Heliyon 7 (2021) e08343

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

# The use of a predictive threat analysis to propose revisions to existing risk assessments for precursor chemicals used in the manufacture of home-made explosives (HME)

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ARTICLE INFO

*Keywords:*
Home-made explosives (HME)
Explosives manufacturing
Potassium chlorate (PC)
Ammonium nitrate (AN)
Hydrogen peroxide (HP)
Improvised explosive device (IED)

ABSTRACT

Improvised explosive devices (IEDs) have generated over 137,000 civilian casualties in the past decade, more than any other explosive weapon system in the same period with a far-reaching impact on personal security freedoms across 50 affected countries. The aim of this paper is to consolidate existing risk management processes to control the availability of chemical precursors used in the manufacture of home-made explosives (HME) and to recommend global standards for market regulations in their composition, sale and use. This will be achieved by assessing the current regional regulations for three common chemical precursors (hydrogen peroxide, ammonium nitrate and potassium chlorate), and proposing a risk management process to identify key precursor chemicals that require greater control.

## 1. Introduction

Approximately USD $5.7 trillion dollars-worth of chemicals are purchased on a yearly basis and transported through supply chains for personal, commercial or industrial use (Oxford Economics, 2019). Dependent upon the restrictions imposed on supply, import/export, use and carriage, they circulate the globe by a variety of platforms where illicit diversion becomes possible. One of the issues facing states is the dual-use nature (where a chemical can be used both for beneficial and harmful purposes) of most chemical precursors that are considered by terrorists in the manufacture of Home-Made Explosives (HME). This makes regulation problematic given that some chemicals considered as explosive precursors (such as potassium permanganate and sodium nitrite) appear on the World Health Organisation list of essential medicines (WHO, 2019), whilst others such as sulphuric acid are essential for industry. Therefore, many explosive precursors of interest can be found in retail stores, people's homes or in specialist applications.

The vast majority of the global population pays little attention to explosive precursors; this is helpful to the terrorist as HME can exist as loose or compacted powder, as an emulsion, gel or plasticine, as a free-flowing liquid or a fine powder dispersed in the air. It can be prepared well in advance of planned activity or mixed prior to use.

The production of HME is not novel in terms of explosive chemistry, but rather the types of fuel and oxidiser that are combined to deliver an explosive outcome are in constant flux according to their availability and traceability. When initiated by a suitable stimulus, these fuels and oxidizers deflagrate (burn rapidly) or detonate by the initiation of an explosive train (the passage of stimulus from detonator to main charge) (Akhavan, 2011) (Fox, 1999), dependent upon the 'effect' required (such as blast, fragmentation, heat, shatter, or the displacement of earth and rock by expanding gaseous products). Break the explosive train and an Improvised Explosive Device (IED) containing HME usually fails to function as intended. It is therefore the chemical components within an explosive train, not the physical components of an IED, that this paper considers of interest.

The explosive train may incorporate a mix of commercial, military and HME compositions, dependent upon supply chain availability and the sensitivity of the HME to detonation. For example, ammonium nitrate (AN)-based HME is insensitive to shock alone and requires a booster of more powerful commercial/military explosive to achieve detonation (Jaffe and Price, 1962 and Cook, 1974). This is recognised in Yemen's improvised sea mine where the ammonium nitrate and aluminium (ANAL) main charge requires a booster of more powerful explosive to achieve detonation (Himmiche et al., 2018, pp. 170, Table 41.1). A large critical diameter (the minimum diameter of explosive required to

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https://doi.org/10.1016/j.heliyon.2021.e08343
Received 18 March 2021; Received in revised form 1 June 2021; Accepted 4 November 2021

progress detonation), which exceeds those of military explosives, is also required (Wood and Duffield, 2002) (Zhang, 2016), which is one of the primary reasons why AN-based explosions are often large in mass (in this paper, 25 kg is considered the limit whereby an IED cannot be considered ergonomically man-portable). The fact that an IED comprises many '*standard*' components (UNMAS, 2018) facilitates exploitation. Exploitation informs risk assessment by promoting better understanding of the perpetrator's capability and intent and what opportunities may exist to obtain precursor chemicals. Through predictive threat analysis, these opportunities can be influenced. This is particularly important given that, for example, the current UK list of proscribed terrorist organisations encompasses 76 international organisations under the Terrorism Act 2000 and 14 organisations in Northern Ireland that were proscribed under previous legislation (Home Office, 2020).

HME is most often used by non-state armed groups, terror organisations or criminal groups when access to the reliable performance of military and commercial explosives has been diminished through effective physical stockpile and security management (UNGA-A/63/182, 2008) (UN, 2018). For example, Yemen has experienced many thousands of IED events this past three years, with over 90% of devices incorporating military ordnance, grenade fuzes and military or commercial detonators. There is little recourse for groups to manufacture HME at scale as long as access to other supplies continue.

Existing risk and risk management for precursors is based on standard techniques, which defines risk in terms of the hazard (the precursor) and the consequences of that hazard generating an explosive event. Consequence is based on probability and severity which, in the case of HME, drifts into the bracket of catastrophic on many well-publicised occasions. This approach is buried within complex regulation that influences risk reduction programmes at the national, regional and international level, dependent upon the consequences associated with that precursor. Action on Armed Violence (AOAV) suggests that whilst regulation should be one of our greatest weapons to counter the IED, it may be a significant weakness (Corderoy, 2014).

## 2. Research methodology

This research is exploratory in nature, with the authors utilizing a mixed method approach regarding literature review, data analysis, and case study to establish initial perception of a risk assessment strategy that could be applied to the regulation of explosive chemical precursors (ECP) used in the manufacture of HME. Through case studies certain precursor hazards that have been used in HME compositions and which are available to terrorists and criminals through knowledge exchange or literature are examined. Trends analysis has been used to determine key step changes in historical ECP use when regulation has been amended to establish links to potential precursors of future interest, thereby facilitating pre-emptive mitigation. For example, if a chemical precursor were regulated, which other chemicals could perform a similar function within the supply chain and could that be anticipated?

Given the increased use of IEDs this past decade, and the variety of potential ECP available, the critical reasoning for the application of a Risk Assessment is demonstrated by three specific case studies. Each case study is taken through the proposed risk assessment strategy as an introductory proof of concept. New IED prevention and mitigation strategies are also introduced which, when combined with precursor regulation, can reduce the occurrence of incidents involving HME.

### *2.1. Literature review*

#### *2.1.1. Regulation*

In 2017 the Office of Disarmament Affairs (UNODA) reported that IEDs impacted upon lives and livelihoods within nearly 50 countries and territories globally, particularly Afghanistan, Iraq, Libya, the Syrian Arab Republic, Somalia and Pakistan (UNODA, 2018). As a weapons system they have also killed or injured more than 137,000 civilians this past decade, accounting for 48% of all casualties from incidents of explosive violence (Overton et al., 2020). Wherever possible, regulation has been applied to restrict or regulate the availability of military and commercial explosives, or the ECP that are used in the manufacture of HME. Pivotal literature references by region are as follows: Australia (Australian Government, 2016); Canada (Government of Canada, 2013); the European Union and Norway (EU, 2019); Singapore (Government of Singapore, 2021); the United Kingdom (UKPGA, 2015); and the United States (US) (NASEM, 2018). Minor screening interventions have also formed part of academic study in South Korea (Chung et al., 2013) based on increasing threats to national security.

At the international level, Programme Global Shield (PGS) (WCO, 2013) attempts to enhance public safety through the security of global supply chains. Working with INTERPOL and the United Nations Office on Drugs and Crime (UNODC), PGS enhances awareness and information sharing on the global movement of the most common ECP used in IED manufacture to prevent their illicit diversion and trafficking.

In conjunction with PGS, INTERPOL runs a flagship programme called the Chemical Risk Identification and Mitigation Programme (CRIMP), which, over a period of 5 years, increases the capacity of member state agencies involved in counter-terrorism activities and infrastructure protection to identify chemicals at particular risk of diversion and misuse (INTERPOL, 2021). CRIMP's list of precursor chemicals follows PGS guidelines and a number of additional explosive chemicals that should raise concern within national governments agencies if found in quantity. Other initiatives complement the international approach further by gathering and sharing intelligence on devices with member countries in order to identify, locate and arrest suspected bomb makers.

The United Nations has raised awareness of ECP at the international level over the past five years, specifically with the adoption of General Assembly First Committee resolutions, which integrate the issues of IEDs into broader discussions on peace and security, enabling the arms control and disarmament community to consider their destabilising impact and to agree on steps to reduce their effect. Examples of awareness raising internationally are:

- resource mobilisation to the PGS initiative, recognising its important role in preventing the smuggling and illicit diversion of high-use explosive precursors (UNGA, Resolution 72/36 adopted by the General Assembly - Countering the threat posed by IEDs, 2017);
- establishing an Office of Counter Terrorism to assist Member States in implementing the UN's global counter-terrorism strategy (UNGA, 2017a,b), specifically strengthening cooperation, needs assessment and gap analysis.

The approach to risk adopted by the European Union (EU) is also to categorise certain chemicals by restriction and reporting. Restricted explosives precursors are not generally available to members of the public above a certain limit value and their acquisition is subject to control and (possibly) licensing. For reportable explosives precursors, the emphasis is placed at online and offline retail, as well as online marketplaces, to report suspicious transactions. Specific detail lies within Regulation (EU) 2019/1148, which came into effect on 1$^{st}$ February 2021 (EU, 2019). The criteria for determining which measures should apply include:

- the level of threat associated with the explosive precursor;
- the volume of trade in the explosive precursor; and
- whether it is possible to establish a concentration level (threshold) below which the explosive precursor could still be used for the legitimate purpose it was intended but making it less likely to form a viable HME.

Regulation (EU) 2019/1148 does not permit the general public to acquire, introduce, possess or use certain ECP at concentrations above certain limit values, expressed as a percentage of weight in weight (% w/

w). However, members of the general public are permitted to acquire, introduce, possess or use some explosive precursors at concentrations above those limit values for legitimate purposes, provided that they hold a licence to do so. This approach has been adopted by all EU Member States, as well as non-members (Norway and the UK), however certain aspects of the regulation will require transposition into national law through a new Statutory Instrument to come into effect. Table 1 summarises the EU legal concentration limits (thresholds) for precursors where access by the general public is required.

Regulation (EU) 2019/1148 also requires that suspicious transactions and significant disappearances/thefts of the precursor chemicals shown in Table 2 be reported within 24 h, although the definition of *suspicious* and *significant* is difficult to define.

From the UK's perspective, Schedule 21 of the Poisons and Explosive Precursors Act (OGL, 2015) regulates the explosive precursors as per Table 1, but barium salts, mercury and phenol (above 60% w/w) are also listed. Reportable explosive precursors also mirror those in Table 2, with hydrochloric acid (10% w/w), hydroxides of potassium and sodium, and sodium nitrite being listed as reportable poisons.

Most recent developments at the national level have taken place in the US where the Department for Homeland Security (DHS) has worked with the National Academies of Sciences, Engineering, and Medicine (NASEM) in an attempt to augment/update Chemical Facility Anti-Terrorism Standards (CISA, 2007) and to establish a committee of cross-government experts to prioritize precursor chemicals and substances, analyse their movement through the national supply chain, examine national/international legislation and regulations pertaining to precursor chemicals, and identify potential control strategies. The committee's report (NASEM, 2018) provides an excellent reference for potential mitigation strategies, which are adaptable in response to a variety of threats, specifically risk assessments pertaining to vehicle borne and person borne IEDs (VBIED and PBIED), which have killed and injured more civilians than any other IED system. In the report, three specific criteria are examined as a risk assessment strategy:

1. the precursor's use in VBIED and PBIED;
2. the precursor's history of use in IED attacks (looking back over the past 50 years at large scale events);
3. the precursor's ability to be used in HME independent of the presence of another specific chemical.

On that basis, the report established three groups of precursor 'risk' as follows:

Group A – chemical precursors that satisfy all 3 risk assessment criteria;

**Table 1.** Precursor chemicals – EU concentration limits (2019).

| Precursor | Standard Limit Value (% w/w) | Upper Limit (% w/w) | Remarks |
|---|---|---|---|
| Hydrogen peroxide | 12% | 35% | |
| Nitromethane | 16% | 100% | Also explosive in own right |
| Sulphuric acid | 15% | 40% | |
| Nitric acid | 3% | 10% | |
| Ammonium Nitrate | 16% | No licencing permitted | Maximum 16% by weight nitrogen content in relation to AN (which means 45.7% AN, discarding impurities) |
| Potassium chlorate | 40% | No licencing permitted | |
| Potassium perchlorate | 40% | No licencing permitted | |
| Sodium chlorate | 40% | No licencing permitted | |
| Sodium perchlorate | 40% | No licencing permitted | |

**Table 2.** EU reportable precursor chemicals (2019).

| Precursors | Remarks |
|---|---|
| Acetone, calcium nitrate, calcium ammonium nitrate, hexamine, potassium nitrate, sodium nitrate, magnesium and aluminium powders, magnesium nitrate hexahydrate | For metal powders: with a particle size <200um; as a substance or in mixtures 70% w/w or more of Al or Mg |

Group B – chemical precursors that satisfy 2 of the 3 risk assessment criteria; and

Group C – chemical precursors that satisfy one of the 3 risk assessment criteria.

Whilst Group A precursors are the ones where US national effort is principally focused, the precursors listed in Groups B and C provide a degree of predictive threat analysis whereby restrictions imposed on Group A would force perpetrators to change approaches over time.

As can be seen, there are a number of methods applied to minimise accessibility of precursors by their regulation and standardisation, but there is no single unified approach that sufficiently interrogates the associated hazards of such a fast-moving commodity in today's climate. Revised assessment methods underpinned by rigorous, yet simple practical steps are required so that they can be understood and replicated widely.

#### *2.1.2. Precursor chemicals: fundamental case study materials*

Based on the wide selection of fuels and oxidisers that could be used to manufacture HME, three case study materials have been identified, each being widely available and having explosive properties reported in literature.

Ammonium nitrate (AN), a white crystalline salt of ammonia and nitric acid, is used widely in fertilizers, freezing mixtures (cool packs), anaesthetics (manufacture of nitrous oxide) and is the most important raw material in the manufacture of commercial explosives and as a gasifiable oxygen carrier in rocket propellants (James and Speight, 2017).

Hydrogen peroxide is listed as one of the 100 most important chemical compounds (Pesterfield, 2009) given its wide utility ranging from bleaching applications to rocket mono-propellants and oxidizers in the aerospace industry. In HME applications, hydrogen peroxide can be exploited to make detonators and main charges (De Ruiter & Lemmens). The most commonly encountered peroxide-based explosives include triacetone triperoxide (TATP), hexamethylene triperoxide diamine (HMTD) and methyl ethyl ketone peroxide (MEKP).

Potassium chlorate ($KClO_3$) is a stable, white, crystalline solid with low toxicity to humans, commonly used as an oxidising agent, in the preparation of oxygen, and as a disinfectant. Since its discovery by Berthollet in 1787, it is the principal component of chlorate-based explosives (known as Cheddites), incendiaries, primer formulations, pyrotechnics and matchhead compositions (Meyer et al., 2007). Pure potassium chlorate cannot be detonated, but when mixed with a small percentage of fuel, an extremely sensitive explosive can be formed (Cackett, 1965).

### *2.2. Applying an appropriate risk assessment*

To apply an appropriate risk assessment to these types of chemicals the following topics need to be considered:

1. the intended end user of the chemical and their status on the Corruption Perceptions Index – this index denotes the ease of illicit diversion that may be possible within a national or regional supply chain (Transparency International, 2021);
2. the appropriateness of national or regional legislation. For example, if a particular threat does not transcend borders, is a national or regional regulation appropriate? If this is the case, then what monitoring is required to flag escalation?

3. the ease with which the precursor chemical can be substituted or standardised (the mitigation).

The solution calls for a simple iterative risk assessment which can be easily followed by any State that wishes to do so, and which allows precursors of significant interest to be referred to an appropriate higher authority (where necessary) for inclusion in a global regulation. Therefore, this paper proposes a risk management process to prioritise chemical precursors to ensure that the ones most readily available chemically and commercially are effectively managed by global standardisation.

The process is based on a series of assessments into key factors that influence the likelihood of a chemical precursor being used in HME. The more likely a precursor is to be used, the higher priority the chemical is given. The process begins when a new chemical precursor is identified in HME manufacture. If the chemical is already listed or known, but has not been assessed, it would be a priority 1 and move to the next decision point. If the chemical is dependent on other chemicals listed (i.e. HME cannot be synthesised without access to another chemical on the list), then it is designated priority 2 and can be considered after all priority 1 substances have been assessed and regulated.

The second step in the process is to determine the role of the chemical precursor in an explosive device. For example, if the chemical is used in detonator and main charge compositions it is designated a priority 1 and progresses to the next step. The reason for this is that the chemical can be used to generate the entire explosive train for a viable IED without recourse to any other chemicals. If the chemical is used in the main charge composition it is designated priority 2. If a detonator composition, it would be designated priority 3 (based on quantitative rate of use of improvised detonators in IEDs).

The way in which the chemical precursor has been used is the third step with priority being given to VBIED compositions (where loss of life and damage to property is significant) over man portable or person borne IED's. Analysis of historical use gives an indication of the intent and probability of encounter as well as the potential severity or lethality.

The fourth step is the commercial availability of the chemical in the global marketplace, which takes into account the quantity of the chemical manufactured annually and its availability within the supply chain as well as the volume of annual trade. Chemicals are prioritised based on whether they are readily available (priority 1), moderately available (priority 2) or have very limited availability (priority 3) within a region. For the purposes of this paper, volumes for high production chemicals within OECD countries were considered, with priorities ranging from less than 1000 kg per year (priority 3) to in excess of 500,000 kg per year (priority 1). These reports do contain sensitive data but can be accessed for public research with permission.

The final assessment step for prioritisation is to consider the suitability of existing regulation (national, regional or international). Chemicals which have been designated a priority 1 through all other steps and that are not regulated should be prioritised for global regulation. Where regulation already exists but is not appropriate (based on precursor potential), these chemicals can be assigned priority 2 and held for action at a later date.

Future steps in this process may be to assess the specific hazard posed by these chemicals in accordance with the data acquired from steps 1–5. Involving an international expert panel, both the ease of standardisation and the ease of substitution can be accurately assessed and dynamically monitored to react quickly to any evolving precursors that are encountered by predictive threat analysis or forensics exploitation. Any significant risks can then be referred to the United Nations Counter-Terrorism Committee (CTC) for advocacy within a global regulation. Whilst these remarks seem relatively straightforward, substitutions may not be obvious, requiring funded research to progress them. Given the costs of research, development and implementation, there also need to be clear incentives from the market or elsewhere to initiate the process.

Figure 1 describes the possible process that the risk assessment could follow. It covers all elements of IED manufacture, not just the process by which the precursors are assembled to make HME.

## 3. Results and discussion

### 3.1. Case study 1 – ammonium nitrate

#### 3.1.1. Historic/examples of use

AN can be supplied at high density/low porosity at percentage concentrations greater than 90% w/w for Type A fertiliser applications or at low density/high porosity for use as an industrial grade explosive (Wood and Duffield, 2002). Where the percentage concentration is high, the product must be accompanied by a resistance to detonation certificate (UK Government, 2003). As such, the variation in limit ranges and legitimate use allows viable HME compositions to be pursued anywhere where AN is supplied, where security regulations are poorly observed, or where there is the potential for exploitation within global crypto markets (Martin, 2014).

Ammonium nitrate is not a new form of HME; it was identified as an explosive of choice during the historic bombing campaigns in Ireland/UK mainland circa 1970–72 (Bowyer-Bell, 1990). Bomb disposal experts in Northern Ireland regularly identified the use of commercial blasting explosives such as AN and dynamite acquired from quarries (Foulger and Hubbard, 1995). In August 1971 alone, there were over 100 bomb explosions across Northern Ireland, the vast majority involving AN with a dynamite booster (Byrne, 2012). As such, access to commercial blasting explosives became a debate for governments of that time (Lords, 1972). These devices regularly involved quantities exceeding 25 kg and there is detailed evidence from over 19000 IED attacks on UK territory, with 541 recorded incidents of main charge masses exceeding 25 kg between 1970 and 2007 (CAIN, 2010). Attacks such as this resulted in increased controls being applied to AN and dynamite with large quantities becoming impossible to obtain and with restrictions in nitrogen content of no more than 27.5% by weight (78% AN) a designated amount. This amount is not an arbitrary decision, and was based on experimentation of AN and diluents (such as ammonium sulphate, calcium carbonate and dolomite) going as far back as 1924 (Naoum and Aufschlager, 1924), throughout the 1950's (Burns et al., 1953) and more recently (Shalini and Pragnesh, 2013).

In 2016 an example of the catastrophic effect of the use of AN in HME and its strategic impact was the bombing of the Hadi shopping centre in Baghdad on 3rd July 2016 by Daesh, which killed 341 people and injured 246 others. The blast, fragmentation and enhanced heat of explosion destroyed the shopping centre causing damage estimated at USD $4,300,000. The AN used in the attack comprised approximately 33% nitrogen by weight (94% AN), based on seizures of AN fertilizers from Islamic State forces in Anbar province earlier that year, which were suspected to have been diverted from national sales in Turkey (Bevan, 2016).

#### 3.1.2. Availability of ammonium nitrate on the global market

With so many agricultural economies relying on AN, the requirement for fertilizer has endured and the solution was thought to be the development of calcium ammonium nitrate (CAN). In 1967, research confirmed that the diluent, when added to AN, drastically reduced its detonability (Clancey and Turner, 1967). However, non-state actors soon developed a countermeasure to the 'dumbing down' and were able to separate the AN from the diluent and produce almost pure AN in the process. Detonations approaching TNT unity were achieved with certain fuels. As such, AN distilled from CAN continued to be used but its introduction made the manufacturing process time-consuming, thereby reducing the number of large-scale attacks and thus undoubtedly saving lives. The Provisional Irish Republican Army (PIRA) continued to

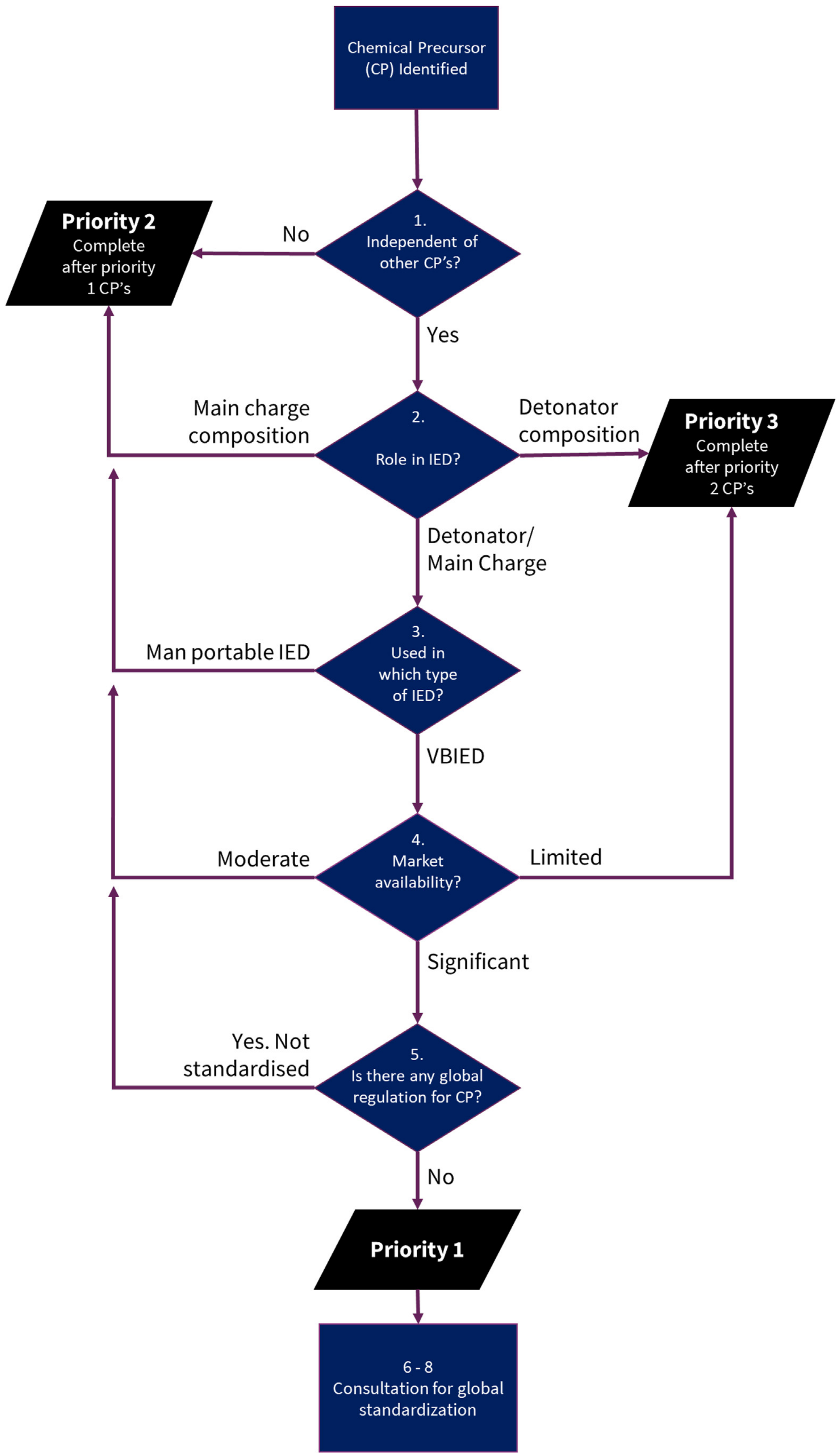


**Figure 1.** Criteria for hazard identification, risk assessment and risk control criteria process in relation to global regulation. (CP = Chemical Precursor).

experiment with CAN and in the early 1990's orchestrated several successful attacks on the UK mainland by manipulation. This countermeasure may have existed as early as 1937, with Blinov articulating that desensitised AN could become detonable if manipulated (Blinov, 1937).

Ammonium nitrate is also a common chemical found in cold packs (as are CAN and urea). Upon mixture with water, the reaction is extremely endothermic, producing ice almost instantly. The ammonium nitrate within a cold pack is readily exploitable and able to create energetic compositions. On 28th June 2012 the FBI issued a bulletin warning that cold packs containing AN had been used to manufacture IEDs (FBI and DHS, 2012), with several packs capable of yielding kilograms of almost pure product. Today, AN cold packs are still readily available within the global supply chain.

Annual production of AN sits in the region of 7 million tonnes, with Uzbekistan, Poland and the USA being the key manufacturers (Knomea, 2021). By 2026 the volume in AN manufacture is expected to have grown by 3.8% given the demands on food production for a growing global population (GMI, 2020). AN therefore dominates the HME spectrum and has driven considerable legislative changes since 1969. These examples suggest either a determination by terrorists to seek out a notoriously insensitive precursor, or that it is relatively simple for non-state actors to access the supply chain.

### 3.1.3. Existing regulation on ammonium nitrate

One of the most prolific occasions of ammonium nitrate use in an IED is the Oklahoma bombing on 19$^{th}$ April 1995. There was a reported \$510M damage (US Dollar). Incidents such as this, and a succession of others using AN/CAN between 1995 and 2007 (NASEM, 2018, pp. 24–25), led to Homeland Security Presidential Directive (HSPD) 19/2007 (Bush, 2007), which established a national policy, strategy and implementation plan on the prevention, detection of, protection against, and response to terrorist use of explosives in the United States. This directive established the Department of Homeland Security (DHS) as the lead agency for implementation. Soon thereafter, CFATS (Chemical Facility Anti-Terrorism Standards) were published, regulating over 300 chemicals that could be used domestically in a subversive fashion (CISA, 2007).

Table 3 below examines AN through the regulatory approaches adopted by NASEM, CFATS, the EU, Australia, Canada, PGS, Singapore, Norway and the UK. Subsequently, Table 4 demonstrates the global demand for varied compositions of AN (Van-Belken, 2002).

In summary, there is a still a large likelihood that AN will continue to be used at a global scale. It is acknowledged that its use in HME is prolific and that regulation must be applied to restrict access to nitrogen content above 28% (80% AN by weight) for non-technical purposes to circumvent its use in HME. However, that regulation is not set at 28% across the board for public consumption and improved policing, security and education is required within the supply chain for all product types. Further mitigation will require advocacy, time and money. As such, AN should sit within a global regulation where all these conditions can be supported through effective resource mobilisation.

## 3.2. Case study 2 – hydrogen peroxide

### 3.2.1. Historic/examples of use

Peroxide based explosives have been used in 43% of Jihadist attacks involving explosives in the West between 2014 and 2018 (Bergen and Sterman, 2018). In other regions of the world such as Indonesia, hydrogen peroxide use is seen as a new trajectory in terror-related attacks (Nasir, 2019). The primary solution to HME initiation problems evolved in the form of organic peroxide explosives (OPE), known since the 19$^{th}$ century (Wolffenstein, 1895, Muraour, 1932 and Fedoroff and Sheffield, 1960), and concentrated hydrogen peroxide (CHP) compositions, using hydrogen peroxide as the principal oxidizer with a variety of solid fuels. OPE and CHP are shock sensitive without the requirement of boosters (Agrawal and Hodgson, 2007) and unlike AN-based HME, could be manufactured in liquid or gel form, or even mixed at point of use, thereby improving versatility. Organisations such as al-Qa'ida soon began to provide knowledge exchange to other groups operating in the Middle East, Europe and the United States (raising the probability of encounter to high, and severity catastrophic (Beveridge, 2011)).

On 7 July 2005, 52 people were killed and over 700 were injured when four suicide bombers detonated 3 explosive devices on the London Underground and one on a London bus. Each bomb comprised mixtures of CHP. The Coroner's Inquest (HM Government, 2012) identified that all the items necessary to manufacture the main charges and detonators used during 7/7 had been purchased within the local supply chain.

### 3.2.2. Availability of hydrogen peroxide

The global hydrogen peroxide market was valued at USD \$1.44 billion in 2020 and is expected to grow at a compound annual growth rate (CAGR) of 5.7% from 2020 to 2028 (GVR, 2021). Rising demand for the product as a result of COVID 19 within the health industry is projected to remain a key factor fuelling market growth. The use of hydrogen peroxide is becoming more and more important in other fields of modern industry and may replace ammonium nitrate in a variety of emulsion and blended ANFO-emulsion commercial explosives given its 'green' nature (there are no toxic by-products such as nitrogen dioxide) (Rarata and Smetek, 2016).

**Table 4.** Ammonium nitrate classifications by weight concentration.

| Ammonium Nitrate Use | Chemical Composition | Hazard |
|---|---|---|
| Fertilizer Type A- UN/ADR Class 5.1. AN and AN-based high nitrogen fertilizers (high density & low porosity) | Mixtures of ammonium nitrate with added matter, ranging from 45% weight concentration to in excess of 90% | Oxidising; Non-combustible; May decompose; High resistance to detonation |
| Fertilizer Type B - UN/ADR Class 9 | Non segregating mixtures between 45 and 70% weight concentration AN | Decompose when heated; self-sustaining decomposition |
| Fertilizer Type C – Unclassified. Self-sustained decomposition not possible | Mixtures of AN between 45 and 80% weight concentration with calcium carbonate/ dolomite/ammonium sulphate | Decomposes when heated; decomposition stops when heat source removed |
| Industrial Grade Explosive - UN/ADR Class 1. Low density, high porosity prills combined with fuel oil (ANFO) | AN with more than 0.2% combustible material; sensitive AN fertilizer with 0.2% combustible materials; explosive preparations of AN | Deflagration to detonation following rapid decomposition; detonates with external shock |

**Table 3.** Comparison of percentage nitrogen content quoted in ammonium nitrate regulation.

| Precursor/ Regulation | NAS | CFATS | EU | AUS | CAN | PGS | Singapore | UK/Norway |
|---|---|---|---|---|---|---|---|---|
| Ammonium Nitrate | Category A | ≥23% N content w/w | ≥16% N content w/w | Solid mixtures >45% w/w | ≥28% N content w/w | 14 Watch list | ≥28% N content w/w | ≥16% N content w/w |
| CAN | Category A | - | Regulated through suspicious transactions | | - | 14 Watch list | - | Regulated through suspicious transactions |

**Table 5.** Regulatory control of hydrogen peroxide.

| Precursor w/w/Regulation | NAS | CFATS | EU | AUS | CAN | PGS | Singapore | UK/Norway |
|---|---|---|---|---|---|---|---|---|
| Hydrogen peroxide | Category A | ≥35% | >12% | ≥65% | ≥30% | Watch list | ≥20% | >12% |

**Table 6.** Regulations pertaining to potassium chlorate.

| Precursor/Regulation | NAS | CFATS | EU | AUS | CAN | PGS | Singapore | UK/Norway |
|---|---|---|---|---|---|---|---|---|
| Potassium chlorate | Category A | Theft >180 kg | >40% | ≥65%(s)<br>≥ 10%(*a*) | Licence required | Watch list | Licence required | >40% |

#### *3.2.3. Existing regulation relating to hydrogen peroxide*

In response to the 7/7 incident, EU regulations were passed that limited the concentration by which the general public could access hydrogen peroxide (European Parliament and and Council of the European Union, 2013) and the manner in which it could be marketed as an identified explosive precursor. Further updates have since been published (see Table 1). Therefore, examination of existing regulations (Table 5) identifies the following trend regarding hydrogen peroxide:

With the exception of Australia, the general thrust in regulation is to regulate public access to hydrogen peroxide where its concentration is below 35% w/w. This does deter use to a degree but does not remove the means by which enhancement increases the concentration to useable levels (Easton et al., 1952).

In summary, regulation has been amended to reflect OPE and CHP development (*mitigation*) but public-use concentration limits need to be considered at the global level (to reduce *probability*). Consideration should also be given to pre-empting the manner by which perborates and percarbonates could be exploited given their inherent source of readily available hydrogen peroxide within their chemistry (decreasing *probability*).

As such, hydrogen peroxide is another chemical precursor whereby there should be global harmonisation to restrict the specific w/w concentrations to levels that complicate the chemistry for determined individuals or groups, or by adding decomposition-promoting substances (such as enzymes) that frustrate attempts at concentration.

### *3.3. Case study 3 – potassium chlorate*

#### *3.3.1. Historic/examples of use for potassium chlorate*

One of the key factors of potassium chlorate that represents an area of concern to first responders is the presence of impurities that find their way into the composition during HME manufacture, whether they be chemical species such as acids, or low melting point solids. Each impurity lowers the melting point further and can lead to instability (Tanner, 1959) (Conkling and Mocella, 2011, pp. 65–69). Despite such sensitivity, potassium chlorate is a highly sought-after explosive precursor and one where predictive threat analysis provides some important observations. For example, potassium chlorate succeeded nitrate-based fertilizer as the HME of choice with the Taliban in 2013. It was used in 80% of all IEDs between March and May of that year, comprising a mixtures of potassium chlorate (Vanden-Brook, 2013). Inappropriate controls in the match and textile industry were cited as the primary reason for potassium chlorate use following successful control of military stockpiles and the banning of AN (Case study 1) as a fertilizer in 2011 (Casey, 2011). In this instance the research and development process for the Taliban took less than 2 years from the ban being put in place.

Potassium chlorate has been linked to a number of major vehicle-borne IED attacks in recent years, with its close cousin (sodium chlorate) traced to at least three al-Shabaab vehicle-borne IED attacks between 2016 and 2017 (Umarov, 2017).

#### *3.3.2. Availability of potassium chlorate*

The potassium chlorate market is driven by the increasing demand for wood pulp bleaching to manufacture white paper and paperboard. This demand is set to increase by 5% between 2021 and 2026 according to global market key insights (EMR, 2021), with India's production in 2019 alone being in the region of 700 metric tons (Statistica, 2020). As such, potassium chlorate will remain a much sought-after commodity within the global supply chain.

In 2016, UN embargo monitors first flagged al-Shabaab's escalating use of commercial precursors in domestic IED production (Ramires-Carreno, 2016). Al-Shabaab had infiltrated and gained covert access to the manifests of legitimate cargo vessels and was able to prosecute successful seizure operations of potassium chlorate. Based on this tactic, Somali security forces have recovered a broad variety of IED chemical precursors in the group's custody. In 2019, the UN Sanctions Committee added both potassium chlorate and sodium chlorate to a list of high-risk precursors requiring additional scrutiny due to their heightened risk of diversion into IED production (Pecsteen de Buytswerve, 2019). The sanctions committee warned that Al-Shabaab's interest in the production of HME was escalating and that the effective seizure and use of commercial chemical precursors were an established part of their capability.

#### *3.3.3. Existing regulation on potassium chlorate*

Analysis of the regulation surrounding potassium chlorate identifies the following (see Table 6):

Table 6 demonstrates that regulation continues to focus on variations in percentage w/w, or that illicit diversion of quantities greater than 180 kg should be reported to the authorities. This would seem to be rather an excessive quantity for such a potent precursor. And, whilst this regulation may be appropriate for countries that enjoy effective security regimes within the supply chain, potassium chlorate remains exploitable in destinations where receipt and onward movement is questionable. Given that potassium chlorate is independent of other precursors and a natural (but less stable) second for AN, suggests it should also be another precursor considered within global regulation. Ultimately, the regulation of some precursors essentially begins a ‘cause and effect’ relationship where the use of potassium chlorate has become more prolific due to the regulations and therefore the difficulties in obtaining AN.

### *3.4. Application of risk assessment criteria*

Table 7 provides the projected priorities that should be afforded to AN, PC and hydrogen peroxide based on the assessment criteria proposed at Figure 1. Hexamine is also offered as a chemically dependent comparator for hydrogen peroxide since the production of HMTD, for example, is dependent upon it. Whilst hexamine requires no further action, AN, PC and hydrogen peroxide are not sufficiently regulated.

**Table 7.** Example of ammonium nitrate, potassium chlorate, hydrogen peroxide and hexamine being considered within a revised R.A. process.

| Chemical | Ammonium Nitrate | Potassium Chlorate | Hydrogen Peroxide | Hexamine |
|---|---|---|---|---|
| STEP 1 | 1 (independent) | 1 (independent) | 1 (independent) | 2 (dependent upon hydrogen peroxide >30% w/w to produce HMTD) |
| STEP 2 | 2 (main charge) | 1 (main charge and detonator) | 1 (main charge and detonator) | 3 (detonators and boosters) |
| STEP 3 | 1 (VBIED - frequent) | 1 (VBIED and PBIED) | 1 (VBIED and PBIED) | 2 (all types of IED - infrequent) |
| STEP 4 | 1 (Significant) | 1 (Significant) | 1 (Significant) | 3 (many applications of limited scale) |
| STEP 5 | 2 (International but not standardised) | 2 (International but not standardised) | 2 (International but not standardised) | 2 (national/ regional appropriate) |
| STEP 6 | Variance in nitrogen content (standardise) and control for specialist applications | Chemical is already standardised, so control, substitute or 'dumb down' for specialist applications | Variance in w/w % by region and country. Not possible to substitute or standardise dependent upon applications | Not possible to substitute or standardise in a number of applications. Regulation is essential. |
| STEP 7 | Other oxidizers are available, what is the status on their regulation – refer these precursors to STEP 1 | Other less potent oxidizers are available, what is the status of their regulation – refer these precursors to STEP 1 | Standardize and substitute where possible. Consider use of decomposition promoting chemicals | Other detonators compositions exist, what is the status on their regulation – refer precursors to STEP 1 |
| STEP 8 | Refer to CTC | Refer to CTC | Refer to CTC | No further action |

### *3.5. Future steps*

Having now considered PC, AN and hydrogen peroxide in this manner, a cursory comparison of international, regional and national risk mitigation strategies demonstrates that the importance given to an explosive precursor often varies.

With 193 Member States and 2 non-voting Members, the UN has by far the greatest reach and is therefore the most appropriate vehicle for advocacy in precursor risk reduction. The Counter Terrorist Committee (CTC) would, perhaps, be the most appropriate focal point since it is guided by resolutions 1373 (UNSCR 1373, 2001) and 1624 (UNSCR 1624, 2005) that attract funding to bolster the ability of Member States to prevent terrorist acts within their borders and across regions, and which can also direct technical assistance.

Most specifically, UNIDIR has completed research on C-IED threat mitigation and launched the C-IED Capability Assessment Maturity Model on 24$^{th}$ June 2020 (UNIDIR, 2020). This model allows Member States to conduct a risk assessment on their ability to counter the threat posed by IEDs. The use of precursors is specifically mentioned in *'Upstream Capacity Development Measure 6 [Control of IED Precursors]'*, which assists a State recognise that certain materials may be misused in the manufacture of HME, how licencing and regulation might be applied, and that exploitation of recovered IED components can assist the protection of communities and improve information flow to entities such as border forces. Understanding of a State's precursor control is pivotal to any risk assessment being conducted at the national or regional level.

This paper supports the development of a systematic step approach to risk management whereby the hazard (severity/probability) associated with precursor chemicals are identified through rigorous analysis of their current and historic use, the importance of their role in the explosion process, and whether or not they are dependent or independent of other chemicals in application. The risk assessment must allocate priorities to those of most concern, weighted by their availability within the global marketplace and the appropriateness of the current level in regulation applied. If the level of regulation is inappropriate at any level then referral to the next step is required until the point is reached whereby a global intervention is required to direct the appropriate mitigation such as substitution or standardisation.

## 4. Conclusion

No precursor risk strategy can effectively prevent the ingenuity of non-state actors making HME. Nor is it possible to impose a blanket ban on certain chemicals due to their role in society. Real success in restricting the proliferation of explosive precursors can only be achieved through advocacy and cooperation between manufacturers, suppliers, retailers, and local/international law enforcement agencies, combined with the development and application of sound intelligence.

The common response has been to restrict their access by limiting supply of chemicals above certain concentrations and making reportable the supply of other precursor chemicals in large quantities, or to suspicious individuals. This type of risk assessment does make it much more difficult for individuals to develop HME, but the approach is inconsistent and loses sight of chemical precursors in countries where institutional oversight is lacking. Local security forces in countries where the rule of law is fragile become overwhelmed by extensive lists of chemicals, which limits effective control, suggesting that regulation must be applied more intelligently at point of manufacture for the repeated offenders.

The establishment of such global regulation on restriction, substitution or standardization must include those available at retail and online and requires advocacy. The United Nations is considered the most appropriate vehicle for advocacy given that the IED is now a matter of global security concern and resolutions pertaining to their use through terrorism are in force. Such a global risk reduction system would cost time and money to implement, would delay (not deny) access to a determined perpetrator, but knowing the direction of travel allows the international community the necessary space to implement focused and proactive strategies to preserve life and property.

Therefore, this paper offers an exploratory risk management process to prioritise chemical precursors to ensure that the ones most readily available chemically and commercially are effectively managed by global standardisation.

## Declarations

### *Author contribution statement*

Gareth Collett: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Melissa Ladyman, Rachael Hazael & Tracey Temple: Analyzed and interpreted the data; Wrote the paper.

### *Funding statement*

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

### *Data availability statement*

The data that has been used is confidential.

## Declaration of interests statement

The authors declare the following conflict of interests: Tracey Temple is an Associate Editor at Heliyon Environment.

## Additional information

No additional information is available for this paper.

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