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REVIEW PAPER

Landmine Detection Technologies to Trace Explosive Vapour Detection Techniques

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ABSTRACT

Large quantity of explosive is manufactured worldwide for use in various types of ammunition, arms, and mines, and used in armed conflicts. During manufacturing and usage of the explosive equipment, some of the explosive residues are released into the environment in the form of contaminated effluents, unburnt explosives fumes and vapours. Limited but uncontrolled continuous release of trace vapours also takes place when explosive-laden landmines are deployed in the field. One of the major technological challenges in post-war scenario worldwide is the detection of landmines using these trace vapour signatures and neutralising them safely. Different types of explosives are utilised as the main charge in antipersonnel and antitank landmines. In this paper, an effort has been made to review the techniques so far available based on explosive vapour detection especially to detect the landmines. A comprehensive compilation of relevant information on the techniques is presented, and their maturity levels, shortcomings, and difficulties faced are highlighted.

Keywords: Landmine detection, trace explosive vapour detection, multi-sensor devices, sensor fusion

1. INTRODUCTION

To achieve superiority over other nations, every country strives to enhance the capabilities of its own security system by innovating and developing new materials and technologies in the field of arms, ammunition, and weapon systems. Obsolete, life-expired and rejected ammunition are discarded and disposed in the environment, which leads to release of explosive vapours into the environment[1]. Deployment of antipersonnel (AP) and antitank (AT) landmines during wartime is another big menaces. Apart from locating these materials, explosive vapour detection is one of the useful and important techniques for: (a) forensic investigations such as arson[2], (b) post-blast residue determinations[3], (c) mapping mine fields, military bases, remediation sites[4], etc, and (d) workplace monitoring. For detecting explosives vapours, many techniques such as electrochemical[5], chromatographic techniques[6], optical fibre[7], fluorescence detection[8,9], x-ray diffraction[10], and surface acoustic wave (SAW) sensor[11,12], have been reported.

A number of other techniques such as: (i) antibodies, (ii) artificial noses, (iii) canine nose, (iv) TNT-seeking insects, (iv) ion mobility spectrometry, (v) ion-trap mass spectrometry, (vi) neutron analysis, (vii) photoacoustic spectroscopy, (viii) nuclear quadruple resonance, (ix) reversal electron attachment detector, and (x) chemical polymer-coated sensor are under development for the detection of explosives with limited success and still development work is continuing[13].

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Development of chemical vapour sensors is based on obtaining specific explosive signature, pertaining to poly-nitro-aromatic compound of explosive charges[14].

Some of the important and critical factors for this application are very low-detection limits (ppt), short-detector response time for operations, involving moving platforms, good baseline stability, and minimum interferences from environmental species and conditions. It has been reported that these factors are key to the successful application of polymer-based chemical vapour sensors systems[15]. This paper has covered various vapour detection techniques developed worldwide with special reference to landmine detection, and also highlights the shortcomings of various such techniques in addressing the landmine menace.

2. VAPOUR IN THE VICINITY OF LANDMINE

Different types of explosives are utilised as the main charge in antipersonnel (AP) and antitank (AT) landmines. However, the most commonly used explosive in landmines is TNT (trinitrotoluene). Almost 80 per cent of different types of landmines manufactured worldwide contain TNT or mixtures of explosives containing TNT[16]. It is estimated that TNT-containing landmines have 80 per cent of the total number of landmines now deployed[17].

It has been observed that explosive charge is always accompanied with impurities such as 2,4-dinitrotoluene (DNT), 2,6-DNT, 1,3-dinitrobenzene (DNB) and 2,4-DNB in the military grade TNT, and these impurities generate higher vapour concentrations than 2,4,6-TNT itself[18,19]. 2,4-DNT is an impurity, as a solid constituent in the range 9.32×10^{-5}–7.43×10^{-4} g/g of TNT at 22 °C in the military grade TNT. A headspace vapour constituent of 2,4-DNT was 6.9×10^{-11}–1.9×10^{-9} g/g[18], which is significantly higher than 2,4,6-TNT. Similarly, 1,3-DNB is another impurity in the range 1.39×10^{-5}–8.88×10^{-4} g/g of TNT at 22 °C. A headspace vapour constituent of 1,3-DNB was 2.2×10^{-11}–4.3×10^{-9} g/g. This is because of the fact that the vapour pressure of 2,4-DNT and 1,3-DNB are approximately 40–1000 times greater than the vapour pressure of TNT. Recently it was found that the explosive detection techniques are highly advantageous to look for 2,4-DNT and 2,3-DNB vapours as signature of TNT-based explosives.

Flux measurement of DNB, DNT, and TNT of few landmines at various temperatures, viz., 3.0 °C, 13.0 °C, 22.5 °C, 23.0 °C and 34.0 °C is presented in Figs 1 and 2. The graph clearly indicates that more vapours from impurities are emitted than the main charge. The extrapolated values for few more levels of temperatures are also shown in the same figure. For Indian tropical weather, where the temperatures in the western, northwestern, eastern and northeastern borders are above 40 °C in a major part of the year, and hence, good amount of explosives vapour signature around the hidden explosives are expected[18].

Figure 3 shows a conceptual model of the environmental fate and transport processes that

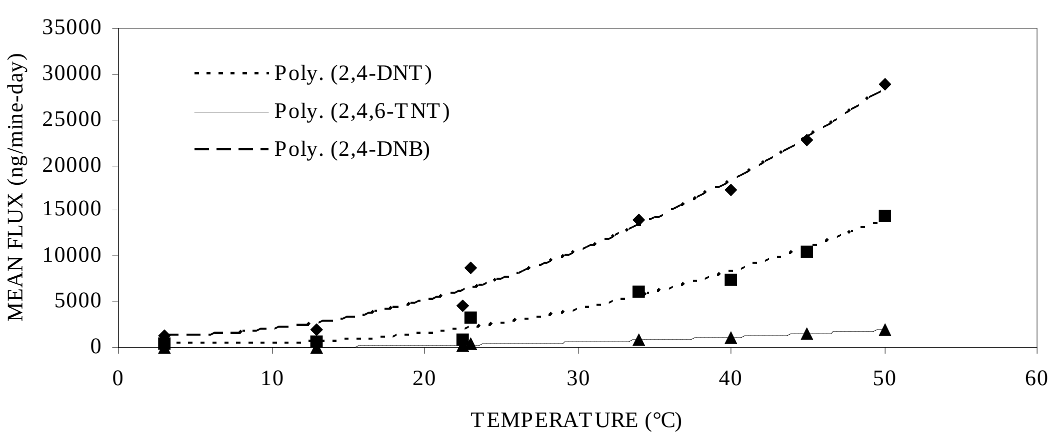

Figure 1. Mean flux into air for 2,4-DNB, 2,4-DNT, and 2,4,6-TNT from PMA1A landmines.

impact the movement of landmine chemical constituents to the land surface for chemical detection. Chemical vapours emanate from buried landmines by permeation through plastic case materials or leakage through seals and seams, and also from surface contamination of the mine case. Transport through the surrounding soil occurs in the liquid and vapour phases by diffusion and advection. Liquid phase advection occurs through precipitation and evaporation of water from the soil, and gas phase advection can occur due to barometric pressure changes[20].

Because of the shallow burial depth of landmines, land surface processes may play a significant role in the transport chemicals. Figure 4 depicts the principal surface boundary conditions that may affect chemical signature movement. Another report is available on the evaluation of movement and availability of explosive vapour from the buried landmines with experimental models[21] and using gas chromatograph mass spectrometer analysis for DNT and DNB concentration around the landmine[22].

3. EXPLOSIVE VAPOUR IN THE ENVIRONMENTAL CONCERN

Although the inherent physical properties of explosives do not encourage these vapours to emanate

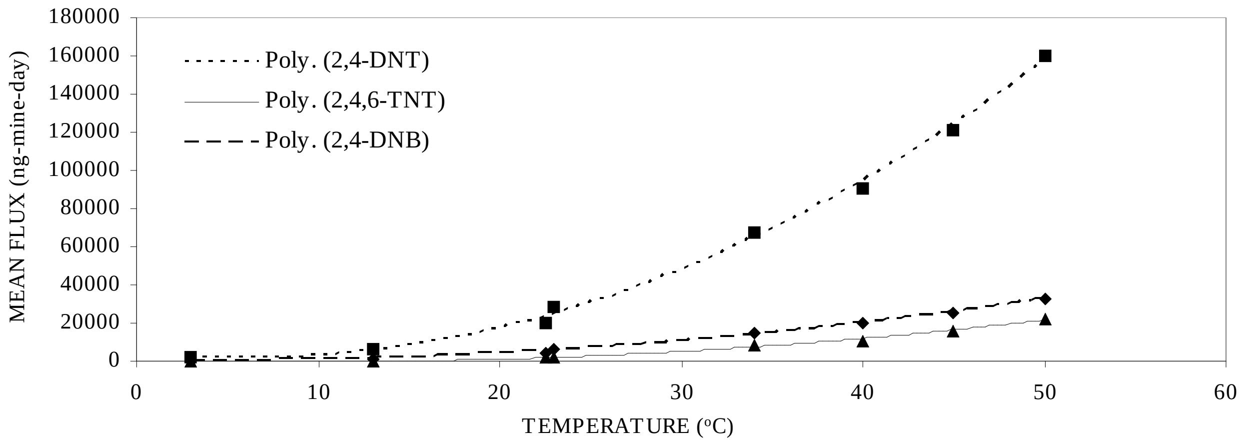

Figure 2. Mean flux into air for 2,4-DNB, 2,4-DNT, and 2,4,6-TNT from TMA5 landmines.

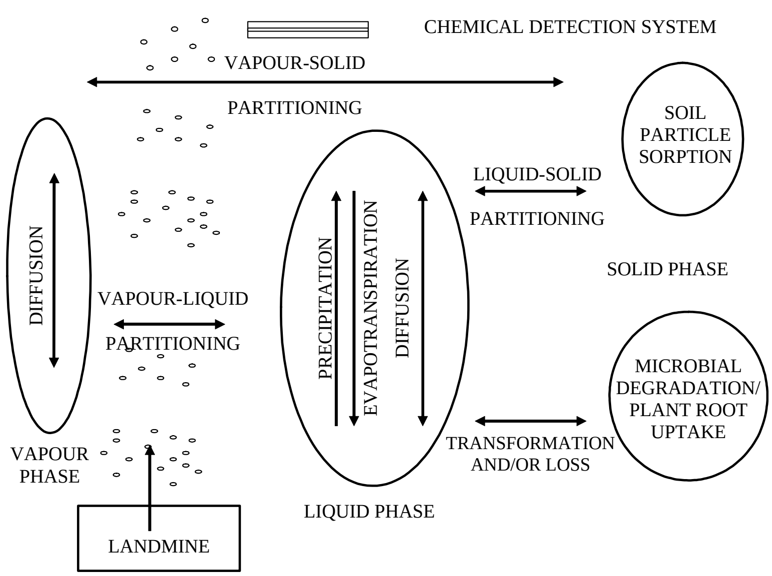

Figure 3. Conceptual model of the environmental fate and transport.

in large quantities into the air environement, still considerable quantaity of TNT vapours are expected to enter the workplace environment. This poses threat to the safety and health of the personnel working there[23]. Explosives are known to be toxic for many years and present a health hazard for ammunition workers and military personnel who handle them[24].

In one of such studies, total suspended particulate matter (SPM) of explosives was found to be significantly high in the dentex and composite modified doublebase section and found to exceed the permissible limits[25]. In an another study of the solid propellant shell assembling facility, the total SPM of propellant dust was 0.059 mg/m^3 outside the room and 0.303-0.312 mg/m^3 inside the assembling. The particulate distribution showed major fraction (> 90 %) of the SPM generated in the assembling facility was in the non-respirable range (>10 µm). However, in the same study carried out in the solid propellant firing facility, the personnel exposure (2.551 mg/m^3) and workplace (1.191 mg/m^3) were found to be within the permissible limits. The number size distribution shows that a large fraction (42-85 %) are in the respirable range[26] (<10 µm).

4. AIRPORT/TRAIN SECURITY SYSTEM

New technology and sensor systems could eventually be employed to monitor the airport bagage and packages at postal offices or could be incorporated in conventional metal detectors used for landmine detection[27]. A high-speed SAW-based gas chromatography system for the detection of illicit materials such as drugs or explosives have been developed and its analysis time is 10-15 s. The system can be useful in airports security checks[28].

5. NECESSITY OF LANDMINE DETECTION

International Committee for the Red Cross estimates that 120 million unexploded landmines are scattered throughout about 70 countries. A United Nations (UN) estimate indicates that by 1995 only, 80,000 of this huge number were cleared and 2.5 million more were installed during the same period. This UN study estimates that it is likely to take around 1,100 years to clear all the mined areas in the world with the current technology. The mine menace is worst in many countries. For example the following countries have millions of unexploded landmines scattered in the area:

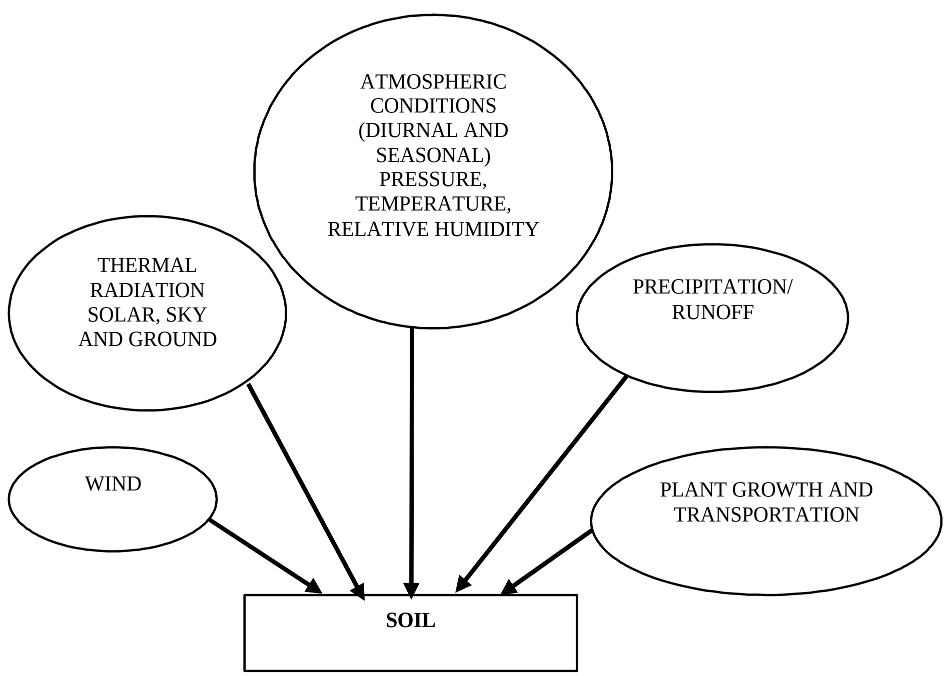

Figure 4. Principal surface boundary conditions that may affect chemical signature movement[20].

Afghanistan (10 million)
Angola (15 million)
Bosnia and Herzegovina (3-6 million)
Cambodia (10 million)
Croatia (3 million)
Egypt (23 million)
Iran (16 million)
Iraq (10 million)
Mozambique[27] (2 million).

6. EXPLOSIVE VAPOUR DETECTION

A number of techniques are available to detect the explosives, either in bulk detection or vapour-based detection. Even live animals are used to detect the explosives. Since the explosives vapour pressure is very low and hence the vapour concentration around the explosive storage, mine, etc. is also low. Hence the detection has become very difficult. In this paper, an attempt has been made to cover the various techniques available and their maturity-level.

6.1 Explosive Vapour Generation

The inherent physical properties of explosives do not encourage the vapours to emanate in large quantities into the air, still a considerable quantity of explosive vapour is expected to be present in the environment around the explosives. Since explosives at normal temperature are solid and do not emanate vapours, for sensing and related experiments, it is necessary to convert these into vapour phase. Way back as a pioneer, Pella[29] has developed an explosive vapour generator for 2,4,6-TNT, 2,4-DNT and ethylene glycol dinitrate for calibrating explosive vapour detectors[29] and with modification and improvement, a vapour generation unit has been designed to produce vapour concentration[30] of 2,4,6-TNT as shown in Fig. 5.

The same has been used to generate 2,4-DNT, 2,6-DNT,1,3-DNB and 2,4-DNB with minor modifications in the system[31]. Apart from these type of generator, other types such as permeation explosive source (a permeation bag) has also been used[32]. Another type of generator consisting a heated block to thermostat the sample container has also been developed[33]. Pulsed vapour generator have also been designed and used in various studies[34-36]. Activated carbon or XAD have been used to standardise these explosive vapour generators using liquid chromatography or gas chromatography[30,37]. In one of the research, in place of glass column, a copper column was used and the TNT and DNT were coated on sand granule before filling the column.

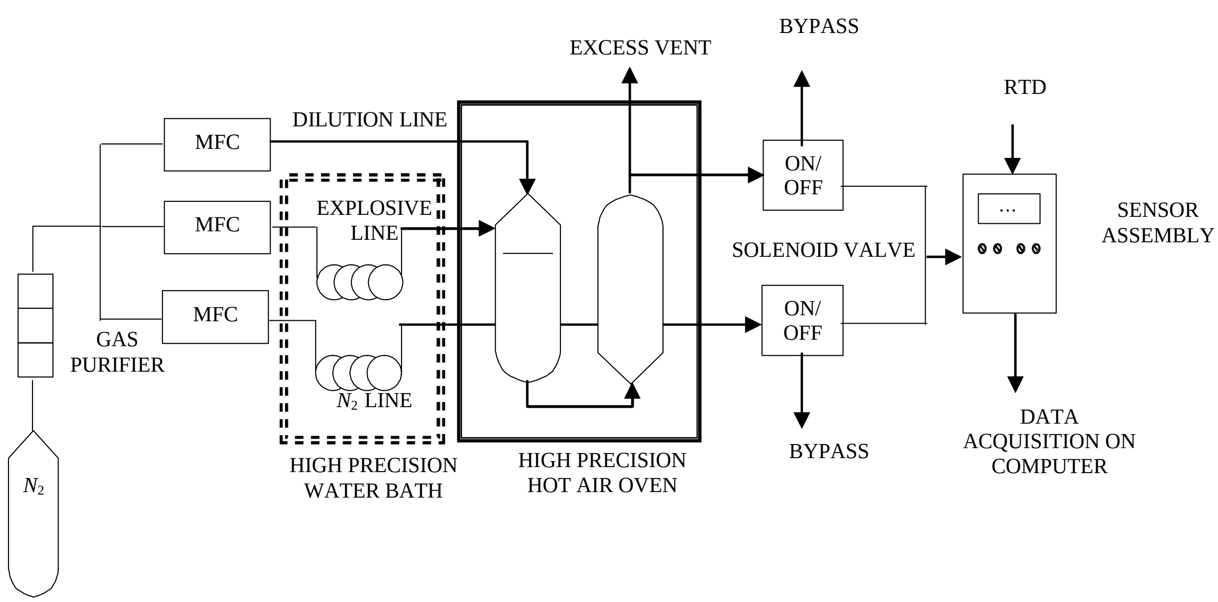

Figure 5. Schematic diagram of explosive vapour generation unit along with sensor calibration assembly [30].

6.2 Electrochemical Detection Method

One of the explosive vapour detection pursued is electrochemical detection in amperometric gas sensors, recording the current in the electrochemical cell between sensing and counter electrodes at a certain potential. Amperometric sensors produce a current when exposed to a vapour containing an eloectroactive analyte reacting within the cell, either producing or consuming electrons, in which case the analyte is elecrtro-oxidised or electro-reduced at the electrode[38]. Thermal decomposition of explosives over heated noble metal surfaces generates characteristic pyrolysis products that can be detected by amperometric gas sensors. This effect was used to develop a method for the detection of TNT vapours in soils[5,39]. The distribution of thermal products depends primarily on the temperature and nature of the catalytic surface, which can be controlled and on the compound undergoing pyrolysis. The characteristic vapours generated by pyrolysis of TNT and other explosives contain NO and other nitrogen-oxygen compounds in addition to CO, CO_2, and H_2O.

In another study, the probe covered by sulphuric acid hanging in the air was used. Pure TNT was placed approx. 10 cm below the tip of the probe and the current as a functions of time was recorded. The clear reduction in the peak was found to have been the signature of explosive vapour and suggested fast detection of explosives[41].

6.3 Fluorescence Techniques

This is another type of technique widely explored. A study has been carried out using amplifying fluorescne polymer-based sensor prototype which showed excellent promise as a viable landmine detection tool. The sensor has demonstrated, during field and laboratory tests, the sensitivity and selectivity needed to detect the landmines. The reported minimum detection limit of the sensor for nitroaromatics even lower into the mid to low attogram (10^{-16} to 10^{-18}) range. The sensor is reported to detect the ultra trace concentrations of TNT vapours and other nitroaromartic compounds found in many landmine explosives[42].

Another researcher has used sniffer system employing two types of fluorescnece-based vapour sensors. One sensor type is semiselective for nitroaromatic compound vapours[8,42-43], while the other sensor type is designed to be non-specific and cross-reactive array, fluorensce response patterns are monitored before, during, and after vapour exposure to produce time-dependent vapour response patterns. This detection system have been used to detect 2,4-DNT on the soil surface of landmines. The system has been characterised to detect 120 ppb of 2,4-DNT vapours[7].

Porous silica microspheres with an incorporated environmentally-sensitive fluorescent dye are employed in high-density sensor arrays to monitor the fluorescence changes during nitroaromatic vapour exposure. Using this technique, 2,4-DNT and DNB are detected at low ppm levels within seconds[9]. Also studies on fluorescence quenching have been carried out to realise explosive vapour sensors. Many polymers have been evaluated to the equilibrium vapour pressure of TNT, DNT at variable length of time[45]. The fluorescence-quenching method has been applied to RDX, HMX, TNT, nitromethane, ammonium nitrate in various commercial explosive supply using capillary liquid chromatography by laser-induced fluorescence[46].

6.4 Ion Mobility Spectrophotometer

A limited progress has been reported in this detection. Ion mobility spectrophotometer has been used to demonstrate TNT vapour detection for landmine detection. The rough test proved that the improvement could be made. However, after burial of landmine, 0.1 ppb for TNT and 0.8 ppb for DNT was found on the soil surface. This has been found to be a very low concentration for ion mobility spectrophotometer to detect[21]. Gas chromatography mass spectrometer has also been reported to be used for explosive vapour detection[47].

6.5 Polymer-coated SAW Sensor

In recent years, a lot of research has been made on the exploration of surface acoustic waves (SAWs) for possible usage in the explosive vapour detection. In a SAW device, entire device operation takes place on the free surface of a piezoelectric substrate. The sensing attributes are imparted through deposition of a chemical interface on the device surface that selectively sorbs the target analyte from environment and causes mass loading[48]. A number of polymers have been tested for their efficacy in responding to the explosive vapours. The most promising materials tested include siloxane polymers functionalised with acidic pendent groups that are complimentary in their solubility properties for nitroaromatic compounds[14].

A great variety of materials have been employed as layers on the surfaces of acoustic wave devices to modify the sensitivity and selectivity for chemical analytes. Materials applied range from conventional chromatographic stationary phases and polymers to such unusual materials as soot extracts[49] as well as structured materails such as bullfrog olfactory receptor proteins, dendimers and cavitands.

A number of polymers have been tested for their use as sensing polymers for nitroaromatics for the detection of explosive vapour-sensing SAW, use of various adsorbent materials such as carbowax-1000 for mononitrotoluene using 9 MHz SAW device and observed the frequency shift[11] of $\Delta f = 11.4\ \text{MNT}^{0.319}$ found useful for the detection of MNT with good selectivity and fast response. Also quadrol has also been used for the explosives detection[50] and fluoropolyol and its modified compound, viz., SXPHFA and SXFA on low-frequency devices[12,51] have also been reported. The most sensitive of the new polymers exhibit SAW sensor detection limits[14] for nitrobenzene and 2,4- dinitrolune at 3ppb, and 235 ppt respectively.

In the recent past, carbowax 1000 has been tried for its explosive detection for 2,4-DNT using 150 MHz device and the response observed[52] to be 0.56 - 1.1 Hz/ppb. The typical linear response curve reported for the 2,4-DNT is shown in Fig. 6. Poly- dimethylsiloxane has also been used as a sensing material for TNT using 37 MHz SAW devices and the frequency shift observed[53] has been 10 Hz/ppb. In another study, 37 MHz device has been used with carbowax 1000 for the detection of TNT vapours. The response was 8Hz/ppb of TNT vapours at room temperature[54]. Thin-film bulk acoustic wave resonators have been used and demonstrated to detect 5 ppb levels of TNT vapours[55]. Some of the responses of SAW sensor shown in the literature are presented in Table 1.

7. ELECTRONIC NOSE

The concept of using sensor arrays for chemical analysis gained widespread recognition in the 1980s and has continued vigorously in the 1990s. The advantages that sensor arrays offer over individual sensors are sensitivity to a wider range of anlytes, improved selectivity, simultaneous multicomponent analysis and the capability for anlayte recognition. By analogy with olfaction systems comprising multiple receptors and neural pattern recognition, sensor arrays for gas phase detection are sometimes dubbed electronic noses[50]. This approach reduces the demand for highly selective sensors and places more emphasis on sensor reproducibility, sensor stability, and the computational analysis software employed to differentiate the sensor-analyte.

One study has been done on the development, characterisation, and use of a field deployable system to detect the 2,4-DNT vapours based on the artificial nose technology[56] and also employing an array of cross-reactive optical sensors, the array differentially responds to different analytes[57].

The initial investigations of SAW sensor arrays with pattern recognition analysis were publised[58,59] in 1986 and 1988 with an additional investigation in 1993 describing a self-contained SAW array systems with automated sampling and preconcentration[60]. In one of the studies, 12 polymers coating on 112 MHz SAW delay lines were tested against 11 vapours[58].

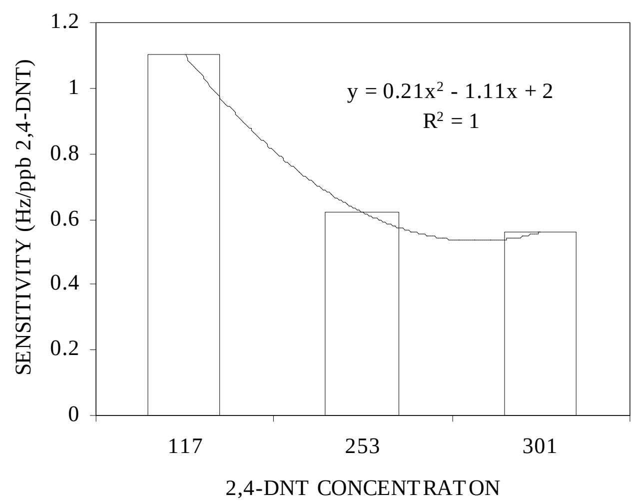

Figure 6. Typical linear response curve reported for the 2,4-DNT using 150 MHz SAW device.

Table 1. Some of the responses of SAW sensors[31]

Vapour	Vapour temp. (°C)	Vapour conc. (ppb)	SAW sensor frequency change (Hz)	Frequency shift (Hz/ppb)	Coating material	Sensing SAW device (MHz)
2,4-DNT[52]	40	117	130	1.1	Carbowax	150
	50	253	158	0.62		
	55	301	168	0.56		
2,4,6-TNT[61]	45	50	400	8	Carbowax	37
2,4,6-TNT[53]	55	50	400	8	PDMS	37
MNT[11]	50	7500	193	0.025	Carbowax	9
2,4-DNT	40	90	99	Frequency shift was computed deriving K [as per Eqn (4)] from vapour concentration and frequency shift of earlier published work[52] for 150 MHz SAW device coated with Carbowax-1000. Sensor response has been computed based on the Hz/ppb shift of carbowax-1000 coated on 150 MHz SAW device study carried out earlier for 2,4-DNT[31].		
	50	253	157			
	60	366	205			
2,6-DNT	40	4.9	5.4			
	50	16	9.9			
	60	44.3	24.8			
1,3-DNB	40	129	98.0			
	50	225	171.0			
	60	256	194.5			
1,4-DNB	40	8	6.1			
	50	14.7	11.2			
	60	30.7	23.3			

A typical response of the polymer for various isomers and other nitroaromatic compounds reported[31] is depicted in Fig. 7.

8. CURRENT STATUS OF EXPLOSIVE VAPOUR DETECTION TECHNIQUES

Various landmine detection techniques have been developed and are in progress. In Table 2, some of the techniques[62] have been listed along with their effectives and limitations. In Table 3, all types of landmine detections, including the bulk detection, have been included and also the maturity-levels of these techniques have been summarised. Also, the cost and complexity of the techniques have been enumerated.

9. CONCLUSIONS

The challenge for researcher is not only to develop the techniques that can meet such high-end demanding level of trace vapour detection requirements in real-time, but also to tailor such techniques to their local conditions. Detecting landmines in the sandy desert is very different from detecting them in the fertile soil, and these are very different for detecting ppb or ppt levels in the laboratory. It will be difficult to device a fast technique for detection of landmines using any one detection technique even if the nature of the mine, soil and background

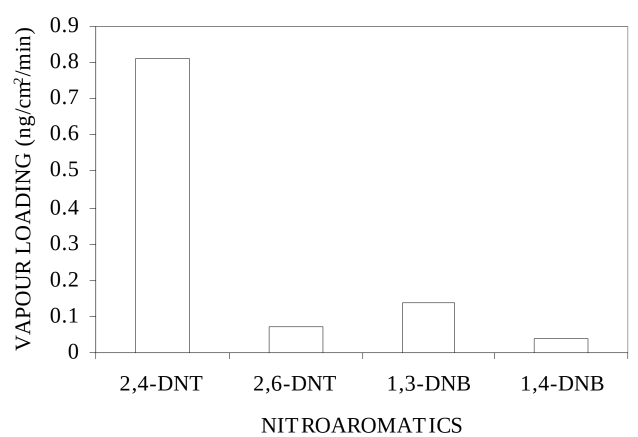

Figure 7. A typical response of the carbowax polymer for various isomers and other nitroaromatic compounds reported.

Table 2. Details of various mine detection techniques employed and their limitations[62]

Techniques	Remarks
Manual mine clearance (prodding)	20-50 m^2/day/man
Automated mine detection	20-50 m^2/day
Metal detectors and magnetometers	Ineffective for plastic, wood and cardboard mines; not differentiate mine and metal scrapes
Mechanical detection techniques	15000 m^2/day /flail
GPR and passive millimeter wave detection	Surrounding characteristics should be different; not effective in wet ground
Infrared imaging	Effective maximum to 10-15 cm depth
Acoustics resonance spectroscopy	Used to detect mines in water
Backscattered x-rays	Useful only in plastic mines
Multi sensor mine detectors (sensor fusion)	May be useful
Chemical sensing of explosives (vapour -sniffing detectors, canine nose, artificial sensors, polymer chemical sensors, thin- film resonators, microbial mine detection)	SAW lowest detection is 235 ppt for 2,4-DNT

clutter is known *a priory*. Special detector technology that can detect ppt-level vapours in real-time with very fast response times will be needed to detect the landmines and carry out demining of the landmine that have escaped the detection with the present techniques, and one is sure that those are the majority of the initially deployed.

It is inconceivable that a single detection technique will be able to meet all such needs. In fact, none of the techniques at present appears capable of reaching, in a large number of situations, desirable detection efficiencies and also maintaining low-false alarm rate. Rather, each one will probably has to find, if it exists, a specific area of applicability, determined by technological as well as economical or even social factors, and possibly forming inter-communicating networks with other sensors loosely termed at present as sensor fusion. Anomaly detectors detect objects which are not expected in their natural environment. In contrast to anomaly detectors, which look for the container holding the explosive, chemical sensors look for the explosives contained inside the mines, either by sniffing the explosive vapour or by bulk detection. Many technologies in use for the detection of landmines and unexploded ordnance suffer from high-false alarm rates, even at the modest probabilities of detection. A fusion of systems such as large area scan (remote aerial), macro-area scanning (remote ground-vehicle), and local scans (man-portable) appears nearest to an ideal solution. For an unmanned aerial vehicle, infrared thermograph, or suitable laser sensors based on resonance fluorescence may be suited while

Table 3. Summary of available land mine detection techniques[62]

Sensor technology	Maturity	Cost and complexity
Passive infrared	Near	Medium
Active infrared	Near	Medium
Polarized infrared	Near	Medium
Passive electro-optical	Near	Medium
Multi-hyperspectral	Far	High
Passive mm wave	Far	High
mm-wave radar	Near	High
Ground penetrating radar	Near	Medium
Ultra-wideband radar	Far	High
Active acoustic	Middle	Medium
Active seismic	Middle	Medium
Magnetic field sensing	Near	Medium
Neutron activation analysis	Available	Low
Metal detection	Near	High
Charged particle detection	Far	High
Nuclear quadrupole reson	Far	High
Chemical sensing	Middle	High
Biosensors	Far	High
Dogs	Available	Medium
Prodding	Available	Low

for ground vehicles, forward-looking infrared (FLIR), ground-penetrating radar, or pulsed-induction metal detectors can be employed. Man-portable machines are likely to involve metal detectors. Standoff sensors are likely to include x-ray backscattering, laser acoustics, neutron activation and/or scattering, and artificial sniffing biosensors. The largest factor contributing to poor detection rates and high-false alarm rates for anomaly mine detections systems is clutter[63]. The source of this clutter can be either naturally occurring or man-made objects in the ground. To determine the source apportionment of these sensor response anomalies, a large-scale study by actual excavation of a densely mined site has been carried out[64].

In developing a system that has a reasonable chance for being successfully implemented, it needs to be cost-effective, dependable, easy to operate and maintain, and provides results within a reasonable short time. It is still a long way before the required technologies are developed and integrated into system platform with a single control for landmine detection and de-mining action and realise a better, fast, economical and accurate detection tools, to rid this planet of the single largest continuing threat to the individual human beings in the mine-infected areas.

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