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ORIGINAL RESEARCH PAPER

Green chemistry approach to formaldehyde detection using fish albumin-modified gold electrodes

T.P.H. Hutapea[1], Suprapto[2], M.Y. Syaputra[2,3], F. Kurniawan[2,*]

[1] *Fisheries Product Technology Department, Faculty of Fishery and Marine Science, University of Borneo Tarakan, North Borneo 77115 Indonesia*

[2] *Chemistry Department, Institute Teknologi Sepuluh Nopember, Surabaya, East Java 60111 Indonesia*

[3] *Graduate School of Science and Engineering, Saga University, Honjomachi, Saga 840-8502, Japan*

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ABSTRACT

BACKGROUND AND OBJECTIVES: Formaldehyde in food or the environment poses significant health risks, as it is a known carcinogen that can cause respiratory issues skin irritation, and long-term exposure can lead to serious diseases such as cancer. The presence of formaldehyde is detectable in various environments, including food and water. A newly developed gold electrode, enhanced with fish albumin, has been created for the purpose of detecting formaldehyde, adhering to the principles of green chemistry. Fish albumin, which contains amino acids such as glycine, lysine, and histidine, can react with formaldehyde. This level of reactivity implies that fish albumin can serve as an effective and sustainable material for formaldehyde sensor applications. The objectives of this study were to make albumin-modified electrodes used for formaldehyde detection applied for the fish in case fishermen generally use formaldehyde to preserve the fish they bring ashore. This formaldehyde helps maintain the freshness of the fish during the handling and transportation process.
METHODS: The fish albumin was used from the self-extraction of snakehead fish (Channa striata) using water as a solvent. Fish albumin was combined with paraffin in a specific ratio, subsequently heated on a hot plate and stirred until a homogeneous mixture was achieved. The liquid was poured into a small glass tube, with one of the ends connected to gold. The electrode was ready to be used after the liquid became solid. All experiments conducted for the detection of formaldehyde utilized the cyclic voltammetry method. The potential measurement was between 0 volt and +1.8 volt with a 100 millivolt per second scan rate.
FINDINGS: The electrode works well in acidic conditions by showing a significant formaldehyde signal compared to alkaline and neutral conditions. The linear analysis range was 0.1 ~ 3 millimolars with a detection limit of 4.07 micromolars, and the sensitivity was 20.365 microampere millimolars per square millimeter. This electrode was utilized to assess the level of formaldehyde while accounting for the interference from methanol, ethanol, glycerol, and glucose. This method was also applied to the real samples and simultaneously compared to the standard method (Nash method) for formaldehyde detection.
CONCLUSION: The electrode exhibits excellent performance with high sensitivity and selectivity for formaldehyde detection under acidic conditions. With its low detection limit, the electrode allows for highly accurate detection of formaldehyde measurement. Methanol, ethanol, glucose, and glycerol do not interfere with detection. Additionally, the electrode demonstrates good repeatability and delivers accuracy comparable to the standard Nash method, making it a promising alternative for formaldehyde detection. A key benefit of the proposed method is that it eliminates the need to add reagents to the samples.

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33	8	5

*Corresponding Author:
Email: *fredy@its.ac.id*
Phone: +821 4126 4818
ORCID: 0000-0002-9777-0989

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INTRODUCTION

Albumin is a globular protein characterized by its solubility in water and its tendency to coagulate when heated. It contains over 500 amino acids and is present in humans, plants, and animals alike. It is usually called human serum albumin (HSA) in humans and 2S albumin in plants. Albumin is widely present among different animal species; for instance, bovine serum albumin (BSA) is sourced from cattle, while ovalbumin (OVA) is derived from eggs (Hutapea *et al*., 2023; Hou *et al*., 2023). Other sources of albumin are found in various groups of animals, such as mammals, reptiles, amphibians, birds and fishes. One fish species with a high albumin content, fish albumin (FA), widely found in Indonesia and used in this study is *Channa striata*. Albumin can be applied in various fields, such as drug delivery (Tiwari *et al*., 2021), wound healing (Liu *et al*., 2023), corrosion inhibitors (Kaseem and Ko, 2021) and sensors (Li *et al*., 2024). In sensor applications, albumin serves as an effective sensor material, as its proteins possess active sites that can engage with compatible molecule. Various previous studies have reported the use of protein-based materials in sensor technology, such as egg white (Padmalaya *et al*., 2024), gelatin (Hutapea *et al*., 2024) and including albumin. In these applications, the commonly used forms of albumin are HSA and Bovine BSA. In contrast, there is no documented use of FA in sensor technologies. FA has been reported in various industrial sectors, such as the fish feed industry to improve nutritional quality, the food industry as an additive, as well as in the health and pharmaceutical sectors as a component in drug formulations for wound healing (Soedjanaatmadja *et al*., 2021). The extensive applicability of fish albumin underscores its diverse and high value properties. However, although there have been many studies exploring its use in various fields, to date there have been no reports that specifically discuss its use as a sensor material. The composition of FA includes multiple amino acids, such as glycine, lysine, and histidine (Nurfaidah *et al*., 2024). On the other work, these amino acids can react with formaldehyde (Jia *et al*., 2024). It is conceivable that FA could engage with formaldehyde. Consequently, this study will incorporate FA in sensor applications aimed at formaldehyde detection. Formaldehyde is a compound absorbed quickly in human and animal respiratory and gastrointestinal tracts. It can be converted into formic acid and, after that, into carbon dioxide in the human body's metabolism. In humans and animals, formaldehyde has a very short biological half-life, estimated to be approximately 60 seconds. It explains that formaldehyde is very harmful to human health. Formaldehyde is also a carcinogenic compound that can cause cancer (Soltanpour *et al*., 2022). Nevertheless, formaldehyde is widely used in various industries as a raw material for adhesives (Torun, 2022; Dorieh *et al*., 2022), disinfectants (Fadeyibi *et al*., 2024), and cosmetics (Sánchez *et al*., 2021). Additionally, the use of formaldehyde as a food preservative is conducted illegally (Nayak *et al*., 2024). The use of formaldehyde compounds in industry and foodstuffs can cause formaldehyde pollution. Controlling formaldehyde pollution is imperative. Timely detection of formaldehyde plays a vital role in the effective management of this pollutant. Various methods have been carried out in determining formaldehyde, including chromatographic methods, spectrophotometry (Lian *et al*., 2021) and electrochemical sensor (Li *et al*., 2022; Wicaksono *et al*., 2022). The chromatographic method generally takes a relatively long time to accomplish. Furthermore, the process of preparing and selecting the suitable solvent is time-consuming. Like the chromatographic method, the spectrophotometric method also requires a relatively long time and process in sample preparation. The measured sample must be reacted with other compounds to form complex compounds that can absorb light with wavelengths >185 nanometers (nm). In contrast, the electrochemical sensor technique is not only easier and faster but also provides greater accuracy at a lower expense, positioning it as the optimal choice for formaldehyde control. Consequently, the study aimed to design a new sensor for formaldehyde detection by implementing an electrochemical method. The sensor was a gold electrode (GE) modified with FA extracted independently from snakehead fish (*Channa striata*). The fabrication of the sensor is very simple, namely by immobilizing FA on the surface of a gold electrode. The sensor has good selectivity and sensitivity to formaldehyde with a low limit of detection (LOD). Moreover, the results of formaldehyde assessments on real samples conducted with the sensor and the conventional method did not exhibit significant differences at the 95 percent (%) confidence level. The aims of this study

is to make albumin-modified electrodes used for formaldehyde detection applied for the fish in case fishermen generally use formaldehyde to preserve the fish they bring ashore. This formaldehyde helps maintain the freshness of the fish during the handling and transportation process. The study aims to make an environmentally friendly sensor from FA to detect formaldehyde. The use of environmentally conscious sensors represents a viable strategy for achieving sustainability in the environment. Apart from that, other methods such as adsorption of dangerous compounds (Samimi, 2023), use of environmentally friendly polymers (Rizki *et al*., 2024), effective waste management (Suprihatin *et al*., 2024), and early detection of toxic compounds (Hermanto *et al.,* 2023) also play an important role in maintaining a healthy, safe and protected environment from toxic compounds (Kiswandono *et al.,* 2024). This study has been carried out in Surabaya, Indonesia, in 2024.

MATERIALS AND METHODS

Materials

The materials used in this study were paraffin, potassium hydroxide, potassium chloride, glucose, chloric acid 37%, methanol 99.98%, ethanol 99,98%, glycerol 98%, and formaldehyde 37% purchased from Sigma-Aldrich. The FA was utilized for the self-extraction of snakehead fish (*Channa striata*), following previously documented procedures that involved water as a solvent (Hutapea *et al*., 2022). In short, the snakehead fish meat is blended until smooth, and water is added. Then, the extraction process was done by heating the mixture at 50 degrees Celsius (^{0}C) for 20 minutes. Then, the mixture was filtered, and n-hexane was added with a ratio of 1:0.25 in a separation funnel. Once whisked and allowed to sit for one minute, the liquid separates into two distinct phases. In the final stage, the aqueous phase was separated and dried in an oven at 50 ^{0}C until a solid extract was obtained. The fish sample used was Tongkol fish (*Euthynnus affinis*) obtained from a traditional market in Surabaya, Indonesia.

Apparatus

The main instrumentation for all measurements in this study was an AUTO LAB PGSTAT 128 N with the three-electrode system (Metrohm, Germany). The working electrode was a fish albumin modified gold electrodes (FA-GE), with silver/silver chloride (Ag/AgCl) in potassium chloride three molars (KCl 3M) as the reference electrode and platinum wire as the auxiliary electrode. In addition to the primary equipment, the experiment incorporated an analytical balance, hot plates, an ultrasonic cleaner, and a stereo microscope, specifically the Olympus SZ61, which was equipped with a digital camera.

Fabrication of FA-GE

Gold wire with a diameter of 1 millimeter (mm) was cut into 5 centimeters (cm) long and then inserted into tubular glass. On the other hand, FA and paraffin were mixed in a watch glass at a definite ratio. The ratios of FA and paraffin used in this experiment were 10:0, 9:1, 8:2, 7:3, and 6:4, respectively, to get optimum composition. The mixture was subjected to heating on a hot plate until the paraffin melted and achieved a homogeneous consistency. Subsequently, this uniform mixture was transferred into the end of the tubular glass that had been prepared with gold wire in advance. The mixture on the end of the tubular is flattened and allowed to cool and solidify to form a working electrode ready for further experiment. Fig. 1 shows the fabrication process of the FA-GE.

Electrochemical characterization of FA-GE

All performances of FA-GE for formaldehyde detection used the cyclic voltammetry (CV) technique; otherwise, it will be mentioned. The potential measurement was between 0 volt (V) and +1.8 V with a 100 millivolt per second (mV/s) scan rate. The effect of electrode modification using FA was studied by measuring 1 millimolar (mM) formaldehyde in 0.1 normality of hydrochloride acid (NHCl). Using GE, paraffin-modified gold electrodes (P-GE), and FA-GE, respectively. The effect of potential of hydrogen (pH) on the measurement was investigated by analyzing the same solution at pH values of 1,7 and 13. The effect of the scan rate was studied by measuring the same solution at various scan rates (50, 100, 150, 200, 250, 300, and 350/mVs). The concentration dependence was also studied by measuring various concentrations of formaldehyde solutions (0.1, 0.25, 0.50, 1, 1.5, 2.0, 2.5, and 3 mM). The selectivity of FA-GE was studied by individuals measuring methanol, ethanol, glucose, and glycerol solutions of 3 mM in 0.1 N HCl. Measurements were also taken for the mixtures of formaldehyde with methanol, ethanol, glucose, and glycerol. The repeatability of the electrode was performed by measuring 1 mM

of formaldehyde 3 times using a single electrode. Supplementary experiments were undertaken to investigate the performance of electrode fabrication by testing the same solution using 5 different FA-GEs. The performance of FA-GE was compared with the standard method (nash method) in real sample (fish) measurements with 3 samples repeated 3 times.

RESULTS AND DISCUSSION

Fabrication of FA-GE

The function of the paraffin in fabricating the electrode is as a binder. Given that paraffin exhibits non-conductive characteristics, it is preferable to use it sparingly in sensor-related applications. A potential drawback of minimizing binder content is the decreased fragility of the electrode. Table 1 illustrates the optimization of the paraffin ratio employed. It shows that the best ratio FA: Paraffin with the minimum paraffin is 6:4. At this ratio, the mixture of fish albumin and paraffin blends perfectly, forming a material that can solidify optimally in the electrode tube. This combination demonstrates excellent mechanical stability, guaranteeing that the material remains intact and does not dissolve or lose color when immersed in a solution. Consequently, this combination can be dependably utilized in electrode applications without undergoing considerable structural deterioration. An alternative ratio fails to create a solid structure, rendering it unsuitable for electrode use. This specific ratio is employed to fabricate electrodes for subsequent experiments.

The electrode surface was prepared by smoothing it with abrasive paper, rinsing it with deionized water, and then drying it at room temperature before use. The layer thickness has an important role in determining the sensitivity and detection limit, because it directly influences the electron transfer rate. Therefore, in the FA-GE fabrication process, efforts are made to

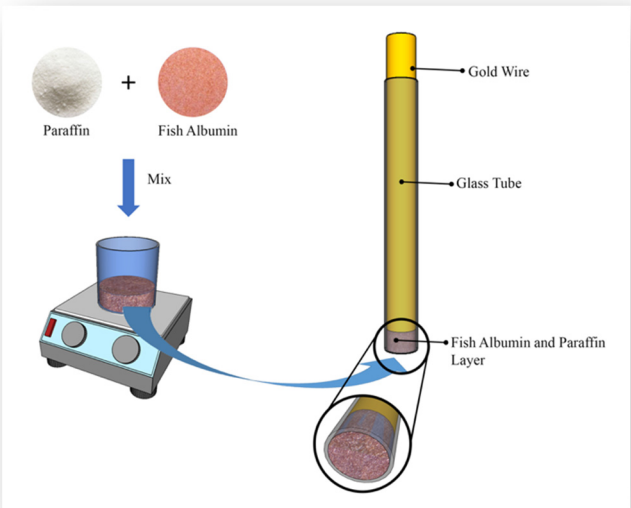

Fig. 1: The fabrication process of FA-GE

Table 1: Mass ratio FA and paraffin in FA-GE fabrication

FA	Paraffin	Solid form	Explanation
10	0	No	Non-homogeneous mixture
9	1	No	Non-homogeneous mixture
8	2	No	Non-homogeneous mixture
7	3	No	Non-homogeneous mixture
6	4	Yes	Homogeneous mixture

produce a very thin layer, around 0.2 mm, in order to optimize sensor performance. In Fig. 2, the electrode surface is depicted in two states: before coating (A) and after coating (B). The noticeable change in color between these two images confirms the successful application of the coating on the GE. This particular electrode is designated as FA-GE.

Electrochemical characterization of FA-GE

The effect of FA as an electrode modification

Fig. 3 shows the effect of FA modification on the GE using CV. GE voltammogram (green) has no response to formaldehyde. In comparison to formaldehyde, the blank (dashed) demonstrated a higher peak oxidation current. A similar condition was also shown

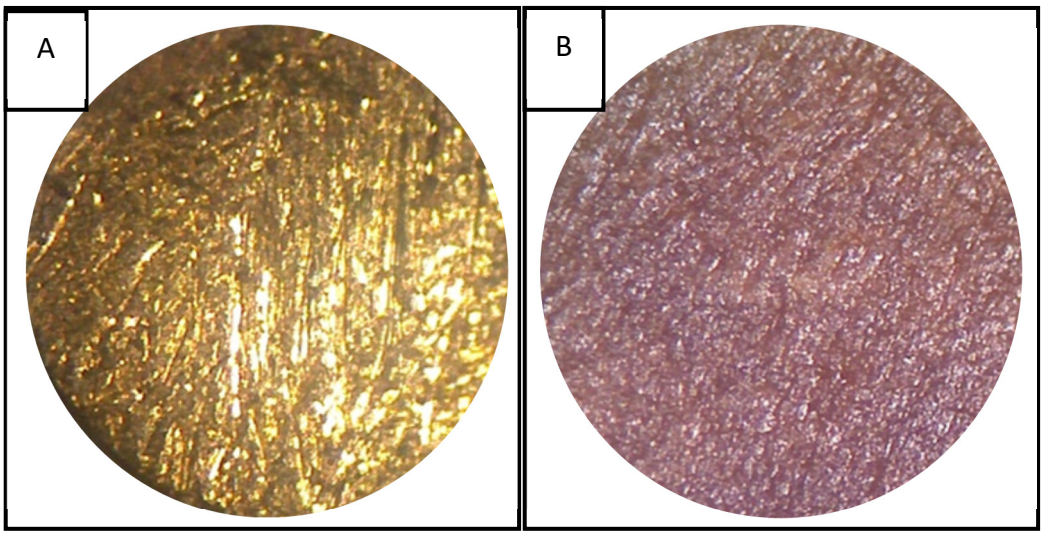

Fig. 2: The electrode surface image before (A) and after (B) coating a mixture of FA and paraffin (Magnification 45X)

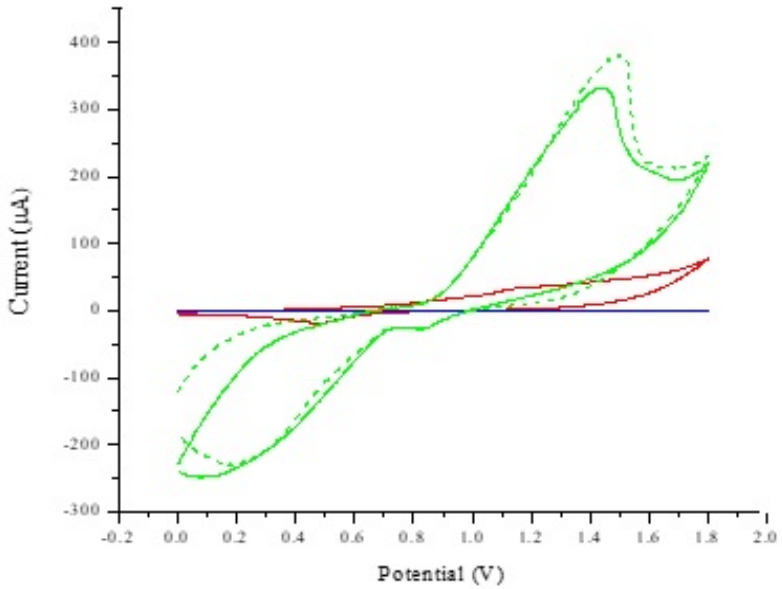

Fig. 3: Cyclic voltammogram of GE (green), P-GE (blue), and FA-GE (red) at 1 mM formaldehyde in 0.1 N HCl (solid line) and blank (dashes line)

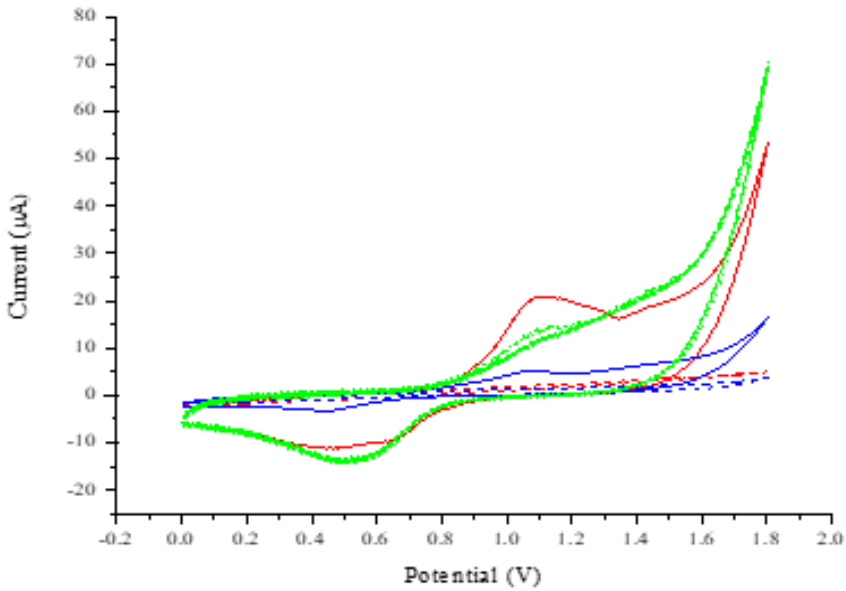

Fig. 4: Cyclic voltammogram of FA-GE to blank (dashed line) and 1 mM Formaldehyde (solid line) in pH 1 (red), pH 7 (blue), and pH 13 (green).

for P-GE (blue), which did not show any response to formaldehyde at all because paraffin is a non-conductive compound that functions as a binder in this experiment. Concurrently, FA-GE (red) exhibits a remarkable response to solid formaldehyde, highlighted by a current peak, but does not respond to the blank (dashed) (inset). The oxidation current peak is at a potential of +1.13V, and the reduction current peak is at a potential of +0.79 V. So, it can be concluded that FA is electrochemically active toward formaldehyde.

The effect of pH measurement

Fig. 4 shows 1 mM of formaldehyde by FA-GE in various pH measurements. The electrode shows no response against formaldehyde at pH 13 (green) because the blank voltammogram (dash line) overlaps with the formaldehyde voltammogram (solid line). This suggests that at this pH, formaldehyde does not undergo any oxidation or reduction reactions. On the other hand, there is a different response between the blank voltammogram (dash line) and a formaldehyde voltammogram (solid line) to formaldehyde at pH 7 (blue) and pH 1 (red), but the oxidation and The findings indicate that FA-GE exhibits optimal performance against formaldehyde at a pH of 1. The abundance of H^+ ions is likely instrumental in catalyzing the electrooxidation reaction. Consequently, pH 1 will be utilized in future experimental procedures.

The effect of scan rate

The voltammograms of 1 mM formaldehyde by FA-GE at various scan rates (50 – 350 mV/s) were shown in Fig. 5A. The current peak increases along with the scan rate using Randles-Sevcik Eq. 1 (Lee *et al*., 2024):

$$ip = (2.69\times105)\, n^{3/2} AC\, D^{1/2} v^{1/2} \quad (1)$$

Where, ip is the peak current, n is the number of electrons, A is the electrode area, C is the concentration, D is the diffusion coefficient, and v is the potential scan rate. Fig. 5B shows that the peak current for the anodic oxidation is proportional to the square root of the scan rate with the linear regression equation anodic peak current (Ipa) (microampere (μA)) = 6.967x + 37.355 (R^2 = 0.9925). A corresponding calculation has likewise been executed for the cathodic current. Fig. 5C shows that the peak current for the cathodic reduction is proportional to the square root of the scan rate with the linear regression equation cathodic peak current (Ipc) (μA) = -3.9959x + 21.114 (R^2 = 0.9916. The results indicated that the process that occurred at the electrodes was diffusion-controlled. The analysis revealed that the

Fig. 5:

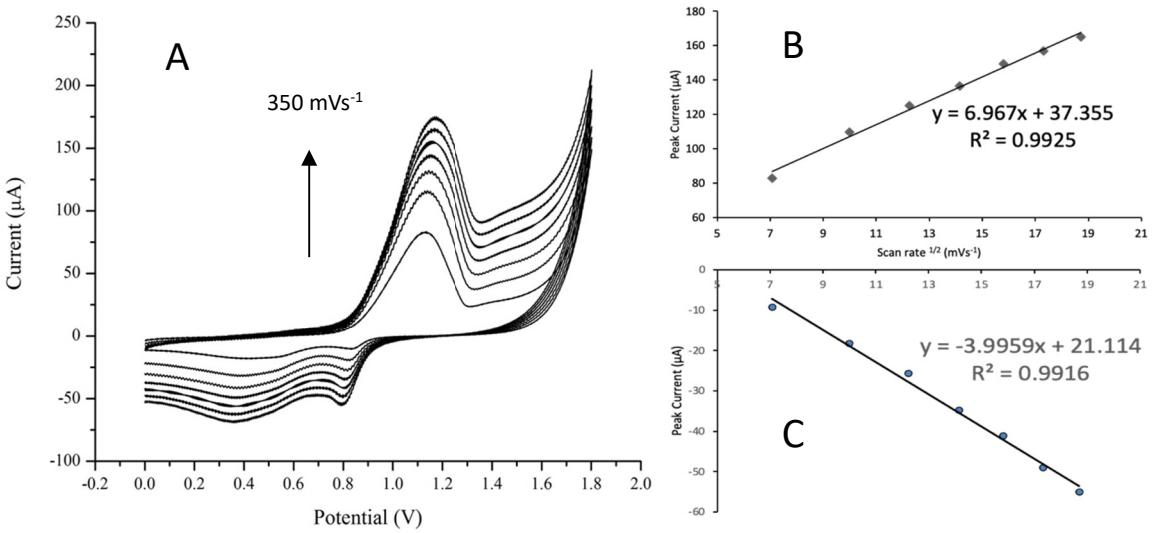

Fig. 5: Voltammograms of 1 mM Formaldehyde on FA-GE with scan rates 50, 100, 150, 200, 250, 300, and 350 mV/s (A). The plot of peak anodic current at +1.13 V vs. Square root of the scan rate (B). The plot of peak/ cathodic current at +0.79 V vs. Square root of the scan rate (C).

mechanisms at the electrodes were predominantly controlled by diffusion processes. Eq. 2 presents the reaction mechanism, highlighting the various reactions that may occur on the FA-GE surface (Wei *et al*., 2024):

$$CH_2O \rightleftarrows CH_2O_2 \quad (2)$$

This reaction represents a reversible oxidation-reduction process of formaldehyde. During this process, formaldehyde is oxidized to generate formic acid, which can then be reduced back to its original form, formaldehyde.

Calibration Curve for formaldehyde detection using FA-GE

Fig. 6A is a voltammogram of formaldehyde using FA-GE in various concentrations ranging from 0.1 to 3 mM. It is evident that as the concentration of formaldehyde increases, the anodic current peak also shows an upward trend. It shows the Ipa at +1.13 V and the Ipc at +0.79 V. Both Ipa and Ipc provide a linear relationship but with the opposite direction to the increase in concentration. It gives a linear equation of i = 15.987c + 7.3901 for the anodic current with R^2 = 0.9984 (Fig. 6B) and i = -5.5115c - 3.1776 for the cathodic current with R^2 = 0.9939 (Fig. 6C). While both can be utilized for quantitative analysis, the oxidation current offers enhanced sensitivity over the reduction current. The sensitivity of the oxidation and reduction currents is 20.365 microampere millimolar per square millimeter (µA mM/mm²) and 7.021 µA mM/mm², respectively.

The LOD calculation in this report uses the formula 3σ/m, where m is the slope of the line, and σ is the blank standard deviation for five measurements. The levels of detection for the oxidation and reduction currents are recorded at 4.07 µM and 15.14 µM, respectively. The performance of FA-GE compared to other electrodes can be found in Table 2. The detection limits established in this study are the most minimal in relation to the other electrodes evaluated.

Selectivity, repeatability, and reproducibility

The voltammograms depicted in Fig. 7 represent various compounds that may exist in the sample when assessing formaldehyde through FA-GE. The identified compounds are methanol, ethanol, glycerol, and glucose (Nurlely *et al*., 2021; Teišerskytė *et al*., 2021). The voltammograms of ethanol, glycerol, and glucose show no interference against formaldehyde. Simultaneously, the capacitive current response recorded for methanol measurements was significantly high. The relatively high capacitive current response recorded for the methanol measurement reflects the interaction between the

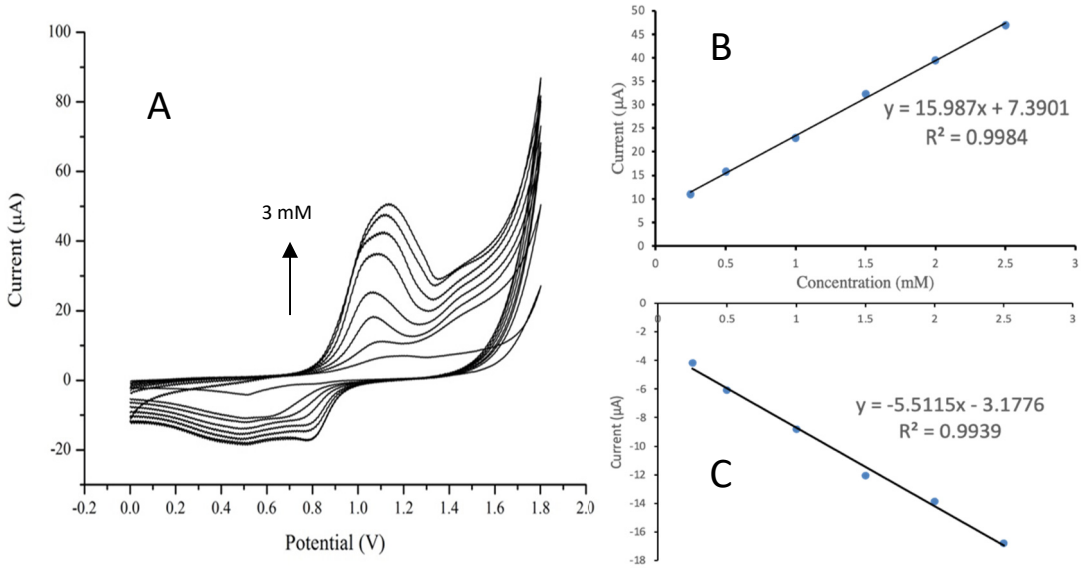

Fig. 6: Cyclic voltammogram of FA-GE in various formaldehyde concentrations (0.1–3 mM) in HCl 0.1 N (A). The calibration curve for anodic current at +1.13 V (B). The calibration curve for cathodic current at +0.79 V (C)

Table 2: Performance of selected electrodes to formaldehyde determination

Measurement technique	Electrodes	Range concentrations (mM)	LOD (µM)	Sensitivity (µA mM/cm^2)	Sources
Chronoampero metric	CuO/Cu/TNAs	0.065 – 7.80	25	814.0	Zhang *et al.*, 2020
Linear sweep voltammetry	Ni(OH)2/rGO/GCE	0.1– 100	60	47.53	Li *et al.*, 2022
CV	CuO/Cu_2O/CILE	0.1 – 110	10	186.0	Momeni and Sedaghati, 2018
CV	GPE/ZnO NPs	0 – 100	18	281.69	Wicaksono *et al.*, 2022
CV	FA-GE	0.1 – 3	4.07	2036.5	The current study

electrode surface and methanol molecules in the solution, resulting in a current increase that does not involve a distinct electrochemical reaction. However, the absence of an oxidation peak at a potential of +1.13 V and a reduction peak at a potential of +0.79 V indicates that a significant electron transfer process does not occur in this potential range. The underlying causes of this phenomenon may include the electrode's lack of capability to catalyze the methanol oxidation-reduction reaction, the presence of a substantial kinetic barrier, or electrolyte conditions that do not facilitate optimal electrochemical reactions. In addition, the interaction between methanol and the electrode may be more adsorptive than electrocatalytic, resulting in a dominant capacitive current compared to the faradaic current expected in oxidation and reduction processes. Analyzing formaldehyde mixtures with all conceivable interference compounds can help clarify their influence.

The current peaks of individual compounds and formaldehyde mixtures, as determined by FA-GE, are depicted in Fig. 8. The peak anodic current value was measured at a potential of +1.13V (Fig. 8A), and the

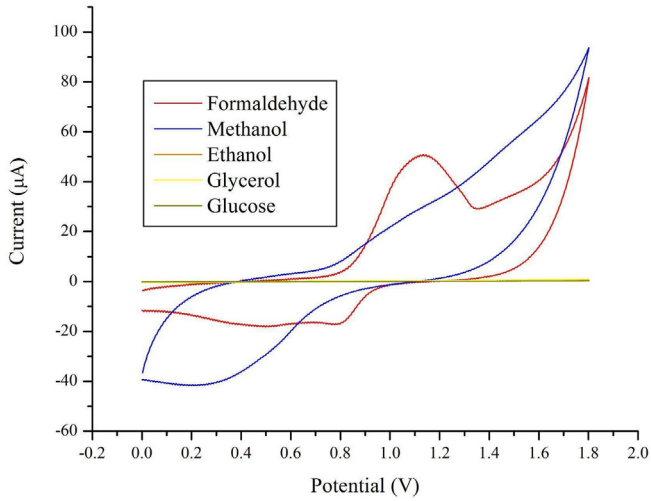

Fig. 7: Cyclic voltammogram of various compounds (3 mM in 0.1 N HCl) using FA-GE

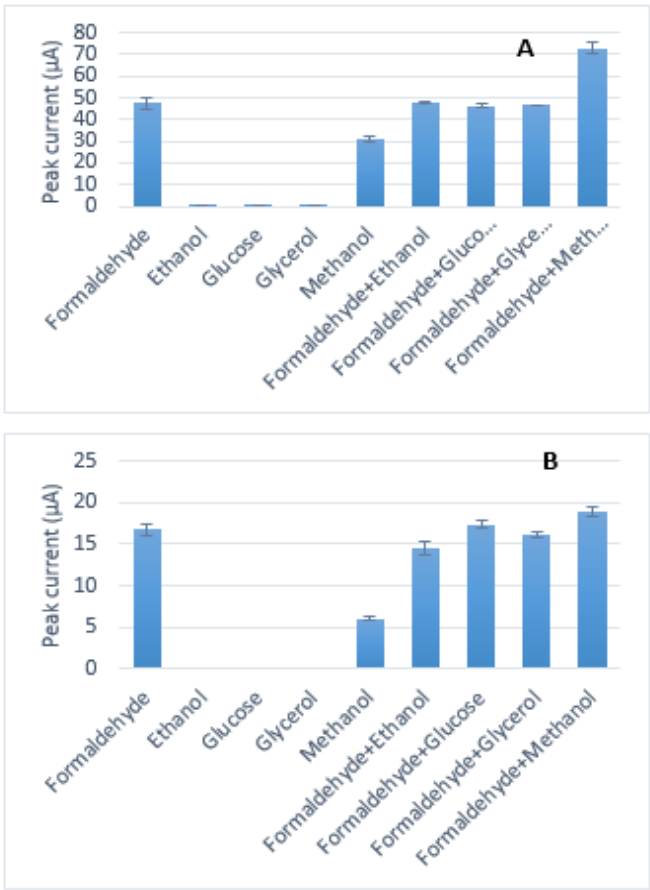

Fig. 8: Oxidation peak current (A) and reduction peak current (B) of various compounds And formaldehyde mixtures (3 mM in 0.1 N HCl) by FA-GE

cathodic current was measured at +0.79V (Fig. 8B). Aside from the methanol mixture, formaldehyde measurements at the anode current are largely unaffected by significant interference, while no such interference is noted at the cathode current. The mixture of methanol-formaldehyde shows a current that was not significantly different from the formaldehyde current alone at the cathodic current. This implies that the assessment of formaldehyde is devoid of interference. Therefore, it was concluded that FA-GE displays significant selectivity towards formaldehyde.

Using FA-GE, 1 mM Formaldehyde was measured 3 times, each repeated 5 times. The result is presented in Table 3. The analysis of variance (ANOVA) single-factor test is conducted at a 95% confidence level utilizing Microsoft Excel. The F-value of the calculation is lower than the F critical value, meaning no significant difference in variance between measurements. The calculated least square difference (LSD) stands at 1.44169, which signifies that there are no substantial differences among the measurements. This finding confirms that the electrode has a high level of repeatability.

Additionally, five separate electrodes were utilized to evaluate 1 mM formaldehyde, with each electrode conducting five measurements. The results obtained are presented in Table 4. Analogous calculations are utilized to evaluate the effectiveness of the electrodes. The F value is lower than the F critical value, meaning no significant difference variance between electrodes. Moreover, the LSD value is greater than the disparity between the maximum and minimum average values of the measurements, suggesting that there is no notable difference in the readings from the electrodes. Therefore, it can be concluded that the reproducibility fabrication of the electrodes is good.

Performance FA-GE versus UV-Vis spectrophotometric Nash method for real sample measurement

The method used in this work was compared to the standard method. The standard procedure for assessing formaldehyde concentration in samples is primarily based on the UV-Vis spectrophotometry technique (Qian *et al*., 2023). Formaldehyde content in real samples (fish) was measured using FA-GE and Nash methods. The result is shown in Table 5. The

Table 3: Peak current 1 mM Formaldehyde measurement using one FA-GE

Number of cyclic	Current at +1.13 V (µA)		
	First Measurement	Second Measurement	Third Measurement
1	32.2357	33.08165	33.08592
2	31.97299	31.91104	33.11371
3	33.76954	31.48803	32.2357
4	30.28746	31.15476	31.55215
5	30.56305	32.17165	31.19326
Mean	31.76575	31.96143	32.23615
F value	0.25507		
F critical value	3.88529		
LSD	1.44169		

Table 4: Peak current 1 mM formaldehyde measurement using five FA-GE

Measurement	FA-GE				
	1	2	3	4	5
1	35.7086	34.2529	34.0576	34.6375	34.6802
2	31.1707	32.6874	32.8827	31.4209	33.0231
3	30.1758	31.1310	32.0984	30.3375	32.4615
4	30.1575	30.0079	28.2440	29.4739	31.1798
5	29.8950	28.8055	27.2491	28.7415	29.3518
Mean	31.4215	31.3769	30.9064	30.9223	32.1393
F value	0.21838				
F critical value	2.86608				
LSD	3.16980				

Table 5: Performance of FA-GE and Nash method for determining formaldehyde content in fish samples

Sample	Method	The concentration of formaldehyde (mg/L)	t value
Fish	Nash method	3.97 ± 0.098	1.47
	FA-GE	4.21 ± 0.180	

t-critical value = 4.303 (P = 0.05)

mean of the two methods is calculated using the t-test: paired two samples for mean using Microsoft Excel at P = 0.05. Since the t value derived is below the critical t value, it suggests that there is no significant difference observed for both electrodes. This indicates that FA-GE can be used as an alternative method for formaldehyde analysis in place of the Nash Method. Compared to the Nash method, FA-GE presents various advantages, notably in efficiency, affordability, and simplicity of use. FA-GE is more economical because it does not require complex or expensive reagents, so it can reduce operational costs in the long term. Moreover, this method allows for a more efficient measurement process and does not involve elaborate sample preparation, making it more accessible for users to perform analyses. In terms of speed, FA-GE allows the detection of formaldehyde in a shorter time than the Nash method, which usually requires an additional chemical reaction step before measurements are made. One of the key advantages is the versatility of FA-GE-based sensors in field applications. They can function without the requirement for bulky laboratory equipment, thereby increasing their practicality for monitoring in a variety of environmental conditions.

CONCLUSION

A novel FA-GE has been developed for formaldehyde detection, utilizing FA that contains amino acids, such as glycine, lysine, and histidine, which react with formaldehyde. This cutting-edge sensor reveals remarkable sensitivity and low detection limits in acidic settings, exhibiting significant formaldehyde signals compared to alkaline and neutral environments. The FA-GE electrode showed a linear detection range of 0.1 to 3 mM, with a detection limit of 4.07 µM and a sensitivity of 20.365 µA mM^{-1} mm^{-2}. The application of this method to fish samples yielded results that were on par with the traditional Nash method, while also providing the benefit of eliminating the need for additional reagents. Albumin, a versatile protein found in various organisms, including humans, plants, and animals, has diverse applications in fields such as drug delivery, wound healing, corrosion inhibition, and sensor technology. The potential of FA from *Channa striata* as a sensor material has been explored in this study, leading to the fabrication of the FA-GE by immobilizing fish albumin on a gold electrode. Demonstrating effectiveness in acidic conditions, this electrochemical sensor offers a viable alternative for the detection of formaldehyde, with significant applications in food safety and environmental monitoring. Formaldehyde sensors find significant applications in various important fields. Within the food industry, these techniques are implemented to assess and ensure the safety of food products, effectively preventing the unauthorized use of formaldehyde for preservation purposes. In the environmental sector, these sensors help monitor formaldehyde levels in air and water, contributing to pollution control and public health safety. Furthermore, in industrial environment, the use of formaldehyde sensors is essential for ensuring safety standards are met by continuously monitoring formaldehyde emissions from production activities, which helps protect employees from the risks associated with this toxic chemical. These versatile applications highlight the critical role of formaldehyde sensors in ensuring safety and compliance across different industries. Furthermore, in the ecological field, formaldehyde sensors are vital for assessing the impact of formaldehyde pollution on ecosystems. The detection and monitoring of formaldehyde levels in natural habitats by these sensors facilitate the identification of pollution sources and the assessment of mitigation strategies, thereby contributing to the safeguarding of biodiversity and the stability of ecological systems.

AUTHOR CONTRIBUTIONS

T.P.H. Hutapea conducted the literature review, designed the experiments, analyzed and interpreted the data, and prepared and edited the manuscript. Suprapto carried out the experiments and literature review, compiled the data, and contributed to manuscript preparation. M.Y. Syahputra assisted with

manuscript preparation and project administration. F. Kurniawan conducted the literature review, designed the experiments, analyzed and interpreted the data, and prepared and edited the manuscript.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Percent
^0C	Degrees Celsius
µA	Microamprere
µA mM/mm^2	Microampere millimolar per square millimeter
µM	Micromolar
Ag/AgCl	silver/silver chloride
ANOVA	Analysis of variance
BSA	Bovine serum albumin
cm	Centimeter
CV	Cyclic voltammetry
FA	Fish albumin
FA-GE	Fish albumin-modified gold electrodes
GE	Gold electrodes
HSA	Human serum albumin
HCl	Hydrochloride acid
Ipa	Anodic peak current
Ipc	Cathodic peak current
KCl	Potassium chloride
LOD	Limit of detection
LSD	Least square different
M	Molar
mm	Millimeter
mM	Millimolar
mV/s	Millivolt per second
N	Normality
nm	Nanometer
OVA	Ovalbumin
P-GE	Paraffin-modified gold electrodes
pH	Potential of hydrogen
V	Volt

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AUTHOR (S) BIOSKETCHES

Hutapea, T.P.H., Ph.D., Assistant Professor, Fisheries Product Technology Department, Faculty of Fishery and Marine Science, University of Borneo Tarakan, North Borneo, Indonesia.
▪ Email: *hutapea@borneo.ac.id*
▪ ORCID: 0000-0003-0154-2680
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57194337088
▪ Homepage: https://www.ubt.ac.id/fakultas/fakultas-perikanan-dan-ilmu-kelautan/program-studi-teknologi-hasil-perikanan/

Suprapto, Ph.D., Associate Professor, Chemistry Department, Institute Teknologi Sepuluh Nopember, Surabaya, East Java, Indonesia.
▪ Email: *suprapto@chem.its.ac.id*
▪ ORCID: 0000-0002-1490-0726
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 55626183800
▪ Homepage: https://scholar.its.ac.id/en/persons/suprapto-2

Syahputra, M.Y., [1]Ph.D. Candidate, Saga University Japan. [2]Chemistry Department, Institut Teknologi Sepuluh Nopember, Surabaya, East Java 60111 Indonesia.
▪ Email: *23808291@edu.cc.saga-u.ac.jp*
▪ ORCID: 0000-0003-6232-839X
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57190936674
▪ Homepage: https://www.bioelectrochem.chem.saga-u.ac.jp/en/member

Kurniawan, F., Ph.D. Professor, Chemistry Department, Institute Teknologi Sepuluh Nopember, Surabaya, East Java, Indonesia.
▪ Email: *fredy@its.ac.id*
▪ ORCID: 0000-0002-9777-0989
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 25627866400
▪ Homepage: https://scholar.its.ac.id/en/persons/fredy-kurniawan

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