Tetramethylammonium hydroxide-Doped Starch Film as a Colorimetric Sensor for Trinitrotoluene Detection

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Abstract

A tetramethylammonium hydroxide (TMAH)-doped starch film was developed for trinitrotoluene (TNT) detection. A purple Janowsky anion was obtained from the reaction of TNT with released TMAH. When the film was used in conjunction with digital image colorimetry (DIC), rapid quantitative analysis of TNT was achieved. The Red-Green-Blue (RGB) intensities analyzed from digital photographs of the purple product were used to establish calibration curves for TNT. A wide linear range (2.5 to 50 mgL$^{-1}$) with good linearity ($R^2 > 0.99$) was achieved for the quantification of TNT. Good precision (1.73 to 3.74 %RSD) was obtained for inter-day tests ($n = 5$). The films were applied to test four post-blast soil samples and two positive results were observed. The concentrations quantified by DIC were in good agreement with spectrophotometry. The film was able to be stored in a freezer for 3 months with < 4.3 % change in performance.

Keywords: Starch film, TNT detection, Digital image colorimetry, Webcam
Introduction

The development of novel materials as sensing elements for the simple and rapid detection of analytes of interest with high sensitivity and selectivity has received a lot of attention. Colorimetric sensors are attractive as they represent a simple low cost means of visually detecting target analytes in-situ, which provides rapid results. Various analytes have been reported as being capable of detection by sensors developed from various materials e.g., trinitrotoluene (TNT) by cryogel, hydrogel, polyvinyl chloride (PVC) thin-film, and methamphetamine and formaldehyde by sol-gel. Polymers are one of the most attractive materials commonly used as the substrate for the fabrication of colorimetric sensors, especially synthetic polymers, such as PVC and polyvinyl alcohol (PVA). Although cost-effective sensors with good characteristic have been obtained using these substrates, their use creates environmental hazards which need to be considered. For example, non-biodegradable PVC can retain its form for decades, while its breakdown products can block the digestive tract of animals. Moreover, the organic solvent commonly used to dissolve PVC, tetrahydrofuran (THF), is also toxic to the environment. Therefore, the development of colorimetric sensors using natural polymers as substrates is a subject of interest.

Natural polymers, especially those made from starch, have received growing attention in recent decades due to their inherent biodegradability. Starch is one of the most abundant naturally occurring polysaccharides stored by plants and generated from photosynthesis using carbon dioxide and water. It is composed of two D-glucose homopolymers, amylose and amylopectin. Amylose is a linear polymer with \( \alpha-D-(1 \rightarrow 4) \) glycosidic linkages, while amylopectin is a branched polymer which contains \( \alpha-D-(1 \rightarrow 6) \) glycosidic linkages at the branching points in addition to \( \alpha-D-(1 \rightarrow 4) \) glycosidic linkages. The proportions of amylose and amylopectin in
starch depend on the type and source, e.g., tapioca starch contains about 15.9 - 22.4 % amylose. Due to its film-forming property, low cost, wide availability and functional diversity, starch has been widely used to fabricate renewable and biodegradable films. The mechanical properties of those films are related to the ratio of amylose and amyllopectin since amylose produces better film properties than amyllopectin. Further, the residual water content of films also affects their mechanical properties. The limitation of starch-based films is their brittleness and their hydrophilic nature which could be improved by the addition of plasticizers such as glycerol.

The widely used explosive material, 2,4,6-TNT has been reported to contaminate the environment. Because it is highly toxic for many macro- and microorganisms, a rapid and low-cost method for the detection of TNT is thus required for on-site testing at potentially contaminated sites or to assess improvised explosive devices and post-blast sites. Although several instrumental laboratory-based methods have been reported, these methods are expensive and are not available in many laboratories. A variety of sensors including electrochemical sensors, mass sensors, and optical sensors have been reported for the field detection of explosive materials and colorimetric sensors have also been developed. However, some sensors involve the use of non-degradable materials and toxic solvents, e.g., tetrahydrofuran and PVC, which create environmental concerns.

The work reported in this paper aimed to develop a novel environmentally friendly colorimetric sensor for on-site quantitative analysis of TNT. Colorimetric starch films were developed by entrapping an organic base, tetramethylammonium hydroxide (TMAH), within plasticized and non-plasticized starch films. The colorimetric test was based on the formation of Meisenheimer or Janowsky anions from nitro-aromatic rings with alkaline acetone. TMAH was used as an organic base due to its good solubility in
organic solvents with a lower propensity to cause deterioration of the matrix and form interfering colored products. TMAH-doped starch films were used in conjunction with digital image colorimetry (DIC) instead of conventional spectrophotometric measurement for rapid quantitative analysis. DIC makes on-site TNT detection more convenient and cost effective because it employs cheaper portable detection devices, e.g., a digital camera or smartphone, instead of a spectrophotometer. In the work described in this article, a widely commercially available webcam was used to photograph the colorimetric product obtained from the film developed.

Experimental

Reagents and chemicals

TNT in acetonitrile standard (1 mgmL\(^{-1}\)) was purchased from Supelco (Bellefonte, PA). It was diluted to an appropriate concentration using acetone (Merck, Darmstadt, Germany). Tapioca starch was purchased from a supermarket in Kathu, Phuket, while glycerol was obtained from Ajax Finechem Pty Ltd. TMAH solution (25 wt% in water) was purchased from Sigma-Aldrich Ltd. Ultrapure water was obtained from a Barnstead EasyPure II laboratory water purification system (Barnstead EasyPure II, Thermo Fisher Scientific, OH).

Preparation of the TMAH-doped starch films

The TMAH-doped films were prepared based on the entrapment of the TNT-selective reagent, TMAH, within the thin films of starch. Glycerol was used as a plasticizer. Both plasticized and non-plasticized thin films were investigated. Tapioca starch (0.25 g) was dispersed in ultrapure water (5 mL) before heating on a hotplate
(~100 °C) under continuous stirring until a clear viscous solution was obtained. To create the plasticized thin-film, glycerol (0.25 mL) was added and the resultant solution was then cooled at room temperature. TMAH (0.5 mL) was then added and stirred for 6-8 min to obtain a homogenous solution. The mixture (50 µL) was then transferred into a small flat-cap tube (200 µL) and incubated at 60 °C for 12 h in an oven. After it had cooled to room temperature, the tube was quickly closed in order to avoid contamination before being stored in a refrigerator prior to use.

**Characterization of the TMAH-doped starch films**

The morphology and functional groups of the films were investigated using scanning electron microscope (SEM) (Quanta400, FEI, Czech Republic), and a Fourier transform infrared spectroscope (FTIR) (Equinox55, Bruker, Germany), respectively. The FTIR spectra of the films were measured at a range of 4000 to 400 cm\(^{-1}\) with a resolution of 4 cm\(^{-1}\) using the KBr pellet method.

**DIC for the quantification of TNT**

A series of TNT standards (0.5 to 100 mgL\(^{-1}\)) were prepared by diluting a stock solution (1 mgmL\(^{-1}\) in acetonitrile) with acetone. One hundred microliters of each TNT standard solution was transferred to a plastic tube containing the detection film (sensor) and shaken. Each test was repeated three times with three different sensors. The sensors were mounted in a detection box (13.5 cm \(\times\) 15.5 cm \(\times\) 7.5cm)\(^4\) to be photographed. The resultant color products were photographed using a widely available web cam (5MP CMOS Lifecam Cinema HD, Microsoft). Six images of each sensor were taken. Each image was saved as a JPEG file (640\(\times\)480 pixels, 21.5 KB). The average intensities of the red, green and blue values from the six images of each sensor were determined using
a custom-built RGB analysis program. The average RGB values of all six images of the three sensors (18 values in total) were used as a single data point for each standard concentration in calibration curves produced from the data.

System performance and method validation

The performance of the TMAH-doped sensor and DIC system for TNT detection was evaluated. The accuracy of the method was investigated by analyzing TNT standards with a known concentration (7.5 mgL$^{-1}$) and quantified using the calibration curve established as described in the previous section. The percentage of relative error (%RE) was then determined. The precision (%RSD) for each color component was determined from six images from three sensors ($n = 18$). The limit of detection (LOD) was estimated using the standard formula:

$$y_{LOD} = y_B + 3S_B,$$

(Equation 1)

where $y_{LOD}$ is the limit of detection, $y_B$ is the y-axis intercept, and $S_B$ is the standard deviation of the slope of the calibration curve.$^{4-6,31,35}$

Analysis of post-blast soil samples

Post-blast soil samples were prepared and analyzed using the same procedure as described in previous studies.$^{4-6,31,34}$ Briefly, TNT residues in a post-blast soil sample (1.0 g) were extracted in 2.5 mL acetone under sonication for 15 min. The sample was filtered using Whatman No.1 filter paper and the filtrate was tested using the sensor. Blank soil samples were also prepared and analyzed using the same procedure to investigate the interference effect of the soil on the analysis results.
Stability of the TMAH doped-starch sensors

Forty sensors were prepared at the same time using the same ingredients and procedure to evaluate their stability. Three sensors were used to detect TNT (10 mgL⁻¹) on the day of preparation, and the remaining sensors were stored in a freezer. Three sensors were subsequently removed from storage to test their sensitivity to TNT each day over a one-week period and then tested on a weekly basis for a further 3 weeks and finally after 2 and 3 months.

Results and Discussion

Preparation and characterization of the TMAH-doped starch films

The TMAH-doped starch films for TNT detection were in-situ prepared by coating the bottom of a 200 µL micro-PCR tube with the TMAH-doped starch solution (Fig. 1a). Therefore, only a small amount of each sample (< 200 µL) was required, and the sample solution was able to be directly added for in-tube detection.

The preparation of the films consisted of two steps, the preparation of the polymer mixture and the casting of the thin films. The parameters influencing the properties of the films were systematically optimized by varying the types of starch used (tapioca starch, glutinous rice flour, rice flour, and their composites), the concentrations of starch solutions (2.5-10 w/v in water), the amounts of plasticizer (glycerol, 0-0.5 mL), the amount of colorimetric reagent (TMAH, 0.25-1 mL), the casting (incubation) temperature (40-80 °C) and the time (30 min to 24 h). It was found that the use of tapioca starch provided a clear thin film, while glutinous rice flour, rice flour, and their composites in various proportions provided brownish films. Therefore, tapioca starch was selected for fabrication of the colorimetric films. The optimum starch mixture was
found to consist of 5 mL tapioca starch solution (5 % w/v) and 0.5 mL TMAH. The addition of 0.25 mL glycerol to the starch mixture provided a brownish thin-film after incubation at 80 °C for 6 h, although a lower incubation temperature of 60 °C with a longer time (12 h) provided a clearer plasticized thin film. Meanwhile the non-plasticized thin-film without glycerol had a clear appearance. However, when both types of film were used to test TNT solution there was no difference in the colorimetric products obtained. Although the addition of 5-10 % glycerol to the film-forming mixture was able to prevent the film from being brittle, the non-plasticized film adsorbed less water. As the film developed was to be used as a colorimetric sensor, lower water adsorption would result in a longer storage time. Therefore, the non-plasticized TMAH-doped starch film fabricated at 80 °C for 6 h is recommended for the production of sensors rather than the plasticized film.

The SEM image of the film showed homogeneous entrapment of the TMAH phase dispersed in the starch matrix (Fig. 1b). The FTIR spectrum of the film is presented in Fig. 1c. The O-H and CH\textsubscript{2} symmetrical stretching peaks of the tapioca starch were observed as large bands at 3278 and 2927 cm\textsuperscript{-1}, respectively. The peaks at 857 and 760 cm\textsuperscript{-1} were attributed to the skeletal stretching of the starch, while the absorption bands from 1150 to 927 cm\textsuperscript{-1} were assigned to the C-O vibration of amylopectin from the tapioca. The absorption peaks observed at 1590, 1488, and 949 cm\textsuperscript{-1} were assigned to the vibration of the TMAH.
Colorimetric detection of TNT

The organic-based TMAH was used as a colorimetric reagent because of its solubility in organic solvents and because it has a low propensity to cause deterioration of the matrix with the formation of interfering colored products.\(^4\,^{42}\) A purple product was obtained from the colorimetric test of TNT with the thin-film sensors (Fig. 2) based on the formation of a charge transfer product (Meisenheimer complex). However, the shade of purple color products obtained from the starch sensors was different to those obtained in previous work (red-violet from a TMAH-doped cryogel matrix\(^4\) as shown in Fig. 3c). The purple product observed in this work may contribute to the production of Janowski anions\(^4,^{28,42-44}\) which would gradually change to a stable red-violet color within 10 min.\(^6\) This purple product was easily distinguishable from the color products from other nitroaromatic explosives, e.g., the blue products from dinitrotoluene (2,4-DNT and 2,6-DNT), the violet product from 1,3-dinitrobenzene (1,3-DNB),\(^4\) while no color change was observed with 4-nitrotoluene, composite 4 (C-4), or pentaerythritol tetranitrate (PETN). Several cations and anions (~10,000 mgL\(^{-1}\)), including sodium nitrate, calcium chloride, potassium chloride, chromium (III) chloride, sodium chloride, sodium fluoride, sodium sulfate, cadmium disulfate, zinc acetate, manganese sulfate, and cobalt (II) nitrate also provided clear products nor was any color change observed from real or artificial sugar, paracetamol, salt, or detergent (sodium dodecyl sulfate). These results indicated that the TMAH-doped starch sensors exhibited good selectivity for TNT. The sensors also had good sensitivity as the purple product from 5 mgL\(^{-1}\) TNT could be observed with the naked eye.
Quantification of TNT using the TMAH-doped starch sensors and DIC

The use of DIC for the quantitative analysis of TNT has been previously reported⁴-⁶,³⁰,³³ and in this work, the plasticized and non-plasticized TMAH-doped starch sensors were compared using DIC. The RGB intensities of reflected light from the purple products from testing TNT with the plasticized and non-plasticized sensors are shown in Fig. 3a and 3b, respectively. Red light provided the highest intensities in both sensors corresponding to the results of a previous work in which TMAH was entrapped within a cryogel matrix.⁴ However, the intensities of the blue light were higher than those of green with both sensors, contrasting with the results produced by the TMAH-cryogel.⁴ This difference contributed to the different shades of the color products obtained from the starch sensor in this work (purple) and the cryogel (red-violet as shown in Fig. 3c)⁴. When the concentrations of TNT were increased, the RGB intensities consistently decreased as the products became darker in color.

The absorbance of the colorimetric product was estimated from the color band intensities using equation 2:\³²,⁴⁵

\[
A_X = -\log \left( \frac{I_X - I_{X,b}}{I_{X,w} - I_{X,b}} \right) = -\log \frac{(I_X)_c}{(I_{X,w})_c} = -\log R_X
\]

(Equation 2)

where for each color (R, G, B), \(A_X\) is the absorbance of \(X\), \(I_X\) is the intensity of \(X\), \(I_{X,b} = 0\), \(I_{X,w} = 255\), and \(R_X\) is the reflectance of light \(X\) and \(C\) is the concentration of \(X\). An inverse relationship was obtained, and the green channel (500-580 nm) dominated in absorbance over the blue and the red channels (Fig. 4a-b). This was in good agreement with spectrophotometric results which provided the maximum absorbance at 530 nm. The highest absorption of the green channel instead of the blue channel in the cryogel matrix in the previous study using a cryogel matrix⁴ indicated a different complex occurring from the test. However, two kinds of complexes at wavelengths 460 nm
(blue) and 530 nm (green) have been reported from the Meisenheimer or Janowsky reactions.\textsuperscript{6,46} The estimated absorbance increased with the TNT concentrations because of the increased production of the color products.

Both the intensities and the estimated absorbances exhibited a linear relationship with the TNT concentration which offers a convenient means of quantifying TNT. In the case of the plasticized sensors, the green and the blue channels had linear relationships in the range of 2.5 to 25 mgL\textsuperscript{-1} of TNT. However, a wider linear range (2.5 to 50 mgL\textsuperscript{-1}) was found for the calculated absorbance of the non-plasticized sensors for all channels (Fig. 4c-d).

Since the color of the sample may affect the color of the product,\textsuperscript{4} the interference from other chemical components in blanks may require compensation. All the RGB intensities and absorbances increased with the TNT concentration (Fig. 5a-d) and the relationships showed good linearity ($R^2 > 0.9915$) over a range of 2.5 to 25 mgL\textsuperscript{-1} of TNT, in both zero-calibrated intensity and calculated absorbance.

\textit{System performance and method validation}

The performance of the TMAH-doped starch sensor and DIC system for the quantification of TNT is summarized in Table 1. The green light in the digital images generated from the non-plasticized sensor provided the highest sensitivity (1.11 ± 0.07 a.u. Lmg\textsuperscript{-1}). This sensor also provided the widest linear range of 2.5 to 50 mgL\textsuperscript{-1}, which was wider than that of the spectrophotometric method (5 to 50 mgL\textsuperscript{-1}).\textsuperscript{7} The detection limits\textsuperscript{35} of both sensors were from 0.268 ± 0.002 mgL\textsuperscript{-1} to 3.4 ± 0.2 mgL\textsuperscript{-1} which was better (i.e., lower) than the 3 mgL\textsuperscript{-1} achieved by spectrophotometric detection.\textsuperscript{7} The plasticized sensor provided better detection limits (0.268 ± 0.002 mgL\textsuperscript{-1} to 1.79 ± 0.06 mgL\textsuperscript{-1}) than those of the non-plasticized sensor (1.05 ± 0.02 mgL\textsuperscript{-1} to 3.4 ± 0.2 mgL\textsuperscript{-1})
and also than those previously reported for cryogel\(^4\) (0.48 ± 0.01 mgL\(^{-1}\) to 1.84 ± 0.06 mgL\(^{-1}\)), hydrogel\(^5\) (0.32 ± 0.01 mgL\(^{-1}\)) and PVC thin-film\(^6\) (1.00 ± 0.02 mgL\(^{-1}\) to 5.4 ± 0.3 mgL\(^{-1}\)).

The analysis of three non-plasticized sensors during the same day provided intra-day precision in a range of 0.15 to 0.59 %RSD, while 1.73 to 3.74 %RSD was obtained for fifteen sensors across five days (inter-day precision). This indicated good reproducibility of the developed method. Accuracy in terms of relative error (%RE) by testing a control sample (7.5 mgL\(^{-1}\) TNT) using the non-plasticized sensors was in a range of -0.14 to +1.72 %, with a range of +5.3 to +8.1 % for spiked soil samples.

**Stability of the TMAH-doped starch sensors**

The intensities of the red, green and blue channels in testing TNT solution (10 mgL\(^{-1}\)) using the non-plasticized sensors shifted by -4.3 %, -3.1 %, and -3.3 % after storing them in a freezer for three months. The results thus indicated good stability of the sensors which was able to maintain good performance during three months of storage in a freezer and these results were similar to those achieved from other test kits, i.e., -5.8 %, -0.7 %, and -12.1 % for cryogel\(^4\), -5.4 %, +0.3 %, and +4.0 % for hydrogel\(^5\), and +5.0 % (blue channel for two months) for PVC film\(^6\).

**Analysis of post-blast samples**

Blank soil samples were spiked with TNT standard solution (10 mgL\(^{-1}\)) before extraction with the same procedure as previously reported\(^4\), to investigate the extraction efficiency. Recovery in a range of 106.6 to 113.4 % was obtained using the non-plasticized biodegradable sensor which indicated acceptable efficiency of the extraction method. The blank soil samples were also spiked with TNT standard solution.
after the extraction procedure in order to investigate the potential interference of the soil matrix in the determination of TNT. The relative errors obtained in a range of +5.3 to +8.1% indicated no interference from the color of the soil matrix.

The non-plasticized sensors were applied to test four post-blast soil samples and two positive results were observed. The concentrations quantified by DIC \((I_c)\) were 0.017 and 0.07 mg g\(^{-1}\), which were in good agreement with spectrophotometric results obtained from the same samples (0.012 and 0.06 mg g\(^{-1}\)). These results indicated the excellent performance of the TMAH-doped starch sensor when combined with DIC for the analysis of TNT in soil samples.

**Conclusions**

The TMAH-doped starch thin-film developed in this study is capable of being applied for the selective detection of TNT. It can be used to create a portable test kit for on-site detection with the thin film being used to fabricate a sensor in a small flat-cap plastic tube to which only a small amount of a sample solution needs to be directly added for the purposes of TNT detection. Since the film was fabricated from starch, which is readily biodegradable, the colorimetric sensor developed is environmentally friendly. When the thin-film sensors were used in combination with DIC, accurate and rapid quantitative analysis of TNT was achieved with good system performance and the non-plasticized sensor maintained stable performance over 3 months of storage in a freezer.
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Table 1  Analytical performance in TNT detection of the thin-film test kit.

| Type of film | Feature from image analysis | Sensitivity/a.u. Lmg\(^{-1}\) | Linear range/mgL\(^{-1}\) | Linearity | LOD\(^a\)/mgL\(^{-1}\) |
|--------------|-----------------------------|-------------------------------|----------------------------|-----------|------------------------|
| Plasticized  | IG                          | 1.08±0.04                     | 2.5 – 25                   | 0.9941    | 1.79±0.06              |
|              | IB                          | 0.955±0.006                   | 2.5 – 25                   | 0.9999    | 0.268±0.002            |
|              | AG                          | 0.00380±0.00005               | 2.5 – 25                   | 0.9997    | 0.660±0.008            |
|              | AB                          | 0.00320±0.00006               | 2.5 – 25                   | 0.9996    | 1.01±0.02              |
|              | |IG-IGBlank| 1.07±0.03 | 2.5 – 25 | 0.9987 | 1.34±0.03 |
|              | |IB-IBBlank| 0.955±0.006 | 2.5 – 25 | 0.9999 | 0.304±0.002 |
|              | |AG-AGBlank| 0.00380±0.00005 | 2.5 – 25 | 0.9997 | 0.662±0.008 |
|              | |AB-ABBlank| 0.00320±0.00006 | 2.5 – 25 | 0.9996 | 1.01±0.02 |

\(^a\)LOD = y_B + 3S_B

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### Table 1  Analytical performance in TNT detection of the thin-film test kit. (continued)

| Type of film   | Feature from image analysis | Sensitivity/a.u. Lmg$^{-1}$ | Linear range/mgL$^{-1}$ | Linearity | LOD$^{a}$/mgL$^{-1}$ |
|---------------|-----------------------------|-----------------------------|--------------------------|-----------|---------------------|
| Non-plasticized | IR                          | 0.65±0.02                   | 2.5 – 25                 | 0.9982    | 1.57±0.05           |
|               | IG                          | 1.11±0.07                   | 2.5 – 25                 | 0.9915    | 3.4±0.2             |
|               | IB                          | 0.95±0.02                   | 2.5 – 25                 | 0.9992    | 1.05±0.02           |
|               | AR                          | 0.00200±0.00006             | 2.5 – 50                 | 0.9972    | 2.11±0.08           |
|               | AG                          | 0.0034±0.0002               | 2.5 – 50                 | 0.9912    | 3.1±0.2             |
|               | AB                          | 0.0027±0.0002               | 2.5 – 50                 | 0.9898    | 1.64±0.05           |
|               | $|I_R-I_{Rblank}|$         | 0.65±0.02                   | 2.5 – 25                 | 0.9982    | 1.57±0.05           |
|               | $|I_G-I_{Gblank}|$         | 1.11±0.07                   | 2.5 – 25                 | 0.9915    | 3.4±0.2             |
|               | $|I_B-I_{Bblank}|$         | 0.95±0.02                   | 2.5 – 25                 | 0.9992    | 1.05±0.02           |
|               | $|A_R-A_{Rblank}|$         | 0.00220±0.00009             | 2.5 – 25                 | 0.9973    | 2.12±0.08           |
|               | $|A_G-A_{Gblank}|$         | 0.0039±0.0002               | 2.5 – 25                 | 0.9931    | 3.1±0.2             |
|               | $|A_B-A_{Bblank}|$         | 0.0032±0.0001               | 2.5 – 25                 | 0.9983    | 1.64±0.05           |

$^{a}y_{LOD} = y_B + 3S_B^{35}$
Figure captions

Fig. 1  (a) TMAH-doped starch film (b) Scanning electron microscope (SEM) images (c) FTIR spectrum of the film.

Fig. 2  Colorimetric products of TNT from testing with the TMAH-doped starch sensor.
(a) plasticized sensor (b) non-plasticized sensor.

Fig. 3  Responses in RGB intensities to various TNT concentrations.
(a) plasticized sensor (b) non-plasticized sensor (c) colorimetric product at 100 mgL⁻¹ of TNT (1) plasticized sensor (2) non-plasticized sensor (3) cryogel test kit from a previous study⁴.

Fig. 4  Calculated absorbance vs. TNT concentration.
(a) plasticized sensor (b) non-plasticized sensor (c) linear portion of the calculated absorbance relationships from plasticized sensor and (d) linear portion of the calculated absorbance relationships from non-plasticized sensor.

Fig. 5  (a) Zero-calibrated RGB intensities for plasticized sensor (c) corresponding absorbances for plasticized sensor (b) Zero-calibrated RGB intensities for non-plasticized sensor (d) corresponding absorbances for non-plasticized sensor.
Fig. 1
Fig. 2

(a) 0  2.5  5.0  10  25  50  100 mg L\(^{-1}\)

(b) 0  2.5  5.0  10  25  50  100 mg L\(^{-1}\)
Fig. 3
Fig. 4
Fig. 5

(a) plasticized film

(b) non-plasticized film

(c) plasticized film

(d) non-plasticized film