by zero gas at a flux speed of 1000 ml/min for 600 s, waiting for next measurement.

Data treatment

Principal component analysis

PCA is an unsupervised chemometrics method that can effectively decrease the number of variables through dimensionality reduction.\(^{[27]}\) So, the most original information of samples can
be characterised just by certain new variables.\cite{28} PCA has been frequently utilised in the field of multivariable data analysis.

**Double-layered SR**
SR is a counter-intuitive phenomenon and has inclusive applications in signal processing and data analysis.\cite{29,30} The detailed double-layered SR is described in Section S1 (SI).

**Results and discussion**

**Physicochemical examination results**

**Texture**
Changes in pompano texture profiles including firmness, adhesiveness, and resilience are measured during cold storage for 6 days. The initial firmness value was 345 g, and it increased to 385 g in Day 1, followed by a decrease trend (Fig. 2a). After 6 days, the hardness value was 192 g. Figure 2b presents the adhesiveness change of pompanos. The adhesiveness value was 9.2 g·s in Day 0. This index underwent rapid growth, reaching 56 g·s at the end of storage. However, pompano’s resilience ranged between 0.13 and 0.21 during storage time, as presented in Fig. 2c.

When fish dies, muscle firmness increases and reaches its maximum, due to the formation of rigor mortis compounds.\cite{11} But the link between myogen and actin becomes weak once stiffness relieves and autolysis begins, resulting in reduced hardness and increased adhesiveness.\cite{31} These reactions can be accelerated with the help of microbial propagation. Similar changes in texture profiles have also been reported in large yellow croaker\cite{31} and American shad.\cite{32}
Total volatile basic-nitrogen

TVB-N is an important chemical index for assessing the quality of fish and meat. The initial TVB-N content was 9.5 mg/100 g in Day 0. TVB-N index showed an increase trend (Fig. 2d) and reached 33 mg/100 g in Day 4, which was higher than the upper limit of 30 mg/100 g. Therefore, the samples after Day 4 were regarded as non-fresh. Previous researches have demonstrated that the
The accumulation of TVB-N in fish is closely associated with enzymatic activity and microbial propagation. Proteins and non-protein nitrogenous compounds can be gradually degraded and thereby, releasing amines and other breakdown products. The degradation rate can be significantly improved when microorganisms propagate dramatically, which explains the rapid growth of TVB-N in golden pompanos during storage. Our results are in mirror with the report by Gao et al.

**pH**

pH index examination results are presented in Fig. 2e. It began with a low value of 4.7, and increased with the increase of storage time, except for a minor decline from Day 1 to Day 2. Finally, it reached 6.6 in Day 5. It has been noted that the pH changes of marine fish are related firmly to autolysis reaction and microbial decomposition effect. Acidities including lactic acid and phosphoric acid can gradually generate through glycolysis and nucleotide breakdown, resulting in the decrease in pH value. But this lasts for a very short period after post-mortem. Once alkaline compounds are continuously released as a result of microbial pollution, it can contribute to the significant growth in pH value. Results obtained in our research are supported by the report of Gao et al. Overall, pH is a valuable index for quality assessment of golden pompanos.

**Total viable counts**

Microbial propagation is a crucial factor influencing quality of aquatic products. During storage, pompano samples deteriorate gradually due to microbiology propagation. Microbiological metabolism leads to emission of characteristic gases, which provides the measurement basis of EN analysis. So, it is important to trace the microbiological propagation on the samples. TVC values of the samples are displayed in Fig. 2f. Initial value for TVC was about 4l g3.33 cfu g−1. Then, TVC value increased as the storage time increased. TVC value dramatically increased in the following days, and finally reached about 8l g5 cfu g−1 in Day 5.

**Human sensory evaluation**

Sensory attributes of pompano samples were divided into five elements, whose preference scores were scored from 1 to 5; the higher the preference score, the better the quality of pompano (see Table 1). All samples started with a score of 5 in Day 0. In Fig. 2g, it can be observed that preference scores decrease with the increase of storage days. Choosing 3.5 as the acceptable limitation, the samples can maintain its shelf life by 3 days, and the preference score in Day3 was about 3.1. Sensory evaluation results accord to TVB-N results well. Combined with TVB-N and TVC examination results, sensory evaluation results might be affected by microbial activities and changes of samples' self components. Mirror experimental results are also reported by other research groups.

**Spectroscopy analysis results**

**Original responses**

Figure 3a presents the original diffuse reflection spectrum of golden pompanos during storage. The absorption wavebands primarily concentrate within the wavelength range from 360 to 900 nm. Finally, five main absorption peaks appear, at wavelength of about 468, 513, 561, 630, and 702 nm, respectively. Responses in the regions of 500 and 630 nm indicate the changes in myoglobin, where the peak difference at around 630 nm corresponds to absorption characteristics of methemoglobin and metmyoglobin. These findings well suggest internal quality changes in golden pompanos.

**PCA results**

PCA score plots based on spectral feature data are obtained after dimensionality reduction. Figure 3b presents the principal components score projected onto a two-dimensional plane. The first two components capture 84.4% of data variance, covering most information. Although pompanos
undergone different storage time can be classified into different categories, samples stored for 0, 2, and 3 days gather so closely that cannot be well-discriminated.

**SR analysis results**

After inputting spectroscopic signals into a non-linear SR system, stochastic resonance (SR) signal-to-noise ratio (SNR) can be calculated by adjusting noise intensity ranging from zero to 900. As presented in Fig. 3c, SNR intensity is all lower than −50 dB. With the increase of noise intensity, all SNR values first decrease, then increase rapidly, followed by gradual decrease. At noise intensity of about 300, SNR maximum (MaxSNR) values of different samples appear. Also, MaxSNR values of different samples vary from each other. Therefore, spectroscopy SR MaxSNR values successfully characterise all samples in different quality degree.

By linear fitting MaxSNR values, the relationship between SR SNR and pompano storage time can be developed (see Fig. 3d and Eq. 4). After one-step transform, Eq. (5) can be utilised as pompano quality predictive model based on spectroscopy.

\[
Y = -65.55931 + 1.63705 \cdot t \quad (R^2 = 0.98592)
\]

*Figure 3.* Spectroscopy analysis results: (a) original diffuse reflection responses; (b) two-dimensional PCA score plot; (c) SR SNR; (d) pompano quality predictive model using SR MaxSNR values of spectroscopy; and (e) forecasting accuracy evaluation of spectroscopy-based model.
\[ Time = \frac{MaxSNR + 65.55931}{1.63705} \]  

Figure 3e displays the predicting accuracy of developed model (Eq. 5). The regression coefficient between predicting values and true values is 0.98616, indicating that the developed method based on spectroscopy analysis presents good accuracy.

**EN analysis results**

**Original responses**

EN sensor array original responses to pompanos are presented in Fig. 4a. The initiative responses of eight sensors are close to zero. Sensors’ responses increase with the increase of measurement time. A rapid growth can be observed between 5 and 30 s. Finally, responses of all sensors trend to stable. EN responses to air as blank sample were measured during the experiment for 6 days. Results suggest that the EN shows high stability and their responses to air are lower than 0.005 V.

![Figure 4. EN analysis results: (a) original response; (b) two-dimensional PCA score plot; (c) SR SNR spectrum; (d) pompano quality predictive model using SR MaxSNR values of EN; (e) forecasting accuracy evaluation of EN based model; and (f) forecasting accuracy evaluation of combined model.](image-url)
The volatiles emitted by pompanos are inhaled into EN gas chamber, and absorbed by the functional chemical materials located within the gas sensors. The selectivity of eight sensors (see Section 2.5) induces change in sensing material’s characteristics. Besides, sensor responses change with gas concentrations. EN sensor array stable values can be used to characterise pompano volatile concentrations. During experiment, diverse signals of EN sensor array were measured. The stable values presented an increase trend during storage, especially for sensors S1, S3, S4, S5, S6, and S7, indicating that ethanol, hydrogen sulphide, and alkanes are the main volatile spoilage products in pompano quality loss procedure. This phenomenon can be explained by fish spoilage as a result of microbial pollution.\(^1\)

**PCA results**

EN sensor array stable values are extracted as the input of PCA. Figure 4b presents the two-dimensional PCA score plot. The first two components capture 93.7% of data variance. Although pompanos of different storage time showed an approximate trend, there is no obvious discriminating border between each other. PCA method cannot totally discriminate all samples.

**SR analysing results and freshness forecasting model**

EN SNR is presented in Fig. 4c. Noise intensity ranges from 0 to 900. With the increase of noise intensity, all SNR values first exhibit a decrease trend. Then SNR values present an abrupt increase and a series of Eigen peaks generate at noise intensity of about 180, followed by gradual decreases. MaxSNR values are within the range from \(-85\) to \(-55\) dB. So, pompanos with different quality can be quantitatively characterised by EN MaxSNR values.

Linear fitting regression between MaxSNR and storage time (Time) is conducted (see Fig. 4d and Eq. 6). After one-step transform, Eq. (7) can be utilised as pompano freshness predictive model based on EN.

\[
Y = -64.83153 + 1.52526 x \quad (R^2 = 0.99452) \tag{6}
\]

\[
Time = \frac{\text{MaxSNR} + 64.83153}{1.52526} \tag{7}
\]

Figure 4e displays the predicting accuracy of developed model (Eq. 7). The regression coefficient between predicting values and true values is 0.98714, indicating that the developed method based on EN analysis presents better accuracy than the model based on spectroscopy analysis.

**Pompano freshness predictive model based on spectroscopy combined with EN**

Spectroscopy signals reflect the external image changes of pompano samples. EN reflects the internal chemical content changes of the samples. If these two methods are combined with each other to form a new freshness forecasting model, then the pompano freshness can be characterised from both external and internal aspects. We attempted to develop the mixed predictive model based on spectroscopy combined with EN for forecasting pompano quality. Two parameters, \(a\) and \(b\), were preset. By inputting MaxSNR\textsubscript{spec}, MaxSNR\textsubscript{EN}, and Time values into Eq. (8), \(a\) and \(b\) were calculated as 0.8764 and \(-0.2195\), respectively. So, Eq. (9) could be utilised as pompano freshness mixed predictive model based on spectroscopy combined with EN.

\[
Time = a \times \frac{\text{MaxSNR}_{\text{spec}} + 65.55931}{1.63705} + b \times \frac{\text{MaxSNR}_{\text{EN}} + 64.83153}{1.52526} \tag{8}
\]

\[
Time = 0.8764 \times \frac{\text{MaxSNR}_{\text{spec}} + 65.55931}{1.63705} - 0.2195 \times \frac{\text{MaxSNR}_{\text{EN}} + 64.83153}{1.52526} \tag{9}
\]

Figure 4f displays the predicting accuracy of developed combined model (Eq. 9). The regression coefficient between predicting values and true values is 0.98965, indicating that the combined method presents better accuracy than the model based on spectroscopy analysis or EN analysis.
Table 2. Validating experiment results (✓ = right; x = wrong; / = not calculated).

| Sample no. | Forecasting time (d) | Practical Time (d) | Predicting error (%) | Freshness | Result |
|------------|-----------------------|--------------------|-----------------------|-----------|--------|
| 03         | 4.87                  | 5                  | 2.6                   | Non-fresh | ✓      |
| 12         | 1.85                  | 2                  | 7.5                   | Fresh     | ✓      |
| 14         | 2.74                  | 3                  | 8.67                  | Fresh     | ✓      |
| 25         | 3.96                  | 5                  | 20.8                  | Non-fresh | x      |
| 04         | 0.88                  | 1                  | 12                    | Fresh     | ✓      |
| 09         | 0.11                  | 0                  | /                     | Fresh     | ✓      |
| 21         | 3.12                  | 3                  | 4                     | Non-fresh | ✓      |
| 32         | 2.11                  | 2                  | 5.5                   | Fresh     | ✓      |
| 45         | 5.13                  | 5                  | 2.6                   | Non-fresh | ✓      |
| 27         | 4.15                  | 4                  | 3.75                  | Non-fresh | ✓      |
| 36         | 1.11                  | 1                  | 11                    | Fresh     | ✓      |
| 29         | 2.87                  | 3                  | 4.33                  | Fresh     | ✓      |
| 54         | 2.14                  | 2                  | 7                     | Fresh     | ✓      |
| 52         | 0.08                  | 0                  | /                     | Fresh     | ✓      |
| 37         | 3.77                  | 4                  | 5.75                  | Non-fresh | ✓      |

Validating experiments

Validating experiments are carried out to examine predicting accuracy of the developed model. Eq. (9) is used to examine the freshness of validating samples. Another 84 new pompanos are prepared, and 15 samples are randomly selected for EN measurement. Results are displayed in Table 2. The forecasting accuracy of the predicting model is 93.3%. Validating experiment results demonstrate that the developed model forecasts fish freshness with good accuracy.

Conclusions

In this article, golden pompano freshness forecasting method by utilising Vis/NIR spectroscopy combined with EN was investigated. The results were listed as follows,

(1) Physical/chemical examination results demonstrated that the freshness of pompanos decreased. The shelf life of the sample was 4 days.
(2) Both spectroscopy and EN sensitively responded to samples with different freshness. The use of two-dimensional PCA showed partially qualitative classification abilities for fish samples, while SR MaxSNR values of spectroscopy and EN measurement data discriminated freshness degree of all samples.
(3) Golden pompano freshness predictive model

\[
\text{Time} = 0.8764 \times \frac{\text{MaxSNR}_{\text{spec}} + 65.55931}{1.63705} - 0.2195 \times \frac{\text{MaxSNR}_{\text{EN}} + 64.83153}{1.52526}
\]

was developed based on spectroscopy combined with EN. Validating experiment results demonstrated that the forecasting accuracy of the developed model is about 93.3%. We will carry out a long-term plan to explore the field applications of this proposed method in aquatic product freshness rapid determination.

Disclosure statement

The authors report no conflict of interest. All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

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