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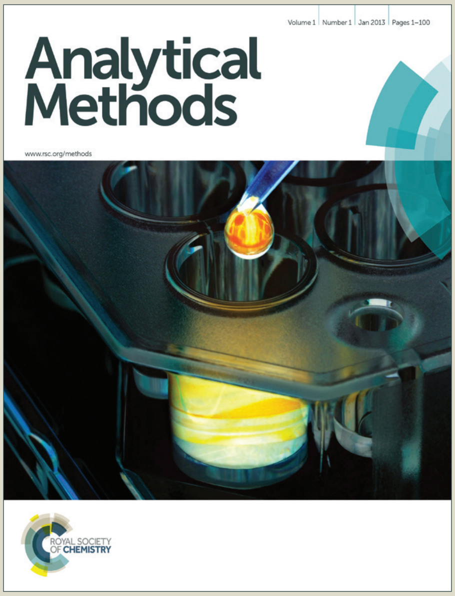

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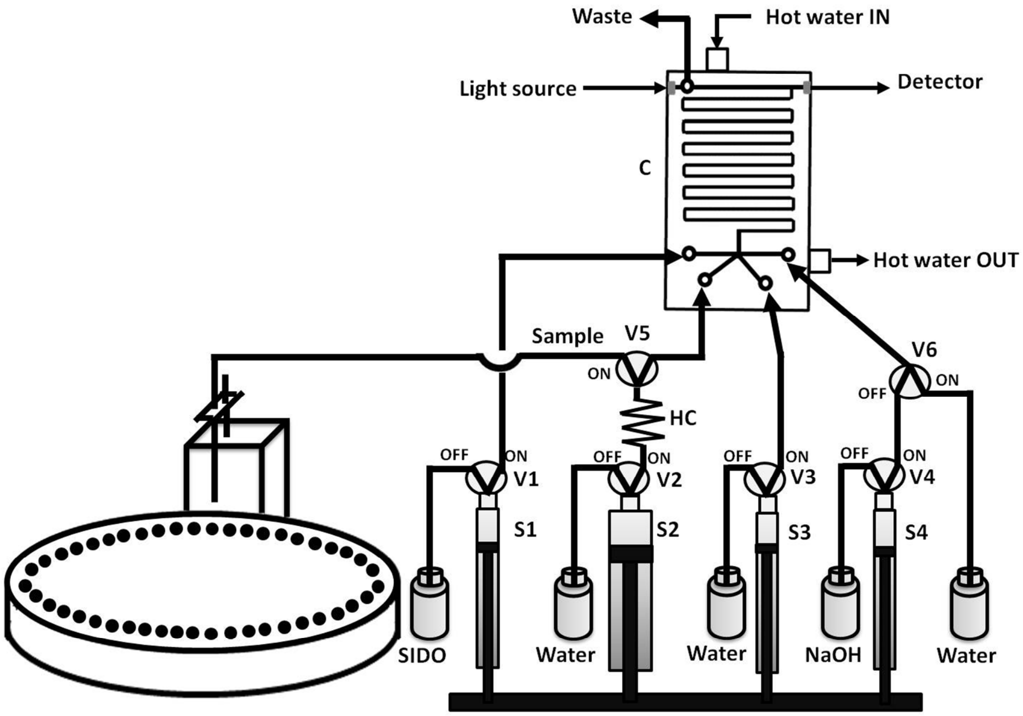
Graphical Abstract



Automated kinetic- catalytic method for manganese determination using a chip-multisyringe flow injection system

Automated catalytic spectrophotometric method for manganese analysis using a chip-multisyringe flow injection system (Chip-MSFIA)

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Abstract

In this work, we present an automated catalytic spectrophotometric method for determination of Mn(II) by using a multisyringe burette coupled to a chip microfluidic-conductor (Chip-MSFIA). The reaction is based on the catalytic effect of Mn(II) in the auto-oxidation reaction of succinimidedioxime (SIDO). Reagents and sample were simultaneously dispensed to the chip for their complete mixing, heating, and measurement. The absorbance of the reaction product was measured at 700 nm. The product concentration could be determined by the fixed-time and the initial rate method under optimum conditions (temperature 35 °C, 4.70 mmol L^{-1} SIDO, and 0.60 mol L^{-1} NaOH). Both fixed-time and initial rate methods have been developed, with the fixed-time method giving higher reproducibility and wider working range. Therefore it was selected for Mn(II) samples in the working range of 1-20 µg L^{-1} of Mn(II). The estimated precision was 0.67 % (5 µg L^{-1}, n=15) and the limit of detection of 0.33 µg L^{-1} of Mn(II). The proposed method is highly sensitive, selective, and simple for trace Mn(II) determination without extraction and separation steps. The system was successfully applied to water samples with an injection throughput of 22 injections h^{-1}.

Keywords: automation, kinetic-catalytic spectrophotometry**,** fixed-time method, initial rate method, succinimidedioxime, microfluidics.

Introduction

Manganese is an essential element for human and animals. It is a component of enzymes, such as glutamine synthetase, and arginase [1, 2]. However, high level of manganese is toxic to human life, affecting DNA replication, causing mutations, and affecting oxidation and proteo-metabolism in the body [1, 3]. Excess intake of manganese could be from food and environment since manganese is widely utilized in metallurgic and chemical industry, which discharge it into the atmosphere, hydrosphere, and biosphere in high levels [4]. Manganese is usually present at trace levels in environmental samples; in fresh waters the levels are 0.02-

130 µg L^{-1} [5, 6]. Maximum level of Mn in water supplies causes an undesirable taste in beverages and stains sanitary ware and laundry. WHO (World Health Organization) recommends a value of 0.1 mg L^{-1} Mn [7]. Therefore, the development of a rapid, sensitive, selective, and accurate analytical method for manganese is required.

There are several sensitive techniques for manganese determination at the µg L^{-1} level [8], such as voltammetry [9, 10], neutron activation analysis [11], inductively coupled plasma atomic emission spectrometry (ICP-AES) [12], flame atomic absorption spectrometry (FAAS) [13-15]. However, these methods need preconcentration and/or separation, and expensive instruments. Catalytic spectrophotometric methods are simple, sensitive, and inexpensive for trace level determination of Mn(II) [16, 17]. .

For the analytical application of kinetic-catalytic spectrophotometry there have been two reported methods: fixed-time and initial rate methods. An advantage of these methods is that they are rapid since there is no need to wait until equilibration of reaction. The calibration curve of fixed-time method was obtained from plotting the absorbance signal *vs* concentration of the analyte [17], while, the calibration curve of the initial rate method was obtained by plotting the slope of initial rate (absorbance values *vs.* time) and concentration of analyte [18-20]. Advantages of the initial rate method are, in general, a wider working range and a higher sampling throughput[21, 22]. However, this method requires a strict control of experimental conditions such as the temperature in the detection cell and the measurement time. For these reasons it is convenient to employ automatic methods, such as flow techniques, to guarantee the reproducibility of the determination.

Flow techniques are widely utilized in analytical field due to its advantages, such as the use of very small sample and reagent volumes (µL), and reproducible measurement before the reaction reaches equilibrium. Furthermore, they provide a high sample throughput, and ease of automation and control of experimental conditions. The Multisyringe Flow Injection Analysis (MSFIA) is a flow technique that have certain advantages over other flow systems, such as better mixing of flowing solutions, and greater robustness and versatility [23, 24]. In the MSFIA there are various syringes working in parallel as liquid pumps, propelling the liquids inside the rigid teflon tubes network. In this way, MSFIA has some of peristaltic pump advantages, such as the multichannel injection, but overcomes some of its drawbacks, such as the presence of pulses, the needs of frequent recalibrations, and corrosion by aggressive reagents and solvents on the peristaltic tubes. Moreover, MSFIA is a complete automation technique by with computer control and data acquisition. Therefore, it is a very appropriate technique for the automation of kinetics method with homogeneous and highly reproducible mixing of the solutions, a critical requirement for this kind of determinations [25, 26].

In this work a multisyringe flow injection system coupled to a chip flow conductor (Chip-MSFIA) is presented for the automation of a catalytic spectrophotometric method for Mn(II) determination. The Chip-MSFIA was presented for first time by Abouhiat et al [25]. This Chip-MSFIA consists of a multisyringe pump coupled to a monolithic poly(methylmethacrylate) (PMMA) flow conductor called “Chip”. The Chip design includes a confluent point and a mixing coil placed over a heating chamber. In the present work, complete mixing, heating, and measurement on the chip was used for Mn(II) analysis. The chip was the first developed by Phansi et al, who designed the detection cell over the heating chamber of a chip [26]. In the present paper, a new analytical application based on the Mn(II) catalytic effect on the autoxidation of succinimidedioxime (SIDO). The SIDO reagent (Fig. 1) was synthesised using a very simple procedure [27, 28]. The characteristics and experimental conditions of this synthesis are also included in this work. The colour evolution of SIDO by oxidation with O_2(aq), catalyzed by low Mn(II) concentration, goes through a sequence of colorless, blue, green, and yellow products [27]. The absorbance of the reaction product was measured using both initial rate and fixed-time method. The performance of the application of these two methods were compared and critically discussed. The proposed Chip-MSFIA system using the fixed-time determination method was validated for Mn(II) quantification in rain water samples, certified reference material (CRM) of river water and waste water. ICP-AES measurement of the samples was used as the reference method.

Experimental

Succinimidedioxime (SIDO) synthesis

Succinimidedioxime (SIDO) reagent for Mn(II) analysis was synthesized [27, 28]. It was prepared by mixing 40.00 g of succinodinitrile ($C_4H_4N_2$) (Merck, Germany) dissolved in 200 ml ethanol (Scharlau, Spain), 70.00 g of hydroxylammonium chloride ($NH_2HO{\cdot}HCl$) (Scharlau, Spain), 40.00 g of calcium carbonate ($CaCO_3$) (Merck, Germany), and 300 mL Milli-Q water [27]. The solution was heated at 65 °C for 4 h. Any undissolved $CaCO_3$ was removed by filtering through a 2.5 µm Whatman 42 paper filter (Whatman GmbH, Dassel, Germany). The filtrate was heated at 65 °C for 4 h to reduce the volume to 250 mL. The solution was then cooled to room temperature and stored in a refrigerator (4 °C) for 1-2 day. The resulting solid SIDO was filtered and purified by recrystallizing from ethanol.

The SIDO product was confirmed by IR, ^{1}H-NMR spectra, and GC-MS (data in the supporting information Fig. A1-3). The IR spectrum presents bands related with the presence of various bonds of SIDO: C=N stretching vibration of the oxime groups at 1671 cm^{-1}, C-N at 1234 cm^{-1} , the CH stretching at 3191 cm^{-1}, and O-H stretching in the region 2800-3400 cm^{-1}. ^{1}H-NMR spectra shows two peaks, one intense and sharp at 2.648 ppm, corresponding to the four H-C bonded hydrogens of the succino group, and the other a very weak and broad peak, corresponding to the mobile hydrogens of the imide and oxime groups. The gc-mass spectrum shows the molecular ion (m/z 129) as the base peak.

Reagents and standards

All chemicals were of analytical reagent grade. Milli-Q water (Milli-Q plus, 18.2 MΩ cm^{-1}) was used for preparing the standard and reagent solutions. Working Mn(II) standard solutions were prepared by appropriate dilution of stock AAS grade 1000 mg L^{-1} Mn(II) solution (manganese nitrate in 0.50 mol L^{-1} HNO_3, Scharlau, Spain). A 0.03 mol L^{-1} SIDO was prepared by dissolving 430 mg SIDO in MilliQ water, and made up to 100 mL. A 4.20 mol L^{-1} NaOH was prepared by dissolving 42.05 g of NaOH (Scharlau, Spain) in water and made up to 250 mL.

Reagents for interference study

Appropriate dilution of Fe(III) were prepared from AAS grade stock 1000 mg L^{-1} Fe(III) (Scharlau, Spain). A stock solution of 1000 mg L^{-1} Fe(II) was prepared by dissolving 1404 mg of ammonium iron(II) sulphate 6-hydrate (Panreac, Spain) in water and made up to 20 mL. Stock 1000 mg L^{-1} Mg(II) was prepared by dissolving 203 mg $MgSO_4.7H_2O$ in 20 mL Milli-Q water. A 0.01 mol L^{-1} EDTA solution was prepared from 372 mg of EDTA dissolved in water, with addition of small volume of 5.0 mol L^{-1} NaOH (Scharlau, Spain) to improve solubility, and made up to 100 mL with Milli-Q water.

Sample collection and preparation

Rain water was obtained from water tanks of houses in Mallorca. The water is used for drinking, cooking, and cleaning, etc. Samples of demolition leachate wastewater were collected from different areas of Mallorca. All water samples were collected in plastic bottles (previously cleaned with HNO_3 10% v/v) and transported to the laboratory, where they were filtered through 0.45 µm cellulose acetate membrane (Sartorious Stedium Biotech, Germany).

A Certified Reference Material of river water (SLRS-4, National Reserch Council Canada) was spiked with 7.5 mmol L^{-1} EDTA for masking Mg before analysis. A stock Quality Control Material of waste water (SPS-WWW2, batch 106, Spectrapure Standards, Norway) was diluted with Milli-Q water, and adjusted to neutral pH.

ICP-AES was used as a reference method for the quantification of Mn(II) in water samples previously acidified with concentrated HNO_3 (65%, Scharlau, Spain) to 2% V/V. An ICP-AES (Optima 5300 DV, Perkin Elmer® Inc.) equipped with a Gem Tip Cross-flow pneumatic nebulizer (Waltham, MA, USA) was operated using the following instrumental parameters: RF generator power 1300 W, RF frequency 40 MHz, plasma argon flow 15 L min^{-1}, nebulizer argon flow 0.8 L min^{-1}, auxiliary argon flow 0.5 L min^{-1}, integration time 5 s and aspiration rate 1.5 mL min^{-1}. Wavelength for emission measurements was 259.372 nm. All measurements were in triplicate.

Flow analyzer

The flow system is shown in Fig. 2. A multisyringe piston pump module (model Bu 4S) was purchased from Crison Instruments S.A. (Allela, Barcelona, Spain). The module was equipped with three 1 mL glass syringes (S1, S3, and S4) and one 5 mL glass syringe (S2). Solenoid valves (V1, V2, V3, and V4) allowed the connection of each syringe with either the chip (position ON, activated) or with the respective solution reservoir (position OFF, deactivated) for refilling. Solutions in the syringes were SIDO reagent in S1, Milli-Q water in S2, Milli-Q water in S3, and NaOH in S4. The Milli-Q water in S3 was used to clean the chip after experiment. Furthermore, two external three-way solenoid valves (V5, V6) from Takasago (STV-3 1/4UKG, Nagoya, Japan) were powered and controlled using an auxiliary supply port of the multisyringe module. V5 was used for sample introduction (position ON). V6 was used for Milli-Q water introduction (position ON) in order to clean syringe (S4) immediately after an experimental session, to avoid problems with the NaOH carbonation. Its common position was connected to a holding coil 255 cm in length and 1.00 mm i.d. which was connected to S2. All tubings of the flow system were of PTFE of 0.8 mm i.d.

The chip was constructed using three PMMA pieces, 85 x 44 x 10 mm, similar to that previously reported by Abouhiat et al [25, 26]. Threads of ¼" 28 fittings were drilled in the upper part to connect the supply tubes for reagents and sample/carrier as well for the output of the integrated detection flow cell. On its bottom side, a confluence and a serpentine reaction coil of 0.8 x 0.8 x 39 mm were made using a 3-axis PC controlled CNC milling machine (Alarsis FR150, Murcia, Spain). In the lateral part two thread holes of UNF ¼" 36 fittings were drilled in order to connect the optical fibers on the extreme ends of the final portion of the coil, as shown in Fig. 2. The middle piece was then glued to cover the flow circuit applying a thin film of acrylic acid prior to clamping and a UV curing time of 1 h. In order to obtain a cavity below the flow circuit for the circulation of thermostat water, in the bottom piece, as well as in the already glued assembly, two rectangular troughs of 50 x 30 x 8 mm were milled prior to gluing both together. After curing, two flow connectors were attached to allow continuous flushing of the cavity with water from the thermostated bath (Selecta, Barcelona, Spain) via silicon tubes (ca. 20 cm, 1 cm id). The cavity served as a heating source to accelerate the reaction in the flow circuit. For sample introduction, an autosampler with 45 x 10 mL sample vials (Crison Instruments S.A., Barcelona, Spain) was connected to the sample tube. The multisyringe module and the autosampler were connected in series via a RS232C interface to a PC for remote software control (AutoAnalysis 5.0, Sciware Systems SL, Bunyola, Spain). A DH-2000 deuterium lamp (TOP Sensor Systems, Eerbeek, Netherlands) was used as the light source, and an USB-2000 miniature CCD spectrophotometer (Ocean Optics Inc., Dunedin, FL, USA) was used as detector. The reaction product was monitored at 700 nm, with elimination of the schlieren effect by also monitoring at 740 nm.

Analytical protocol and flow method

The analytical procedures proposed for fixed-time and initial rate method are shown in Table 1 and Table 2, respectively. For fixed-time method, a 0.500 mL sample was aspirated from V5 (step 1), and 0.300 mL dispensed to the chip to avoid the diluted portion of the sample plug (step 2). The rest 0.200 mL of sample and the equivalent volume of reagents (0.040 mL) were next dispensed to the chip. Then, the flow was stopped and the reaction allowed to take place for 60 seconds. After that, the mixture was dispensed to the detection cell and the absorbance measured at 700 nm, with correction by the absorbance measured at 740 nm to remove the schlieren effect (step 3-7). For initial rate method, the procedure is similar to the fixed-time method, but a larger volume of sample and reagents was used. First, 0.300 mL of the sample were dispensed to the chip followed by 0.450 mL of sample and the equivalent volume of reagents (0.090 mL) to ensure that the detection cell is filled with the reaction mixture. Then the flow was stopped and the kinetics monitored by measuring the absorbance for the first two seconds of the reaction. To facilitate the data analysis and the initial flow rate calculation the measured absorbance were saved in an internal variable of AutoAnalysis for 5 or 10 s and displayed in a “Mark” (step 4). Finally, the sample solution was dispensed to waste and the chip was cleaned (step 5).

Results and discussion

The catalytic effect of Mn(II) in the SIDO oxidation was previously presented for Cerdà et al [28]. They presented the SIDO synthesis and a possible application of this molecule as an analytical reagent for Mn(II) determination. The reaction is based on the colour evolution of SIDO by oxidation with O_2(aq), catalyzed by low Mn(II) concentration. The oxidation products of SIDO probably proceed through coloured radicals, which change in order of a few seconds from colourless to blue to yellow, respectively [27].

Optimization

Multivariate experimental designs were used to optimize the experimental conditions for the fixed-time and initial rate methods. Two level (2^3) full factorial designs were used to screen the most important factors and their effects on both methods. The concentration of SIDO and NaOH, and the temperature were varied within the experimental range of 2.8-4.8 mmol L^{-1}, 0.2-0.6 mol L^{-1}, and 27-35 °C respectively. Afterwards, a three level (3^2) full factorial design was used for the SIDO and NaOH concentration optimization of both fixed time and initial rate methods. The concentration range of SIDO, and NaOH was 4.1-5.5 mmol L^{-1}, and 0.4-0.8 mol L^{-1}, respectively.

The ratio of the analytical signal of standard 5 µg L^{-1} Mn(II) and blank (standard/blank), and slope ((standard-blank)/5) were selected as dependent variables in order to obtain the maximal relation or differences between the catalysed and uncatalysed reaction. Using these two responses we obtained the experimental conditions with the highest sensitivity, taking into account increasing blank signal in some condition**.** For the fixed-time method, the analytical signal was the absorbance peak height. Then the standard/blank variable was the ratio between the absorbance peak height of standard and blank. The slope ((standard-blank)/5) was the difference between the absorbance peak height of standard and blank divided by the concentration of the standard**.** For the initial rate method, the analytical signal was the slope of the first 60 s of the kinetic curve. Then the standard/blank was the ratio between the slope of the kinetic curve obtained using a standard and a blank. Meanwhile, the slope was the difference between the slope of the kinetic curve obtained using a standard and blank divided by concentration of standard ((standard-blank)/[standard]).

Full factorial designs 2^3 fitted well to a 3-way interaction model for both methods without any significant lack of fit and a very low absolute error. The statistical results (shown in the supporting information Table A-1, and Table A-2) indicated that the temperature, the concentration of NaOH, and the interaction between concentration of SIDO and NaOH are significant factors and produced positive effect in the kinetic reaction. The analytical response increases at higher temperature and SIDO concentration. However, higher temperatures favour air bubble formation, affecting the reproducibility of the method since they interfere with the optical measurement. A maximum analytical response was obtained using 0.47 mol L^{-1} of NaOH solution. For all these reasons a new experiment was designed, changing experimental parameters but with the temperature fixed at 35 °C.

Full factorial designs 3^2 fitted well to a 2-way interaction model for both fixed-time and initial rate method without a significant lack of fit and a very low absolute error. The statistical results model (shown in the supporting information Table A-3, and Table A-4) indicated that concentration of SIDO, and NaOH are significant.In order to obtain the optimal conditions taking into account the response of ratio and slope simultaneously. These variables were studied for both methods (Fig 3). As can be seen, the optimal condition obtained for SIDO and NaOH were very similar for both methods and both dependent variables. The optimal conditions were 4.63 mmol L^{-1} SIDO, and 0.64 mol L^{-1} NaOH for fixed-time method (Fig. 3 (a)). For initial rate method, these were 4.87 mmol L^{-1} SIDO and 0.62 mol L^{-1} NaOH (Fig. 3 (b)). These optimal conditions correspond to a maximum zone of the profile of predicted values and the desirability function for both variables are very close or equal to 1 for both methods. Combined optimal conditions obtained for both methods, 4.70 mmol L^{-1} SIDO, 0.60 mol L^{-1} NaOH and 35 °C were chosen for the following experiments.

Analytical characteristics

Two different flow profiles were obtained for the fixed time and initial rate method in this work, as can be seen in Fig 4 and Fig 5, respectively. The MSFIA-gram obtained using the fixed-time method, Fig 4 (a), has peaks, and the calibration curve, Fig 4 (b), was obtained by plotting the height of these peaks *vs* the Mn(II) concentration. However, the MSFIA-gram obtained using the initial rate method, Fig 5 (a), gives the kinetic curve for each injection. In this case, the calibration curve was obtained by plotting the slope of the kinetic reaction *vs* the Mn(II) standard concentration, Fig 5 (b) and (c) [20, 29].

Even though both procedures are very similar and the AutoAnalysis software facilitates the mathematical data processing, the fixed time method has some advantages over the initial rate method. Some of these advantages are a wider working range, lower reagents and sample volume consumption, and better reproducibility. The calibration equation and working range obtained from the fixed-time method was $y = (0.67 \pm 0.02)10^{-2}x + (7.77 \pm 0.20)10^{-2}$ ($r^2 = 0.9972$) and 1-20 μg L^{-1} Mn(II), respectively; and for initial rate method was $y = (0.0518 \pm 0.0005)x + (0.7982 \pm 0.0035)$ ($r^2 = 0.9997$) and 1-12.5 μg L^{-1} Mn(II), respectively. In this case a comparison between the sensitivity based in the slope of the calibration curve is not applicable since the two slopes do not have the same unit: AU/ μg L^{-1} for the fixed time and AU s^{-1}/ μg L^{-1} for the initial rate. However, no significant difference was obtained between the limit of detection (LOD) and quantification (LOQ) calculated from the two methods: LOD=0.33 μg L^{-1} and LOQ=1.10 μg L^{-1} for the fixed time method and LOD= 0.35 μg L^{-1} and LOQ=1.16 μg L^{-1} for the initial rate method.

The reagents and sample volume consumption of fixed-time method was 40, and 500 μL, respectively, while for initial rate method, the volume was 90, and 1000 μL, respectively. The initial rate method employed more reagents and sample volumes than the fixed-time method because of the larger concentration of reagents and volume of sample plug needed at the detection path of the chip. Moreover, the fixed-time method has a higher reproducibility than the initial rate method with 0.67% RSD obtained using 5 μg L^{-1} Mn(II) (n=15), while the %RSD of the initial rate method was 1.9%, under the same conditions. However, the injection throughput of the initial rate method was a bit higher than the fixed-time method. The injection throughput of the initial rate and the fixed-time method were 24, and 22 injection h^{-1}, respectively. Finally, the fixed-time method was selected because of its wider working range, lower amount of reagents required, lower sample volume, greater reproducibility and an easier method to analyze data than the initial rate method.

The sample volume used (500 µL and 1000 µL for fixed time and initial rate method respectively) may be considered quite high. It is necessary to remark that the thermostated spectrophotometric cell is inserted in the "chip", and has a long optic path of 4.0 cm. In order to increase sensitivity a reactive mixture bolus enough to fill totally the detection cell was required. In comparison with flow-batch devices Chip-MSFIA improves the flow configuration system due to the thinness of all channels. Moreover these characteristics also permit the use of very high flow rate, facilitating the system cleaning and increasing the sample throughput. The Chip-MSFIA is fully automated allowing a better control of the kinetics.

Analytical features obtained using the proposed Chip-MSFIA systems with the fixed time method are summarized in Table 3. In order to evaluate the advantages and competitiveness the proposed method, its characteristics has been compared with those obtained by other similar analytical methods currently reported and are presented in Table 3. Most of these methods are not automated, since they are carried out batchwise [16, 30, 31]. Some of these methods are highly sensitive but they are tedious, laborious and very time consuming. Furthermore, the chemical reactions need higher temperature than our method, and require the use of activators [16, 30, 31]. FIA method has also been used for increasing the degree of automation of analysis [17]. However, the reported FIA methods are not totally automated since they use a manual injection valve. In our reaction only succinimidedioxime (SIDO) and NaOH solution are used and no activator is required. The proposed reaction in this work is very simple, and the synthesis of SIDO is simple and easy, with yield of high purity [27, 28]. Moreover, Chip-MSFIA is a complete automated method due to the computer control and data acquisition, which do not require the manual intervention of the analyst. The reagents and samples are dispensed with a high degree of precision, with the multisyringe, allowing complete mixing, heating, and measurement inside the chip [25, 26].

Interferences

According with previous works [28], only Pd(II), and Mg(II) interfered significantly in the reaction. However, usually water samples do not have Pd(II). Therefore, only the interfering effect of Mg(II) was studied in this work. The effect of Fe(III) and Fe(II), were also studied due to high Fe(III) level (about 1000 µg L^{-1} Fe) in water samples in Mallorca. The effect of interfering ion on the determination of 5 µg L^{-1} Mn(II) was examined for the proposed method. The system was found to be tolerant to Fe(III) and Fe(II) at 500 µg L^{-1} level as the ions produced changes in the absorbance of the catalytic reaction less than 10%. Fe(III) and Fe(II) are regarded as positive interferences, i.e. they increase the analytical signal. However, for Mallorca water samples, the Fe effect can be avoided by a simple sample dilution, since the proposed method is very sensitive for Mn(II). The system is tolerant to Mg(II) at 200 µg L^{-1} level. Mg(II) presents a negative interference, since it decreases the analytical signal. However, the tolerance level of Mg(II) was increased up to 2000 µg L^{-1} by masking it with 1.65×10^{-4} mol L^{-1} EDTA. It was shown that the addition of this level of EDTA did not affect the Mn determination. No significant differences between analytical signal of Mn(II) standard solution and the same standard spiked with 1.65 x 10^{-4} mol L^{-1} of EDTA was found.

Application and validation

The method has been validated according with the directive of IUPAC [32]. For this purpose, a certified reference material of water sample was used, as well as a reference method (ICP-AES), and also spiked samples. The Mn(II) content in CRM (SLRS-4, National Research Council , Canada) obtained from the Chip-MSFIA method (3.32 ± 0.09 µg L^{-1}) agrees well with CRM reported value (3.37 ± 0.18 µg L^{-1}). The Mn(II) content in Quality Control Material of wastewater (SPS-WWW2, batch 106, Spectrapure Standards, Norway) obtained from our Chip-MSFIA method (2007.19 ± 4.59 µg L^{-1}) are not significantly different from that QCM reported value (2000 ± 10 µg L^{-1}).

The analysis of rain water and wastewater samples demonstrates the applicability of the proposed method to different matrix of water samples. The concentration values obtained with the Chip-MSFIA agree well with those obtained with ICP-AES (Table 4). No significant differences were found between these methods at a 95% confidence level of t-test (t-obs < t-crit =2.92). The recovery of the comparison was between 98 and 103 %. Three concentration levels (2.5, 5.0 and 10 µg L^{-1} Mn(II)) were spiked into the samples to evaluate the matrix effect on the reaction. The recoveries obtained were between 96 and 106 %. The successful application of this method to very different kind of waters suggests that different amount of O_2 in samples did not has a significant effect to the reaction. A possible explanation is that the oxygen needed for the reaction is very low and the sample has sufficient oxygen for the reaction, or the oxygen dissolved in the reagent is sufficient for the catalytic SIDO oxidation.

Conclusion

The Chip-MSFIA system proposed in this work is a suitable method for kinetic-catalytic determination of Mn(II) in water samples. With this new system, both fixed time and initial rate methods are automated due to the inclusion of the detection cell in the thermostated zone. The proposed method is based on the SIDO oxidation with dissolved oxygen catalyzed by Mn(II) in basic media. This reaction is very simple, rapid, sensitive and do not require any activators. The SIDO reagent can be synthesized with high purity by a simple and easy procedure. This is the first automated method based in SIDO reaction for Mn(II) determination in water samples. The method was validated by means of two different certified reference materials, a reference method and spike-recovery tests using different water samples. No significant differences were obtained between the values measured with the proposed method and those reported or measured with the reference methods. These assays together the spike-recovery tests demonstrate the applicability of the proposed method to Mn(II) analysis in water samples. Finally, we can conclude that the Chip-MSFIA fixed time method based on the SIDO oxidation is fully automated, simple, accurate, sensitive, with high sample throughput, and for these reasons, is very appropriate for Mn(II) determination in different types of water samples.

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Table 1. Measurement using the fixed-time procedure for the determination of Mn(II).

Steps	Device	Operation	Valve position						Comments
			V1	V2	V3	V4	V5	V6	
		Load sample							
1	MS	Pickup 0.500 mL at 2.400 mL min^{-1}	off	on	off	off	on	off	Load sample
		Measure							
2	MS	Dispense 0.300 mL at 1.000 mL min^{-1}	off	on	off	off	off	off	Dispense sample to chip
3	MS	Dispense 0.200 mL at 1.000 mL min^{-1}	on	on	on	on	off	off	Dispense sample and reagents for mixing, and heating at the chip
4		Wait 60 seconds	on	on	on	on	off	off	Reaction time 60 seconds
5	D	Start measure (700-740 nm)							Measure the reaction product at 700 nm, correction at 740 nm
6	MS	Dispense 2.100 mL at 2.000 mL min^{-1}	off	on	off	off	off	off	Dispense the mixing solution to waste
7	D	Stop measure							

Table 2. Measurement using the initial rate procedure for the determination of Mn(II).

Steps	Device	Operation	Valve position						Comments
			V1	V2	V3	V4	V5	V6	
		Load sample							
1	MS	Pickup 1.000 mL at 2.400 mL min^{-1}	off	on	off	off	on	off	Load sample
		Measure							
2	MS	Dispense 0.300 mL at 1.000 mL min^{-1}	off	on	off	off	off	off	Dispense sample to chip
3	MS	Dispense 0.450 mL at 1.000 mL min^{-1}	on	on	on	on	off	off	Dispense sample and reagents for mixing and measure at the chip
4	D	Start measure (700-740 nm), and mark absorbance value at 30, 35, 40, 45, 50, and 60 seconds							Measure the reaction product at 700 nm, correction at 740 nm
5	MS	Dispense 2.100 mL at 6.000 mL min^{-1}	off	on	off	off	off	off	Dispense the mixing solution to waste
6	D	Stop measure							

Table 3. Figure of merit and experimental characteristics of spectrophotometric kinetic-catalytic Mn(II) determination. Comparison with similar methods reported**.**

Ref.	[16]	[30]	[31]	[17]	Present work Chip-MSFIA
Year	2003	2003	2004	2005	
Reaction	1,3-Dimethyl- 2 [4-N(N,Ndimethylamino) phenylazo] imidazolium perchlorate (BR) + potassium periodate	Tropaeolin 00 + potassium periodate	3-Methyl-6-(2-hydroxyethoxy)-2-[2-methoxy-4-N (N, N diethylamino) phenylazo] benzothiazolium methylsulphate + potassium periodate	N,N -bis(2-hydroxy-3-sulfopropyl)tolidine (HSPT) + periodate	autoxidation of succinimidedioxime (SIDO)
Activator	1,10-phenanthroline	1,10-phenanthroline	1,10-phenanthroline	2,2 -bipyridine	without
λmax (nm)	540	445	560	670	700
System	Batch	Batch	Batch	FIA	Chip-MSFIA
Method	Fixed-time method, 5 min	Fixed-time method, 6 min	Fixed-time method, 8 min	Fixed-time	Fixed-time (Stopped flow 60s)
Type of samples	some medicinal plants	some medicinal plants	some medicinal plants	Lake and river waters	Water samples
LOD (µg L^{-1})	0.03	0.02	0.035	0.01	0.33
Working range (µg L^{-1})	0.1-4.5	0.05-2.5	0.1-5	0.02-3.5	1-20
RSD, % (µg L^{-1}, n)	1.0 (2, n=10)	2.6 (1, n=10)	2.2 (2, n=10)	1.1 (0.5)	0.7 (5, n=15)
T (ºC)	70	80	70	15	35
Throughput (h^{-1})	-	-	-	20	22

Table 4. Mn(II) quantification in water samples.

Samples	Dilution factor	Proposed method				ICP-AES	Proposed method vs ICP-AES	
	(Final volume/ sample volume)	Added (µg L^{-1})	Found ± S.D. (µg L^{-1})	Spike-Recovery (%)	Mn in Sample ± S.D. (µg L^{-1})	Found ± S.D. (µg L^{-1})	Found/ICP-AES Recovery (%)	t obs t crit 95%=2.92
collected rain water 1	3	0	7.2 ± 0.05		21.7 ± 0.2	21.0 ± 0.7	103	0.93
		2.5	9.6 ± 0.03	96				
		5	12.4 ± 0.04	104				
		10	17.3 ± 0.10	101				
collected rain water 2	1	0	0.8 ± 0.01		0.80 ± 0.11	0.81 ± 0.54	99	0.02
		2.5	3.2 ± 0.03	96				
		5	5.7 ± 0.04	98				
		10	10.9 ± 0.10	101				
Waste water 1	10	0	6.4 ± 0.04		63.75 ± 0.74	64.89 ± 0.84	98	1.02
		2.5	9.0 ± 0.04	104				
		5	11.3 ± 0.07	98				
		10	16.6 ± 0.10	102				
Waste water 2	25	0	5.9 ± 0.04		148.70 ± 0.97	147.92 ± 0.91	101	0.58
		2.5	8.3 ± 0.02	96				
		5	11.2 ± 0.07	106				
		10	15.7 ± 0.15	98				

Legends to figures:

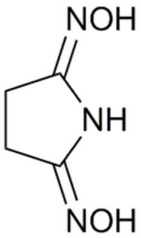
Fig. 1. Succinimidedioxime (SIDO) structure.

Fig. 2. Scheme of the analytical system setup used for the kinetic determination of manganese. S: syringe (S1: 1 mL, S2: 5 mL, S3: 1 mL, S4: 1 mL), V: solenoid valve, HC: holding coil of 255 cm and 1.00 mm id, C: PMMA chip, Detector: CCD miniature optical fiber spectrophotometer (measure: 700 nm, correction: 740 nm).

Fig. 3. Profiles of predicted values and desirability obtained for both determination methods, (a) fixed-time method, and (b) initial rate method.

Fig. 4. Flow profile (a) and calibration curve (b) was obtained from the fixed-time method under the optimal conditions, 4.70 mM SIDO, 0.60 M NaOH and 35 °C.

Fig. 5. Flow profile and calibration curve was obtained from the initial rate method under optimal conditions, 4.70 mM SIDO, 0.60 M NaOH and 35 °C.



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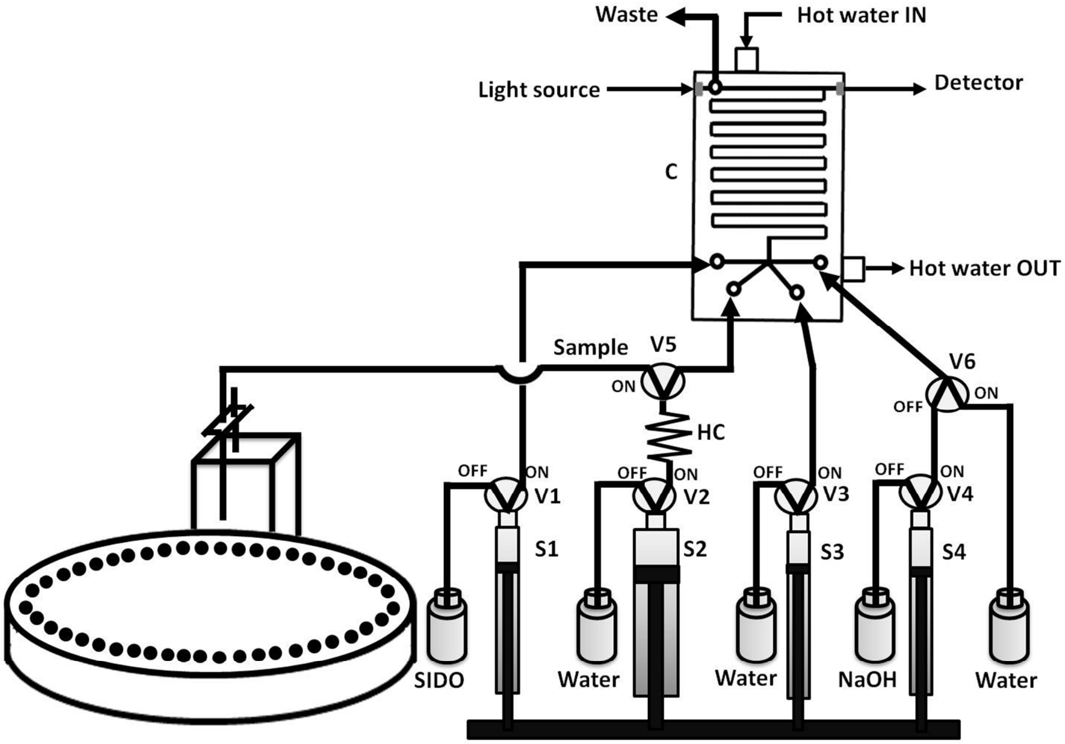

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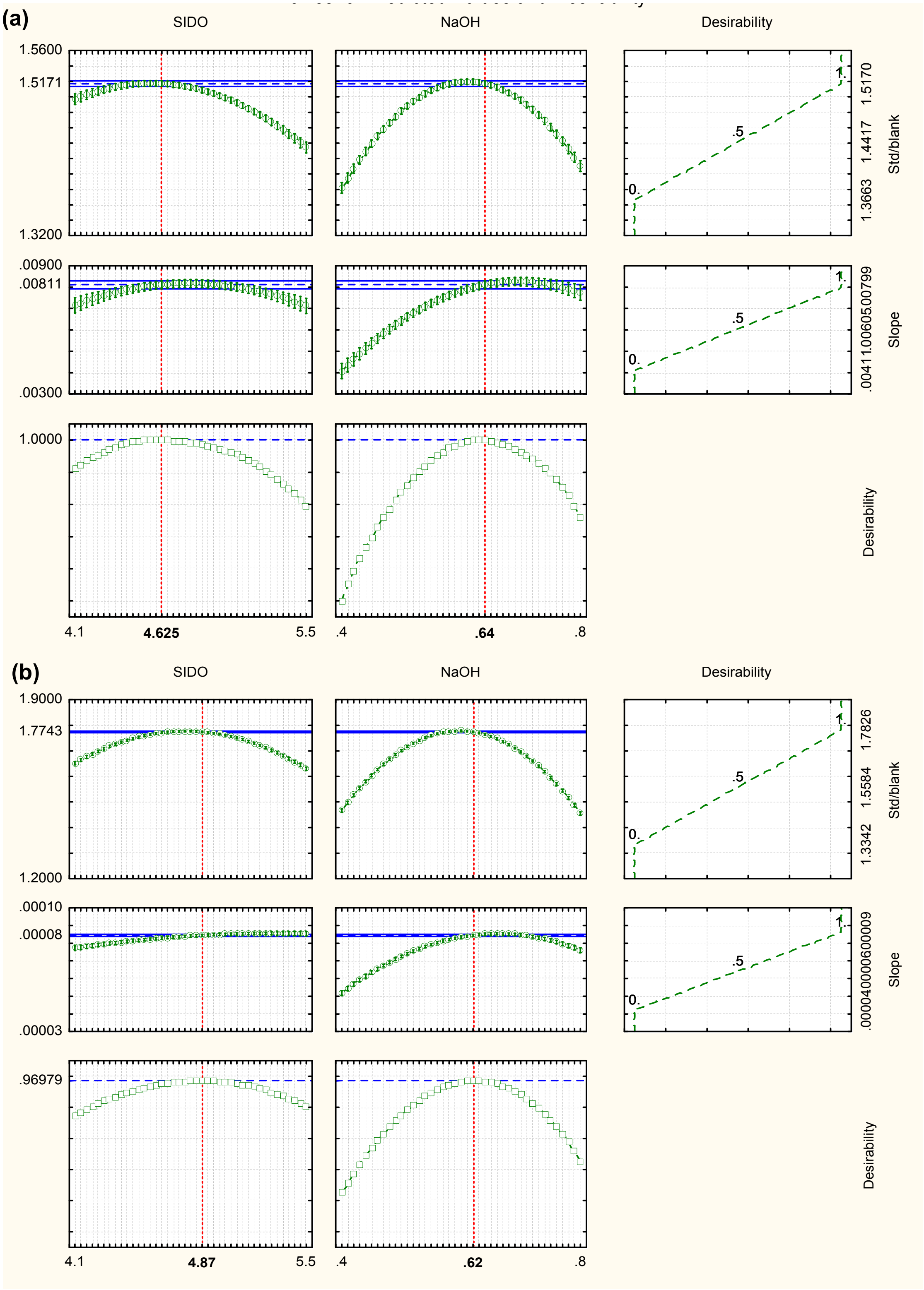

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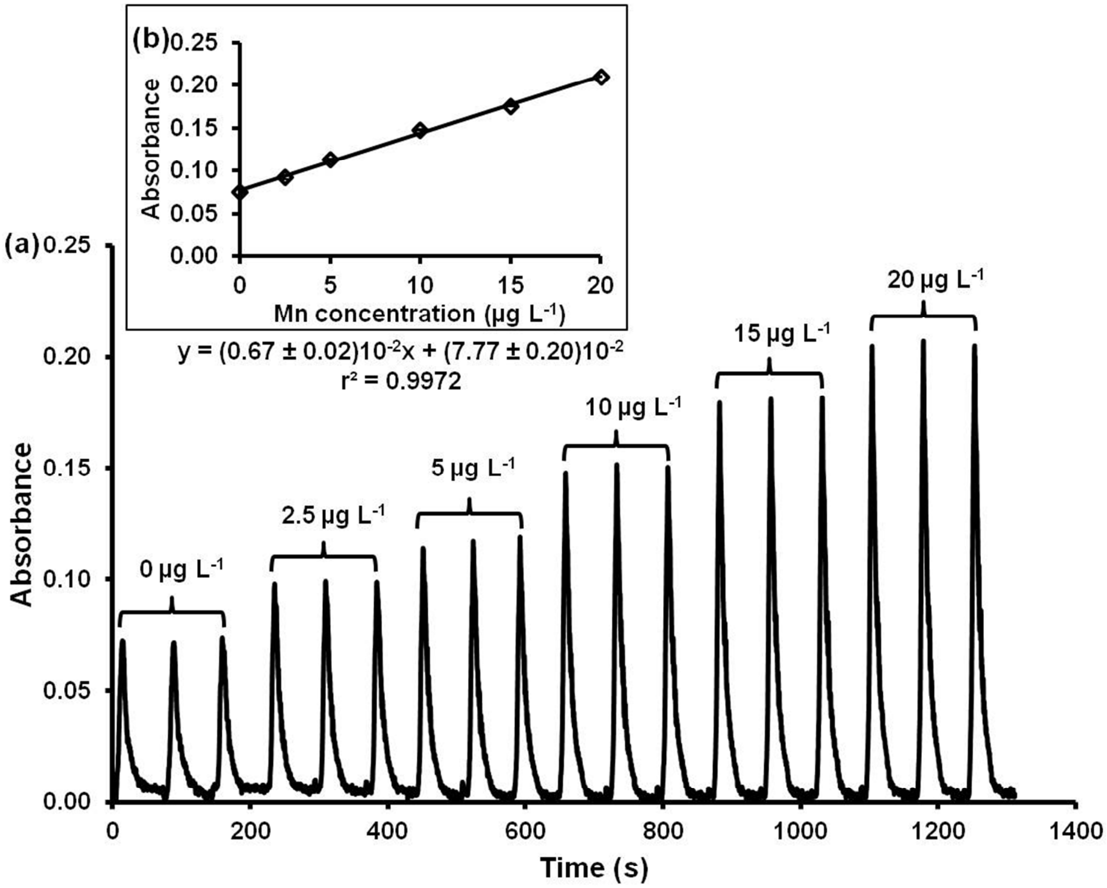

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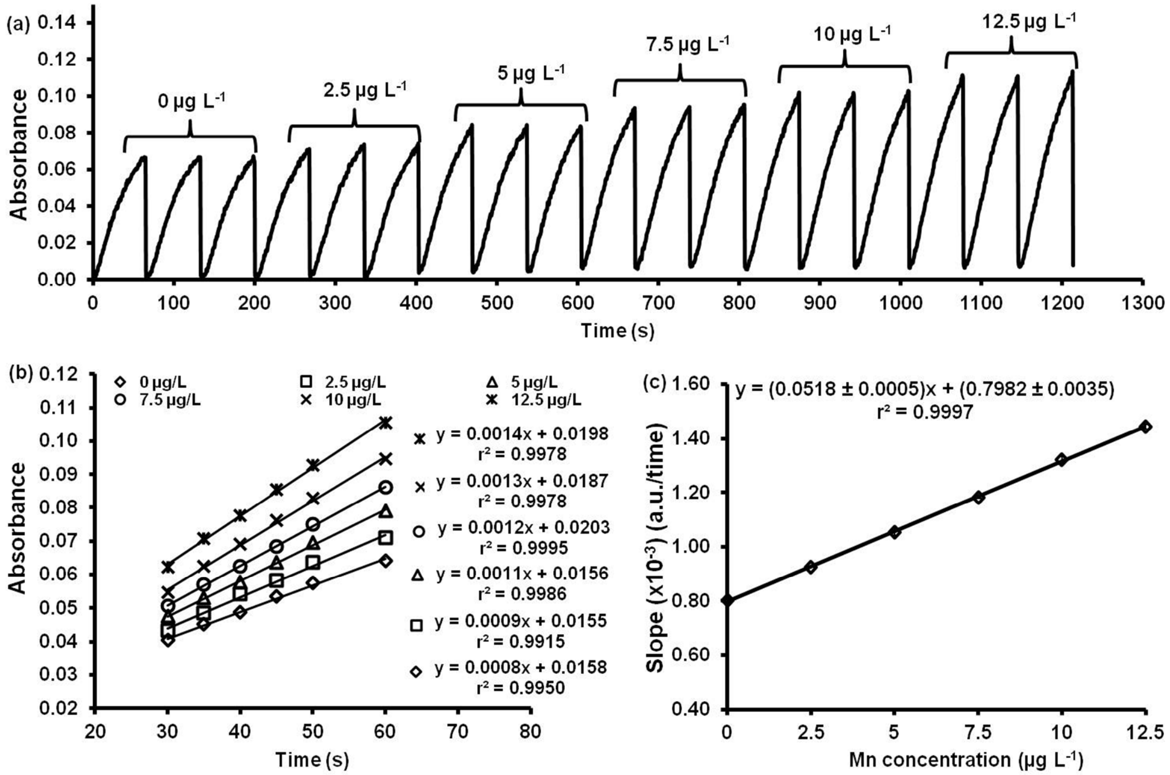

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