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Fluorescence determination of 3-MCPD by combining amino silica nanoparticles with fluorescein isothiocyanate

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Abstract

Using amino silica modified with fluorescein isothiocyanate (FITC), a quick fluorescence analysis technique is used for the detection of 3-monochloropropane-1,2-diol (3-MCPD). At 100 °C and pH 8.5, FITC-modified amino silica exhibits the lowest fluorescence intensity in the presence of 3-MCPD. This can predominantly be explained mostly explained by 3-MCPD's capacity to occupy the amino group that FITC normally binds to. The fluorescence intensity of FITC-modified amino silica was greatly quenched by 3-MCPD's reaction with the amino group under alkaline conditions, and the fluorescence intensity is different at different reaction times, reaction pH, and reaction temperature. The effects of various 3-MCPD concentrations on the optical characteristics of FITC-modified amino silica were also investigated. Fluorescence analysis is used to obtain a linear range from 0.025 to 1.0 mg/L for 3-MCPD detection under optimal experimental conditions, with a detection limit of 0.025 mg/L and a correlation coefficient of 0.9915. The quantity of 3-MCPD in soy sauce was measured under ideal conditions. Using the optimized conditions, the contents of 3-MCPD in soy sauce were determined. These results suggest that this method is sensitive to 3-MCPD and may have a substantial application in the rapid detection of food contaminants particularly, where the quality and safety of food products are of paramount concern.

Keywords 3-MCPD, FITC, Amino silica, Fluorescence analysis, Rapid detection

Introduction

3-MCPD has extremely obvious renal toxicity and highly genotoxicity and has been strictly classified as a 2B carcinogen by the International Organization on Cancer (IARC) Working Group of the United Nations. 3-MCPD is well known to be a food processing contaminant formed by heat as a result of a reaction byproduct of triacylglycerols, phospholipids or glycerol, and hydrochloric acid in fat-based or fat-containing foods (Yang et al. 2020). It should be noticed that the prolonged heating at high temperature in the presence of hydrochloric acid (HCl) is believed to be responsible for the formation of 3-MCPD in food when the sources such as glycerol, lecithin, and other glycerides or other sources of 3-MCPD esters are present. The presence of chloride ions is important for the formation of 3-MCPD and its isomers (Breitling-Utzmann et al. 2003; Buhrke et al. 2015). Owing to the presence of 3-MCPD in a variety of foods, it is imperative to develop a simple and sensitive method for analysis of 3-MCPD (Yuan et al. 2018).

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Many analytical methods such as mass spectrometry (MS) (Bai et al. 2009), gas chromatography–mass spectrometry (GC–MS) (Mezouari et al. 2015), GC–MS/MS (Genualdi et al. 2017), and GC with electron capture detection (GC-ECD) (Pesselman et al. 1988) had been applied for the determination of 3-MCPD. The preconcentration procedures were introduced to improve the sensitivity further. Liquid-phase microextraction combined with magnetic solid-phase extraction (MSPE) was applied to extract 3-MCPD from edible oils, followed by determination of 3-MCPD with GC–MS. The limit of detection was as low as 1.1 ng/mL (Zhao et al. 2012). With headspace on-fiber derivatization solid-phase microextraction combined with GC–MS, the limit of detection for 3-MCPD in soy sauce was 3.91 ng/mL (Lee et al. 2007). González et al. (2011) enriched and concentrated 3-MCPD in water samples by solid-phase extraction, then derivated it by BSTEA, and analyzed it by GC–MS, with the detection limit up to 1.4–11.2 ng/mL. Though the above-mentioned approaches mostly based on GC–MS achieved high sensitivity, they had some defects such as expensive instruments, complicated sample preparation, and long time-consuming and users have higher professional requirements (Bruchez et al. 1998).

Fluorescence analysis refers to the use of certain substances in the excited state of ultraviolet light, and the excited molecules undergo collision and emission excitation. Reflecting the characteristics of the fluorescent material qualitative or quantitative analysis method may be employed. Fluorescence analysis has attracted a great deal of attention from researchers. Researchers have found that fluorescence analysis is a good use for detection. Compared with traditional detection methods, fluorescence analysis has high sensitivity (10^3–10^4 times higher than spectrophotometry), wide linear range, simple instrument structure, and low cost (Valizadeh et al. 2012). Fluorescence analysis is rapidly developed at the same time, and the application is increasingly broad. The fluorescence signal reacts more quickly is one of its major advantages, so it can be applied to real-time detection. The established fluorescence analysis methods have been widely used in the field of analysis, such as determination of inorganic (Ali et al. 2007), organic (Tu et al. 2008) and biological macromolecules (Xu et al. 2011). However, there are still some problems that need to be solved in fluorescence detection, especially in applications outside the laboratory. It is well known that the existing fluorescence detection usually adds a fluorescent substance capable of reacting with the target solution, this process can quench or enhance the fluorescence intensity of the fluorescent substance, and the concentration of the target is determined by this phenomenon. Therefore, it is unavoidable to introduce new fluorescent substances. At the same time, this makes the detection process complicated and has poor selectivity and effectiveness (Xiao et al. 2019).

FITC was first introduced in 1942 by Coons (Coons et al. 1942; Coons et al. 1950) as a method for labeling antibodies. The FITC-synthetic method was simplified and optimized by Metcalf and colleagues (Riggs et al. 1958) in 1958. Since then, more than 22,000 publications have used FITC as an amine-directed fluorescent labeling agent for proteins, and more recently, a variety of nanomaterials (Zhang et al. 2020; Fan et al. 2019; Michlewska et al. 2019; Deng et al. 2018; Yang et al. 2019). The linkage of FITC to these materials is achieved via the isothiocyanate group, which is reactive towards primary amines and thiols. In this work, we reported a simple method for the detection of 3-MCPD based on fluorescence analysis. Under alkaline conditions, FITC can react with amino group to form FITC-modified amino silica, 3-MCPD can also react with the amino group of amino silica, 3-MCPD competes with FITC for the amino group of amino silica at the same time, and the resulting affects the fluorescence intensity of FITC-modified amino silica. Experiments show that the method can be used for simple and rapid detection of 3-MCPD.

Materials and methods

Reagents

3-Monochloropropane-1,2-diol (3-MCPD, 98%) was purchased from Aladdin Reagent Co. Ltd (Shanghai, China, www.aladdin-reagent.com). Fluorescein isothiocyanate (FITC) and 3-aminopropyltriethoxy silane (APTES) were purchased by Macklin Biochemical Co. Ltd (Shanghai, China, www.macklin.cn). Silicon dioxide (SiO_2) was purchased from Sinopharm Chemical Reagent Co. Ltd (Shanghai, China). 2-Monochloroproane-1,3-diol (2-MCPD) was provided by Alta Scientific Ltd (Tianjin, China). Glycerol (GI, 99%) was purchased from Sigma-Aldrich (St. Louis, MO, USA). Propylene glycol (PG, 99.5%) was acquired from Aladdin Biochemical Technology Co. Ltd (Shanghai, China), while ethylene glycol (EG, 99.5%) was supplied by Sinopharm Chemical Reagent Co. Ltd (Shanghai, China). Ultrapure (UP) water was used throughout the experimental procedures.

Equipment

Electronic analytical balance (Shanghai Minqiao Precision Scientific Instrument Co. Ltd), centrifuge (Model SC-3614; Anhui, China), laboratory pH Meter (Ohaus Instruments Co. Ltd), constant temperature mixer (MTH-100; Hangzhou, China), and F-4600 fluorescence spectrophotometer (Varian Instrument Co. Ltd) were used.

Preparation of amino silica

SiO_2 nanoparticles were added to an ethanol solution containing 3% APTES, as shown in Fig. 1, and reacted at 45 °C for 24 h. After the completion of the reaction, the synthetic material was rinsed with distilled water and ethanol to remove the unreacted APTES. Following vacuum drying for 24 h, amino silica was obtained. In addition, amino silica can be also purchased directly on the market.

Preparation of FITC-amino silica

As shown in Fig. 2, 4.0 mg of amino silica was weighed and placed in a 10-mL centrifuge tube, and 4 mL of $NaHCO_3$ solution (0.1 M) was added to it. The mixture was ultrasonicated for 5 min, such that the amino silica was evenly dispersed. 200 µL of ethanol solution containing FITC (0.02 mg/mL) was added to the centrifuge tube, placed in the vortex mixer and vortexed for 2 min and reacted at 60 °C for 20 min in a constant temperature mixer at 300 rpm/min. After the completion of the reaction, the synthetic material was centrifuged at 4500 rpm/min for 5 min, and the supernatant was discarded to obtain FITC-modified amino silica. After rinsing the FITC-modified amino silica with distilled water and ethanol, it was redispersed into an aqueous solution.

Fluorescence analysis method

Calibration was performed before the fluorescence analysis with a fluorescence spectrophotometer. 4.0 mg of amino silica was weighed and placed in a 10-mL centrifuge tube, and 4 mL of $NaHCO_3$ solution (0.1 M) was added to it. The mixture was ultrasonicated for 5 min to achieve an even dispersion of amino silica. Then, 200 µL of ethanol solution containing FITC (0.02 mg/mL) was added to the centrifuge tube, vortexed for 2 min, and reacted at 60 °C for 20 min with a constant temperature mixer at 300 rpm/min. After the reaction, the solution was centrifuged at 4500 rpm/min for 5 min, and the supernatant was discarded to obtain FITC-modified amino silica. After rinsing FITC-modified amino silica with distilled water and ethanol, it was redispersed into an aqueous solution. Then, 3 mL 3-MCPD solution with a concentration ranging from 0 to 1.0 mg/L was added into the centrifuge tube, and the pH was adjusted to 7.0, 7.5, 8.0, 8.5, and 9.0, respectively. Reaction was carried out at 60 °C, 70 °C, 80 °C, 90 °C, 100 °C for 2 min, 4 min, 6 min, 8 min, and 10 min, respectively. After the reaction, the solution was centrifuged at 3600 rpm/min for 5 min, and subsequently, the fluorescence intensity of the supernatant was determined by fluorescence spectrophotometer at an excitation wavelength of 370 nm, wherein the slit width was 10 nm and the scanning voltage was 500 V.

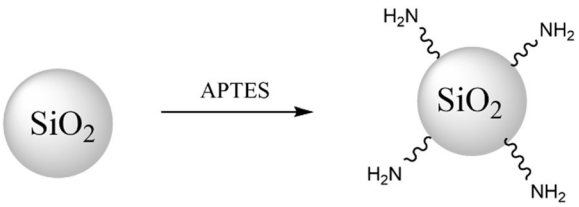

Fig. 1 Preparation of amino silica

Specificity study

Using the procedure elaborated above, then, 1.0 mg/L 3-MCPD, 10 mg/L 2-monochloropropane-1,3-diol (2-MCPD), 10 mg/L glycerol (GI), 10 mg/L propylene glycol (PG), and 10 mg/L ethylene glycol (EG) were prepared, and 3 mL of each was added to the five centrifuge tubes, respectively. The pH was adjusted to 8.5. The reaction was allowed to occur at 90 °C for 8 min. After the reaction, the solution was centrifuged at 3600 rpm/min for 5 min, and the supernatant was analyzed for its fluorescence intensity using a fluorescence spectrophotometer. The excitation wavelength was 370 nm, the slit width was 10 nm, and the scanning voltage was 500 V.

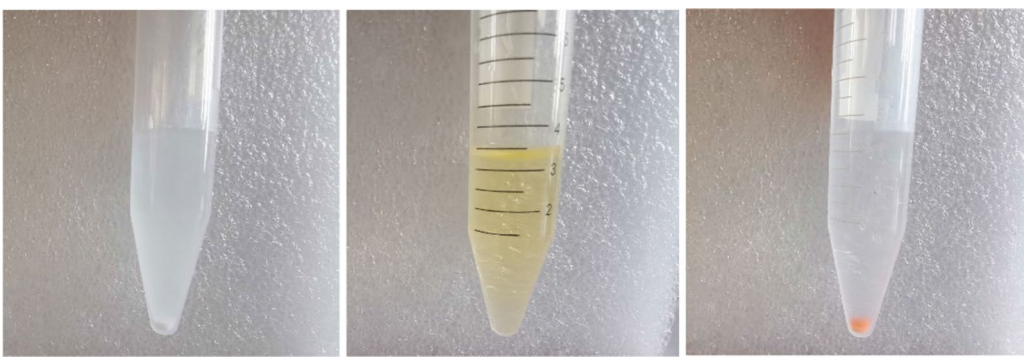

Fig. 2 Preparation of FITC-amino silica

Determination of 3-MCPD in soy sauce

Soy sauce (4 mL) was added to 5 mL ethyl acetate and placed in the vortex mixer and vortexed for 1 min and centrifuged at 3000 rpm/min for 5 min. The supernatant was dried at 40 °C (about 0.2 mL) and redissolved to 3 mL with ultrapure water. 4.0 mg of amino silica was weighed and placed in a 10 mL centrifuge tube, and 4 mL of $NaHCO_3$ solution (0.1 M) was added to it. The mixture was ultrasonicated for 5 min, such that the amino silica was evenly dispersed. 200 µL of ethanol solution containing FITC (0.02 mg/mL) was added to the centrifuge tube, placed in the vortex mixer and vortexed for 2 min, and reacted at 60 °C for 20 min with a constant temperature mixer at 300 rpm/min. After the reaction, the solution was centrifuged at 4500 rpm/min for 5 min, and the supernatant was discarded to obtain FITC-modified amino silica. After rinsing FITC-modified amino silica with distilled water and ethanol, it was redispersed into an aqueous solution. Then, 3 mL of 3-MCPD solution from 0 to 1.0 mg/L was added into the centrifuge tube, and the pH was adjusted to 8.5, and reacted at 90 °C for 8 min. After the reaction, the solution was centrifuged at 3600 rpm/min for 5 min, the supernatant was taken, and its fluorescence intensity was determined by fluorescence spectrophotometer. The excitation wavelength was 370 nm, the slit width was 10 nm, and the scanning voltage was 500 V.

Results and discussion

3-MCPD test principle

The content of FITC is of the greatest importance for the success of detection. Ethanol solution (200 µL) containing FITC (0.02 mg/mL) must be added. As shown in Fig. 3, FITC can react with an amino group to form FITC-modified amino silica, 3-MCPD can also react with the amino group of amino silica, and thus, 3-MCPD competes with FITC for the amino group of amino silica at the same time, thus affecting the fluorescence intensity of FITC-modified amino silica.

After the reaction, the supernatant was withdrawn for fluorescence detection. As shown in Fig. 4, when the concentration of 3-MCPD was 0 mg/L, the fluorescence

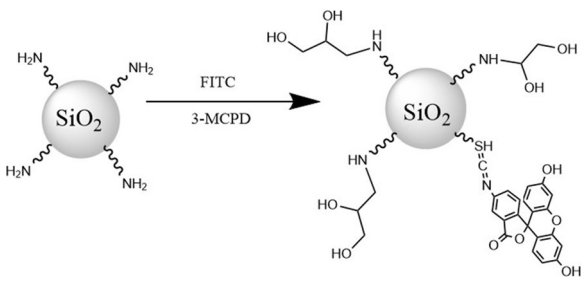

Fig. 3. 3-MCPD detection schematic diagram

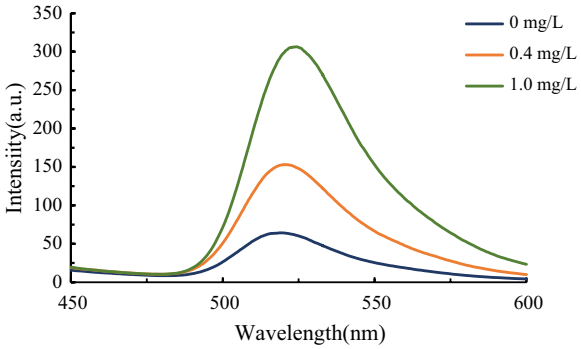

Fig. 4. 3-MCPD competes with FITC for amino groups

intensity of the supernatant was the lowest, indicating that FITC occupied the majority of the binding sites with amino groups. At the same time, the presence of 3-MCPD can quench the fluorescence intensity of FITC-modified amino silica. The higher the concentration of 3-MCPD, the higher the fluorescence intensity of the supernatant. This is presumably because 3-MCPD occupies the binding site of FITC and amino silica. It may be concluded that there was a mathematical relationship between 3-MCPD concentration and fluorescence intensity of FITC-modified amino silica through extensive experiments. This provides us with the feasibility of determining 3-MCPD concentration by using the fluorescence intensity of FITC-modified amino silica.

Optimization of reaction conditions for FITC-amino silica/3-MCPD

The pH of the solution is of utmost importance for successful detection. The effect of different pH values on the fluorescence intensity was also investigated. Figure 5 shows the difference value in fluorescence intensity of the supernatant at different pH values

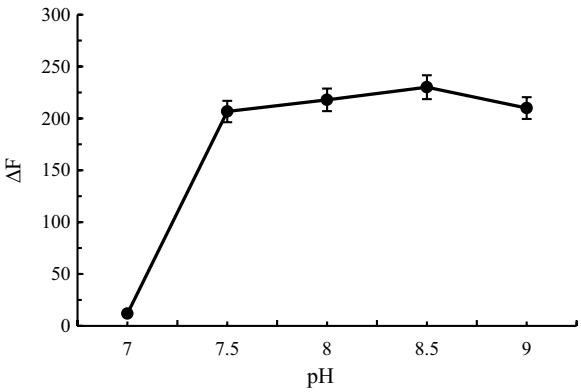

Fig. 5 The difference value in fluorescence intensity of the supernatant at different pH values was reflected

with 3-MCPD concentrations of 0 mg/L and 1 mg/L. As evident, under neutral pH conditions, the fluorescence intensity almost did not change; however, with the increase of pH, the fluorescence intensity gradually increased and reached the highest value at pH 8.5. At a pH higher than 8.5, the fluorescence intensity begins to decrease. Based on these observations, a pH of 8.5 was selected as a reaction condition, to achieve a good degree of sensitivity in the experiment.

Second, with 3-MCPD concentrations of 0 mg/L and 1 mg/L, a significant difference was observed in the fluorescence intensity of the supernatant at various temperature values, which was subsequently used to identify the reaction's ideal temperature. Figure 6 illustrates how the difference in fluorescence intensity rose with temperature and reached its highest value at 90 °C when 3-MCPD and FITC began to compete with one another for more amino binding sites. As a result, 90 °C was determined to be the ideal temperature.

Thirdly, with 3-MCPD concentrations of 0 mg/L and 1 mg/L, a range of 2 to 10 minutes was used to study the impact of reaction time. As seen in Fig. 7, the reaction time was shorter than 4 minutes, which made it difficult to observe the reaction between the amino groups and 3-MCPD. When the reaction time reached 8 min, the difference value of fluorescence intensity of the supernatant reached its maximum. As the reaction time exceeded 4 min, the difference value of fluorescence intensity of the supernatant rose with the increase in the concentration of 3-MCPD. This demonstrated that 3-MCPD had the maximum number of amino group-containing binding sites and that the difference in the fluorescence intensity of the supernatant was unaffected by increasing the reaction time. The ideal response time was therefore determined to be 8 min.

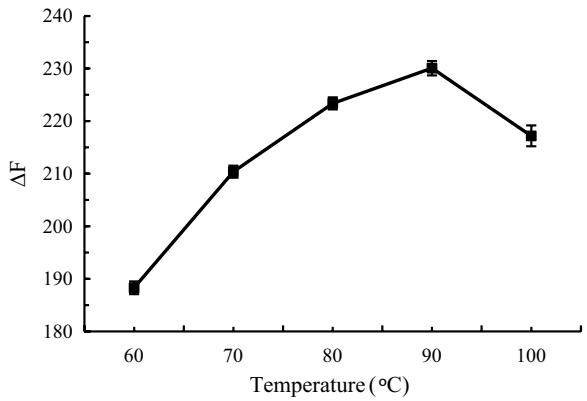

Fig. 6 The difference value in fluorescence intensity of the supernatant at different temperature values was reflected

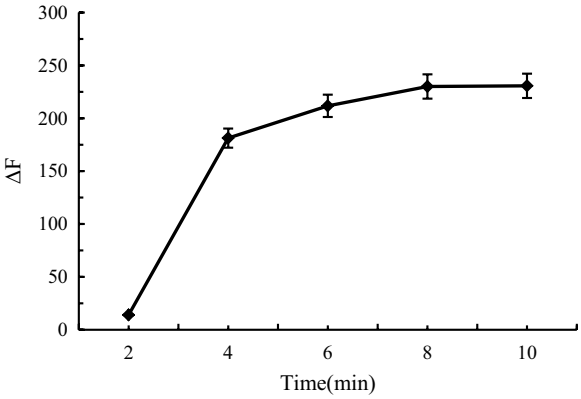

Fig. 7 The difference value in fluorescence intensity of the supernatant at different time values was reflected

Specificity study

The interference of potential chemicals in the determination of 1.0 mg/L 3-MCPD was tested, and the concentration of interfering compounds was 10 mg/L. This was done to assess the viability and selectivity of the proposed technique. According to Fig. 8, the difference in fluorescence intensity between the supernatant before and after the addition of 3-MCPD at 250 nm was 296.1, and at 500 nm, the fluorescence intensities of 2-monochloropropane-1,3-diol (2-MCPD), glycerol (GI), propylene glycol (PG), and ethylene glycol (EG) were, respectively, 384.7, 571, 554.1, and 557.2. Even at high concentrations, the tested interfering compounds failed to provide a significant fluorescence signal. The most noticeable fluorescence signal came from FITC-modified amino silica that was quenched by 3-MCPD. As a result, the selectivity of this technique for the detection of 3-MCPD is very high.

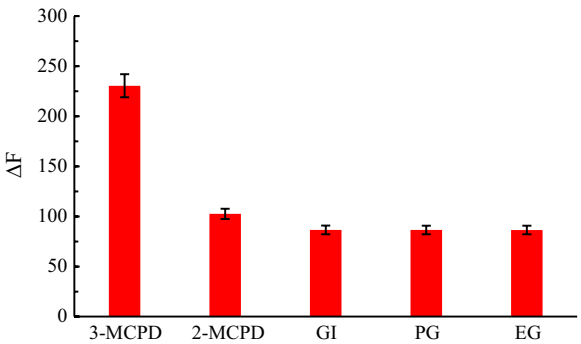

Fig. 8 Selectivity of the 3-MCPD concentration is 1.0 mg/L and the concentration of other substances is 10 mg/L. (3-MCPD, 3-monochloropropane-1,2-diol; 2-MCPD, 2-monochloropropane-1,3-diol; GI, glycerol; PG, propylene glycol; EG, ethylene glycol)

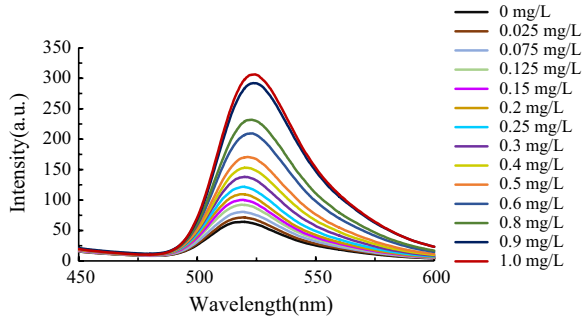

Fig. 9 Fluorescence spectra of test solution taken at different 3-MCPD concentrations

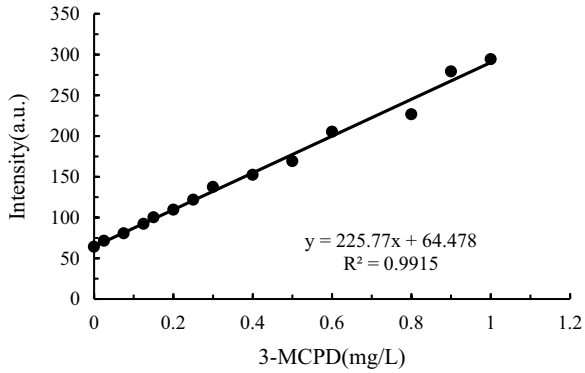

Fig. 10 Standard curve of 3-MCPD

Effect of 3-MCPD concentration on the fluorescence intensity of supernatant

The fluorescence intensity of the supernatant was tested with different 3-MCPD concentrations between 0.025 and 1.0 mg/L. At the optimal conditions, the results are shown in Fig. 9. After several studies, it was clear that the variation in 3-MCPD concentration had a sizable impact on fluorescence intensities. Although the fluorescence intensity of the supernatant grew as 3-MCPD concentration did, the emission peak remained constant at about 250 nm.

Feasibility study

Standard curve, regression equation, and detection limit

The standard curve was drawn with the concentration of 3-MCPD (X) as abscissa and fluorescence intensity of supernatant (Y) as ordinate. The minimal detection limit was calculated simultaneously using a 3 times SNR multiplier. Figure 10 depicts the 3-MCPD standard curve. Table 1 displays the linear range, regression equation, correlation coefficient, and detection limit of this approach.

Table 1 Regression equation, correlation coefficient, linearity range, and limit of detection of 3-MCPD

Regression equation	Correlation coefficient	Linearity range/(mg/L)	Detection limit/(mg/L)
Y = 225.77X + 64.478	0.9915	0.025–1.0	0.025

Table 2 The standard addition experiment of 3-MCPD ($n = 6$)

Add scalar/mg/L	Intra-day precision		Inter-day precision	
	RSD/%	Recovery/%	RSD/%	Recovery/%
1	3.26	97.5	4.23	94.2
0.5	2.85	96.2	3.74	97.4
0.2	2.71	96.0	3.25	106.5

Precision and recovery rate

The soy sauce containing high (1.0 mg/kg), medium (0.5 mg/kg), and low (0.2 mg/kg) concentrations of 3-MCPD as quality control products was investigated for intra-day precision 2 h (n = 5) and inter-day precision 1 d (n = 6). Samples were examined following processing in accordance with 2.6. The recovery of 3-MCPD was between 94.2% and 106.5% under optimal conditions, and the relative standard deviation (RSD) of 3-MCPD ranged between 2.71 and 3.26% and 3.25% to 4.23%. The results are reported in Table 2. The method has the attributes of high sensitivity, good specificity, and high precision for the determination of 3-MCPD in soy sauce according to the regression equation, detection limit, recovery rate, and other methodological factors. It may thus be used to determine 3-MCPD levels in soy sauce.

Determination of 3-MCPD in soy sauce

Four kinds of soy sauce were analyzed by the rapid fluorescence analysis method. According to the experimental method of 2.6, each sample was measured six times in parallel to take the average value, and the content of 3-MCPD was calculated according to fluorescence intensity and linear regression equation obtained by fluorescence analysis method. The content of 3-MCPD in four kinds of soy sauce was determined to be: 2.52, 2.02, 2.85, and 2.74 mg/kg.

Comparison with other techniques

In terms of detection performance, the limit of detection obtained from this new method is comparable to some of those obtained using traditional detection techniques such as GC–MS (Table 3). Besides to its sensibility, the developed method has the advantage of rapid detection and easy to operate in real applications

Table 3 Comparison with other reported methods for 3-MCPD detection

Analytical method	Sample preparation time	LOD	Reference
HPLC/UV	> 30 min	0.080 mg/L	Chung et al. (2018)
GC–MS	> 30 min	< 0.020 mg/L	Karl et al. (2016)
Capillary electrophoresis with electrochemical	> 30 min	0.22 mg/L	Xing et al. (2005)
Fluorescence analysis	30 min	0.025 mg/L	This work

by using fluorescence analysis. No derivation is needed. Therefore, as a rapid method, our method can perform with satisfactory results where short time is required for samples highly suspected of containing 3-MCPD.

Conclusions

A simple, effective, convenient, less-toxic, environmentally friendly, and highly sensitive method for the detection of 3-MCPD has been developed, based on the determination of fluorescence intensity of FITC-modified amino silica quenched by 3-MCPD. Under optimal conditions of pH 8.5, a reaction temperature of 90 °C, and a reaction time of 8 min, the linear range of detection of 3-MCPD was determined to be 0.025 mg/L to 1.0 mg/L by fluorescence analysis, whereas the calculated detection limit was 0.025 mg/L. The developed method is fast, requires minimum sample pretreatment, and does not require large amounts of solvents.

Moreover, the detection of 3-MCPD was not affected by the presence of interfering chemical species such as GI, EG, PG, as well as 2-MCPD. Its application may be useful for testing samples where the presence of 3-MCPD is suspected or confirmed and requires simple and rapid quantification.

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Not applicable

Author contributions
TX contributed to project administration, resources, and writing–review and editing. QZ, ZW, and QF contributed to software and investigation. XL performed supervision and data curation. SX and YL performed validation and investigation. XJ contributed to resources and writing–review and editing. ZG performed investigation and funding acquisition. All authors contributed to and approved the final draft of the manuscript. YW performed reviewing and editing. MF contributed to methodology, software, and writing–original draft.

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Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
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.

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