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Study on the influencing factors of oscillation chemical reaction and application in food safety detection

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Abstract

The influencing factors of oscillation chemical reaction and application in food safety detection were studied. The results showed that oscillation chemical reaction was related to many factors. Taking the melamine in infant formula as tested samples, click the menu to collect data. Inductive time value and the content of melamine in infant formula had a linear relationship in the range of 0-40 μg/g. A detection limit of 0.08 μg/g was obtained. When the maximum dosage of magnesium sulfate, sodium nitrate, potassium iodide, calcium carbonate and urea reagent was 1×10^{-3} ug/mL, respectively, there was no effect on the signal of the spectrum. The proposed method in this study did not need pretreatment for analysis of sample, and was with some anti-interference, simple and effective. At the same time, this study provided a reference for the food safety detection by nonlinear chemical oscillation system.

Keywords: food safety detection; oscillating chemical reaction; adulteration; infant formula; melamine.

Practical Application: Research about a new method for food safety detection by an oscillating chemical reaction.

1 Introduction

Milk and dairy products are essential components of a healthy diet. Owing to the high nutritional value of milk and dairy products, it is consumed by people of all age groups. Food safety related to people's health and it concerned about people's basic livelihood. In recent years, with the fast development of dairy processing industry, the safety issue of dairy products is becoming extremely important, which concerns ordinary people around the world. The "melamine" has caused a major blow to domestic milk powder, which makes the national trust in domestic milk powder to the freezing point. However, recently, many well-known milk powder enterprises were found that the "vanillin" flavor in the milk powder seriously exceeded the standard, and a special medical milk powder called "betamethasone" came out. These milk powders have serious potential food safety hazards (Li et al., 2021; Cai et al., 2022). Some consumers think that improvements of the law and increased attention to food safety by government can improve the quality of domestic milk (Cai et al., 2022).A range of factors affect the quality of milk, including the variety of cow, type of feed and rearing environment (Santiago et al., 2019; Cai et al., 2022; Santos et al., 2022). Detection of residues of feed additives and toxic substances in milk, such as veterinary drugs, bacteria and heavy metals, was important for controlling the quality of milk (Rabelo et al., 2021; Cai et al., 2022; Karaman et al., 2022). The toxic effects of many chemical compounds were used in food, such as melamine, which had attracted attention in the past decade. Melamine (2, 4, 6-triamino-1, 3, 5-triazine) is a nitrogenous chemical substance, with a chemical formula $C_3H_6N_6$, which is commonly found in the form of white crystals. It has been used as an industrial chemical for a wide range of applications, such as plastics, adhesives, laminates, coatings, fertilizer, flame-retardants, kitchenware, commercial filters and other products (Jawaid et al., 2013; Sun et al., 2010). Melamine is not permitted to be directly added to foods as an ingredient. However, food contamination by melamine has been found in many products, which has illustrated that food safety continues to present major health and economic problems. In 2007, melamine was detected in pet food, which caused illnesses and death of many cats and dogs, since kidney stones could be formed by reaction of melamine and cyanuric acid (Dobson et al., 2008; Tyan et al., 2009). The situation was even worse when infant formula and related dairy products of a Chinese company was revealed to have adulterated with high levels of melamine in 2008, which led to urinary problems of more than 51,900 infants and young children, together with deaths of six children (Ma et al., 2017a).

Protein content in milk and milk products has significant impact on nutritional components, and has been used as a standard to evaluate the quality of infant formula. Furthermore, the total nitrogen contents were estimated as an indication of protein levels by Kjeldahl method or Dumas (Ritota & Manzi, 2018; Chan et al., 2008). However, melamine was a nitrogen-rich compound and intentionally added to food and milk in order to increase the protein content, which might lead to adulteration for manufacturers. At present, most consumers judge the quality of infant formula by the appearance and taste, such as color, smell and the rate of solubility among others. Although these methods have advantages of simple operation, as primary test ways, they lack scientificity and accuracy. Consequently, the rapid,

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simple and economical method for scientifically identifying and evaluating melamine adulteration in milk powder is required. To prevent further contamination and protect public health, governments, research groups and industrial regulatory bodies had developed various analytical tools on different platforms. Moreover, melamine limit in food was established, namely, 1 mg/kg was the maximum limit allowed in infant formula and 2.5 mg/kg for other foods, which had been determined by the Chinese Government and United States (US) Food and Drug Administration (FDA) (Huang et al., 2016; Mauer et al., 2009; Lin, 2009; Liu et al., 2010).

Currently, chemical fingerprint analysis has been applied as an effective method for the analysis of melamine in food. These fingerprinting methods include high performance liquid chromatography (HPLC) for infant formula (Jin et al., 2012; Venkatasami & Sowa, 2010), fluorescence polarization immunoassay (FPIA) for milk and milk powders (Wang et al., 2011), surface plasmon resonance (SPR) biosensor assay for infant formula (Fodey et al., 2011), MCT-based short-wave infrared hyperspectral imaging system for milk powders (Lee et al., 2018), gas-chromatography/mass-spectrometry (GC/MS) for milk and milk products (Xu et al., 2009), time of flight mass spectrometry (TOF-MS) for milk powders (Vaclavik et al., 2010), surface-enhanced Raman spectroscopy for milk and milk powders (Ma et al., 2013) and near infrared (NIR) spectroscopy for milk and milk products (Caporaso et al., 2018 ;Szwarcman et al., 2021). Additionally, many alternative methods have also been reported, such as enzyme-linked immunosorbent assay (ELISA) (Lei et al., 2011), capillary electrophoresis (CE) (Liu et al., 2010), chemiluminescence (CL) (Wang et al., 2009), colorimetric nanoparticals (Ai et al., 2009) and so on. Most of these methods exhibit high sensitivity and can meet the requirements for the minimum amount of melamine allowed in infant formula and other related products. However, these methods are generally expensive and labor intensive, and may require harmful reagents, skilled labor and complex procedures, such as separation and purification. According to the aforementioned methods, near-infrared reflectance spectroscopy (NIRS) and Raman spectroscopy have been reported that they are rapid and accurate methods for detecting melamine in milk powder, but they still need sample preparation and well-trained personnel. Therefore, it would be beneficial to develop simple and cost effective methods based on different principles from different aspects for distinguishing and evaluating samples, and the techniques may be complementary with each other (Ma et al., 2017b).

Kinetic-catalytic reaction was one of the simple and rapid analytical methods compared to other methods (Gao et al., 2007). Belousov-Zhabotinsky oscillatory chemical reaction (Belousov and Zhabotinsky were the names of the two Russian scientists, who were the first ones to study the reaction) was typical nonlinear chemical reaction system, which had made a great progress (Ma et al., 2017b), and many scholars had explained the mechanism of the reaction by different kinetic models. The most famous kinetic model was FKN (Field et al., 1972; Field & Schneider, 1989) model, and B-Z oscillatory reaction had been explained by this model. The phenomena of the reaction are complex and involve chemical oscillation, chemical turbulence, chemical pattern and chemical wave and so on (Field & Schneider, 1989). The reaction mechanism and applications of chemical oscillation in single component detection had been investigated extensively and thoroughly by the domestic and foreign scholars (Field et al., 1972; Field & Schneider, 1989; Wang et al., 2005; Gan et al., 2002). However, the research on the application of nonlinear chemical reaction in the authenticity identification and quality evaluation of infant formula was rare. Because the components of infant formula are quite complex and include many sorts of reducing substances among them. According to the literatures (Ma et al., 2017b; Zhang et al., 2007, 2012a), because of the differences in the types and the content of their components, different samples had different influences on an identical nonlinear chemical reaction, which caused that the shapes of the relevant potential-time (*E-t*) curves were different from each other. The *E-t* curve is very helpful for the rapid identification and evaluation of infant formula with melamine, because it contains abundant qualitative and quantitative information. Furthermore, compared with spectrum and chromatogram, nonlinear chemical fingerprint technique could be more suitable for identification and quality evaluation of infant formula. Nonlinear chemical fingerprint is a kinetic fingerprint, and the information reflected is the kinetic information of entire nonlinear chemical reaction added by sample components. In other words, the information and entire course of the chemical reaction are directly correlated (Zhang et al., 2012a). In this work, by adding infant formula into the"H^++Mn^{2+}+BrO– 3+acetone" system could occur oscillation, and melamine adulteration in infant formula was identified and evaluated by a nonlinear chemical fingerprint technique. Moreover, the proposed method avoided the time-consuming and laborious process of separation and purification of samples.

Thus, the objective of this paper was to evaluate the feasibility to study the influencing factors of oscillation chemical reaction and apply nonlinear chemical fingerprint technique to detect and identify melamine adulteration in infant formula. The content of melamine in infant formula was calculated by the least square method, and the interference of magnesium sulfate (I), potassium iodide (III), calcium carbonate (IV) and urea (V) reagent on the spectrum signal was studied, respectively. The method developed in this study had the advantage of low operational cost, no pretreatment for identifying and evaluating melamine adulteration in infant formula, and was with some anti-interference. At the same time, this study provided a reference for the food safety detection by nonlinear chemical oscillation system.

2 Materials and methods

2.1 Materials

All chemicals used were of analytical reagent grade. Sulfuric acid (1.00 mol/L), acetone (1.00 mol/L), sodium bromate (0.85 mol/L), manganese sulfate (0.07 mol/L), magnesium sulfate, sodium nitrate, potassium iodide, calcium carbonate and urea were used. Solutions were kept at a constant temperature (50.0 °C) until used. Double distilled water was used throughout. Melamine (99% purity) was obtained from Sigma-Aldrich Company. Urea was obtained from Ningbo Chemical Reagent (China). Spectroscopic grade potassium bromide was purchased from Beijing yinglaike Technology Development Co., Ltd.

2.2 Milk powder samples

Two brands of infant formula samples were provided by the Institute of Product Quality Supervision and Inspection in Shaanxi Province, which were referred to as infant formula 1# and infant formula 2#. A series of infant formula samples were spiked with known levels of melamine, namely, the content of melamine in infant formula was 0 μg, 5 μg, 10 μg, 20 μg, 30 μg and 40 μg, respectively, and a series of adulteration infant formula were obtained. In addition, one sample of pure infant formula was also prepared for experiment.

2.3 Main apparatus

A nonlinear chemical fingerprint instrument (Model MZ-1B-2) developed by Central South University and Xiangtan Ltd. for making whole set instruments and meters (Hunan, China) was used (Ma et al., 2017a). The electrodes were 217 calomel and 213 platinum (Shanghai Precision & Scientific Instrument Co., China). Among electrodes, 217 calomel electrode was used as reference electrode, and 213 platinum electrode was used as working electrode (Ma et al., 2017a). Nicolet iS10 infrared spectroscopy (Thermo Scientific) was used. The operation process had been interpreted on the basis of the literature (Jawaid et al., 2013).

2.4 Procedure

The following procedure was used in all experiments for the determination of infant formula. The nonlinear chemical reaction mixture was prepared by mixing of 25 mL of 1.00 mol/L sulfuric acid, 15 mL of 1.00 mol/L acetone, 12 mL of 0.07 mol/L manganese sulfate, 10 mL of double distilled water and appropriate volumes of infant formula. All components of reaction mixture were added into the reactor (Ma et al., 2017b). The reactor cover was closed. It was with two injection holes, the electrodes and a thermometer. Then, the instrument was turned on, and the temperature in the reactor was adjusted to a constant temperature. The stir rate was adjusted to 800 r/min. When the constant rate stir just lasted for 5.0 min, 5.00 mL of sodium bromate solutions was injected into the reactor. The menu was immediately dotted for plotting the relevant electric potential-time (E-t) curves until the potential oscillation disappeared (Ma et al., 2017a). All quantitative parameters of nonlinear chemical fingerprint were compiled on Matlab (2010, The Math Works, Natick, USA).

3 Results and discussion

3.1 Influence of experimental variables

Existing studies have reported kinetic and thermodynamic conditions of nonlinear chemical fingerprint, as well as entropy change laws and expression suitable for describing entropy change rates of any thermodynamic system (Zhang et al., 2012a). It was demonstrated that an open system without complementarity of dissipative substances and a close system far from the equilibrium were suitable for studying nonlinear chemical fingerprint since the chemical reaction was able to be accomplished in a properly short period of time in these systems (Ma et al., 2017b).

The nonlinear chemical system was highly sensitive to foreign substances change and the variation of the reaction components in the medium. However, many chemical substances, such as organic acid, amino acid, vitamin, enzyme, ketone and hydroxide, could greatly influence the forms and the quantifiable parameters of nonlinear chemical fingerprint (Ma et al., 2017b). The effect of the variables on the behavior of nonlinear chemical reaction was studied using the maximum amplitude change and inductive time change as the measured parameter. To ensure the maximum possible sensitivity and precision of the determination, working conditions of nonlinear chemical reaction were optimized considering two factors. Firstly, in order to accomplish the oscillating reaction in a properly short period of time, inductive time could not too long. Then, to ensure higher sensitivity, maximum amplitude needed to be maximum value.

In this study, the effect of manganese sulfate concentration was studied over the range from 0.02 to 0.12 mol/L. Low manganese sulfate concentrations were found to prolong inductive time. As manganese sulfate concentrations increased, inductive time was shortened, and maximum amplitude was increased. When manganese sulfate concentration was 0.07 mol/L, inductive time and maximum amplitude were the optimum value. As shown in Figure 1a. When manganese sulfate concentration exceeded 0.07 mol/L, inductive time was prolonged and the oscillation reaction was also prolong, which affected the time of detection and analysis. Therefore, a concentration of 0.07 mol/L was finally adopted.

The effect of sulphuric acid concentration on the oscillatory system was showed in Figure 1b. It could be seen that changes of sulfuric acid had a significant effect on inductive time and maximum amplitude. When it was increased over the range from 0.50 to 1.25 mol/L, maximum amplitude increased strongly. Inductive time began to be decreased, and then it increased. When the concentration of sulfuric acid was 1.25 mol/L, inductive time and maximum amplitude had the optimum values. Therefore, the concentration of 1.00 mol/L was chosen as the optimum concentration.

The effect of acetone concentration was investigated over the range from 0.50 to 2.00 mol/L. As the concentration of acetone increased from 0.75 to 1.00 mol/L, maximum amplitude was increased, and inductive time was shortened. On the contrast, as the concentration of acetone was outside this range, maximum amplitude was decreased, and inductive time was increased roughly proportionally. When the concentration of acetone was 1.00 mol/L, maximum amplitude and inductive time had the optimum values. As shown in Figure 1c. In order to ensure precise measurement, a concentration of 1.00 mol/L acetone was chosen.

The sodium bromate concentration was studied over the range from 0.40 to 1.20 mol/L. As sodium bromate concentration increased from 0.40 to 0.85 mol/L, maximum amplitude was increased, and inductive time was shortened. When sodium bromate concentration was 0.85 mol/L, maximum amplitude and inductive time had the optimum values. As shown in Figure 1d. To ensure the time required to complete whole nonlinear chemical reaction, the concentration chosen was 0.85 mol/L.

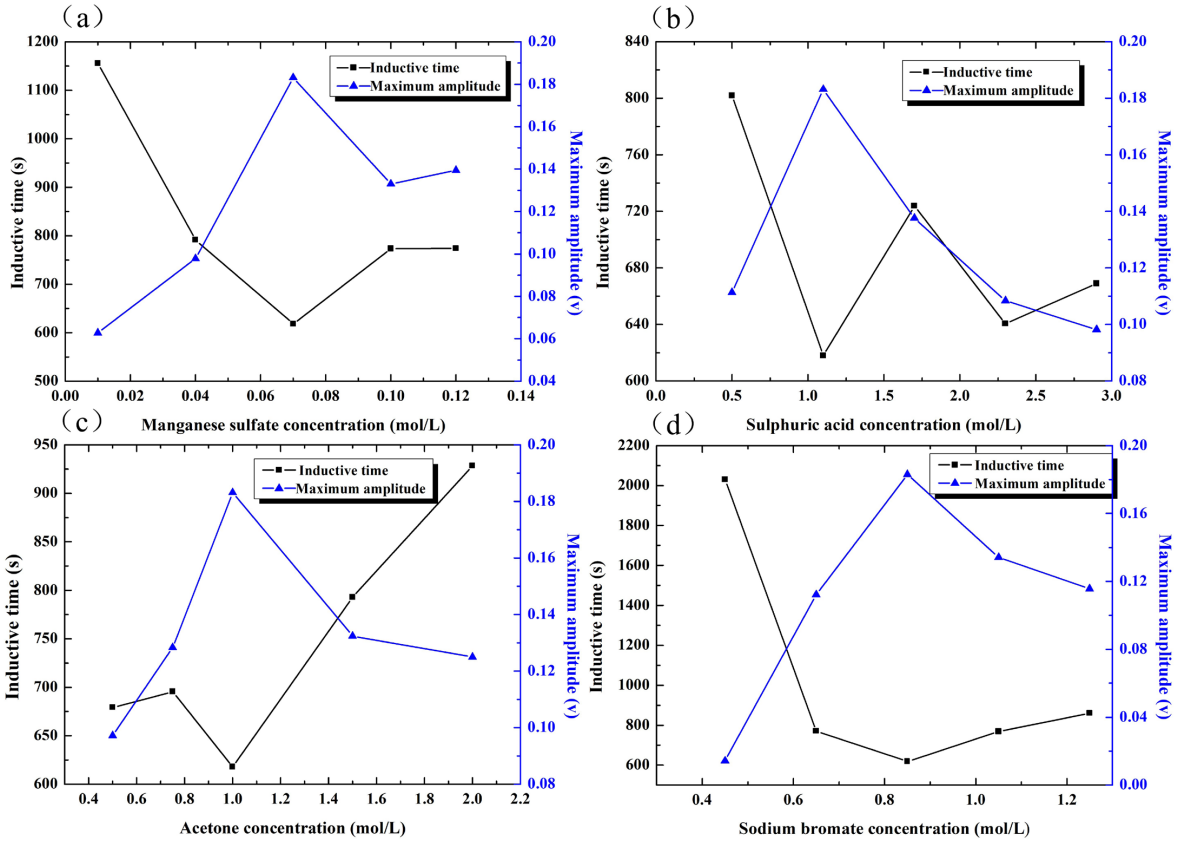

Figure 1. The effects of concentration of different reagents on characteristic parameters of nonlinear chemical fingerprint of infant formula.

3.2 Optimization of detecting dosage of infant formula

Nonlinear chemical reaction can change with the change of determining condition. Therefore, the experiment must be determined under the constant condition. On selecting detecting dosage in order to determine the fingerprint of infant formula, both the characteristic of the fingerprint and determining time must be considered simultaneously. Under the optimal experimental conditions, namely, 25 mL of 1.00 mol/L sulfuric acid, 15 mL of 1.00 mol/L acetone, 5 mL of 0.85 mol/L sodium bromate, 12 mL of 0.07 mol/L manganese sulfate, 10 mL of double distilled water and temperature of 50.0 °C in the reactor, the detecting dosage of infant formula 1# could be evaluated by employing oscillatory end time as the measured parameter. Because of the difference of chemical substances or content, different sorts or qualities of products added into the reactor could result in the E-t curves with different shapes and information parameters (Ma et al., 2017b; Zhang et al., 2012a). Moreover, the holistic content of chemical constituents was higher, while its content of active components was also higher. As shown in Figure 2. Oscillatory end time was found to decrease with increasing detecting dosage of infant formula. Experimental results indicated that the relationship of quantitative parameters and the holistic content of active components was usually complex without considering dosage range. When infant formula samples (0.20 g, 0.40 g, 0.60 g, 0.80 g, 0.90 g, 1.00 g and 1.20 g) were added to the reactor, respectively, quantitative functional relationship was obtained between detecting dosage and quantifiable parameter such as inductive time and oscillatory end time, and the corresponding relation equations might be expressed by Equations 1 and 2

$$t_{ind} = -55.954K^2 - 352.34K + 8731.6 \quad (1)$$

and

$$t_{uns} = 35.728K^4 - 673.45K^3 + 4586.4K^2 - 13466K + 15369 \quad (2)$$

where t_{ind} is inductive time, t_{uns} is oscillatory end time, and K is the dosage of infant formula.

Therefore, the applied dosage of infant formula to the experiment was 1.00 g. Under the condition of the detecting dosage, not only the characteristic differences of the fingerprints were conspicuous, but also the determining time was not too long (Ma et al., 2017b).

3.3 Essential information in nonlinear chemical fingerprint of infant formula

Nonlinear chemical fingerprint possessed abundant quantitative information and intuitionistic information due to its dynamic property. In this study, nonlinear chemical fingerprint was obtained by adding 1.00 g of infant formula 1# into the reactor. The fingerprint was shown in Figure 3. It was obvious from Figure 3 that essential characteristic information of nonlinear chemical fingerprint mainly included inductive time (t_{ind}), undulatory period (τ_{und}), undulatory life (t_{und}), canyon potential

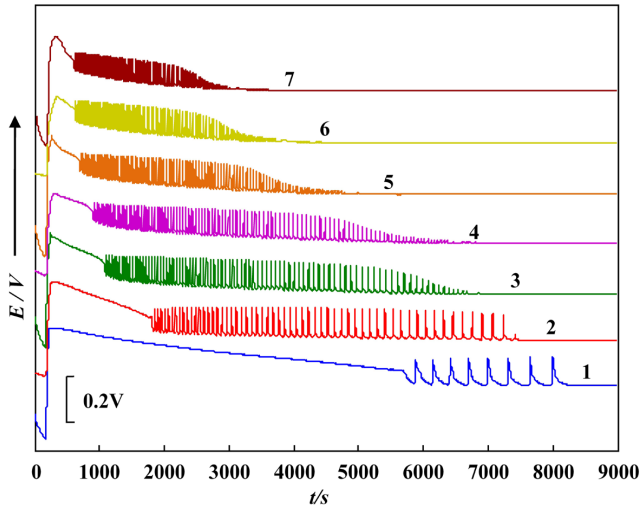

Figure 2. Influence of the different dosage of infant formula on the nonlinear chemical fingerprint. 1 = 0.2 g; 2 = 0.4 g; 3 = 0.6 g; 4 = 0.8 g; 5 = 0.9 g; 6 = 1.0 g; 7 = 1.2 g.

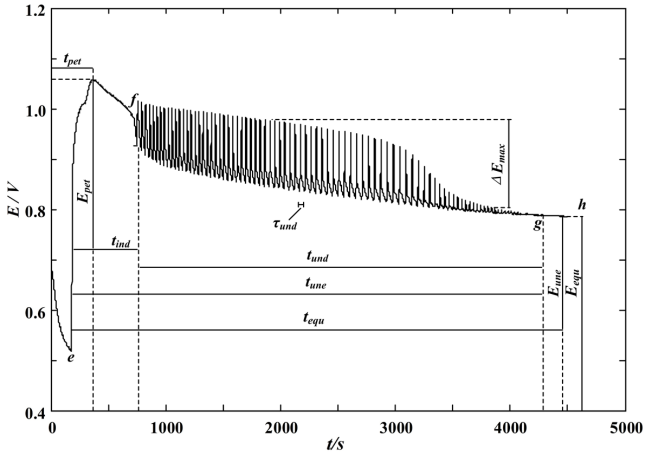

Figure 3. Basic characteristic information of nonlinear chemical fingerprint of infant formula 1#. e-f: inductive curve; f-g: fluctuation curve; g-h: stop wave curve; e and h are the start and end points of reaction, respectively.

(E_{can}), canyon time (t_{can}), peak top potential (E_{pet}), peak top time (t_{pet}), oscillatory start potential (E_{uns}), oscillatory end potential (E_{une}), oscillatory end time (t_{uns}), maximum amplitude (ΔE_{max}) and so on, which were defined as quantitative information (Ma et al., 2017b). All of them were described in detail in the literature (Zhang et al., 2012a). The researchers pointed that the oscillation wave shape of the fingerprint could reflect the characteristics of complex samples, and inductive time, oscillatory life, oscillatory period and oscillatory curve were the holistic quantitative information on chemistry components of samples (Ma et al., 2017b; Zhang et al., 2012a). Furthermore, these fingerprints information was very important and helpful for distinguishing and evaluating of adulterated infant formula. Thus, the whole nonlinear chemical fingerprint generally consisted of inductive curve, oscillatory curve, oscillatory-end curve and a part of the equilibrium curve (Ma et al., 2017b; Zhang et al., 2012a).

3.4 Reproducibility and precision of nonlinear chemical fingerprint of infant formula

Pure infant formula 1# (infant formula known to be melamine free) and mixed infant formula 1# (infant formula known to be melamine of 32 μg/g) were analyzed to evaluate the repeatability and precision of the method, and the detecting dosage was 1.00 g. Under the same determination conditions, according to "Procedure", the appropriate dosage of pure infant formula 1# or mixed infant formula 1# was added into the reactor, and their nonlinear chemical fingerprints were obtained. Each sample was repeated three times. The reproducibility of nonlinear chemical fingerprints of infant formula samples was shown in Figure 4. Two kinds of infant formula had good characteristics and reproducibility. It was obvious from Figure 4a that the time of the first peak in the oscillatory course was short for 642.6 s, so inductive time in the inductive course was also short for 640.3 s. On the contrary, Figure 4b showed that the time of the first peak in the oscillatory course was long for 671.8 s, which resulted in inductive time in the inductive course was also long for 669.7 s. Therefore, pure infant formula and mixed infant formula can be distinguished by the characteristics and differences of their fingerprints. Meanwhile, the abundance of the quantifiable and intuitionistic information of nonlinear chemical fingerprint provides necessary conditions for the quantitative analysis of infant formula and adulterated infant formula.

The precision was assessed by determining the relative standard deviation (RSD). It could be seen from Table 1 that the RSDs were less than or equal to 1.75%. Thus, these values confirmed that nonlinear chemical fingerprint had very good reproducibility and precision (Ma et al., 2017b).

3.5 Method application

A series of infant formula samples 1# (infant formula known to be melamine free) were spiked with melamine at different content (0 μg, 5 μg, 10 μg, 20 μg, 30 μg and 40 μg). Then, the samples were added into the reactor, respectively. The total dosage of each mixed infant formula was 1.00 g, and nonlinear chemical fingerprints of the corresponding infant formula were obtained. The effects of the content of melamine on nonlinear chemical fingerprint of infant formula were shown in Figure 5a. With the increase of the content of melamine, inductive time of nonlinear chemical fingerprints of the corresponding infant formula also increased. As shown in Figure 5a. Furthermore, the time of the first peak for each fingerprint was different, which resulted in the difference of inductive time. There was a linear relationship between inductive time and the content of melamine ranging from 0 to 40 μg/g under optimal conditions, with a linear correlation coefficient of 0.9993. As shown in Figure 5b. The fitted regression equation based on the least square method was given:

$$t_{ind} = 0.9407C + 640.57 \quad (3)$$

where t_{ind} is inductive time and C is the content of melamine in the corresponding infant formula. This linear relationship allows the quantification of adulterant.

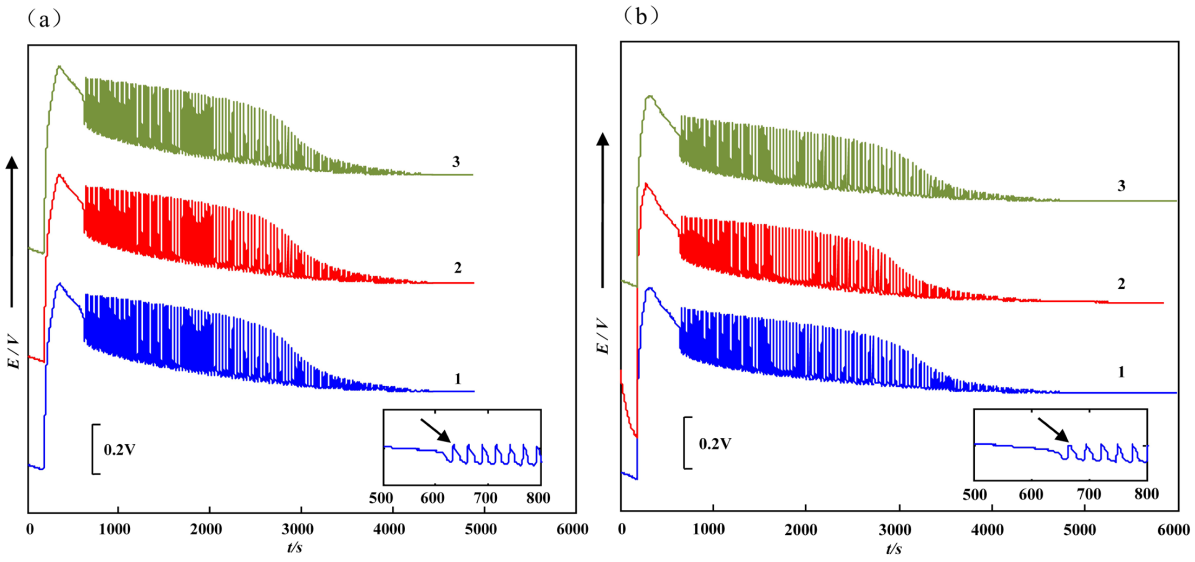

Figure 4. Reproducibility of nonlinear chemical fingerprint of pure infant formula 1# (a) and mixed infant formula 1# (b) (The nonlinear chemical fingerprints of each type of infant formula were obtained in triplicate).

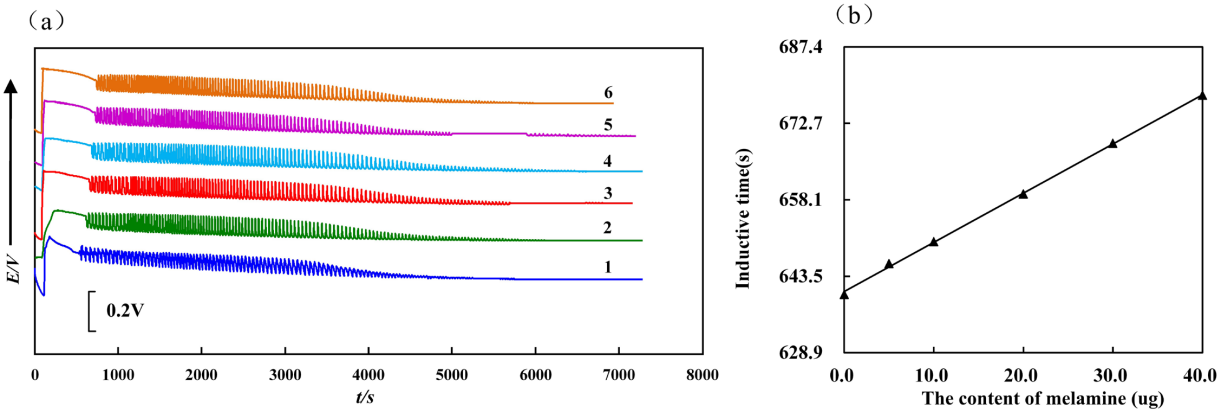

Figure 5. Effects of the content of melamine on infant formula 1#. (a) Effects of the content of melamine on the nonlinear chemical fingerprints of infant formula 1# (1 = 0 μg; 2 = 5 μg; 3 = 10 μg; 4 = 20 μg; 5 = 30 μg; 6 = 40 μg); (b) The linear relationship between the content of melamine in infant formula 1# and the inductive time of nonlinear chemical fingerprint.

Table 1. The reproducibility of nonlinear chemical fingerprints of two kinds of infant formula 1#.

Name of milk	$E_{uns}(V)$	$t_{ind}(S)$	$t_{une}(S)$	$E_{une}(V)$	$\Delta E_{max}(V)$	$\tau_{und}(S)$	$E_{pet}(V)$
Pure infant formula 1#	1.01	638.90	4384.70	0.83	0.12	26.21	1.05
RSD (%)	0.99	0.19	0.02	0.08	0.53	0.40	1.62
Mixed infant formula1#	1.03	670.49	4813.33	0.85	0.11	28.37	1.07
RSD (%)	1.15	0.25	0.07	1.34	0.59	1.75	0.32

The limit of detection and quantization was described with LOD (limit of detection) and LOQ (limit of quantification) in related literature (Jawaid et al., 2013; Ma et al., 2017b). In this study, the selected quantitative parameter of nonlinear chemical fingerprint such as inductive time was measured by adding the different content of melamine to infant formula samples. The infant formula sample with melamine at the lowest content was repeated ten times. The LOD at signal-to-noise ratio of 3.0 (S/N-3.0) and the LOQ (S/N=10.0) were determined to be 0.02 μg/g and 0.08 μg/g, respectively. The proposed method basically met the requirements for detecting melamine at trace levels.

In order to evaluate the feasibility of the method for detecting and evaluating adulterated infant formula samples, five different adulterated infant formula samples (infant formula 1#) were

processed. The experiments were carried out in triplicate. The content of melamine in adulterated infant formula was calculated by the Equation 3. The proposed method was validated using Fourier transform infrared spectroscopy (FT-IR) method (Jawaid et al., 2013).

Satisfactory variations were shown as the relative standard deviation (RSD) in Table 2. The RSDs of the determination were less than or equal to 1.84%, and the recoveries ranged from 96.63% to 100.88%. These values confirmed that nonlinear chemical fingerprint had good accuracy and precision. Therefore, the nonlinear chemical fingerprint method could be used for the detection of melamine in infant formula. In addition, the method could be used for reference in research on the methods for the determination of other components in milk and milk products.

3.6 Method evaluation

To further verify and investigate feasibility and reliability of the proposed method, the different brand infant formula 2# was spiked with melamine at different content (0.08 μg/g, 2.00 μg/g, 12.00 μg/g, 18 μg/g and 24 μg/g), respectively. The total dosage of each infant formula was 1.00 g, and nonlinear chemical fingerprints of the corresponding infant formula were obtained.

Since a large number of samples contained different chemical components and content, which might lead to difference for the quantifiable parameters and intuitionistic shapes in nonlinear chemical fingerprints of different brand infant formula. It was shown in Figure 6a. The regression equation of infant formula 2# was obtained. As shown in Figure 6b. The fitted regression equation based on the least square method was given (Equation 4):

$$t_{ind} = 2.1415C + 1568.9 \quad (4)$$

The corresponding regression coefficient was 0.9991. The content of melamine in adulterated infant formula 2# was calculated by the Equation 2. This statement could be confirmed from the results indicated in Table 3. Therefore, the method was validated that could apply to determine melamine in different infant formula samples. Moreover, the proposed method was capable to detect 0.08 mg/kg in infant formula samples, which met the WHO requirement of 1 mg/kg for powdered infant formula. In addition, for the different batches of the same brand infant formula, qualitative and quantitative analysis of the quality of infant formula could be determined by using the corresponding regression equation. On the contrary, for the different brand infant formula, firstly, the regression equation was established by nonlinear chemical fingerprint and the least square method, and then the quality of infant formula could be evaluated by using the corresponding regression equation. The regression equation established might be used as a permanent calibration model for the same brand infant formula.

3.7 Selectivity

The extreme sensitivity of the reaction matrix to perturbations, which is a positive feature for quantitative analysis, is a negative feature when it comes to interfering species that might be present

Table 2. Results of the determination of melamine in infant formula 1# (n=3).

Sample No.	Original content	Added (μg/g)	Found (μg/g)	FT-IR (μg/g)	RSD/%	Recovery/%
1	-	8.0	7.73	7.82	0.23	96.63
2	-	13.0	12.65	13.01	0.84	97.31
3	-	26.0	26.23	25.78	1.84	100.88
4	-	32.0	31.81	31.65	0.39	99.41
5	-	36.0	36.07	35.82	0.11	100.19

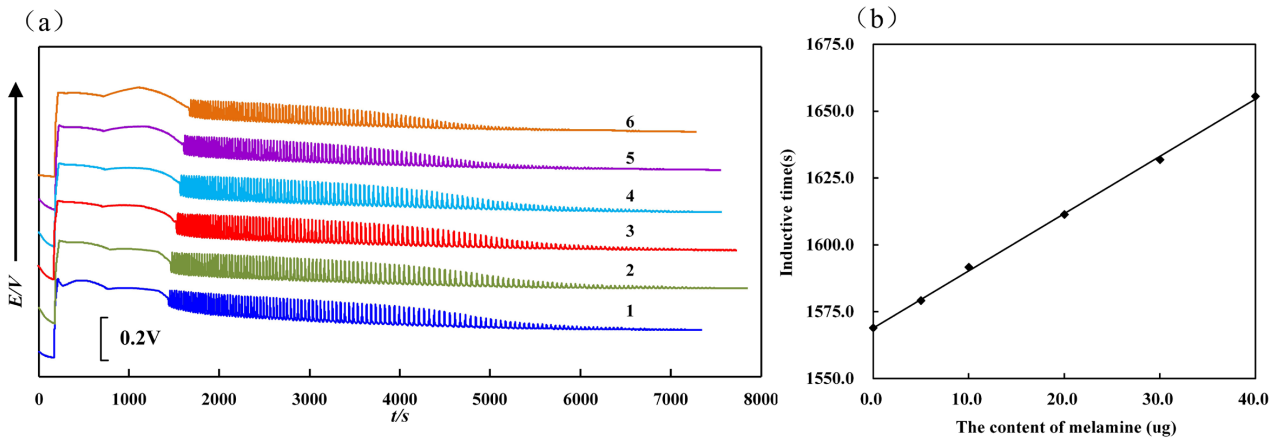

Figure 6. Effects of the content of melamine on infant formula 2#. (a) Effects of the content of melamine on the nonlinear chemical fingerprints of infant formula 2# (1 = 0 μg; 2 = 5 μg; 3 = 10 μg; 4 = 20 μg; 5 = 30 μg; 6 = 40 μg); (b) The linear relationship between the content of melamine in infant formula 2# and inductive time of nonlinear chemical fingerprint.

in complex samples (Pejić et al., 2007). Therefore, we investigated the effect of some potential interferents such as magnesium sulfate, sodium nitrate, potassium iodide, calcium carbonate and urea on spectrum signal. The nonlinear chemical fingerprint of mixed infant formula 1# (infant formula known to be melamine of 32 μg/g) was perturbed with various interfering substances. When magnesium sulfate, sodium nitrate, potassium iodide, calcium carbonate and urea concentration were less than or equal to 1×10^{-3} μg/mL, respectively, the parameter information of nonlinear chemical fingerprint of the corresponding infant formula 1# samples did not change significantly. As shown in Table 4. The selectivity of the method was acceptable.

To further verify and investigate the selectivity of the proposed method, the similarity system theory was used. In this study, on the basis of the relevant literature (Zhang et al., 2007), the signal and the variable function of nonlinear chemical fingerprint are very special, therefore, the mutual mode of the fingerprint and the method for calculating the similarity are different from those of chromatographic and spectral fingerprints, and there are two types of data which may be used to calculate fingerprint similarity (Zhou et al., 2011). One is the parameter information in fingerprints, such as the areas, heights and retention times of the peaks in chromatogram or inductive time, undulatory periods, undulatory amplitudes, undulatory life and so on. The other is the relative intensity information in fingerprints, such as the relative electrical signal at each datum collection point in chromatographic or nonlinear chemical fingerprint. However, the former is intituled parametric similarity for the fingerprint similarity calculation, and the latter is intituled nonparametric similarity for the fingerprint similarity calculation. Both of the two similarities may be calculated by the system similarity. Therefore, in this study, according to the similarity system theory (Meili, 1994; Zhou, 1996), the system similarity Q was calculated by the following Equation 5 (Zhang et al., 2012b):

$$Q=\frac{1}{K+L-n}\sum_{i=1}^{n}\frac{1}{l_i+m_i-o_i}\sum_{j=1}^{o_i}d_{ij}\frac{S_{ij}}{B_{ij}} \quad (5)$$

where and L in the equation are the numbers of the component elements of systems A and B, respectively, n is the number of the pairs of the similar elements between systems A and B, S_{ij} and B_{ij} are the smaller value and the bigger one in the j th pair of comparable eigenvalues a_{ij} and b_{ij} of the i th similar cell between systems A and B, respectively.

Other information parameters have been interpreted in detail in the specialized literature (Gao et al., 2001). Then, disturbed infant formula 1# samples were distinguished and evaluated using the system similarity by taking the parametric mutual mode of each disturbed infant formula 1# sample as reference criterion. Each disturbed infant formula 1# sample was tested in triplicate, and mean values were used as the parametric mutual mode. The results were shown in Table 5. It can be seen from Table 5 that the holistic similarities of disturbed infant formula 1# from the same type were all larger than or equal to 0.9911. For the same kind of distractor, its value was greater than or equal to 0.9981. This indicated that the similarities between fingerprints of the same type of samples were all higher. On the contrary, the similarities between fingerprints of different types of samples were all lower (Pejić et al., 2007). Obviously, when magnesium sulfate, sodium nitrate, potassium iodide, calcium carbonate and urea concentration were less than or equal to 1×10^{-3} μg/mL, respectively, the system similarity could correctly reflect the selectivity of the proposed method.

Table 3. Results of the determination of melamine in infant formula 2# (n=3).

Sample No.	Original content	Added (μg/g)	Found (μg/g)	FT-IR (μg/g)	RSD/%	Recovery/%
1	-	0.08	0.09	-	0.07	112.50
2	-	2.00	2.13	2.11	0.09	106.50
3	-	12.00	11.86	12.11	0.52	98.83
4	-	18.00	18.15	18.07	0.31	100.83
5	-	24.00	23.75	23.82	0.33	98.96

Table 4. Eigenvalue of nonlinear chemical fingerprints parameters of the disturbed infant formula 1# sample (n=3).

Foreign matter	Maximum tolerated Concentration (ug/mL)	$E_{uns}(V)$	$t_{ind}(S)$	$t_{une}(S)$	$E_{une}(V)$	$\Delta E_{\max}(V)$	$\tau_{und}(S)$	$E_{pet}(V)$
I	1×10^{-3}	1.031	670.490	4813.33	0.850	0.110	28.370	1.070
II	1×10^{-3}	1.030	670.487	4813.32	0.851	0.111	28.368	1.071
III	1×10^{-3}	1.030	670.491	4813.33	0.852	0.110	28.375	1.071
IV	1×10^{-3}	1.032	670.489	4813.31	0.850	0.112	28.368	1.072
V	1×10^{-3}	1.031	670.490	4813.33	0.851	0.110	28.371	1.070

Table 5. System similarities calculated for the disturbed infant formula 1# sample by taking common pattern characteristic parameters (n=3) as references.

Sample	System similarity				
	Mutual mode of I	Mutual mode of II	Mutual mode of III	Mutual mode of IV	Mutual mode of V
I	**0.9984**	0.9926	0.9932	0.9965	0.9937
	0.9986	0.9956	0.9937	0.9942	0.9949
	0.9991	0.9947	0.9961	0.9972	0.9951
	0.9966	**0.9985**	0.9941	0.9963	0.9947
II	0.9945	**0.9988**	0.9951	0.9954	0.9941
	0.9953	**0.9982**	0.9959	0.9958	0.9953
III	0.9928	0.9950	**0.9996**	0.9911	0.9936
	0.9931	0.9947	**0.9988**	0.9923	0.9941
	0.9924	0.9942	**0.9981**	0.9928	0.9938
IV	0.9963	0.9938	0.9913	**0.9985**	0.9942
	0.9959	0.9942	0.9925	**0.9981**	0.9951
	0.9952	0.9947	0.9921	**0.9993**	0.9947
V	0.9935	0.9937	0.9951	0.9942	**0.9981**
	0.9947	0.9941	0.9953	0.9939	**0.9985**
	0.9941	0.9932	0.9947	0.9952	**0.9982**

4 Conclusions

A method of the melamine detection in infant formula was established by an oscillating chemical reaction using nonlinear chemical fingerprint technique. The proposed method demonstrated a limit of detection of 0.02 μg/g and a quantifiable range from 0.08 to 40 μg/g. The results indicated that nonlinear chemical fingerprint method could be applied for detection and quantification of melamine in infant formula, and could meet the requirements for the maximum amount of melamine allowed in infant formula. In addition, the maximum dosage of magnesium sulfate, sodium nitrate, potassium iodide, calcium carbonate and urea reagent was 1×10^{-3} ug/mL, respectively, there was no effects on the signal of the spectrum signal. The selectivity of the method was acceptable. Compared with the classical separation method, such as high performance liquid chromatography (HPLC) method, the method developed did not need pretreatment for analysis of sample, and was with some anti-interference, simple and effective. At the same time, this study provided a reference for the food safety detection by nonlinear chemical oscillation system.

Conflict of interest

The authors declare that they have no conflicts of interest.

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