UNIVERSITI PUTRA MALAYSIA

A COLORIMETRIC ASSAY TO DETECT MERCURY (II) IONS IN WATER SOURCES USING CONJUGATED GOLD-NANOPARTICLES

NURFATINI IDAYU BINTI BUSAIRI

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By

NURFATINI IDAYU BINTI BUSAIRI

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A COLORIMETRIC ASSAY TO DETECT MERCURY (II) IONS IN WATER SOURCES USING CONJUGATED GOLD-NANOPARTICLES

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Chairman: Amir Syahir bin Amir Hamzah, PhD
Faculty: Biotechnology and Science Biomolecules

Rapid industrial progress has led to the elevation of heavy metal concentration in the environment, which raised tacit concerns. Among these metals, mercury (II) ion, Hg^{2+} is one of the most detrimental to the human health due to its neurotoxic and nephrotoxic properties. To date, methods to determine the presence of Hg^{2+} ions require expensive equipment and sophisticated operation. This is impractical for a constant monitoring of Hg^{2+} in water sources. Thus, it is necessary to develop a simple yet effective bio sensing method to monitor Hg^{2+} level in our environment. Recently, gold-nanoparticles (AuNPs) have attracted considerable amount of attention due to their nature of strong plasmonic resonance which can be exploited for a simple and rapid colorimetric assay. As the distance between nanoparticles decreases, the plasmon energy band is lowered and consequently it turns the colour of AuNPs from red to blue. The key of utilizing this phenomenon as a bio sensing mechanism is to control the AuNPs aggregation via surface chemistry approach. Here, a sensitive and practical colorimetric assay for *in-situ* detection of Hg^{2+} ions in water using cysteine functionalized gold nanoparticles (Cys-AuNPs) together with the addition of polyamidoamine (PAMAM), G2 dendrimer is reported. In this study, Cys-AuNPs and PAMAM dendrimer specifically capture Hg^{2+} ions and induce colour changes of the solution. The mechanism of Hg^{2+} interaction with the system was investigated using UV-vis spectrophotometer, dynamic light scattering (DLS) and transmission electron microscope (TEM). To increase the practicality value of the system, a custom-made chamber to be integrated with a mobile phone was fabricated. Colour changes can be monitored using a mobile app. The newly developed detection system can detect Hg^{2+} as low as 0.5 part per billion (ppb) in a laboratory prepared sample or in a real river water sample. The results were validated using direct thermal decomposition mercury analyser. This cost-effective colorimetric approach is practical to determine the presence of Hg^{2+} water sources.

Abstrak tesis yang dikemukakan kepada Senat of Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

KOLORIMETRIK ASSAY UNTUK MENGESAN MERKURI (II) ION DALAM SUMBER AIR MENGGUNAKAN KONJUGAT EMAS NANOPARTIKEL

Oleh

NURFATINI IDAYU BINTI BUSAIRI

April 2018

Pengerusi: Amir Syahir Bin Amir Hamzah, PhD
Fakulti: Bioteknologi dan Sains Biomolekul

Kemajuan industri yang pesat telah menyebabkan peningkatan kepekatan logam berat dalam alam sekitar, yang menimbulkan kebimbangan. Di antara logam-logam ini, ion Hg^{2+} adalah salah satu daripada ion logam yang membahayakan kesihatan manusia akibat sifat neurotoksik dan nefrotoksiknya. Sehingga kini, kaedah untuk menentukan kehadiran ion Hg^{2+} memerlukan peralatan mahal dan operasi yang canggih. Ini tidak praktikal untuk pemantauan berterusan Hg^{2+} dalam sumber air. Oleh itu, pembangunkan kaedah yang mudah tetapi berkesan adalah perlu untuk memantau tahap logam berat di persekitaran kita. Baru-baru ini, emas-nanopartikel (AuNPs) telah menarik banyak perhatian kerana sifat resonans plasmoniknya yang kuat yang boleh dieksploitasi untuk pengujian warna yang mudah dan cepat. Apabila jarak antara nanopartikel berkurangan, kumpulan plasmon emas-nanopartikel akan beralih dan seterusnya mengubah warna AuNPs dari merah ke biru. Fenomena ini boleh digunakan sebagai mekanisme penderiaan dengan cara mengawal pengagregatan AuNPs melalui pendekatan kimia permukaan. Di sini dilaporkan ujian kolorimetric yang sensitif dan praktikal untuk pengesanan in-situ ion Hg^{2+} dalam air menggunakan cystiene-nanopartikel emas (Cys-AuNPs) bersama dendrimer polyamidoamine (PAMAM). Dalam kajian ini, dendrimer Cys-AuNPs dan PAMAM secara khusus akan menangkap Hg^{2+} dan mendorong perubahan warna koloid. Mekanisme interaksi Hg^{2+} dengan sistem ini disiasat menggunakan spektrofotometer UV-vis, penyebaran cahaya dinamik (DLS) dan mikroskop pengaliran elektron (TEM). Untuk meningkatkan nilai praktikal sistem, kotak kedap cahaya telah dibina untuk disepadukan dengan telefon bimbit bagi tujuan analisis in-situ. Oleh itu, perubahan warna boleh diiktiraf menggunakan aplikasi mudah alih. Sistem pengesanan yang baru dibangunkan dapat mengesan Hg^{2+} serendah 0.5 bahagian per bilion (ppb) dalam sampel yang disediakan atau dalam sampel air sungai sebenar dan disahkan menggunakan penganalisis merkuri penguraian haba langsung. Pendekatan kolorimetrik yang kos efektif adalah praktikal untuk menentukan kehadiran Hg^{2+} dalam sumber air.

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". And put thy trust in Allah and enough is Allah as a disposer of affairs." [33:3]

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Amir Syahir Bin Amir Hamzah, PhD
Senior Lecturer
Faculty of Biotechnology and Biomolecular Science
Universiti Putra Malaysia
(Chairman)

Abu Bakar Bin Salleh, PhD
Professor
Enzyme Technology, Faculty of Biotechnology and Biomolecular Science
Universiti Putra Malaysia
(Member)

Asilah Binti Ahmad Tajudin, PhD
Senior Lecturer
Faculty of Biotechnology and Biomolecular Science
Universiti Putra Malaysia
(Member)

_____
ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

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Name of Member of Supervisory Committee: _____

Signature: _____
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LIST OF ABREVIATIONS

%	Percent
°C	Degree Celcius
et al,.	And friends
Ag	Silver
As	Arsenic
AuNPs	Gold-nanoparticles
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
Cys-AuNPs	Cysteine-gold nanoparticles
DLS	Dynamic light scattering
g	Gram
Hg	Mercury
M	Molar
mg	Milligram
mL	Milliliter
µL	Microlitre
mM	Millimolar
µM	Micromolar
Ni	Nickel
PAMAM	Polyamidoamine
Pb	Lead
ppb	Part per billion
Ppm	Part per million
POC	Point of care
Ps	Picoseconds
TEM	Transmission electron microscope
Zn	Zinc

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Mercury is classified as heavy metals and regarded as one of the most toxic metals by many international agencies due to its persistence, bioaccumulation, and toxicity (PBT). It is a non-transition metal and exists in three main form; elemental mercury (Hg^0), organic mercury (methylmercury, CH_3Hg & ethyl mercury, C_2H_5Hg) and inorganic mercury (Hg^+, Hg^{2+}). These three forms possess different toxicity and health's implication. Generally, inorganic mercury has a high toxicity level compared to the other two forms. Mercury is known for its neurotoxic and nephrotoxic properties. It can cause neurological and behavioural disorder (Liu et al., 2013) and permanent damage to the kidney and digestive system. Exposure to mercury as low as 0.01 ppm either through breast milk or through water sources, can cause early childhood neurocognitive effects towards babies and toddlers (Karagas et al., 2012). Inorganic mercury exposure can also impaired children's immune system which eventually makes the children susceptible to infections. (Mutter and Yeter, 2008).

Elemental mercury (Hg^0), exist in a form of volatile liquid which can lead to a prolong anthropogenic release since it can remain suspended in the atmosphere for a one or two year long (Eckley et al., 2012; Eckley et al., 2015). Hg^0 can be oxidized to its inorganic form Hg^+ or Hg^{2+} and will be deposited into soil or water sources through the rain. Industrial release such as waste from incinerators, coal-burning power plant and gold mining industry can also be the sources of the inorganic mercury. In the water sources, inorganic mercury will be methylated by aquatic anaerobic sulfate-reducing bacteria to become methylmercury (MeHg). This methylmercury (MeHg) will then be ingested by fish, shellfish and other aquatic life and accumulated as it goes up the food chain.

Due to increasing industrial and mining activity globally, we are now facing a silent threat from mercury contamination. Human exposure to mercury can occur via eating MeHg-contaminated food (fish, shellfish, and other aquatic life), dental amalgam procedure, usage of inorganic mercury products (medication, germicidal soap and skin cream), occupational exposure (mining or mercury-related industry) and usage of any other mercury-based products (thermometer, sphygmomanometer, fluorescent light bulbs and batteries).

The United Nations Environmental Programme (UNEP) and the Arctic Monitoring and Assessment Programme (AMAP), estimated anthropogenic mercury emissions globally in 2010 to about 1960 tonnes·year^{-1} with an uncertainty range of 1010–4070 tonnes·year^{-1}. Artisanal and small-scale gold mining (ASGM) were identified as the major anthropogenic sources (37%) and the dental amalgam emitted through cremation

were identified as the minor anthropogenic sources (0.2%) (United Nations Environment Programme, Global Mercury Assessment, 2013). Figure below shows a mercury emission percentage based on different sources of emission.

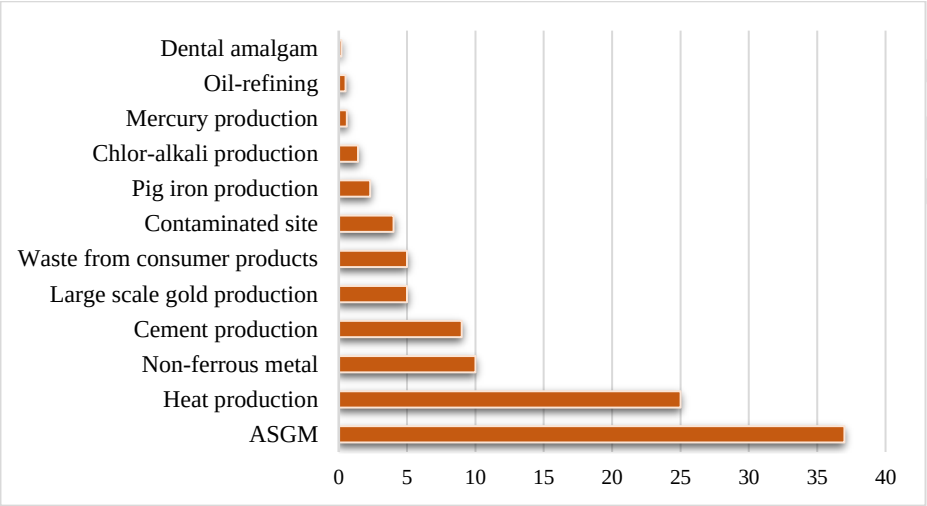

Figure 1.1: Mercury Emission Percentage Based on Different Sources of Emission. Artisanal and small-scale gold mining (ASGM) were identified as the major anthropogenic sources (37%) and the dental amalgam emitted through cremation were identified as the minor anthropogenic sources (0.2%).

There are several cases worth mentioning to show that contaminated water is one of the main sources where mercury contamination could affect most lives. Water sources are the reservoir where all the inorganic mercury would reside before it will be methylated and would be magnified in the higher organism hierarchy as it passes up a food chain. In general population, dietary intake is the most common pathway for mercury contamination. The classic case of Minamata Bay Japan, in 1953 witnessed 2252 victims poisoned with MeHg (5.61ppm to 35.7 ppm) in their marine product (Harada, 1995). In 1964, the similar case has happened in Niigata with approximately 700 victims through the same exposure of the contaminated marine products (Maruyama et al., 2012). In 2006, China faced a threat from mercury pollution due to their mining and coal-burning industry. National Bureau of Oceanography (NBO) of China stated that there is approximately 77 ton of Hg were released into the coastal area through river annually (Jiang et al., 2006; Li et al., 2009).

1.2 Problem Statement

Due to the increasing amount of mercury release to the environment through anthropogenic activities and the alarming health risk of mercury consumption, monitoring it becoming an important yet challenging task to the authorities. In most

cases, mercury contamination in fish can be contained or intervened if authorities are able to constantly monitor the mercury level in water sources, for fast prevention or remediation action to be taken.

There are several detection techniques that have been developed and commercially available to detect mercury in water sources including, atomic absorption spectrometry (AAS) (Bannon and Chisolm, 2001; Fang et al., 1984; Maquieira and Elmahadi, 1994), Synchroton X-ray fluorescence spectrometry (SXRF) spectrometry (Arai et al., 2003), microwave plasma atomic emission spectroscopy (MP-AES) (Poirier et al., 2017; Rios et al., 2017), inductively coupled plasma mass spectrometry (ICP-MS) (Shih et al., 2016; Yamakawa et al., 2017), cold vapor atomic fluorescence spectrometry (CVASF) (Ebdon et al., 2002) and thermal decomposition mercury analyser (TDMA) (Sasamoto et al., 2017). These techniques provide sensitive and accurate result in determining the level of heavy metal in the environment. However, these techniques require expensive instruments, sophisticated method and time-consuming procedure which make them less mobile and certainly non-practical to be used as *in-situ* analytical tools for frequent monitoring (Zhong et.al, 2015 and Xia et.al, 2012). These limitations lead to the needs of developing a simple yet effective technique as a first line screening to detect mercury ions in water sources.

The goal of this research is to overcome limitations of the current methods through biosensor technique. Biosensor is a device that uses biologically based element including cells, proteins, enzymes, nucleic acids or small molecules to detect the presence of targeted compound; in this case, Hg^{2+}. Biosensor can be divided into several types such as electrochemical, thermometric, potentiometric and colorimetric assay. A simple colorimetric assay that can be detected via naked eye is beneficial for *in-situ* analysis since it will provide rapid measurement, generally simple and most importantly, it can be portable (Liu and Lu, 2003; Zhao et al., 2008; Wang et al., 2012).

In a colorimetric assay, there are several colouring agents that are commonly used which are, enzymes (Kaur et.al, 2014), 4-aminoantipyrine (Kim *et.al*, 2015), Prussian Blue (Zhai *et al*, 2013), redox enzyme horseradish peroxide (HRP) (Han *et.al*, 2001) and gold-nanoparticles. Recently, gold nanoparticles as colorimetric assay agent have been widely used for heavy metal detection in aqueous solution (Wang& Ma, 2009).Gold nanoparticles (AuNPs) possess an exploitable plasmonic property that can be manipulated via surface functionalization (Knech & Sethi, 2009). It has high extinction coefficient which makes it suitable to act as a sensing platform (Aragay et al., 2011; Guo et al., 2011) As the distance between particles decreases below 4 nm, plasmon coupling will decrease the plasmon-band energy level results in a change of absorption maxima of AuNP solution that consequently can change the colour of colution from red to blue colour; namely a red shift (Ghosh & Pal, 2007). This is the phenomenon where the absorption peak of the AuNPs, shifts towards the infrared region. Using a bare AuNP will allow the detection of approximately 5 ppm for almost all metal ion. Hence, it requires some surface modifications for it to be more selective and more sensitive towards targeted compound. This is often accomplished using aptamer, DNA or protein (Aragay et al., 2011). Hence, it is a promising approach to enhance the selectivity and sensitivity of the AuNP.

Mercury contamination in Malaysia is a raising concern among authorities. Even though there is no big mercury spillage case Malaysia, but according to Praveena et al (2013), the concentration of mercury in Malaysia water sources specifically in Terengganu, Johor, and Penang is above the permissible limit set by WHO and Department of Environmental of Malaysia (DOE). The current trends demand a development of a cheap, simple, yet sensitive bio sensor method to be used for a constant monitoring of mercury in more than 1000 monitoring points of the Malaysia rivers. These monitoring points are currently being observed by the Department of Environmental of Malaysia quarterly.

To the best of our knowledge, there are only a few studies on using colorimetric assay through bio-conjugated gold nanoparticles to detect inorganic mercury in water sources. There are still problems related to sensitivity as they cannot achieve the sensitivity limit set by World Health Organization (WHO) which is at 0.001 (mg/L) or ppm level. Some study did not provide field study data for *in-situ* analysis of real samples and make it hard for us to see if it can be practical for monitoring mercury (II) ions (Hg^{2+}) in water sources. Therefore, this research comes to fill in the gap and limitations stated above.

1.3 Objectives

The main objective of this study is to build the sensor system where it can detect Hg^{2+} down to at least 1 µg/L (ppb) level to match the WHO permissible limit of mercury in water sources. This objective can be achieved through sub-objective listed below:

1. To conjugate gold-nanoparticles with several groups of compounds to search for the best capturing agent for Hg^{2+}.

2. To fabricate and build a mobile detection system for a practical *in-situ* analysis.

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