A Rapid and Interference-Resistant Formaldehyde Detection Method Based on Surface-Enhanced Raman Spectroscopy with a Reaction-Induced Self-Amplification Strategy

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1. Introduction

Formaldehyde, as a fundamental chemical for the industries, serves a multitude of purposes across various sectors, including food, textiles, and leather production [1–4]. However, on the other side, formaldehyde is classified as 1A carcinogen by the World Health Organization [5,6]. Therefore, meticulous removal of formaldehyde after its use is essential. Its residual concentration is strictly regulated, and corresponding detection methods have been developed [7–10]. Among them, the most commonly employed methods are based on absorption spectroscopy [11,12]. In detail, chromatic products between formaldehyde and sensor molecules are utilized as markers to qualitatively and quantitatively detect formaldehyde. These methods are excellent if the samples are colorless. However, spectral methods encounter challenges when formaldehyde coexists with other dyes, such as those found in food or leather extracts, due to the overlapping spectra of the dyes and the products of formaldehyde [13]. Although some preprocessing methods can further extract formaldehyde or remove interferents, their reliance on additional time, instruments, and operations would significantly undermine the on-field screening efficiency [14].

To achieve a rapid, sensitive, and selective method for direct on-site formaldehyde detection with the constraints of the size and weight of portable detection devices, it is
necessary to develop a technique that provides specific signals for formaldehyde products and a corresponding enhancement strategy for these products. Through a thorough comparative analysis of various methods, surface-enhanced Raman spectroscopy (SERS) was chosen to meet these requirements for several reasons [15–18]. Firstly, the Raman spectra exhibit fingerprint-like features with very narrow bands, providing a large spectral capacity for simultaneously identifying different compounds without any peak overlapping. Moreover, the SERS kit can significantly extend the detectable concentration range into the microgram or even nanogram levels without additional requirements for the original handheld spectrometer and detector, which enables expedient on-field applications. Based on these considerations, a SERS kit was designed and characterized to fulfill these practical demands using a reaction-induced self-amplification strategy. The results demonstrate exceptional detection performance in the direct measurement of ultra-low concentrations of formaldehyde in colored solutions.

In the SERS kit, partly oxidized 3-methyl-2-benzothiazoline hydrazone (MBTH) was selected as the probe molecule and was modified on the surface of silver nanoparticles (AgNPs). Upon the reaction with formaldehyde, an azine formed with the amine group, subsequently reacting with oxidized MBTH to form a complex, as depicted in Figure 1a [19]. Thanks to the interaction between the MBTH and the AgNPs, most of the reaction would happen across different nanoparticles, and once the complex formed, it would act as a lock to closely gather these nanoparticles. This locking mechanism creates favorable “hot-spots” at the interface, enhancing the Raman signals of the product [20–22]. Compared to the condition of colloidal nanoparticles, a great improvement in sensitivity was achieved. In our study, with handheld Raman spectroscopy, a limit of detection (LOD) of sub 10⁻⁴ µg/mL was achieved, and an outstanding interference resistance was also observed compared to conventional UV-Vis absorption spectral methods.

![Figure 1. (a) Reaction diagrams of oxidization of MBTH and the final product between MBTH and formaldehyde; (b) TEM image of the AgNPs; scale bar = 100 nm; (c) typical SERS spectra of the MBTH SERS kit before (blue) and after (orange) the reaction with formaldehyde.](image-url)
2. Materials and Methods

2.1. Materials and Preparation of the AgNPs

AgNO₃, sodium citrate, MBTH, hydrogen peroxide water solution, 3-(dimethylamino) benzoic acid (DMAB), and various dyes were purchased from Aladdin Scientific (Shanghai, China) and were used without any purification. Colloidal AgNPs were prepared following a similar method from the previous literature [23]. To increase the concentration of AgNPs, the concentrations of the precursors were tripled compared to their values in the common method. This strategy was successfully applied in our previous work, and the detailed preparation method can be referred to there [24]. The as-prepared AgNP colloid exhibited excellent dispersion and possessed a brown-gray color.

2.2. Preparation and Verification of the MBTH SERS Kit

Partly oxidized MBTH solution was obtained from MBTH solution which was oxidated by hydrogen peroxide–water solution. A total of 10 mL of MBTH solution was prepared in an amber reagent bottle. The concentrations of MBTH ranged from 0.025 g/L to 0.1 g/L to adjust the coverage of MBTH on the surface of the AgNPs. Then, 200 µL of hydrogen peroxide–water solution was added and mixed thoroughly. The concentrations of hydrogen peroxide ranged from 0.15% to 0.50% to control the different ratios of oxidized MBTH. Finally, 1 mL of the as-prepared AgNP colloid was added to the mixture and left for 15 min to finally make the SERS detection kit. For different control experiments, if some components were not added, an additional amount of ultrapure water for the absent component would be added to ensure that the total volume of the mixture was same as that in the normal SERS kit for fair comparisons. In the standard protocol, 0.1 mL of the sample solution was added to 1.1 mL of the MBTH SERS kit in an amber vial with shaking. After 10 min, the solution was ready for measurement using a Raman spectrometer. The fabrication of the SERS substrate was reported by our group in a previous work [24]. In brief, pure cellulose chromatography paper (Fisherbrand™, Thermo Fisher Scientific Inc., MA, USA, size: 4 cm × 0.5 cm) was dipped into the colloidal AgNPs for 5 s and then was quickly pulled out, followed by 1 min of baking with a 65 °C microheater to fabricate the SERS substrate. When used, the fabricated substrate was directly dipped into the sample solution for 5 s and then was dried using the same microheater before the measurement with the Raman spectrometer. For the confirmation of oxidized MBTH, 2 mL of 0.08 g/L MBTH solution and 0.5 mL of 0.25% hydrogen peroxide solution was mixed and left for 4 h. Then, 2 mL of 0.1 g/L DMAB solution was added to the mixture, and the solution was left for 1 h before the spectroscopic analysis. For the interferent experiments, the concentration of formaldehyde was 0.01 µg/mL. The concentrations of lemon yellow, sunset yellow, and ponceau red 2R were 0.1 mg/mL, and the concentrations of malachite green (MLG) and acid violet R (ACV) were 0.01 mg/mL.

2.3. Morphological and Spectral Characterizations

The morphological observations of the AgNPs were conducted using a transmission electron microscope (TEM, FEI, Tecnai F30, FEI company, Hillsboro, OR, USA). The absorption spectra were recorded using an ultraviolet–visible (UV-Vis) spectrophotometer (U-3900, Hitachi, Tokyo, Japan). All the Raman spectra were acquired using a handheld Raman spectrometer (model CR-2000, HT-NOVA Co., Ltd., Beijing, China). The excitation laser was 785 nm, and the detectable wavelength fell within a range of 200–3200 cm⁻¹ with the spectral resolution within 4–6 cm⁻¹. The laser focus spot was a circular spot with a diameter of 0.2 mm, and the numerical aperture (NA) of the lens was 0.22. The laser output power was set to 350 mW. Each spectrum was acquired in 2 s, and ten of them were averaged and output as the final result for analysis.
3. Results

3.1. Detection of Formaldehyde Using the MBTH SERS Kit

The morphology of the AgNPs is crucial for the SERS performance in this application. It is noted that the reaction between oxidized MBTH and the azine from MBTH and formaldehyde is the force behind the aggregation of the AgNPs, enhancing the sensitivity. Therefore, no soft template, such as polymers or surfactant, was used to synthesize the AgNPs to leave room on the surface for the AgNPs [25,26]. Figure 1b shows a TEM image of the AgNPs in the as-prepared colloid. The diameter of the particles ranged from 20 nm to 50 nm, and the nanoparticles displayed an approximately spherical or polyhedral morphology with several facets. The size of the AgNPs was also confirmed with the UV-Vis absorption spectrum, as shown in Figure S1a. The absorption peak was located at around 430 nm, which was consistent with the spectra of similar particle sizes from the previous literature [27]. Additionally, no clear Raman peaks were observed for the AgNP colloid, as shown in Figure S1b. The surface of these AgNPs was clear and sharp, and no obvious coating was found on the surface of the AgNPs. Macroscopically, the AgNP colloid appeared to be well dispersed and of a brown color, with more intensive visible light absorption compared to the AgNP colloid made from the normal concentrations of the precursors, as shown in Figure S2. These results confirmed the successful synthesis of the AgNPs, and high concentrations of precursors did not change the expected morphology of the AgNPs but increased the concentration of the colloid.

According to the proposed mechanism, half of the MBTH should be transferred into the oxidized state to facilitate the subsequent linkage reaction. In the standard case, oxidation was employed by Fe$^{3+}$ ions in an acid solution. To assess the effect of the Fe$^{3+}$ agent for the SERS kit, 200 µL of 1% ferric ammonium sulfate was added to the MBTH solution with the following mixture of AgNPs. When the AgNP colloid made contact with the acidic solution, small aggregations slowly appeared and grew in the mixture area. Then, some larger aggregations started to fall down. After 10 min, several visible aggregations were found at the bottom, indicating the significant clustering of the AgNPs. Furthermore, in a control experiment, an equal amount of hydrochloric acid was added to the mixture of MBTH and the AgNPs, resulting in similar aggregations at the bottom, as shown in Figure S3. These results indicate Fe$^{3+}$ ions are not suitable because the low pH of the solution can lead to significant aggregation of the AgNPs. This aggregation may result from the decrease in electrostatic repulsion provided by the negative surface charge of the AgNPs [28,29]. Hence, hydrogen peroxide was chosen as the ionization agent due to its efficient and clean oxidation ability without the requirement to alter the pH. The oxidized state of MBTH resulted from the dehydrogenation of the amine group in MBTH, which could be verified by the formation of a blue complex with a trapper, DMAB, as shown in Figure S4a [30]. The absorption spectra of MBTH, oxidized MBTH, and DMAB exhibited no discernible peaks in the visible region, as depicted in Figure S4b. Meanwhile, the mixture of oxidized MBTH and DMAB displayed a strong absorption band from 500 nm to 650 nm, indicating complex formation, as shown in Figure S4c. Hence, it was confirmed that hydrogen peroxide was sufficient for MBTH oxidization, yielding the desired oxidized MBTH structure. Following oxidation, the AgNPs were subsequently mixed, and it took 15 min for the partly oxidized MBTH to migrate onto the surface of the AgNPs due to the strong interaction between the sulfur atoms of MBTH and the silver atoms of the AgNPs.

An optimized detection kit was prepared using 0.08 g/L of MBTH and 0.25% hydrogen peroxide following the described method. The SERS spectra were obtained before and after 0.1 mL of 0.01 µg/mL formaldehyde solution was added for comparison, as shown in Figure 1c. In the absence of formaldehyde, no clear Raman peaks were observed in the range of 300–1500 cm$^{-1}$. Meanwhile, the addition of formaldehyde induced a series of peaks in the same range, including peaks at 373 cm$^{-1}$, 422 cm$^{-1}$, 596 cm$^{-1}$, 833 cm$^{-1}$, 962 cm$^{-1}$, 1122 cm$^{-1}$, 1257 cm$^{-1}$, and 1380 cm$^{-1}$. Notably, the peak at 596 cm$^{-1}$ exhibited the highest intensity and was selected as the performance criterion for the optimization of the kit. Based on this result, the effectiveness of the detection kit was confirmed. Although the literature
suggests that reactions of attached molecules on the surface of AgNPs often lead to Raman peak shifts or relative intensity changes due to alterations in the chemical bonds, it was interesting to observe that the signals from the MBTH SERS kit were activated only upon reaction with formaldehyde [31,32]. Hence, further characterizations and explorations were conducted to elucidate the underlying mechanism.

3.2. Optimization of the MBTH SERS Kit

As previously stated, Fe$^{3+}$ was found to be unsuitable for the MBTH SERS kit, leading to the aggregation of the AgNPs. To assess the performance of the aggregated kit, 0.1 mL of formaldehyde solution was added into the kit in which the oxidation agent was replaced by acidic ferric ammonium sulfate. After a 10 min reaction period, the SERS spectrum was measured and shown in Figure 2a. Most of the peaks observed in the normal kit disappeared, leaving only a single weak peak at 596 cm$^{-1}$. This observation suggests that the aggregation induced by the change in pH did not significantly contribute to the final SERS signals. It appeared that the interface between the AgNPs in the aggregation was already formed due to aggregation, limiting the participation of formaldehyde in the reaction and resulting in very low SERS signals. Thus, although “hot-spots” were formed due to aggregation, the presence of target molecules at the interface was crucial for signal enhancement.

![Figure 2](image_url)

*Figure 2.* With the addition of 0.01 µg/mL of formaldehyde, the Raman spectra of (a) the MBTH SERS kit in which the oxidation agent was replaced by Fe$^{3+}$; (b) the MBTH SERS kits made with different concentrations of MBTH and (c) the MBTH SERS kits made with different concentrations of hydrogen peroxide; (d) the Raman spectra of the blank optimized MBTH SERS kit and the kit with the addition of different concentrations of formaldehyde from $1 \times 10^{-5}$ to $1 \times 10^{-1}$ µg/mL. Inset: The 596 cm$^{-1}$ peak intensity plotting for different concentrations of formaldehyde in the logarithmic form.
Since the concentration of AgNPs in the colloids was fixed upon synthesis, the quantities of MBTH and hydrogen peroxide required optimization to match them for the optimal kit. An excess of MBTH would result in both MBTH and oxidized MBTH existing in the solution and on the surface of the AgNPs. Consequently, the azine from MBTH on the AgNPs could be quenched by free oxidized MBTH, and vice versa. Conversely, if MBTH was deficient, the detection performance would decrease due to the reduced effectiveness of the random collision of AgNPs to form the final product. Therefore, a range of MBTH concentrations from 0.025 g/L to 0.1 g/L was investigated, as shown in Figure 2b. According to the peak intensity at 596 cm\(^{-1}\), 0.08 g/L was determined to be optimal. Within the reaction of MBTH and formaldehyde, half of the MBTH should be oxidized to react with the azine from the other half of the MBTH. Both excess and deficient hydrogen peroxide would lower the transfer ratio of formaldehyde in the linkage between the AgNPs. Thus, the concentration of hydrogen peroxide was also optimized from 0.15% to 0.5%. The results are shown in Figure 2c, and 0.25% was selected for the MBTH SERS kit preparation based on the intensity criterion.

To further evaluate the limit of detection (LoD) of the MBTH SERS kit, a series of concentrations of formaldehyde solution ranging from \(1 \times 10^{-5}\) \(\mu\)g/mL to \(1 \times 10^{-1}\) \(\mu\)g/mL were mixed with the MBTH SERS kit to measure the SERS spectra, as shown in Figure 2d. The 596 cm\(^{-1}\) peak was not clearly observed when the concentration of formaldehyde was \(1 \times 10^{-5}\) \(\mu\)g/mL. In contrast, when 0.1 mL of \(1 \times 10^{-4}\) \(\mu\)g/mL formaldehyde was tested, the signal-to-noise ratio of the peak at 596 cm\(^{-1}\) was high enough to observe. Moreover, the peak intensity exhibited a high correlation with the concentration, as shown in the inset of Figure 2d. Hence, the LoD of the MBTH SERS kit based on the characteristic peak was determined at the level of sub \(1 \times 10^{-4}\) \(\mu\)g/mL, confirming its suitability for the qualitative and quantitative detection of formaldehyde in solution. To calculate the enhancement factor of the MBTH SERS kit, the Raman spectra of the product of partly oxidized MBTH and 1 \(\mu\)g/mL of formaldehyde in the solution were measured, as shown in Figure S5a. No obvious Raman peak was observed, and even when the concentrations of the reactants were increased ten-fold, the Raman spectra was similar with bare peak, as shown in Figure S5b. Based on these results and the noise level of the instrument, we could estimate the enhancement factor was more than \(10^5\) [33].

3.3. Mechanism Discussion

To confirm the origin of the high sensitivity of the MBTH SERS kit, several control experiments were designed. As illustrated in Figure 1a, both MBTH and oxidized MBTH were required for the final product. Indeed, in the experiments aiming to optimize the amount of hydrogen peroxide, it was observed that when the amount of hydrogen peroxide was over a certain threshold, the 596 cm\(^{-1}\) peak intensity decreased, and no more peak emerged. These findings suggested that as more MBTH transitioned into the oxidized state, fewer reactions occurred, and crucially, oxidized MBTH could not directly react with formaldehyde to enhance the Raman signal. When the concentration of hydrogen peroxide was increased to 1.0%, the MBTH was fully oxidized. After the addition of formaldehyde, no obvious peak at 596 cm\(^{-1}\) appeared, as shown in Figure 3a. Therefore, the presence of unoxidized MBTH was crucial for the detection enhancement by the MBTH. On the other hand, since MBTH itself could react with formaldehyde to form the azine, it was necessary to determine whether the oxidized MBTH was necessary. Figure 3b shows the SERS spectrum of a mixture comprising freshly prepared MBTH solution, colloidal AgNPs, and formaldehyde. Surprisingly, no clear peak emerged. Although the reaction was believed to occur, its occurrence did not guarantee the appearance of a SERS signal. This may be attributed not only to the relatively long distance between the reaction point and the attachment point but also to no “hot-spot” participating in the enhancement of the azines. If this were the case, the distance between the AgNPs would become crucial. However, for the colloidal AgNPs, the distance between two AgNPs was not close enough, resulting in an overall low enhancement.
µAgNPs and the partly oxidized MBTH with 0.01 g/mL of formaldehyde. As previously reported, this method enables the tuning of the sensitivity, five cycles of dip-coating were conducted to prepare the SERS substrates. Subsequently, the substrate was transferred into the solution for Raman spectra measurement. Partly oxidized MBTH was mixed with formaldehyde and left for 10 min to enable the reaction. Subsequently, the substrate was transferred into the solution for Raman spectra measurement. Meanwhile, partly oxidized MBTH without formaldehyde was also transferred and measured as the blank control sample. Both results are shown in Figure 3c.

Several identical Raman peaks were observed both in the blank control and the mixture containing formaldehyde, and they did not match the results from the MBTH SERS kit. This suggests that the sensitivity of the substrate might be higher, but the enhanced chemical bonds in MBTH and the product do not directly relate to the hydrazone part. It may be the case that in the colloid, the MBTH molecules had greater time and access to the solvent.
media to adjust their direction in attaching to the AgNPs. Meanwhile, on the substrate, the molecules were forcibly transferred and randomly located at the interface of the AgNPs. In the kit, the amount of unreacted MBTH, including the oxidized MBTH, was much greater than the product of formaldehyde. Consequently, due to random enhancement of all the components on the substrate, the characteristic peak of the formaldehyde product would be heavily suppressed, and the signal would be determined only by the molar ratio. Without specific enhancement, even though the signal of the product was obtained, sensitivity may have been another obstacle. In an optimized system for chemical detection, the product signal would turn on with the concentration increasing, and less of the background of the reactors would be measured or cause interference with the final spectra.

From the substrate experiment, it was known that the enhancement of the product in the colloidal AgNPs was much higher than that in the AgNP substrates. To understand this selective effect, the partly oxidized MBTH was mixed with a small amount of formaldehyde and left for 10 min. Then, the product was added into the AgNP colloid to measure the Raman spectra. Interestingly, at the very beginning of mixing, no obvious Raman peak was observed. However, with time elapsing, the Raman peak gradually increased, and the process lasted approximately 15 min. Eventually, the final stable Raman spectra were closely similar to the results of the original MBTH SERS kit, as shown in Figure 3d. These results suggest that the reaction between the AgNPs and the formaldehyde product required a certain period of time, unlike the common rapid interactions between AgNPs and target molecules. This time-dependent enhancement suggested a complex interplay between the MBTH SERS kit and formaldehyde, possibly involving the selective enhancement observed with the MBTH SERS kit.

The present results have been comprehensively considered to understand the unique interplay between the MBTH SERS kit and formaldehyde. In the colloids, both MBTH and oxidized MBTH were necessary for the final product. The enhancement of the product was much stronger than when using MBTH and oxidized MBTH individually. If the AgNPs were introduced after the reaction, an additional period of time was required for optimal enhancement. But if the AgNPs were added when making the MBTH SERS kit, only the reaction time between the partly oxidized MBTH and formaldehyde was needed. The probable reason for this was that the additional time needed to obtain the Raman signals after contact with the AgNPs in the separated process was incurred during the preparation of the MBTH SERS kit, corresponding to the attachment of the MBTH to the AgNPs via the Ag-S interaction. Consequently, the reaction position between the azine and the oxidized MBTH was only at the interface between different AgNPs. From the viewpoint of the AgNPs, the product acted as linkage to gather the AgNPs, forming “hot-spots” and thereby benefiting from significant SERS enhancement through the self-induced process occurring at the very interface between the AgNPs. In other words, the high sensitivity and selectivity of the product originated from the real-time generation of “hot-spots” driven by the reaction across the AgNPs. No other chemicals, such as MBTH, could occupy such a favorable position for enhancement because this position was held by the reaction product. Additionally, based on the similar spectra of the MBTH SERS kits in which the concentrations of hydrogen peroxide were 0.5% and 1.0%, most of the MBTH should already be oxidized. If no oxidizer is added, the oxidation ratio of MBTH should be 0%. So, 0.25% hydrogen peroxide would result in about a 50% oxidation ratio for the MBTH. On the other hand, the mechanism required a one-to-one ratio of MBTH and the oxidized MBTH to maximize the use of formaldehyde to produce the aggregation of the AgNPs. Indeed, based on the optimization data on the hydrogen peroxide concentration, 0.25% was optimal due to the highest characteristic Raman peak. The consistency of the results and analysis further confirmed the reaction-induced mechanism. And due to the existing attachment of the MBTH to the AgNPs in the kit, the detection time only included the reaction, making it a rapid detection method. This unique process is illustrated in Figure 4, with the dashed line framing the key components and their states in the MBTH SERS kit. In short, the MBTH SERS kit effectively transfers the solution-based homogeneous
reaction illustrated in Figure 1a to the favorable AgNP interface, resulting in significant enhancements in sensitivity and selectivity.

**Figure 4.** A scheme to illustrate the detection mechanism of the MBTH SERS kit. The dashed line frames the key components of the MBTH SERS kit.

### 3.4. Interference Resistance of the MBTH SERS Kit

With the development of the MBTH SERS kit, the practicality of the kit was convincingly demonstrated through a series of experiments. As stated, the standard absorption spectroscopy-based methods face the great challenge posed by colored interferents, and tedious pre-processing work can hardly be avoided. However, these situations usually happen, for example, when the samples are foods and leathers. In contrast, the MBTH SERS kit exploited a unique mechanism and a narrow characteristic peak at 596 cm$^{-1}$, enabling direct detection of formaldehyde in complex solutions without interference or the need for tedious pre-processing.

To demonstrate the robustness of the MBTH SERS kit, formaldehyde solutions containing malachite green (MLG) and acid violet R (ACV) were measured using both the MBTH SERS kit and MBTH absorption spectroscopy, respectively. The results are shown in Figure 5 for parallel comparison. Despite the presence of more peaks in the Raman spectra due to the additional dyes, the characteristic peak at 596 cm$^{-1}$ remained clear and sharp. Based on this peak intensity, the concentration of formaldehyde was estimated to be at the level of 0.01 μg/mL, with a deviation of less than 10%. The other observed peaks in the MBTH SERS kit spectra were attributed to MLG and ACV, as reported in the literature [34,35]. Meanwhile, in the absorption spectra of the two solutions, changes in absorbance at the 630 nm band were unreliable and indistinct for calculating the formaldehyde concentrations due to the strong absorption of the dyes. In addition, more samples containing food-grade dyes and formaldehyde were measured using the MBTH SERS kit, consistently showing the presence of the 596 cm$^{-1}$ Raman peak with little interference. These results, presented in Figure S6, underscore the MBTH SERS kit’s excellent resistance to interference for the detection of formaldehyde in complex solutions. Overall, these side-by-side experiments provided compelling evidence of the MBTH SERS kit’s efficacy in real-world applications, particularly in scenarios involving complex solutions.
Figure 5. (a) The Raman spectrum of the MBTH SERS kit with the addition of 0.01 µg/mL of formaldehyde and 0.01 mg/mL of MLG; (b) the absorption spectra of the solution containing 0.01 µg/mL of formaldehyde and 0.01 mg/mL of MLG before (blue) and after (orange) the MBTH reaction; (c) the Raman spectrum of the MBTH SERS kit with the addition of 0.01 µg/mL of formaldehyde and 0.01 mg/mL of ACV; (d) the absorption spectra of the solution containing 0.01 µg/mL of formaldehyde and 0.01 mg/mL of ACV before (blue) and after (orange) the MBTH reaction.

4. Conclusions

In this article, we present a novel MBTH SERS kit for the rapid detection of formaldehyde with outstanding interference resistance. The key components of the kit consisted of MBTH partly oxidized by hydrogen peroxide and colloidal AgNPs. When employed for formaldehyde detection, the reaction between the formaldehyde and the partly oxidized MBTH occurs across the AgNPs, with the resulting product serving as a lock to aggregate the AgNPs into SERS “hot-spots”. This unique process provides significant enhancement to the product, leading to an overall strengthening of the Raman spectra compared to those in the blank kit. Among the observed peaks, the 596 cm⁻¹ peak exhibited the highest intensity, enabling the LOD to be reduced down to the sub 1 × 10⁻⁴ µg/mL level. In addition to its high sensitivity, the MBTH SERS kit demonstrated remarkable interference resistance. Unlike the overlapping in the absorption spectra, the characteristic peak at 596 cm⁻¹ remained stable with no overlapping, enabling the direct detection of formaldehyde in complex solutions. These promising results suggest that the MBTH SERS kit holds great potential for applications across various industries, including printing and dyeing, food processing, leather production, and numerous other fields, where reliable, sensitive, and rapid detection methods for formaldehyde are essential.
Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/chemosensors12070132/s1, Figure S1: The UV-Vis absorption and Raman spectrum of the AgNPs synthesized in this work; Figure S2: Photos of SERS colloids with hydrochloric acid, acidic ferric ammonium sulfate, and MBTH partly oxidized by hydrogen peroxide; Figure S3: Time-series photos of solutions containing MBTH and AgNPs mixed with hydrochloric acid, acidic ferric ammonium sulfate, and hydrogen peroxide; Figure S4: The reaction between oxidized MBTH and DMAB and the spectral evidence; Figure S5: The Raman spectra of the mixture of partly oxidized MBTH and formaldehyde; Figure S6: The Raman spectra of the detection of formaldehyde with the MBTH SERS kit in the solutions containing lemon yellow, sunset yellow, and ponceau red 2R, respectively.

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