MJFAS
Malaysian Journal of Fundamental and Applied Sciences

Nazir *et al.* | Malaysian Journal of Fundamental and Applied Sciences, Vol. 22 (2026) 355–363

RESEARCH ARTICLE

Methacrylate-Functionalised Porphyrin for Photo-Polymerised Fluorescent Films in Pb(II) Ion Detection

Siti Nur Nasiha Nazir, Fuad Mohamad

Department of Chemistry, Faculty of Science, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Abstract Herein, 5,10,15,20-tetrakis(4-hydroxyphenyl)-21H,23H-porphine (TPP-$(OH)_4$) was functionalised with methacrylate group to convert it to a crosslinker (TPP-M) which later was used in photo-polymerisation alongside acrylamide. TPP-M obtained was characterised using proton nuclear magnetic resonance (^{1}H-NMR), Fourier-Transform infrared (FTIR), ultraviolet-visible (UV-Vis) and fluorescence spectroscopy. The ability of TPP-M to detect Pb(II) ions was tested, and the resulted spectrum showed the reduced fluorescence intensity upon addition of Pb(II) ions. Then, the TPP-M was made into a polymer film through photo-polymerisation using UV light as a light source and diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO) as a photo-initiator. The film obtained was tested for Pb(II) ion detection using fluorescence spectroscopy and showed reduced fluorescence intensities.

Keywords: Porphyrins, functionalisation, sensor, thin film, quenching, fluorescence, luminescence.

Introduction

Some heavy metal ions, in minute amount, are required for human metabolic processes such as Zn(II), Fe(II), Cu(II), and Mn(II) but some are highly toxic such as Hg(II), Pb(II) and Cd(II). Lead (Pb), one of the substantial toxic heavy metals can pose a harmful threat to our health related to central nervous system, brain and intelligence [1]. Pb(II) poisoning can either be acute that resulted in effects such as abdominal pain, headache and fatigue whereas chronic Pb(II) poisoning can cause mental retardation, birth defects, kidney damage and others. Pb(II) can be stemmed from domestic sources like drinking water, cigarette and food or through industrial sources such as house paints, gasoline and storage batteries. These Pb(II) ions will enter the body through gastrointestinal route, inhalation or absorbed through skin and then they will be distributed to the tissues by the blood [2].

Studies in sensor field is gaining lots of attention especially in producing low cost, environmentally friendly and high sensitivity sensor. One of the ways is by using fluorescence probe as they have interesting photophysical properties; one of it is the ability to modify the fluorophore into different ways such as charge transfer, electron transfer or influence of metal ions [3]. Optical sensors using fluorescent compounds are gaining popularity as they are selective, rapid and high sensitivity. Apart from chemical analysis field, researchers in biology (Zhong *et al*., 2020) and environmental sciences (Han *et al*., 2016) have conducted extensive studies on fluorescent devices for sensing and determination of toxic metal ions [4, 5]. For instance, Faraz *et al.* (2018) developed a multi-ion fluorescence sensor using polyindole/cadmium sulphide nanocomposite that showed great performance in detecting Cr(III), Fe(III) and Sn(II) in drinking water samples [6]. The development of robust sensing films with controlled structure and long-term signal reliability still presents difficulties, despite the substantial advancements in fluorescence sensors.

Porphyrins are polycyclic compounds with nitrogen bridges. They are recognised as pigments of life due to their contribution to photosynthesis and oxygen carrier in the blood [7]. Porphyrins compound can be found in nature and synthesised in the lab according to desired properties. The photophysical properties of porphyrins are varied, for example the absorption spectra that are made up of a broad Soret band and a few Q bands, and they also exhibit fluorescence activity [8]. Some of the porphyrins-based metal

***For correspondence:**
m.fuad@utm.my

Received: 13 August 2025
Accepted: 28 Feb. 2026

sensors developed are polythymine with 5,10,15,20-tetrakis(N-methyl-4-pyridyl) porphyrin for Hg(II) ions detection [9] and water soluble 5,10,15,20-tetrakis(4-hydroxy- 3,5- dimethoxyphenyl)porphyrin (THMPP) for Cd(II) ions detection [10]. The majority of sensing systems rely on traditional synthesis or immobilization techniques, which provide little control over film generation and stability, despite the potential sensitivity of these porphyrin-based sensors.

Porphyrins-based polymers are attaining more attention as they can possess both porphyrinic and polymeric properties. They are employed as catalyst, initiators, monomers or conjugates and mostly incorporates tetraphenyl porphyrin (TPP). Polymerisation of porphyrin monomers can proceed *via* condensation and free radical polymerisation [11]. In photo-polymerisation, hydrophilic monomers such as acrylates and methacrylates are polymerised in the presence of light sensitive molecules (photo-initiators) [12]. The photo-initiator will form radicals upon exposure to light to initiate the polymerisation of monomers. Photo-polymerisation technique offers several advantages which include temperature independence, faster reaction compared to thermal initiation method, and the ability to stop the reaction by simply removing the light source [13, 14]. In contrast to conventional free-radical or condensation polymerisation approaches, the photo-polymerisation technique in this work enables controlled formation of porphyrin-functionalised sensing films under mild conditions, representing a distinct methodological advancement.

A problem that might rise in incorporation of porphyrins into matrixes is leaching of the porphyrin molecules. Leaching of the sensing molecules will generate effects such as instability of signals, inaccurate measurement and shorter life-time. A study by Tian *et al*. (2010) explained oxygen sensors made by physically trapping of porphyrin is unstable while sensors with covalently bonded porphyrin reduced the leaching problem. Covalent bonding of porphyrin is done through cross-linkable porphyrin monomers with poly(2- hydroxyethyl methacrylate)-co-polyacrylamide monomers, generating a sensing film [15]. In the present study, the porphyrins used was transformed into a cross-linker, followed by photo-polymerisation that generated the sensing material films for Pb(II) ions detection. This photo-polymerisation-based cross-linking strategy not only addresses leaching issues but also provides a versatile platform for the development of robust fluorescence sensing films.

Materials and Methods

Chemicals and Materials

5,10,15,20-tetrakis(4-hydroxyphenyl)-21H,23H-porphine (TPP-$(OH)_4$), tetrahydrofuran (THF), triethylamine (TEA), methacryloyl chloride, dichloromethane (DCM), ethanol (EtOH), acrylamide, ethyl acetate, diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO), *N,N*'-methylenebisacrylamide (MBA), methanol, and lead(II) nitrate ($Pb(NO_3)_2$) were used as purchased without further purification.

Synthesis of Methacrylate-Functionalised Porphyrins (TPP-M)

The synthesis of methacrylate-functionalised porphyrins (TPP-M) was adapted from a previous study by Flouraki *et al*. (2016) [16]. 5,10,15,20-tetrakis(4-hydroxyphenyl)-21H,23H-porphine (TPP-$(OH)_4$) (0.4 g) was weighed into a 500 mL round-bottom flask. THF (30 mL) was added, and the solution was stirred until complete dissolution. Next, TEA (2 mL) was added, followed by the slow addition of methacryloyl chloride (2 mL) at 0°C under stirring. The reaction mixture was stirred overnight at room temperature. Thin layer chromatography (TLC) was performed using a DCM:EtOH (9:1) solvent system. The reaction was stopped when a single spot was observed on the TLC plate, indicating completion. The retention factor (R_f) was calculated based on the TLC plate. After completion, the solvent was removed by distillation, and the product was dried in a desiccator for three days. The crude product was filtered using vacuum filtration, rinsed several times with sodium carbonate solution, followed by distilled water, and finally dried in an oven for one hour. The final product, TPP-M (0.6944 g) was obtained as a greenish-purple solid that formed a brownish-purple solution in THF. Figure 1 illustrates the formation of TPP-M (2).

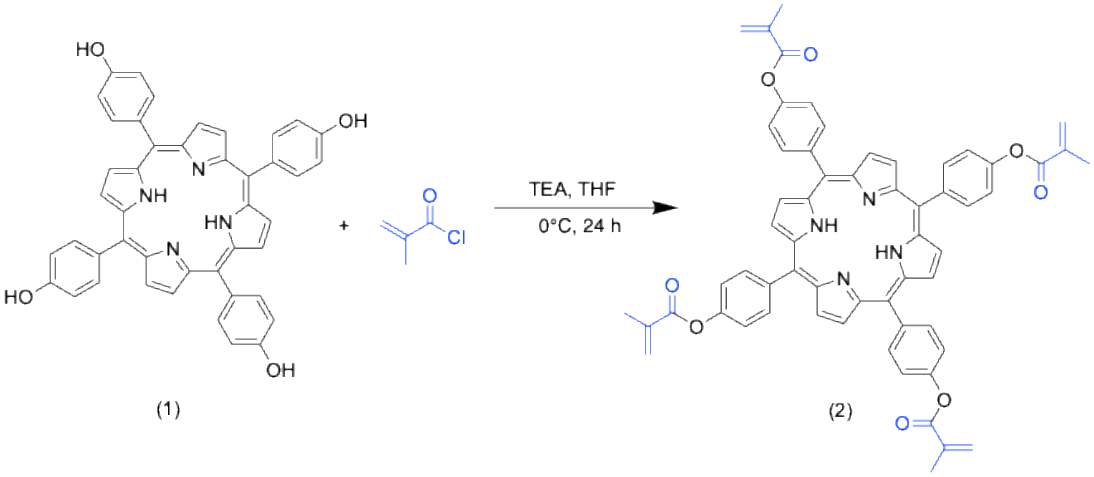

Figure 1. Functionalisation of TPP-$(OH)_4$ (1) with methacryloyl chloride to yield methacrylate-functionalised porphyrin (TPP-M) (2)

Characterisation Methods

The synthesised TPP-M was characterised by proton nuclear magnetic resonance (^{1}H-NMR) using a Bruker 400 MHz Avance II spectrometer to obtain the ^{1}H NMR spectrum. NMR analysis was carried out in deuterated dimethyl sulfoxide (d-DMSO) with tetramethylsilane (TMS) as the internal standard. Fourier-transform infrared (FTIR) spectra were recorded using a PerkinElmer spectrometer in the potassium bromide (KBr) pellet method (1:100 TPP-M:KBr ratio). The Agilent Cary Eclipse fluorescence spectrometer was used to measure the emission of TPP-M at room temperature, with an excitation wavelength of 500 nm and an emission range of 550–800 nm. UV-Vis absorption spectra were recorded using a Shimadzu UV-Vis spectrometer in the wavelength range of 350–800 nm

Fluorescence Activity of TPP-M in the Presence of Pb(II) Ions

The fluorescence quenching of TPP-M in Pb(II) ions solution prepared from lead(II) nitrate were carried out. TPP-M (0.4 ml, 6.508×10^{-4} M and Pb(II) ions solution (2.2 ml, 0.2 M) were pipetted into a cuvette and the emission spectrum of the porphyrin was recorded to observe its quenching ability in Pb(II) ions. A control experiment was conducted under identical conditions without Pb(II) ions.

Thin Film Fabrication through Photo-polymerisation of TPP-M and Acrylamide

The thin film fabrication was carried out using the modified method from Ayub *et al*. (2017) [17]. TPP-M (0.015 g), acrylamide (2 g), TPO (0.1 g) and MBA (0.1 g) were weighed into separate 20 mL glass vials. TPP-M was dissolved in 5 ml THF, the TPO in 1 mL THF and 1 mL of distilled water while the acrylamide and MBA were dissolved in 2 mL and 1 mL of distilled water respectively. Acrylamide acted as the monomer, MBA as the crosslinker and TPO as the photo-initiator. The following volumes were mixed in a 20 mL glass vial: 800 µL of acrylamide solution, and 400 µL each of MBA, TPP-M, and TPO solutions. The mixture was thoroughly mixed and exposed to UV light (405 nm, 17.323 mW) using a UV LED flashlight until a solidified polymer film formed (~30 seconds). After solidification, distilled water was added, and the film was carefully removed using a spatula. The film was cut to a size of 0.8 cm × 2.8 cm to fit into a cuvette.

Characterisation of TPP-M Film

The TPP-M film fabricated was characterised using ATR-FTIR and fluorescence spectroscopy. A 0.8 cm × 2.8 cm piece of TPP-M film was mounted inside the cuvette for fluorescence spectroscopy whereas a 0.5 cm × 0.5 cm dried TPP-M film was used for ATR-FTIR analysis. The FTIR spectrometer with an attenuated total reflectance (ATR) accessory was used in the frequency range of 4000 to 400 cm^{-1}, and the Agilent Cary Eclipse fluorescence spectrometer in the emission wavelength range of 550 nm to 800 nm with excitation at 500 nm.

Fluorescence Sensing of Pb(II) Ions by TPP-M Film

The prepared TPP-M film was used for the detection of Pb^{2+} ions via fluorescence spectroscopy. Pb(II) ion solutions with concentrations of 0.2 – 1.0 M were prepared. A thin-film strip (0.8 cm × 2.8 cm) was

immersed in the solutions within a cuvette. Fluorescence measurements were performed by exciting at 500 nm and recording the emission spectra in the 550–800 nm range. Emission peaks were collected for TPP-M films in the presence and without Pb(II) ions.

Results and Discussion

Characterisation of Methacrylate-Functionalised Porphyrins (TPP-M)

The reaction involving TPP-$(OH)_4$, methacryloyl chloride, trimethylamine (TEA) and tetrahydrofuran (THF) was carried out for 24 hours at room temperature with constant stirring. This esterification of TPP-$(OH)_4$ with methacryloyl chloride was monitored by thin layer chromatography (TLC), indicating completion when only one spot corresponding to the product appeared on the plate. The reaction proceeded *via* nucleophilic attack by the hydroxyl group on the carbonyl carbon of methacryloyl chloride, with triethylamine (TEA) added to neutralize the by-product HCl, forming TEA hydrochloride, which was subsequently removed [18]. The R_f values for TPP-$(OH)_4$ and the product TPP-M were 0.22 and 0.82, respectively. The lower R_f value for TPP-$(OH)_4$ reflects its higher affinity for the polar stationary phase due to the hydroxyl groups, while TPP-M migrated further due to increased interaction with the less polar mobile phase [19].

The successful synthesis of TPP-M was confirmed through ^{1}H-NMR analysis, which revealed several distinct peaks (see Figure 2a). For the methacrylate moieties, two peaks were observed at 6.49 ppm and 6.05 ppm correspond to the vinyl protons H5 and H6, respectively. The methyl (CH_3) protons (H7) appeared as a single peak at 2.20 ppm. A single peak for the β-protons (H2) was observed at 8.88 ppm, indicating the most de-shielded environment. Meanwhile, the aromatic protons of the phenyl group (H3 and H4) produced peaks at 7.65 ppm and 8.28 ppm, respectively. Notably, the peak for H4 at 8.28 ppm shifted from its original position at 8.00 ppm (as reported in TPP-$(OH)_4$ (1)), provided further confirmation of successful TPP-M monomer synthesis, attributed to functionalisation by the methacrylate group. H1 signal is not observed due to extreme shielding (negative chemical shielding around -2.73 ppm) due to the shielding effect of the porphyrin macrocycle [20, 21].

The IR spectrum of TPP-M exhibited several characteristic peaks that further confirmed the successful functionalisation of TPP-$(OH)_4$ with the methacrylate group (see Figure 2b). An absorption band at 1733.29 cm^{-1}, attributed to C=O stretching, indicated the presence of the carbonyl group within the methacrylate moiety [22]. Additionally, peaks observed between 2853.62 cm^{-1} and 2956.07 cm^{-1} were associated with C–H stretching vibrations in the methacrylate group [23], further verifying that the synthesised product was indeed TPP-M.

The absorbance and emission of TPP-M were recorded using UV-Vis and fluorescence spectroscopy in THF solvent (see Figure 2c). From the UV-Vis spectrum, five absorption bands consisting of four Q bands from 500 nm to 655 nm along with one Soret band at around 400 nm were observed. These peaks are usually found in non-metallated porphyrin absorption spectra. Comparing the TPP-M absorption peak to TPP-$(OH)_4$ peaks, it is slightly blue-shifted due to the methacrylate group that contributed to the enrichment of the π system via conjugation [24]. For the characterisation of TPP-M using fluorescence spectroscopy, the photoexcitation of TPP-M exhibited two distinguished peaks at 657 nm and 720 nm following a typical tetraphenylporphyrin (TPP) emission peak. The fluorescence quenching activity of TPP-M was investigated. Both porphyrins were dissolved in THF and tested in the presence and absence of Pb(II) ions. Upon the addition of Pb(II) ions, a reduction in fluorescence intensity was observed, confirming the sensing capability of TPP-M (see Figure 2d).

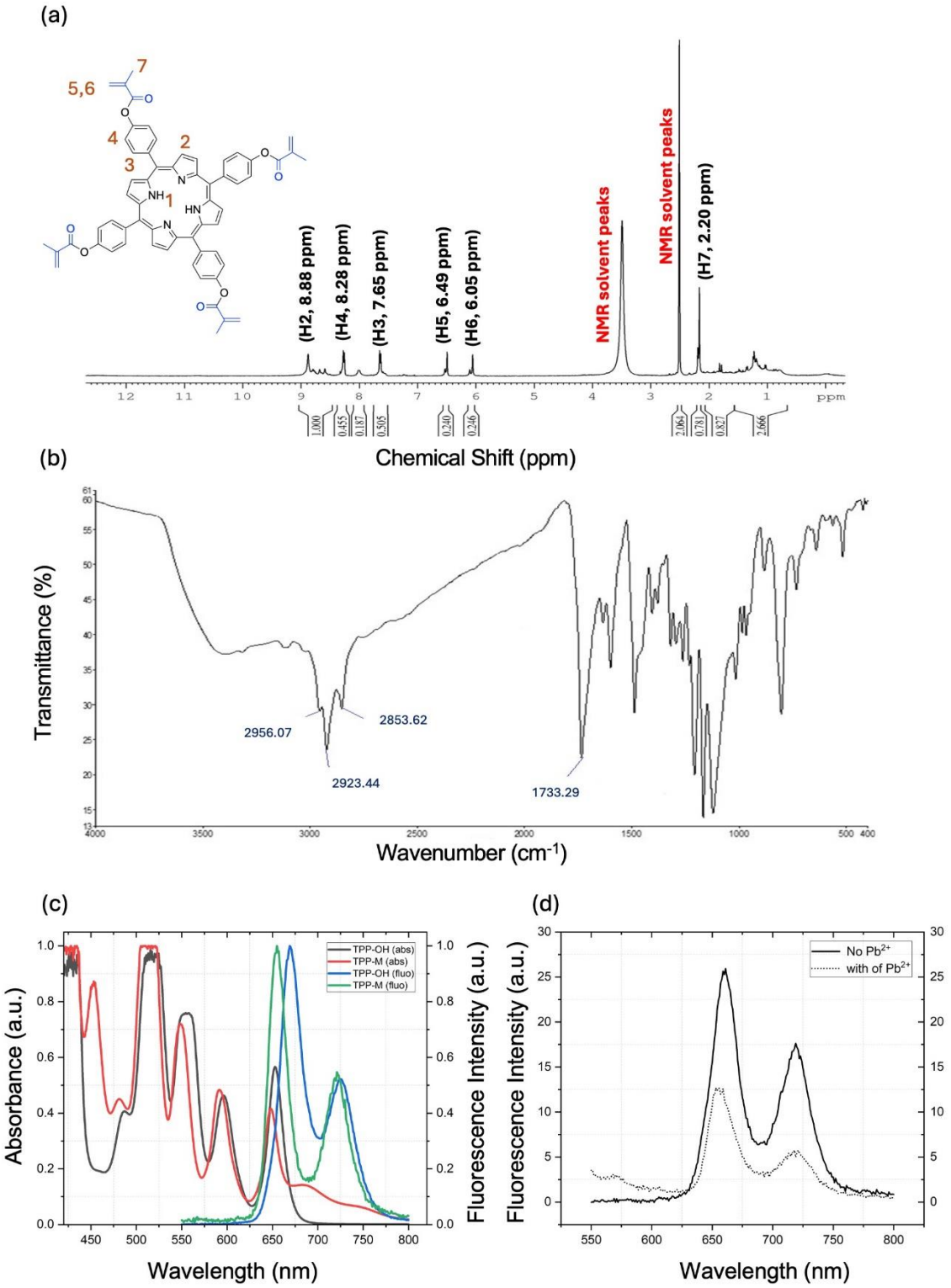

Figure 2. (a) ^{1}H-NMR spectrum, (b) Infrared spectrum, and (c) UV-Vis and fluorescence spectra of TPP-M. (d) Fluorescence quenching by Pb(II) ions where the addition of Pb(II) ions led to reduced fluorescence intensity, confirming sensing ability of TPP-M

Photo-polymerisation of TPP-M into film sensor and Quenching Study

The characterised TPP-M was then used in the photo-polymerisation of acrylamide using an UV LED as the light source producing an opaque sensing film (see Figure 3). Acrylamide acted as the monomer while TPP-M and MBA as tetra-functional and bi-functional cross-linkers as reported by Flouraki *et al.* (2016) [16]. TPO was used as the photo-initiator due to its efficient UV absorption at 395 nm that closely matched the UV LED wavelength output [24]. It is important to note that the curing process for this photo-polymerization technique only takes about 30 seconds – one of the major advantages of this technique.

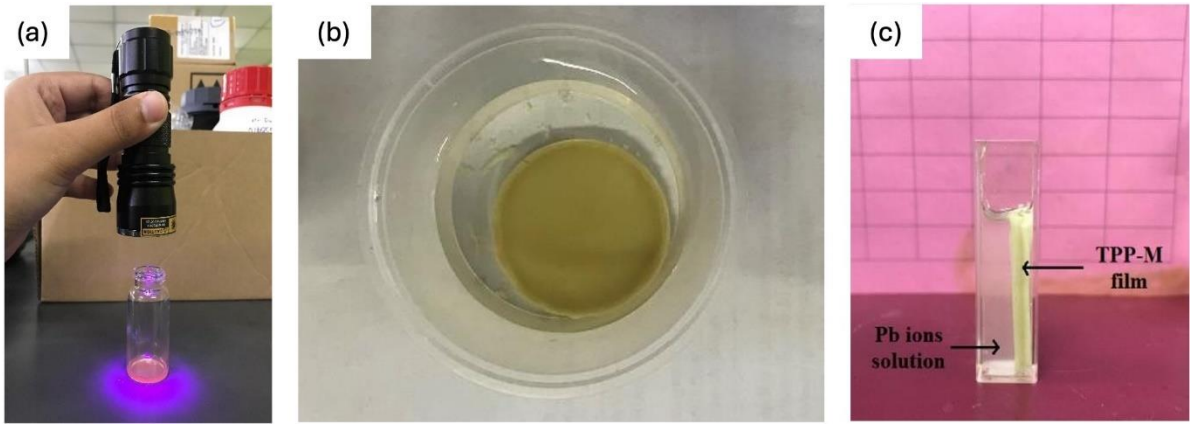

Figure 3. (a) The photo-polymerisation of TPP-M with acrylamide-based monomers using a UV LED light source, initiated by the photo-initiator (TPO), (b) the sensing thin film formed after photo-polymerisation, and (c) the sensing film was cut to fit into a cuvette

IR spectra for acrylamide and TPP-M films are shown in Figure 4a. The spectrum of the TPP-M film closely resembled that of the acrylamide film, likely due to the high acrylamide content dominating the spectral features [26]. FTIR Spectrum of TPP-M-acrylamide film key peaks confirm successful polymerisation of monomers and TPP-M: C=O stretch at ~1733 cm^{-1} (methacrylate group) and C–H stretch between 2853–2956 cm^{-1}.

The quenching activity of Pb(II) ions on the TPP-M film was evaluated, with results shown in Figure 4b. The TPP-M film exhibited slight fluorescence quenching in the presence of Pb(II) ion solutions. The fluorescence peak profile confirms that the TPP-M molecules were successfully embedded within the polymer matrix. However, the TPP-M film demonstrated lower sensitivity towards Pb(II) (in terms of fluorescence quenching) compared to its solution form (Figure 2d). Figure 4(c) presents the calibration plot of fluorescence intensity for the sensing film over a Pb(II) concentration range of 0.2–1.0 M. The low correlation coefficient (R^2 = 0.3384) indicates poor concentration dependence, suggesting that the fluorescence response does not change distinctly between lower and higher Pb(II) concentrations within this range. This reduced sensitivity is likely due to decreased pore size in the film, resulting from the high concentration of cross-linker used during polymerisation [27]. It is hypothesised that smaller pore sizes limit the diffusion of Pb(II) ions into the film, thereby reducing their interaction with the embedded TPP-M and diminishing the overall quenching effect. Although no pore size characterisation was conducted, the observation is consistent with the opaque appearance of the fabricated thin film. Further studies involving porosity and surface area analysis are recommended to better understand and optimise mass transport within the sensing film.

Compared to physical entrapment, covalent immobilization of porphyrins inside polymer matrices has been shown to efficiently prevent leaching [28,29]. After soaking the TPP-M film, the fluorescence intensity of water remained very low, as seen in Figure 4d, suggesting very little porphyrin leaching. These findings reinforce TPP-M's applicability for fluorescence-based sensing applications by showing that its photo-polymerization-based integration results in a stable sensing film with little dye loss.

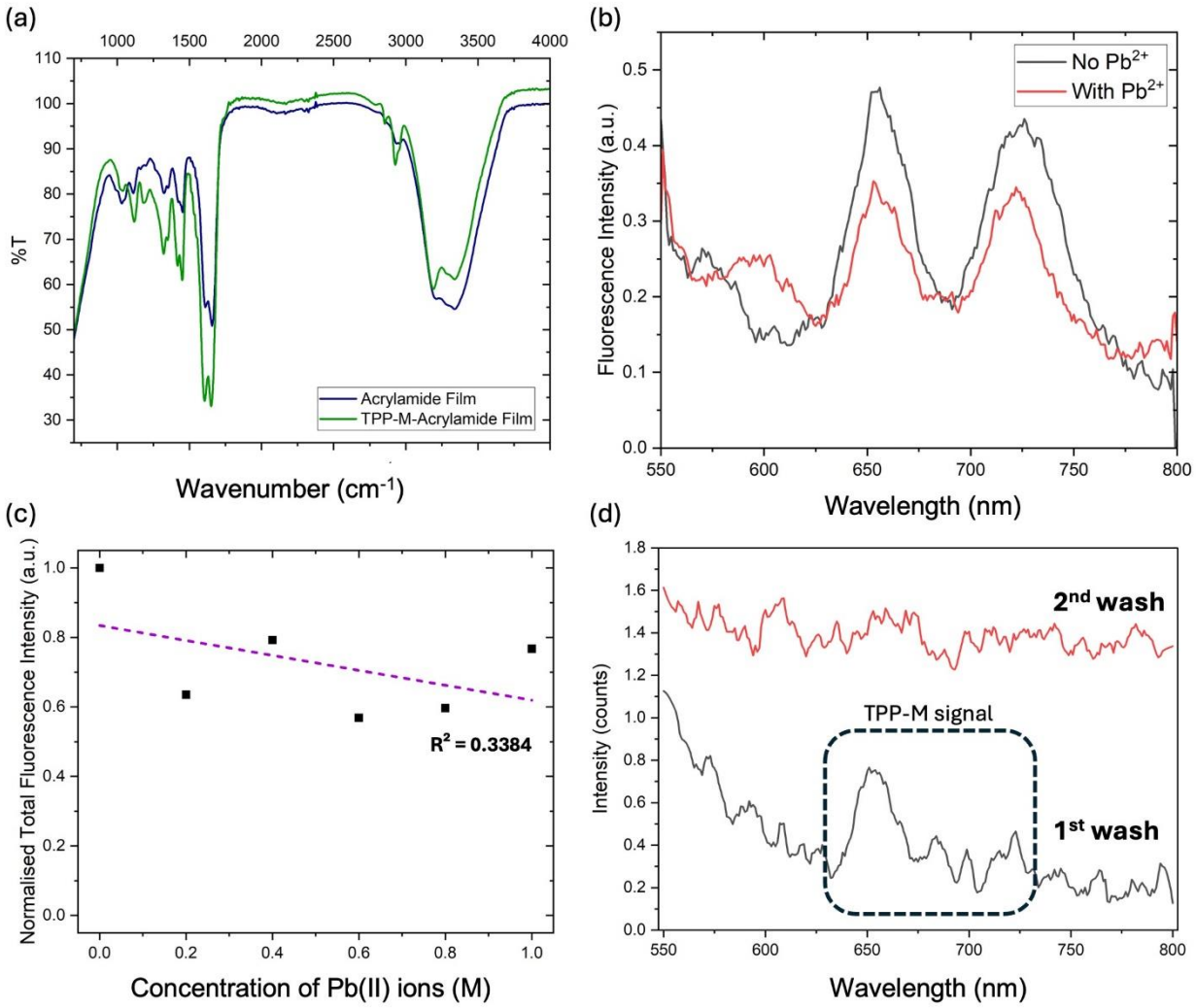

Figure 4. (a) FTIR spectrum of the TPP-M–acrylamide film, where key characteristic peaks confirm successful polymerisation of the monomers and incorporation of TPP-M; (b) fluorescence spectra of the sensing film in the absence and presence of Pb(II) ions, showing a moderate decrease in intensity, which suggests limited quenching performance and indicates scope for further optimisation; (c) calibration plot of total fluorescence intensity of the thin film at different Pb(II) ion concentrations ranging from 0.2 to 1.0 M (0 M represents the thin film in the absence of Pb(II) ions); and (d) leaching test showing the first and second wash of the thin film using distilled water, where the fluorescence spectra of the wash solutions indicate very low intensity in the first wash and no detectable peaks in the second wash, suggesting minimal porphyrin leaching

Conclusions

In conclusion, a methacrylate-functionalised porphyrin derivative (TPP-M) was successfully synthesised for the detection of Pb(II) ions *via* fluorescence quenching. The functionalisation was achieved by modifying TPP-$(OH)_4$ with methacrylate groups, yielding a greenish-purple solid which was characterised using ^{1}H NMR, UV-Vis, FTIR, and fluorescence spectroscopy. The UV-Vis spectrum displayed one Soret band around 400 nm and four Q bands between 500–655 nm, consistent with free-base porphyrins. FTIR analysis confirmed the presence of the methacrylate carbonyl group and the absence of hydroxyl peaks, while fluorescence spectra showed two characteristic emission peaks at 657 nm and 720 nm. Quenching studies indicated that Pb(II) ions caused moderate fluorescence quenching in TPP-M. Although TPP-M in solution exhibited stronger fluorescence quenching than in its thin-film form, incorporating TPP-M into an acrylamide-based polymer film enabled covalent immobilisation, thereby minimising leaching, a parameter that warrants further investigation. The lower quenching sensitivity in TPP-M film is likely due to reduced porosity from high cross-linker concentrations, limiting Pb(II) diffusion. Future research should assess comprehensive sensor performance, including concentration-dependent

sensing at lower Pb(II) ions concentrations, long-term stability, selectivity, and quantitative analytical parameters like limit of detection (LOD) and limit of quantification (LOQ), as well as real sample testing to determine practical applicability in environmental lead monitoring. Overall, this work demonstrates that photo-polymerisation of TPP-M in an acrylamide matrix is a promising method for creating fluorescent sensing thin films, with the benefits of room-temperature processing and rapid film creation in around 30 seconds.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgment

This work is part of a research project funded by Universiti Teknologi Malaysia (UTM) under Matching Grant UTM-Universitas Indonesia (UI) with cost centres of Q.J130000.3054.04M61 and R.J130000.7654.1U004.

References

[1] Dashtian, K., & Zare-Dorabei, R. (2017). An easily organic–inorganic hybrid optical sensor based on dithizone impregnation on mesoporous SBA-15 for simultaneous detection and removal of Pb(II) ions from water samples: Response-surface methodology. *Applied Organometallic Chemistry*, *31*(12), 1–14.

[2] Engwa, G. A., Nwalo, P. U. F. F. N., & Unachukwu, M. N. (2018). Mechanism and health effects of heavy metal toxicity in humans. Poisoning in the Modern World – New Tricks for an Old Dog? 1–23. IntechOpen.

[3] Ahmed, M., Faisal, M., Ihsan, A., & Naseer, M. M. (2019). Fluorescent organic nanoparticles (FONs) as convenient probes for metal ions detection in aqueous medium. *Analyst*, *144*.

[4] Zhong, W., Wang, L., Qin, D., Zhou, J., & Duan, H. (2020). Two novel fluorescent probes as systematic sensors for multiple metal ions: Focus on detection of Hg^{2+}. *ACS Omega*, *5*, 24285–24295.

[5] Han, S., Zhou, X., Tang, Y., He, M., Zhang, X., Shi, H., & Xiang, Y. (2016). Practical, highly sensitive, and regenerable evanescent-wave biosensor for detection of Hg^{2+} and Pb^{2+} in water. *Biosensors and Bioelectronics*, *80*, 265–272.

[6] Faraz, M., Abbasi, A., Naqvi, F., Khare, N., Prasad, R., Barman, I., & Pandey, R. (2018). Polyindole/cadmium sulphide nanocomposite based turn-on, multi-ion fluorescence sensor for detection of Cr^{3+}, Fe^{3+} and Sn^{2+} ions. *Sensors and Actuators B: Chemical*, *269*.

[7] Prasad, S. S., Naidu, B. R., Hanafiah, M. M., Lakshmidevi, J., Marella, R. K., Lakkaboyana, S. K., & Venkateswarlu, K. (2021). Porphyrin N-pincer Pd(II) complexes in water: A base-free and nature-inspired protocol for the oxidative self-coupling of potassium aryltrifluoroborates in open-air. *Molecules*. *26*(17), 5390. https://doi.org/10.3390/molecules26175390.

[8] Šindelka, K., Limpouchová, Z., & Procházka, K. (2021). Solubilization of charged porphyrins in interpolyelectrolyte complexes: A computer study. *Polymers*, *13*(4), 1–17.

[9] Wu, D., Huang, Y., Hu, S., Yi, X., & Wang, J. (2018). Sensitive Hg^{2+} sensing via quenching the fluorescence of the complex between polythymine and 5,10,15,20-tetrakis(N-methyl-4-pyridyl)porphyrin (TMPyP). *Sensors*, *18*(11).

[10] Namitha, P. P., Saji, A., Francis, S., & Rajith, L. (2020). Water soluble porphyrin for the fluorescent determination of cadmium ions. *Journal of Fluorescence*, *30*(5), 1215–1222. https://doi.org/10.1007/s10895-020-02574-9.

[11] Tian, J., & Zhang, W. (2019). Synthesis, self-assembly and applications of functional polymers based on porphyrins. *Progress in Polymer Science*, *95*.

[12] Chamkouri, H. (2021). A review of hydrogels, their properties and applications in medicine. *American Journal of Biomedical Science & Research*, *11*, 485–493.

[13] Su, WF. (2013). Ionic Chain Polymerization. In: Principles of Polymer Design and Synthesis. Lecture Notes in Chemistry, vol 82. Springer, Berlin, Heidelberg. *82*, 185–218.

[14] Mohamad, F., Tanner, M. G., Choudhury, D., Choudhary, T. R., Wood, H. A. C., Harrington, K., & Bradley, M. (2017). Controlled core-to-core photo-polymerisation – fabrication of an optical fibre-based pH sensor. *Analyst*, *142*(19), 3569–3572.

[15] Tian, Y., Shumway, B. R., & Meldrum, D. R. (2010). A new cross-linkable oxygen sensor covalently bonded into poly(2-hydroxyethylmethacrylate)-co-polyacrylamide thin film for dissolved oxygen sensing. *Chemistry of Materials*, 2069–2078.

[16] Flouraki, C., Kaliva, M., Papadas, I. T., Armatas, G. S., & Vamvakaki, M. (2016). Nanoporous polystyrene–porphyrin nanoparticles for selective gas separation. *Polymer Chemistry*, *7*(17), 3026–3033.

[17] Ayub, N. F., Hashim, S., Jamaluddin, J., & Adrus, N. (2017). New UV LED curing approach for polyacrylamide and poly(N-isopropylacrylamide) hydrogels. *New Journal of Chemistry*. *41*(12), 5617–5623. https://doi.org/10.1039/C7NJ00894A.

[18] Chinelatto, M. A., Agnelli, J. A. M., & Canevarolo, S. V. (2014). Synthesis and characterization of copolymers from hindered amines and vinyl monomers. *Polímeros*, *24*(1), 30–36.

[19] Chacón-Patiño, M. L., Blanco-Tirado, C., Orrego-Ruiz, J. A., Gómez-Escudero, A., & Combariza, M. Y. (2015). High resolution mass spectrometric view of asphaltene-SiO_2 interactions. *Energy and Fuels*, *29*(3), 1323–1331.

[20] Gujarathi, P. (2016). New meso-substituted unsymmetrical porphyrins: Synthesis and spectral studies. *Acta Chimica & Pharmaceutica Indica*, *6*(3), 104–110.

[21] Tuerdi, G., Nizamidin, P., Kari, N., Yimit, A., & Wang, F. (2018). Optochemical properties of gas-phase protonated tetraphenylporphyrin investigated using an optical waveguide NH_3 sensor. *RSC Advances*, *8*(10), 5614–5621.

[22] Nandiyanto, A., Oktiani, R., Ragadhita, R., & Ijost, I. (2019). How to read and interpret FTIR spectroscopy of organic material. *Indonesian Journal of Science and Technology*, *4*, 97–118.

[23] Clemente, C., Ribeiro, V., Sousa, J., Maia, F., Barreto, A., Andrade, N., Denardin, J., Mele, G., Carbone, L., Mazzetto, S., & Fechine, P. (2013). Porphyrin synthesized from cashew nut shell liquid as part of a novel superparamagnetic fluorescence nanosystem. *Journal of Nanoparticle Research*, *15*.

[24] Ibnaouf, K. H., Elzupir, A. O., Alsalhi, M. S., & Alaamer, A. S. (2018). Influence of functional groups on the photophysical properties of dimethylamino chalcones as laser dyes. *Optical Materials*, *76*, 216–221.

[25] Green, W. A. (2010). Industrial photoinitiators. *Industrial Photoinitiators*, 1–20. Taylor & Francis Group.

[26] Nikolić, L., Skala, D., Nikolić, V., Stamenković, J., Babić, D., & Ilić-Stojanović, S. (2004). Methyl methacrylate and acrylamide crosslinked macroporous copolymers. *Journal of Applied Polymer Science*, *91*(1), 387–395.

[27] Celebioglu, N., & Yilmaz, Y. (2017). Investigation of the luminescence, mechanical, and thermal properties of ZnO-entrapped poly(N-isopropylacrylamide) gels. *Journal of Composite Materials*, *51*(29), 4079–4090.

[28] Välimäki, H., Hyvärinen, T., Leivo, J., Iftikhar, H., Pekkanen-Mattila, M., Rajan, D. K., Verho, J., Kreutzer, J., Ryynänen, T., Pirhonen, J., Aalto-Setälä, K., Kallio, P., Narkilahti, S., & Lekkala, J. (2020). Covalent immobilization of luminescent oxygen indicators reduces cytotoxicity. Biomedical Microdevices, *22*(2).

[29] Mao, Y., Mei, Z., Wen, J., Li, G., Tian, Y., Zhou, B., & Tian, Y. (2018). Honeycomb structured porous films from a platinum porphyrin-grafted poly(styrene-co-4- vinylpyridine) copolymer as an optical oxygen sensor. Sensors and Actuators, B: Chemical, *257*, 944–953.