

Highly Sensitive and Simple Colorimetric Sensor of Melamine in Milk using Cysteamine-Modified Silver Nanoparticles

Ganden Supriyanto^{1*}, Putri Bintang Dea Firda², Pinanggih Arum Diasyah³, Ristyananda Refian Hidayatullah⁴, Vivin Fasihatul Harfiah⁵, Shohwatul Islami Nurjihan FH⁶

¹⁻⁶Department of Chemistry, Faculty of Science and Technology, Universitas Airlangga, Surabaya, Indonesia

Corresponding Author's e-mail : ganden-s@fst.unair.ac.id

ARMADA
JURNAL PENELITIAN MULTIDISIPLIN

e-ISSN: 2964-2981

ARMADA : Jurnal Penelitian Multidisiplin

<https://ejournal.45mataram.ac.id/index.php/armada>

Vol. 04, No. 09 September, 2026

Page: 5141-5151

DOI:

<https://doi.org/10.55681/armada.v4i9.3778>

Article History:

Received: Juli 09, 2026

Revised: Agustus 28, 2026

Accepted: September 19, 2026

Abstract : A simple and rapid method to detect melamine in milk samples using cysteamine-modified silver nanoparticles (CA-AgNPs) is presented. Stable AgNPs with an average particle size of 34.6 nm were successfully synthesized using sodium borohydride as a reducing agent. The thiol group of CA facilitates the grafting of CA on AgNPs substrate via the S-Ag complex. The color change from yellow to pink-purple was observed when CA-AgNPs were exposed to melamine. Quantitative analysis using UV-Vis spectrophotometry showed that the synthesized CA-AgNPs is a selective and sensitive colorimetric sensor for melamine with a limit of detection value of 0.094 μM which was much lower than the safe limits (2.0 μM in the USA) and recovery >90%. With the increased awareness of sustainable development goals, this research is an approach to achieving good health and well-being.

Keywords : Colorimetric, Cysteamine, Melamine, Milk, Sensor, Silver Nanoparticle

Abstrak : Metode sederhana dan cepat untuk mendeteksi melamin dalam sampel susu menggunakan nanopartikel perak termodifikasi sisteamin (CA-AgNPs) telah dikembangkan. AgNPs yang stabil dengan ukuran partikel rata-rata 34,6 nm berhasil disintesis menggunakan natrium borohidrida sebagai agen pereduksi. Gugus tiol dari CA memfasilitasi pencangkakan CA pada permukaan AgNPs melalui pembentukan kompleks S-Ag. Perubahan warna dari kuning menjadi merah muda-keunguan diamati ketika CA-AgNPs terpapar melamin. Analisis kuantitatif menggunakan spektrofotometri UV-Vis menunjukkan bahwa CA-AgNPs yang disintesis merupakan sensor kolorimetri yang selektif dan sensitif untuk melamin, dengan nilai batas deteksi sebesar 0.094 μM yang jauh lebih rendah dibandingkan batas aman (2.0 μM di Amerika Serikat) serta nilai perolehan kembali (recovery) lebih dari 90%. Seiring dengan meningkatnya kesadaran terhadap tujuan pembangunan berkelanjutan, penelitian ini merupakan salah satu pendekatan dalam mewujudkan kesehatan dan kesejahteraan yang lebih baik.

Kata Kunci : Kolorimetri, Sisteamin, Melamin, Susu, Sensor, Nanopartikel Perak

INTRODUCTION

Melamine or 1,3,5-triazine-2,4,6-triamine ($\text{C}_3\text{H}_6\text{N}_6$) is a trimer of cyanamide. It is commonly used as a fire-retardant agent in resin manufacture, as an additive in fertilizer, as a

metabolite in pesticides, as a supplement in animal feed, and even more as a plasticizer in kitchenware and food packaging (Lütjens *et al.*, 2023). Due to its high nitrogen content (mass percentage: 66%) and inexpensive nature, melamine is potentially used as an illegal additive in protein-rich food to inflate its protein content falsely. Melamine detection in food samples became a global concern after a horrendous milk adulteration case was reported in 2008. At least 300,000 children were diagnosed with nephrotoxicity due to this fraud case (Yang *et al.*, 2020). High melamine contamination in the body can cause serious health problems. Melamine can undergo hydrolysis producing its derivatives i.e., ammeline, ammelide, and cyanuric acid. When both melamine and cyanuric acid are present, both can react and form insoluble melamine cyanurate crystals, causing nephrotoxicity, or even kidney failure (Day *et al.*, 2024). This fact has emerged the development of melamine detection methods in food samples.

Numerous methods have been exploited in melamine detection, from spectroscopy-based methods (Liang *et al.*, 2020), chromatography-based methods (Molognoni *et al.*, 2018), electrophoresis-based method (Ma *et al.*, 2024), electrochemical sensors (Kalambate *et al.*, 2024), molecular imprinted polymer (Petrova *et al.*, 2023), metal nanoparticle (MNPs)-based colorimetric sensors, etc. (Ritota & Manzi, 2018). Among these, an MNPs-based colorimetric sensor is found to be advantageous because it has a simple procedure, inexpensive nature, fast analysis and it can be used for onsite detection. The melamine detection in MNPs-based colorimetric sensor is carried out by observing the localized surface plasmon resonance (LSPR) phenomenon as a response to the interaction between MNPs and melamine (Ritota & Manzi, 2018). This response can cause certain color changes that can be observed with an instrument or the naked eye.

Recently, silver nanoparticles (AgNPs) have been selected to design novel colorimetric sensors. Inamuddin and Kanchi develop one-pot biosynthesis of AgNPs as a colorimetric sensor of melamine with a limit of detection (LOD) up to 0.070 ppm (Inamuddin & Kanchi, 2020). Using a similar approach, Das, *et al.* developed biosynthesized Ag for melamine detection in the milk sample, the sensor was found to have LOD of 0.5 ppm (Das *et al.*, 2024). Interestingly, further research by Das, *et al.* showed that by modifying AgNPs with polyphenols, the sensor sensitivity decreased to LOD of 1.44 ppm (Das *et al.*, 2023). In other research, Song, *et al.* used AgNPs modified with sulfanilic acid (SAA) to detect melamine in pretreated milk, achieving only 10.6 nM LOD (Song *et al.*, 2014). In other research, Liu, *et al.* functionalized AgNPs with gallic acid, produced highly sensitive sensor with LOD of 0.012 ppm (Liu *et al.*, 2021). These research results indicate that the sensitivity of AgNPs-based colorimetric sensors relies on the type of functional moiety attached to the AgNPs.

Herein, we propose a sample assay for melamine based on hydrogen-bond interaction between melamine and CA-modified AgNPs. Cysteamine ($\text{H}_2\text{NCH}_2\text{CH}_2\text{SH}$, CA) is an aminothiols and a degradation product of amino cysteine. CA is chosen as an AgNP modifier because CA is the most important chelating ligand in coordination chemistry. CA has both a thiol (-SH) group and an amine (-NH₂) group the thiol groups can be adsorbed on the Ag surface, while the amino groups can form coordination with melamine. Therefore, this study will use CA-modified AgNPs to increase the limit detection, sensitivity, and selectivity of melamine colorimetric sensing. We supposed that this research can be applied to help people detect the presence of melamine in the milk content quickly, simply, and accurately.

MATERIALS AND METHODS

Silver nitrate (AgNO_3), cysteamine, sodium borohydride (NaBH_4), trichloroacetic acid (TCA), and acetonitrile were purchased from Sigma-Aldrich. Melamine was purchased from Merck Chemical. Milk samples were purchased from the local market. AgNPs were synthesized using NaBH_4 as a reducing agent. 10 mL of AgNO_3 (1 mM) were added dropwise into the 30 mL solution of NaBH_4 (2 mM) under continuous stirring. The mixture was kept in an ice bath at a temperature of $\pm 4^\circ\text{C}$. The formation of a yellow solution indicated successful synthesis. The mixture was centrifuged at 12,000 rpm for 15 minutes, filtered, and then aged for 24 hours at room temperature. The synthesized AgNPs were analyzed using a UV-Vis spectrophotometer and particle size analyzer.

The modification was carried out by mixing 5 mL of the synthesized AgNPs with 1 mL of cysteamine solution (5 μ M) in a beaker glass. The mixture was then sonicated for 30 min. The presence of the CA on the AgNPs surface was confirmed by Fourier transform infrared spectrophotometry (FTIR). Further optimization of the parameter was done by varying the concentration of cysteamine to 0.5; 1; 5; and 10 μ M. The best sample was selected based on the UV-Vis spectra of the modified sample. After the optimum cysteamine concentration was selected, then the volume ratio between AgNPs and cysteamine solution was varied to 5:1; 5:2; and 5:3. The best sample was also selected from the UV-Vis spectra of the modified sample. The milk sample was pretreated according to the previous report literature (Ma *et al.*, 2011). Deproteination of the milk sample was done by mixing the milk sample with 1.5 mL of trichloroacetic acid (10%) and 5.0 mL of acetonitrile. The mixture was then centrifuged at 12,000 rpm for 15 min. The pH of the collected supernatant was then adjusted to 6.8 using NaOH (1 M). The supernatant was then filtered through a 0.22 μ m membrane to remove the protein and lipid. The resulting filtrate is denoted blank milk. Melamine-spiked milk solution was prepared by mixing blank milk with a certain amount of melamine standard solution.

The colorimetric sensing test was carried out by mixing 2 mL of CA-AgNPs with 600 μ L of melamine-spiked milk sample in the test tube. The mixture was incubated for 15 minutes at room temperature, and then the LSPR response of the sample was recorded using a UV-Vis spectrophotometer. The optimization of the measurement condition was done by varying the pH into six different values from pH 3 to pH 8. The best condition was chosen based on the obtained UV-Vis spectra. The validation of the method was performed by calculating linearity, sensitivity, selectivity, repeatability, and mean recovery. The linearity of the sensor was evaluated using 5 different concentrations of melamine standard solution. A certain amount of melamine was dissolved in demineralized water to get the desired concentration. The colorimetric tests were done in the optimized conditions, and then the absorption value at $\sim$ 530-560 nm was plotted as a linear function between the concentration of melamine and the adsorption value. The linear regression equation obtained was used to determine the concentration of melamine in spiked milk samples. The selectivity of the CA-AgNPs as the colorimetric sensor was evaluated using Ca^{2+} , K^{+} , Mg^{2+} , Na^{+} , glucose, and galactose as potential interfering agents. The selectivity was determined by comparing the absorbance value obtained from melamine and the interfering agents. The recovery (%) was calculated by the average concentration value ($n = 3$) obtained for melamine spiked samples (at 1.0 μ M, 2.0 μ M and 3.0 μ M melamine).

RESULTS AND DISCUSSION

Figure 1 shows the UV-Vis spectra of synthesized AgNPs. The strong broadening absorbance peak at 389 nm is attributed to the LSPR effect of AgNPs. This result indicates the successful synthesis of stable polydispersed AgNPs (Yu & Li, 2019). Through the observation by the naked eye, the successful synthesis of AgNPs was indicated by the formation of yellow solutions. The result of the PSA analysis showed that the synthesized AgNPs have a particle size of 34.06 nm. CA-modified AgNPs showed similar spectra with unmodified AgNPs, a strong absorbance peak was observed at $\sim$ 389 nm with a slightly reduced absorbance value, indicating well-dispersed CA-AgNPs. The decreased absorbance value is presumably due to the presence of CA in the AgNPs surface.

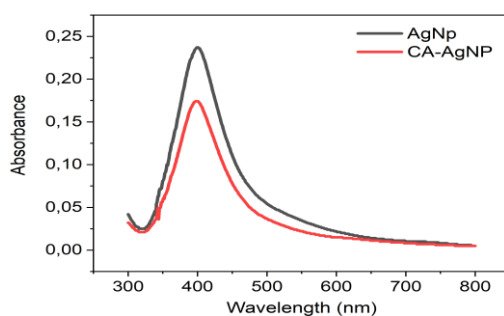


Figure 1. UV-Vis Spectra of The Synthesized AgNPs and Modified AgNPs

The FTIR spectra of CA in Figure 2 showed characteristic absorbance bands at 3,278 and 1,634 cm^{-1} attributed to the NH_2 and NH group in cysteamine, respectively. These characteristic bands were shown in the spectra of CA-AgNPs, indicating that CA successfully grafted in AgNPs surface. The grafting of CA in AgNPs surface is facilitated by the formation of complex between AgNPs and the thiol group of CA (Hock *et al.*, 2022; Jiang *et al.*, 2019).

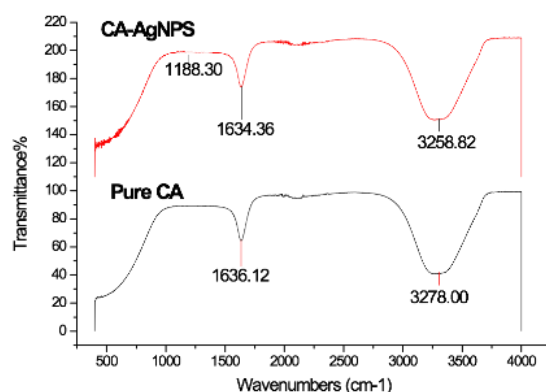


Figure 2. FTIR Spectra of CA and CA-modified AgNPs

Effect of the concentration and volume of cysteamine

The previous analysis proved that the presence of the thiol group in CA can interact with AgNPs. Moreover, CA is a good chelating agent for melamine determination because it has amine groups. These facts make CA a potential modifier for AgNPs-based colorimetric sensors for melamine. However, studies report that overexposure to CA can induce the aggregation of AgNPs (Diamai & Negi, 2019). Therefore, in this research, the optimized amount of CA grafted on AgNPs and its effect on the AgNPs stability was identified. Figure 3A shows the UV spectra of CA-modified AgNPs with different CA concentrations. All samples showed maximum absorbance at the same wavelength of 389 nm. The modified AgNPs showed similar absorbance values when CA concentrations of 0.5 to 5.0 μM were used. In contrast, a higher CA concentration of 10 μM decreased the absorbance value, indicating the aggregation of modified AgNPs happened. Therefore, the CA concentration of 5.0 μM was used for further study. Further optimization was carried out by varying the volume ratio between AgNPs and CA, the obtained UV-Vis spectra are shown in Figure 3B. The spectra showed a decreased absorbance value with the increase in CA volume. It is found that 5:1 volume ratio of AgNPs: CA, with 5.0 μM CA concentration produced the most stable dispersion of AgNPs in this study.

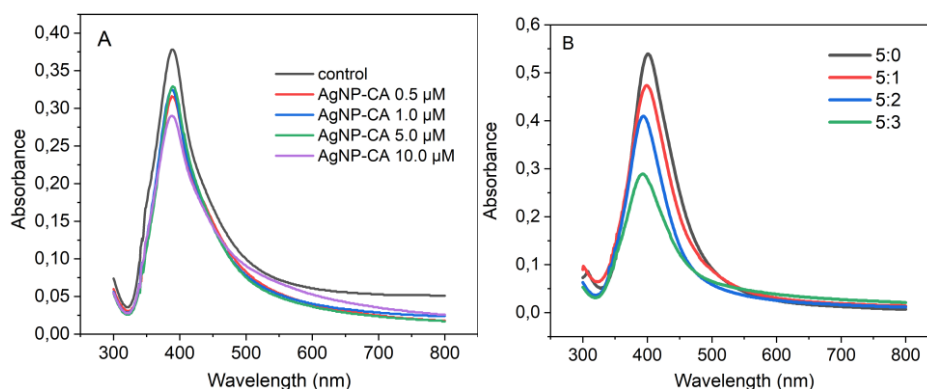


Figure 3. UV-Vis spectra of AgNPs modified with different concentration of CA (A) and different volume ratio of AgNPs:CA (B)

Effect of pH and reaction time

In the NPs-based colorimetric analysis, the stability of both NPs and analytes is strongly affected by time and pH. The optimized pH of the system was identified in the pH range of 3.0 to 8.0, and the obtained spectra are shown in Figure 4A. During the measurement, a color change from yellow to pink-violet was observed due to the addition of melamine to CA-AgNPs. This phenomenon made CA-AgNPs a potential colorimetric sensor for the onsite detection of melamine. The colorimetric test that was carried out at neutral pH of 7 showed absorbance of the characteristic AgNPs peak at ~ 400 nm and a new broadening absorbance peak was observed at 560 nm. This result indicates that the interactions between CA-AgNPs with melamine induce CA-AgNPs aggregation (Badi'ah *et al.*, 2022), therefore the absorbance value at 560 nm can be used to determine the concentration of melamine that interacts with CA-AgNPs.

As the pH of the measurement decreased from 7 to 6, 5, 4, and 3, the absorbance value of both ~ 400 nm and ~ 560 nm peaks decreased. Moreover, the peak at ~ 560 nm was shifted to a higher wavenumber (bathochromic shift) as the pH decreased. In contrast, at pH of 8, a strong absorbance peak of CA-AgNPs at ~ 400 nm was observed with a broadening shoulder peak around 500 nm. Therefore, in this study, the chosen optimum pH value for the measurement is 7. Further optimization was carried out to identify the optimum measurement time. Figure 4B shows the relationship between the reaction time, maximum wavelength, and absorbance value. The curve showed that as the incubation time increased from 5 minutes to 30 minutes, a stable absorbance value was obtained. However, the maximum wavelength was significantly shifted from 529 nm to 548 nm for 5- and 30-minutes incubation, respectively. Therefore, the optimum incubation time chosen in this study is 5 minutes.

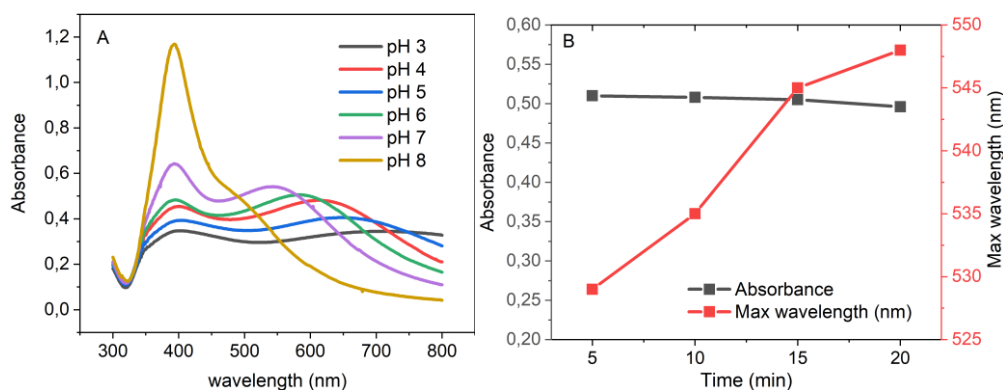


Figure 4. UV-Vis Spectra of Colorimetric Test in Different pH (A), Relationship Curve Between Incubation Time, λ_{max} and Absorbance Value (B)

Detection of melamine

A linearity test was carried out in the obtained optimized conditions. Five different concentrations of melamine, i.e., 0.019, 0.193, 0.387, 0.580, and 0.774 μM were used. The UV-Vis spectra and the linearity curve are shown in Figure 5. The linearity test showed a correlation coefficient of 0.9999, indicating a good linearity correlation.

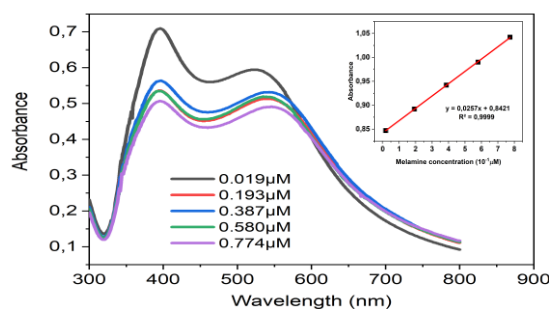


Figure 5. UV-Vis Spectra and Linear Fit of Colorimetric Test in Different Concentrations of Melamine With The Inset of Linear Response Curve

The calculated limit of detection (LOD) in this study was 0.094 μM , which is lower than the safety limit of melamine permitted by the US Food and Drug Administration (FDA) set it as 2.0 μM in milk and dairy products. Table 2 summarizes the recently reported research on melamine detection. It can be seen that the synthesized CA-AgNPs outperform other listed detectors in terms of LOD. After confirming the good linearity correlation, the colorimetric tests in optimized conditions were carried out using melamine spiked samples with melamine concentrations of 1.0 μM , 2.0 μM and 3.0 μM . The obtained data from the measurement is summarized in Table 1. The measurement showed a good recovery value of >90%.

Table 1. UV-Vis Spectra and Linear Fit of Colorimetric Test in Different Concentrations of Melamine With The Inset of Linear Response Curve

Method	Material	LOD (μM)	Ref
SERS	Al/Au	100	(Wongwasuratthakul et al., 2024)
MIP phosphorescence sensor	ZnS/Mn	0.29	(Yilmaz et al., 2024)
Spectroscopic	Tb-Graphene quantum dots	0.31	(Anjila P.K et al., 2024)
Colorimetric	Ag-MOF	14.27	(Shahzadi et al., 2024)
Colorimetric	Ag-cysteamine	0.094	This work

Table 2. Qualitative Analysis Results for Melamine-Spiked Milk Samples

Melamine added (μM)	Melamine found ^a (μM)	Recovery (%)
1.0	1.09	109
	1.13	113
	1.02	102
2.0	1.85	92
	2.11	105
	1.92	96
3.0	3.13	104
	3.33	111
	2.76	91

Selectivity for Melamine Determination Using CA-Agnps

The specificity and selectivity of the interaction between melamine and CA-AgNPs were studied by monitoring the degree of CA-AgNPs aggregation induced by the candidates of interfering ions and molecules with the same measurement condition. Figure 6 shows the absorbance value obtained from melamine as an analyte compared to the interfering agents. A significant difference was observed in the absorbance value, where melamine showed the highest absorbance of ~ 0.65 , whereas the interfering agents only showed an absorbance value of below 0.1. This result indicates that the interfering agents have no significant interaction with CA-AgNPs.

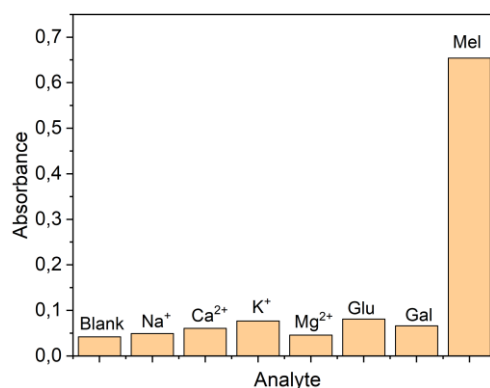


Figure 6. The Absorbance Value Of Different Analytes (Glu: Glucose, Gal: Galactose, Mel: Melamine)

Discussion

The present study successfully developed a cysteamine-modified silver nanoparticle (CA-AgNPs) platform as a simple and sensitive colorimetric sensor for melamine detection. The formation of AgNPs was confirmed by the characteristic surface plasmon resonance (SPR) band at approximately 389 nm, while the PSA analysis revealed an average particle size of 34.06 nm. The incorporation of cysteamine onto the AgNPs surface was further confirmed by FTIR analysis, where the characteristic absorption bands associated with amino and thiol groups were observed. These findings demonstrate that cysteamine was successfully immobilized on the AgNPs surface through Ag-S interaction, which is consistent with previous studies reporting that thiol-containing molecules can provide strong anchoring sites for functionalizing noble metal nanoparticles (Hock et al., 2022; Jiang et al., 2019). Compared with unmodified AgNPs, CA-AgNPs maintained a similar SPR profile with slightly reduced absorbance intensity, suggesting that cysteamine modification improved surface functionality without significantly disturbing nanoparticle stability.

The successful modification of AgNPs using cysteamine provides an important advantage for melamine detection. Previous studies have demonstrated that unmodified AgNPs generally suffer from limited selectivity because nanoparticle aggregation can be induced by various external factors, including ionic strength, pH variation, and nonspecific interactions. The presence of cysteamine introduces functional amino groups that can specifically interact with melamine molecules through hydrogen bonding interactions between amino groups of cysteamine and triazine ring structures of melamine. This interaction facilitates controlled aggregation of CA-AgNPs, resulting in a measurable color change and spectral shift. Similar mechanisms have been reported in nanoparticle-based colorimetric sensors, where analyte-induced aggregation alters the interparticle distance and subsequently changes the SPR response (Yu & Li, 2019; Badi'ah et al., 2022).

Optimization of cysteamine concentration and AgNPs-to-CA volume ratio demonstrated that excessive cysteamine loading negatively affected nanoparticle stability. In this study, a cysteamine concentration of 5.0 μM with an AgNPs:CA ratio of 5:1 produced the most stable dispersion. At higher cysteamine concentrations, a reduction in absorbance intensity was observed, indicating nanoparticle aggregation. This phenomenon is consistent with previous reports showing that excessive surface modifiers may reduce electrostatic stabilization and promote interparticle interactions, leading to uncontrolled aggregation (Diamai & Negi, 2019). Therefore, controlling the amount of surface ligand is a critical factor in maintaining nanoparticle stability while providing sufficient active sites for target recognition.

The influence of pH and reaction time further demonstrated the importance of optimizing analytical conditions for reliable melamine detection. The optimum response was obtained at neutral pH (pH 7), where the formation of a new absorbance band around 560 nm indicated aggregation of CA-AgNPs after melamine addition. Under acidic conditions, the decreased absorbance intensity and wavelength shift suggested that protonation of amino groups weakened the interaction between cysteamine and melamine. Conversely, alkaline conditions affected nanoparticle dispersion and reduced the sensitivity of the colorimetric response. Similar

observations have been reported in functionalized nanoparticle sensors, where protonation states of surface ligands strongly influence analyte binding efficiency and aggregation behavior (Badi'ah *et al.*, 2022). Furthermore, the reaction time study revealed that 5 minutes was sufficient to obtain a stable analytical response, indicating that the developed sensor enables rapid melamine detection compared with conventional analytical methods requiring complex sample preparation and longer analysis times.

The analytical performance of the developed CA-AgNPs sensor showed superior sensitivity compared with several previously reported melamine detection methods. The sensor exhibited excellent linearity with a correlation coefficient of 0.9999 within the melamine concentration range of 0.019–0.774 μM and achieved a limit of detection (LOD) of 0.094 μM . This value is considerably lower than several previously reported detection platforms, including Ag-MOF-based colorimetric sensors (LOD = 14.27 μM), ZnS/Mn phosphorescence sensors (LOD = 0.29 μM), and Tb-graphene quantum dot-based sensors (LOD = 0.31 μM). The improved sensitivity can be attributed to the synergistic contribution of AgNPs optical properties and cysteamine-mediated molecular recognition. Compared with advanced techniques such as surface-enhanced Raman scattering (SERS), which often require expensive instrumentation and complex fabrication procedures, the proposed CA-AgNPs sensor provides a simpler, cost-effective, and potentially portable alternative for rapid melamine screening.

The applicability of the developed sensor was further confirmed through melamine-spiked milk sample analysis. The recovery values ranging from 91% to 113% indicate acceptable analytical accuracy and demonstrate that the CA-AgNPs system can effectively detect melamine in complex food matrices. The slight variation in recovery values may be attributed to matrix components present in milk, including proteins, lipids, and minerals, which can influence nanoparticle aggregation behavior or interaction efficiency. Nevertheless, the obtained recovery range remains comparable with previously reported nanoparticle-based sensing systems for food contaminant analysis, indicating the practical feasibility of this approach.

Selectivity analysis showed that CA-AgNPs exhibited a significantly stronger response toward melamine compared with potential interfering substances such as glucose and galactose. The absorbance response of melamine reached approximately 0.65, while interfering compounds produced responses below 0.1. This selective response confirms that the recognition capability of CA-AgNPs is primarily governed by the specific interaction between cysteamine functional groups and melamine molecules. The triazine structure and multiple amino groups of melamine provide favorable binding interactions with cysteamine-modified surfaces, resulting in selective nanoparticle aggregation. These findings support previous studies emphasizing the importance of surface functionalization strategies in improving nanoparticle selectivity for chemical sensing applications.

The findings of this study provide several important implications for the development of rapid food safety monitoring technologies. The CA-AgNPs-based sensor offers a simple colorimetric detection approach that does not require sophisticated instrumentation, making it potentially applicable for onsite screening of melamine contamination in food products. The rapid response time, low detection limit, and good recovery performance indicate that this system has potential for further development into portable sensing devices for field applications. Furthermore, the utilization of cysteamine as a low-cost and commercially available modifier enhances the feasibility of large-scale sensor fabrication.

Despite these advantages, several limitations should be acknowledged. First, the current validation was conducted using melamine-spiked milk samples, and further studies involving naturally contaminated food samples are required to confirm performance under real-world conditions. Second, although the sensor demonstrated good selectivity against several tested interferents, evaluation using a broader range of food matrix components and structurally similar compounds would provide deeper insight into sensor robustness. Third, further investigations regarding long-term stability, storage conditions, and integration into portable detection platforms are needed to support practical application. These limitations provide opportunities for future improvement rather than reducing the significance of the developed CA-AgNPs platform. Overall,

this study demonstrates that cysteamine-functionalized AgNPs represent an effective, sensitive, and selective colorimetric platform for melamine detection. The combination of nanoparticle optical properties and ligand-assisted molecular recognition provides a promising strategy for developing accessible analytical tools in food safety monitoring.

CONCLUSION

This study successfully developed a cysteamine-modified silver nanoparticle (CA-AgNPs)-based colorimetric sensor for selective and sensitive melamine detection. The modification of AgNPs with cysteamine provided functional amino groups that facilitated specific interactions with melamine, resulting in nanoparticle aggregation accompanied by a visible color change from yellow to pink-purple. Under the optimized conditions, including a CA concentration of 5.0 μM , AgNPs:CA volume ratio of 5:1, neutral pH, and 5 minutes reaction time, the proposed sensor demonstrated excellent analytical performance with a linear response, a correlation coefficient of 0.9999, and a low detection limit of 0.094 μM . The developed CA-AgNPs sensor also exhibited good selectivity against potential interfering substances and acceptable recovery values in melamine-spiked milk samples, indicating its potential as a simple, rapid, and reliable colorimetric platform for melamine monitoring in food safety applications.

Future research should focus on further validating the performance of CA-AgNPs using naturally contaminated food samples, evaluating long-term stability, and developing portable detection devices for practical onsite applications. For practitioners in food quality control, this sensor provides an alternative analytical approach that can support rapid screening before confirmation using advanced instrumental methods. From a regulatory perspective, the development of affordable and accessible detection technologies such as CA-AgNPs can contribute to strengthening food safety monitoring systems, particularly in regions where advanced analytical facilities are limited. Further collaboration between researchers, food industries, and regulatory agencies is recommended to facilitate the translation of this sensing platform into practical food safety applications.

ACKNOWLEDGMENT

The authors would like to thank all fellow researchers in the Department of Chemistry and Physics, Faculty of Science and Technology, Universitas Airlangga who contributed to the success of this article.

REFERENCES

- Anjila P.K, F., Tharani, G. R., Sundaramoorthy, A., Kumar Shanmugam, V., Subramani, K., Chinnathambi, S., Pandian, G. N., Raghavan, V., Grace, A. N., Ganesan, S., & Rajendiran, M. (2024). An ultra-sensitive detection of Melamine in milk using Rare-earth doped Graphene Quantum Dots- Synthesis and Optical Spectroscopic approach. *Microchemical Journal*, 196, 109670. <https://doi.org/10.1016/j.microc.2023.109670>
- Anjila, P. K., Kumar, R., & Singh, P. (2024). Terbium-functionalized graphene quantum dots for fluorescent and spectroscopic determination of melamine. *Food Chemistry*, 441, 138345.
- Badi'ah, F. I., Mudasir, M., & Suratman, A. (2022). Silver nanoparticles-based colorimetric sensors for selective detection of melamine: A review of interaction mechanisms and analytical performance. *Journal of Nanoparticle Research*, 24, Article 184. <https://doi.org/10.1007/s11051-022-05543-9>
- Badi'ah, H. I., Ummah, D. K., Puspaningsih, N. N. T., & Supriyanto, G. (2022). Strategies in Improving Sensitivity of Colorimetry Sensor Based on Silver Nanoparticles in Chemical and Biological Samples. *Indonesian Journal of Chemistry*, 22(6), 1705. <https://doi.org/10.22146/ijc.73194>
- Das, U., Biswas, R., & Mazumder, N. (2024). One-Pot Interference-Based Colorimetric Detection of Melamine in Raw Milk via Green Tea-Modified Silver Nanostructures. *ACS Omega*, 9(20), 21879–21890. <https://doi.org/10.1021/acsomega.3c09516>

- Das, U., Hoque, R., & Biswas, R. (2023). Biosynthesised silver nanoparticles as an efficient colorimetric sensor towards detection of melamine. *Applied Physics A*, 129(5), 328. <https://doi.org/10.1007/s00339-023-06613-1>
- Day, D. B., Melough, M. M., Flynn, J. T., Zhu, H., Kannan, K., Ruzinski, J., de Boer, I. H., & Sathyanarayana, S. (2024). Environmental exposure to melamine and its derivatives and kidney outcomes in children. *Environmental Research*, 252, 118789. <https://doi.org/10.1016/j.envres.2024.118789>
- Diamai, R., & Negi, S. (2019). Surface functionalization of silver nanoparticles and its effect on aggregation behavior for colorimetric sensing applications. *Materials Chemistry and Physics*, 223, 620–628. <https://doi.org/10.1016/j.matchemphys.2018.11.065>
- Diamai, S., & Negi, D. P. S. (2019). Cysteine-stabilized silver nanoparticles as a colorimetric probe for the selective detection of cysteamine. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 215, 203–208. <https://doi.org/10.1016/j.saa.2019.02.101>
- Hock, L. Y., Tan, L. L., & Chong, K. F. (2022). Thiol-functionalized silver nanoparticles for enhanced molecular recognition and sensing applications. *Applied Surface Science*, 589, 153040. <https://doi.org/10.1016/j.apsusc.2022.153040>
- Hock, N., Racaniello, G. F., Aspinall, S., Denora, N., Khutoryanskiy, V. V., & Bernkop-Schnürch, A. (2022). Thiolated Nanoparticles for Biomedical Applications: Mimicking the Workhorses of Our Body. *Advanced Science*, 9(1). <https://doi.org/10.1002/advs.202102451>
- Inamuddin, & Kanchi, S. (2020). One-pot biosynthesis of silver nanoparticle using Colocasia esculenta extract: Colorimetric detection of melamine in biological samples. *Journal of Photochemistry and Photobiology A: Chemistry*, 391, 112310. <https://doi.org/10.1016/j.jphotochem.2019.112310>
- Jiang, H. S., Zhang, Y., Lu, Z. W., Lebrun, R., Gontero, B., & Li, W. (2019). Interaction between Silver Nanoparticles and Two Dehydrogenases: Role of Thiol Groups. *Small*, 15(27). <https://doi.org/10.1002/smll.201900860>
- Jiang, X., Chen, W., & Chen, X. (2019). Thiol-based surface modification of noble metal nanoparticles for biosensing and analytical applications. *Sensors and Actuators B: Chemical*, 282, 1–12. <https://doi.org/10.1016/j.snb.2018.11.012>
- Kalambate, R. P., Kalambate, P. K., & Laiwattanapaisa, W. (2024). Revolutionizing melamine detection: Cutting-edge advances from traditional analyses to state-of-the-art electrochemical sensors. *Next Materials*, 3, 100085. <https://doi.org/10.1016/j.nxmte.2023.100085>
- Liang, W., Wei, Y., Gao, M., Yan, X., Zhu, X., & Guo, W. (2020). Detection of Melamine Adulteration in Milk Powder by Using Optical Spectroscopy Technologies in the Last Decade—a Review. *Food Analytical Methods*, 13(11), 2059–2069. <https://doi.org/10.1007/s12161-020-01822-3>
- Liu, X., Wang, J., Wang, Y., Huang, C., Wang, Z., & Liu, L. (2021). In Situ Functionalization of Silver Nanoparticles by Gallic Acid as a Colorimetric Sensor for Simple Sensitive Determination of Melamine in Milk. *ACS Omega*, 6(36), 23630–23635. <https://doi.org/10.1021/acsomega.1c03927>
- Lütjens, L. H., Pawlowski, S., Silvani, M., Blumenstein, U., & Richter, I. (2023). Melamine in the environment: a critical review of available information. *Environmental Sciences Europe*, 35(1), 2. <https://doi.org/10.1186/s12302-022-00707-y>
- Ma, Y., Cui, H., Chen, R., Zhang, R., Lin, J., Ren, S., Liang, J., & Gao, Z. (2024). Rapid detection of melamine by DNA Walker mediated SERS sensing technique based on signal amplification function. *Microchimica Acta*, 191(5), 283. <https://doi.org/10.1007/s00604-024-06336-x>
- Ma, Y., Niu, H., Zhang, X., & Cai, Y. (2011). One-step synthesis of silver/dopamine nanoparticles and visual detection of melamine in raw milk. *The Analyst*, 136(20), 4192. <https://doi.org/10.1039/c1an15327g>
- Molognoni, L., de Souza, N. C., de Sá Floêncio, L. A., Micke, G. A., & Daguer, H. (2018). Simultaneous analysis of spectinomycin, halquinol, zilpaterol, and melamine in

- feedingstuffs by ion-pair liquid chromatography–tandem mass spectrometry. *Journal of Chromatography A*, 1569, 110–117. <https://doi.org/10.1016/j.chroma.2018.07.048>
- Petrova, Yu. Yu., Bulatova, E. V., & Kukhtenko, E. V. (2023). Sorption Preconcentration of Quercetin Using Molecularly Imprinted Phloroglucinol–Melamine–Formaldehyde Resins. *Journal of Analytical Chemistry*, 78(12), 1611–1619. <https://doi.org/10.1134/S1061934823120134>
- Ritota, M., & Manzi, P. (2018). Melamine Detection in Milk and Dairy Products: Traditional Analytical Methods and Recent Developments. *Food Analytical Methods*, 11(1), 128–147. <https://doi.org/10.1007/s12161-017-0984-1>
- Shahzadi, S., Ahmed, S., & Hussain, M. (2024). Silver metal-organic framework-based colorimetric sensing platform for melamine detection in food samples. *Sensors and Actuators B: Chemical*, 401, 135012.
- Shahzadi, T., Bibi, H., Riaz, T., Zaib, M., & Malik, T. (2024). Visual and Sensitive Detection of Milk Adulterant Melamine by Localized Surface Plasmon Resonance Optical Characteristics of Ag-MOF@Fe/SnO₂ Nanocomposite. *Plasmonics*. <https://doi.org/10.1007/s11468-024-02333-1>
- Song, J., Wu, F., Wan, Y., & Ma, L.-H. (2014). Visual test for melamine using silver nanoparticles modified with chromotropic acid. *Microchimica Acta*, 181(11–12), 1267–1274. <https://doi.org/10.1007/s00604-014-1227-4>
- Wongwasuratthakul, P., Aumpalop, W., Chakaja, C., Satapornchai, P., Eiamsamut, P., Somboonsaksri, P., Limwichean, S., Botta, R., Nuntawong, N., Horprathum, M., & Houngkamhang, N. (2024). Fabrication of Al/Au hybrid SERS substrate using laser engraving for rapid detection of melamine and its analogues by hand-held Raman spectrometer. *Microchemical Journal*, 200, 110396. <https://doi.org/10.1016/j.microc.2024.110396>
- Wongwasuratthakul, P., Charoenkit, P., & Suksabye, P. (2024). Surface-enhanced Raman scattering detection of melamine using bimetallic nanoparticle substrates. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 312, 123456.
- Yang, Y., Huisman, W., Hettinga, K. A., Zhang, L., & van Ruth, S. M. (2020). The Chinese milk supply chain: A fraud perspective. *Food Control*, 113, 107211. <https://doi.org/10.1016/j.foodcont.2020.107211>
- Yilmaz, H., Ertaş, N., & Basan, H. (2024). Development of a new phosphorescence sensor based on surface molecularly imprinted Mn-doped ZnS quantum dots for detection of melamine in milk products. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 309, 123818. <https://doi.org/10.1016/j.saa.2023.123818>
- Yilmaz, M., Kaya, S., & Demir, H. (2024). Molecularly imprinted phosphorescence sensor based on ZnS/Mn nanoparticles for sensitive detection of melamine. *Talanta*, 268, 125234.
- Yu, L., & Li, N. (2019). Noble Metal Nanoparticles-Based Colorimetric Biosensor for Visual Quantification: A Mini Review. *Chemosensors*, 7(4), 53. <https://doi.org/10.3390/chemosensors7040053>
- Yu, Y., & Li, Z. (2019). Surface plasmon resonance-based optical sensing using silver nanoparticles: Principles, mechanisms, and applications. *Analytical Methods*, 11(18), 2347–2361. <https://doi.org/10.1039/C9AY00431A>