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Strengthening the norms against chemical and biological weapons

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S&T Developments and CW Terrorism

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Abbreviations
BWC: Biological Weapons Convention
CBW: Chemical and Biological Weapons
CWA: Chemical Warfare Agent
CWC: Chemical Weapons Convention
DURC: Dual-Use Research of Concern
OPCW: Organisation for the Prohibition of Chemical Weapons
SAB: Scientific Advisory Board (an OPCW subsidiary body)
S&T: Science and Technology
WMD: Weapons of Mass Destruction

Executive Summary
- Progress in science and technology (S&T) is a double-edged sword: it can improve our quality of life, but simultaneously, some of its applications may be misused by malicious non-state actors to develop, produce, and disseminate biological and chemical weapons prohibited by the Biological Weapons Convention (BWC) and the Chemical Weapons Convention (CWC).
- The number of historically documented cases of chemical terrorism or assassination attempts with chemical agents is higher than the number of bioterrorism events. This suggests that developing biological weapons remains more challenging than producing chemical ones, due to the complexity of biological systems and the technical hurdles that still exist in developing a functional biological weapon that produces predictable effects in an organism, ensures environmental and metabolic stability, and/or has established pathways for distribution and administration within the body.
- It is crucial to closely examine progress in the relevant scientific and technological fields, analyze the potential for misuse of certain applications, understand the current technical challenges that could prevent such misuse, and take into account future trends that could have a significant impact on the current threat landscape. The current analysis focuses on chemical terrorism, reviewing scientific and technological advancements that could be misused to identify alternative routes for synthesizing known chemical warfare agents (CWAs), to design and develop new CWAs, and to deploy and disseminate them.
- The existing legal framework is not flexible or comprehensive enough to address potential emerging threats in the domain of chemical weapons, resulting from rapid advancements in S&T. A careful examination of the relevant goals, objects, and the tools of governance leads to the conclusion that none of the existing tools on the national or international level is apt to deal with convergent and multifaceted technologies such as, e.g., AI. At present, there is no uniform or comprehensive solution, and such a solution may not even be feasible. A multi-layered and targeted approach that encompasses schedule-based controls where possible, technology-based monitoring where necessary, and behavioral and institutional measures where the legal framework alone is insufficient is required. For chemical terrorism, this means that the effectiveness of control measures should be measured not only by whether they can eliminate all risks, but also by whether they can raise the threshold for abuse, improve detection, and make it more difficult for adversaries to adapt.

1. Introduction

Progress in various fields of science and technology (S&T) is happening at an unprecedented pace, driven by public and private investments aimed at sustaining competitive sectors that promise to shape and improve our daily lives through continuous advancements in medicine, pharmacology, the chemical industry, materials science, and more. Such developments are undoubtedly beneficial to society as a whole. However, concerns have often been raised that malicious non-state actors could misuse some of these advancements to produce and deploy chemical and biological weapons (CBW), as they may lower the barriers to accessing advanced technologies and enable the evasion of existing regulations.

Multilateral treaties such as the Chemical Weapons Convention (CWC) and the Biological Weapons Convention (BWC) are cornerstones of international disarmament regimes, prohibiting the acquisition and use (although not explicitly mentioned in the BWC) of CBW. The provisions of the CWC require each State Party to undertake the destruction of chemical weapons "that are located in any place under its jurisdiction or control" (Art. I) and prohibit "natural and legal persons anywhere on its territory or in any other place under its jurisdiction as recognized by international law from undertaking any activity" forbidden by the CWC (Art. VII). Each State Party must also prevent the development of CBW by malicious non-state actors by implementing national regulations, as required by both the CWC and the BWC. This is in particular important since the "borderlines between war, civil war, large-scale violations of human rights, revolutions and uprisings, insurgencies and terrorism as well as organized crime are blurred"[1].

Malicious non-state actors have deployed (or attempted to deploy) CBW in the past. Yet, the number of known terrorism cases in which perpetrators used chemical weapons exceeds the number of cases in which a bioagent (i.e., a pathogenic microorganism) was deployed as a weapon. Note that toxins (and some other biological substances, e.g., bioregulators) represent the so-called mid-spectrum agents, as they are regulated under both the CWC and the BWC. According to reports based on data from the Violent Non-State Actor (VNSA) CBRN Event database, 565 unique events of deploying CBRN weapons were recorded from 1990 to 2020.[2] Of these, 67.3% involve chemical substances and 13.1% involve biological substances (note: cases that primarily involved biological or chemical toxins were counted as biological or chemical agent incidents, respectively).[2] This apparent imbalance might indicate that using modern biotechnology to produce bioweapons (i.e., the entire pathway from the bioagent to the operational bioweapon) remains a complex endeavor that presents hurdles for malicious actors. Due to the difference between chemical and biological weapons, developments in S&T that could potentially be misused for producing chemical or biological warfare agents will be the focus of separate analyses. This manuscript mainly focuses on chemical weapons.

Assessing the threat of a terrorist attack is a challenging task. The probability of the threat is often expressed as a product of intent, capability, and opportunity.[3] The critical factor behind every case of terrorism is intent, which cannot be analytically assessed (e.g., without access to insider sources or a sufficient number of historical cases) to provide meaningful information about potential future threats. Nevertheless, changes in capability that may be significant for malicious non-state actors can be assessed to some extent by analyzing advancements in S&T that could create benefit in undertaking certain activities. Technology has proven to play an important role in the evolution of terrorism in the past, with the progress in communication technology and electronics, expansion of

[1] Note by the Director General. Report of the advisory panel on future priorities of the Organisation for Prohibition of Chemical Weapons. S/951/2011 25 July (2011).

[2] Tin D., Cheng L., Shin H., et al. A Descriptive Analysis of the Use of Chemical, Biological, Radiological, and Nuclear Weapons by Violent Non-State Actors and the Modern-Day Environment of Threat. *Prehosp. Disaster Med.* 38(3), 395-400, (2023).

[3] Riehle K.P. Assessing Foreign Intelligence Threats. *Am. Intell. J.* 31(1), 96-101, (2013).

commercial aviation, revolution in the digital world and media, etc.[4] In particular, the era of digitalization provided new powerful means for terrorist groups to spread fear, disruption, misinformation, and propaganda, reaching a huge number of people worldwide and recruiting new followers of ideological movements, etc. Hence, discussing S&T developments remains at the core of the analysis of terrorism of any kind.

The discussion presented here might seem speculative, as some experts argue that terrorists foremost use available, accessible, and easy-to-adopt options, rather than embrace new technologies. There are, however, many unknowns regarding any future scenarios of terrorist attacks. In particular, the question of which technologies can be considered appealing to terrorists and which criteria and characteristics are crucial in this case has been a matter of extensive scholarly debate.[5] Concerning chemical terrorism, some experts believe that an attack using widely available toxins or industrial chemicals would be far more likely than the use of blister or nerve agents like sulfur mustard or sarin. This view aligns with the report on chemical agents used in terrorist incidents. According to data from 1970-2019, acid (unspecified) was the most commonly used chemical weapon in terrorism-related attacks, followed by tear gas and chlorine.[6] Consequently, the familiar old threats will not disappear, whilst new technologies could potentially broaden the spectrum further. Therefore, the possibility of deploying accessible toxic industrial chemicals by malicious non-state actors is by no means ruled out. However, this is not the focus of this manuscript, which aims to discuss alternative strategies and scenarios made possible by some more or less recent developments in S&T (some technologies such as continuous flow techniques discussed here have a longer history of development) to provide a more comprehensive overview and to stimulate discussion on this topic as well as on existing and necessary policy measures to address it. It is also widely recognized that non-state actors can benefit from certain S&T advancements that make technologies increasingly user-friendly and accessible, leading to a diversification of existing and established approaches. Furthermore, “classical” and “emerging” approaches can become interlinked when non-state actors explore, e.g., alternative synthetic routes for known CWAs, circumventing regulated precursors, as discussed below.

The methodology applied in this manuscript is limited to monitoring developments and trends, as well as changes across various contexts (social, geopolitical, economic, etc.). This approach enables a rough picture of the potential threat landscape, identifies regulatory gaps, and determines the need for action. In line with this concept, this manuscript aims to provide a concise overview of recent advances in life sciences and related converging disciplines that can be relevant in the discussion on chemical terrorism. However, the sheer volume of scientific knowledge and relevant applications makes a comprehensive review a challenging task. Subsequently, we consider selected applications and techniques in this paper. Readers are referred to other publications and reports for further information.[7,8,9,10]

4 Glazzard, A., McIlhatton, D., Martin, P. Will Generative AI Fundamentally Change Terrorist Threats? *CTC Sentinel*, *19*(5), 25-31. Article 4. https://ctc.westpoint.edu/will-generative-ai-fundamentally-change-terrorist-threats/ (2026).

5 Freilich J. D., Gruenewald J, Mandala M. Situational Crime Prevention and Terrorism: An Assessment of 10 Years of Research. *Crim. Justice Policy Rev.* 30(9), (2018).

6 Tin D., Ciottone G.R. Chemical Agent Use in Terrorist Events: A Gathering Storm Requiring Enhanced Civilian Preparedness. *Prehosp. Disaster Med.* 37(3), 327-332 (2022).

7 Warmbrod. K. L., Revill. J., Connell. N. 2020. “Advances in Science and Technology in the Life Sciences: Implications for Biosecurity and Arms Control”. Geneva, Switzerland: UNIDIR. https://doi.org/10.37559/SecTec/20/SandT, (accessed 2026).

8 Brockmann K., Bauer S., Boulanin V. Bio, Plus X: Arms Control and the Convergence of Biology and Emerging Technologies, Stockholm International Peace Research Institute (SIPRI), (2019).

9 OPCW. Report of the Scientific Advisory Board, 30 April, 2018, RC-4/DG-1 https://www.opcw.org/sites/default/files/documents/CSP/RC-4/en/rc4dg01_e_.pdf (accessed 2026).

10 National Research Council (US) Committee on Trends in Science and Technology Relevant to the Biological Weapons Convention: An International Workshop. Life Sciences and Related Fields: Trends Relevant to the Biological Weapons Convention. Washington (DC): National Academies Press (US), (2011).

2. S&T advancements that might impact the development and production of chemical warfare agents

There is a vast number of chemical compounds. The Chemical Abstracts Service (CAS) registry database currently includes over 275 million registered substances.[11] The known chemical warfare agents (CWAs), their precursors, and several other chemicals that pose "a risk to the object and purpose"[12] of the Convention are included in the schedules of the Organisation for the Prohibition of Chemical Weapons (OPCW), the implementing body of the CWC. They are subject to specific restrictions and declarations by the State Parties, followed by close monitoring and verification by the OPCW. The Schedules of Chemicals are normally reviewed at the occasion of an upcoming Review Conference. This procedure may lead to their amendment, in particular as an after-the-event adjustment, as occurred in response to the use of so-called "Novichok" agents. Thus, in 2019, four new entries were added to Schedule 1.A of the Annex on Chemicals.[13]

Cases of chemical terrorism or assassination (attempts) involving chemicals listed in the CWC Annex on Chemicals are scarce. An incomplete list since the 1970s includes:

- The use of ricin to assassinate the Bulgarian dissident Georgi Markov (1978);[14]
- The release of sarin in the residential area of the city of Matsumoto, Japan (1994);[15]
- The intentional use of sarin on the Tokyo subway system by the Japanese cult Aum Shinrikyo (1995);[16]
- The use of toxic chemicals (i.e., sulfur mustard) by ISIS in Syria (2013) and Iraq (2015)[17];
- use of the nerve agent VX during the assassination of the half-brother of the leader of North Korea at the Kuala Lumpur International Airport in Malaysia (2017);[18]
- The attempted assassination cases of S. and Y. Skripals with an A-series agent ("Novichok") in Salisbury, United Kingdom (UK), and two related subsequent cases of accidental poisoning in Amesbury, UK, by the same nerve agent (2018);[19]
- The case of ricin acquisition/production for terrorist use in Germany (2019);[20]
- The poisoning of Russian opposition leader A. Navalny with an A-series agent ("Novichok") in Russia (2020).[21]

Above, cases of chemical terrorism are listed together with events of state-sponsored assassination attempts with chemical agents. While the latter do not fall under the definition of "chemical terrorism", their consideration is important in the present context, shaping the discussions on an international level around the prohibitive norms against chemical weapons. The list is by far not comprehensive. However, it provides a glimpse at some of the CWAs deployed in the past by terrorists (although, as explained in the introduction, toxic industrial chemicals have more often played a role in the documented cases of terrorist attacks than listed CWAs). Many of the chemicals deployed in the cases listed above (such as G-agent sarin, V-agent VX, and A-agents Novichoks)[22] are CWAs belonging to the nerve agents of the group of organophosphorus

11 CAS Databases https://www.cas.org/support/documentation/cas-databases (assessed 2026).
12 OPCW. Annex on Chemicals https://www.opcw.org/chemical-weapons-convention/annexes/annex-chemicals/annex-chemicals (assessed 2025).
13 OPCW. Report of the Scientific Advisory Board, SAB 37/1, 1. September 2023, https://www.opcw.org/sites/default/files/documents/2023/10/sab-37-01%28e%29.pdf (accessed 2026).
14 Crompton R., Gall D. Georgi Markov–death in a pellet. *Med Leg J.* 48(2), 51-62, (1980).
15 Morita H., Yanagisawa N., Nakajima T., et al. Sarin poisoning in Matsumoto, Japan. *Lancet*, 346(8970), 290-293, (1995).
16 Vale A. What lessons can we learn from the Japanese sarin attacks? *Przegl. Lek.* 62(6), 528-532 (2005).
17 Starck C. The Evolution of the Islamic State's Chemical Weapons Efforts. *CTC Sentinel*, 10(9), (2017).
18 Aroniadou-Anderjaska V., Apland J., Figueiredo T., et al. Acetylcholinesterase inhibitors (nerve agents) as weapons of mass destruction: History, mechanisms of action, and medical countermeasures. Neuropharmacology, 181(41), (2020).
19 McLeish C. The Skripal case: Assassination attempt in the United Kingdom using a toxic chemical. SIPRI Year Book 2019. Chemical and biological security threats, 408-417, (2018).
20 Brown T. Couple charged with BW offence in Germany, *Trust & Verify* 164, (2019).
21 Howes L. Novichok compound poisoned Navalny. *C&EN* 98(35), (2020).
22 The G, V-, and A-agents are categories of organophosphorus nerve agents, grouped mainly according to their chemical characteristics and historical development; G-type: GA (Tabun), GB (Sarin), GD (Soman), and GF (Cyclosarin); V-type: VX and VR; A-type: A-series agents associated with the Novichok family, such as A-230, A-232, and A-234, etc.

compounds. The physiological effect of organophosphorus compounds is based on the inhibition of the enzyme acetylcholinesterase (AChE), which breaks down the neurotransmitter acetylcholine. This blockage leads to an accumulation of acetylcholine, overstimulation of the corresponding receptors in the central and peripheral nervous systems, and impaired neurotransmission to the muscles.[23]

Notably, during the sarin attacks carried out by Aum Shinrikyo (1995), the chemical was synthesized by cult members using the "classical" procedure and then disseminated with self-made equipment.[24] This illustrates that established "traditional" methods and approaches must be considered alongside discussions of emerging technologies and their possible impact on chemical terrorism. Considerations regarding which methods terrorists would use to produce chemical weapons are fraught with many unknowns. CWAs can be obtained using established synthesis routes (particularly in areas with weak or weakened national regulations where they might escape detection and prosecution), acquired from resourceful allies (e.g., in cases of state-sponsored chemical terrorism), or produced using alternative synthetic routes to avoid regulated precursors. This latter approach can be facilitated by current developments in S&T, as discussed in this manuscript.

Another compound involved in some of the documented cases of terrorism is ricin obtained from castor beans. It is a highly potent toxin that inhibits protein biosynthesis in the body. Due to the availability of castor beans and the relatively simple procedure for the isolation of the toxin, ricin has attracted the interest of terrorists and criminals for small-scale poisoning or for causing disruption.[25] With respect to the usage of toxins in a large-scale terrorist attack, some results from past research conducted for military purposes point out, however, that toxins can be less effectively disseminated in the field compared to nerve agents. For instance, according the research into the military uses of natural poisons the area affected by botulinum toxin is stated to be three times smaller than that of V-agent VX.[26,27]

In the following, we will analyze some S&T advancements that might be misused by malicious non-state actors to develop and produce some of the CWAs listed above. The focus will be primarily on a) identification of potentially new CWAs and determination of alternative synthesis routes using computational tools, b) the current progress in the synthesis of these compounds, and c) converging technologies that can be potentially deployed to disseminate the CWAs.

a) Identification of potentially new CWAs and determination of alternative synthesis routes using computational tools

As mentioned above, CWAs and their precursors are subject to stringent regulations and monitoring under the auspices of the OPCW. However, recent progress in computational methods appears to open up an entirely new avenue for actors seeking to circumvent regulated compounds and explore alternative synthetic pathways that involve only readily available, non-regulated reagents to obtain the desired product. Here we will have a look at some of the examples.

In one of the studies, Fuller et al. demonstrate how the algorithmic search through the available network of synthetic-organic knowledge, comprising about 10^7 reactions, can deliver information on the synthesis of nerve agents "not only from unregulated substances obtained from licensed chemical suppliers [...], but also from substances that can be freely bought in a local

[23] Colović M.B., Krstić D.Z., Lazarević-Pašti T.D., et al. Acetylcholinesterase inhibitors: pharmacology and toxicology. *Curr. Neuropharmacol*. 11(3), 315-335, (2013).
[24] Danzig P. et al. Aum Shinrikyo: insights into how terrorists develop biological and chemical weapons, JSTOR 2nd edition (2015).
[25] OPCW Ricin Fact Sheet. p.6. https://www.opcw.org/sites/default/files/documents/SAB/en/sab-21-wp05_e_.pdf (accessed 2026)
[26] Antonov N.S. Chemical Weapons at the Turn of the Century; Progress: Moscow, Russia, (1994).
[27] Pitschmann V., Hon Z. Drugs as Chemical Weapons: Past and Perspectives. *Toxics.* 11, 52, 1-15, (2023).

supermarket"[28].The authors of the study further state that it is possible to identify the synthesis route for the nerve agent VX from household items, "as simple as clarifiers, garden fertilizers, and kitchen salt" that "can be carried out even by amateur chemists"[28].

This example aligns well with the discussion on the impact of other computational tools, in particular the **artificial intelligence (AI)-driven** ones, in the CW realm. Such tools can, e.g., be used to design chemical compounds with desired properties and determine their retrosynthesis pathways (backwards from a target molecule). For instance, the AI-enabled software DarkNPS automatically elucidates structures of novel psychoactive substances based on available mass spectrometry measurement data.[29] An additional example is the software called Allchemy that "combines state-of-the-art computational synthesis with AI algorithms to predict molecular properties"[30]. The potential of the software has been demonstrated in numerous publications.[31] On the other hand, as expected, such tools have a dual-use nature. As the principal investigator of the involved research group mentioned during the 38th Session of the SAB of OPCW, the software could be used to generate possible analogues of the Novichoks (A-agents).[32] Furthermore, the algorithm could be applied to identify synthetic routes for chemicals belonging to the group of incapacitating chemical agents, such as fentanyl. The proposed synthetic routes involved around 350 different chemicals, of which „only 13 are subject to regulation in the United States of America"[32,33] . The lethal toxicity of some of the fentanyl derivatives, such as carfentanyl, is close to that of some G-type nerve agents.[34] More broadly, this would mean that nefarious non-state actors can misuse computational tools in designing synthetic pathways for highly toxic chemicals, including known CWAs that can evade current monitoring by national authorities, or search for novel (more potent) CWAs or analogs to the known CWAs.

In principle, the possibility of discovering new chemical compounds with desired properties is underscored by the fact that there are about 10^{60} drug-like molecules[35], a number that exceeds any currently available libraries, databases, and registers. Some of these not-yet-identified compounds might be potent disrupters of important physiological pathways and belong to the next generation of CWAs. Perhaps the most widely cited example in this context is the study by Urbina et al., where the AI-driven drug-design algorithm could be repurposed to explore the chemical space around such potent CWAs as VX.[36] This resulted in a list of chemicals, some of which were predicted to have higher toxicity than VX. This analysis is undoubtedly an important "wake-up call" for chemical security. On a side note, toxicity is an important but not the only parameter to consider. A prominent example is the so-called EA-3148, the most potent V-agent[37], which proved to be unsuitable for weaponization and has therefore never been stockpiled.[38,39,40]

Other examples of computational tools reviewed in the present context include openly available software that aims at the characterization of the affinity of various nerve agents to the enzyme

[28] Fuller P.E., Gothard .CM., Gothard N.A., et al. Chemical network algorithms for the risk assessment and management of chemical threats. *Angew. Chem. Int. Ed. Engl.* 51(32), 7933-7937, (2012).
[29] Skinnider M.A., Wang F., Pasin D. et al. A deep generative model enables automated structure elucidation of novel psychoactive substances. *Nat Mach Intell* 3, 973–984, (2021).
[30] Software Allchemy https://allchemy.net/ (accessed 2026).
[31] Ibid. see information on the homepage for more details.
[32] Report of the Scientific Advisory Board at its thirty-eighth session, 27-31 May, SAB 38/1, (2024).
[33] Mikulak-Klucznik B., Klucznik T., Beker W., et al. Catalyst: Curtailing the scalable supply of fentanyl by using chemical AI. *Chem.* 10(5), 1319-1326, (2024).
[34] Pitschmann V., Hon Z. Drugs as Chemical Weapons: Past and Perspectives. *Toxics* 11(1), 52, 1-15, (2023).
[35] Bohacek R.S., McMartin C., Guida, W. C. The art and practice of structure-based drug design: a molecular modeling perspective. *Med. Res. Rev.* 16, 3–50, (1996).
[36] Urbina, F., Lentzos, F., Invernizzi, C. *et al.* Dual use of artificial-intelligence-powered drug discovery. *Nat Mach Intell* 4, 189–191 (2022).
[37] Commission on Life Sciences. Possible Long-Term Health Effects of Short-Term Exposure to Chemical Agents. *The National Academies Press*, Washington D.C. Vol. 1, p.7 (1982).
[38] *Mirzayanov V. S. State Secrets. An Insider's Chronicle of the Russian Chemical Weapons Program., Outskirts Press, 127–128 (2009).*
[39] EA-3148, https://en.wikipedia.org/wiki/EA-3148#cite_note-2 (accessed 2026).
[40] Blum M.M. No chemical killer AI (yet). *Nat. Mach. Intell.* 4, 506–507, (2022).

AChE, which they inhibit as part of their mechanism of action (see above). For instance, one published computational approach aims at designing "molecules with similar biological functions as organophosphorus-based CWAs with less potency"[41]. A further example is a computational modeling approach to predict the AChE inhibitory potency of organophosphates.[42] In principle, these approaches can be repurposed to screen libraries of chemical compounds in the search for new, effective AChE inhibitors.

Another possibility is to apply computational tools to discover the structures of (novel) toxins. Many of the toxins (e.g., ricin) belong to the group of proteins. Currently, the Protein Data Bank[43] contains over 200 thousand entries related to experimental structures, while the AlphaFold Protein Structure Database[44] encompasses over 200 million AI-predicted proteins, "almost every protein known to science"[45]. Even more striking, another sequence-to-structure predictor, ESMFold,[46] has demonstrated the ability to predict the structures of more than 617 million proteins "from bacteria, viruses, and other microorganisms that haven't been characterized"[47]. Lately, a debate around the question of whether the proteins designed by AI could be weaponized has been published, along with outlines for the required safety guidelines for the design community.[48] In a recently published study, authors used a Large Language Model (LLM; a type of AI system), Moremi Bio Agent, and demonstrated that without the safety guardrails, the algorithm was capable of designing "1020 novel toxic proteins and 5,000 toxic small molecules"[49], some of which were similar to known toxins like ricin and saxitoxin. This result is analogous to the findings reported by Urbina et al.

All of these examples illustrate how impactful such computational tools might be in the hands of malicious non-state actors. However, it should be emphasized that "translating designs into physical molecules requires significant expertise and equipment"[50]. Although AI tools can be potentially misused to design toxins, this does not eliminate the need for building and testing the simulated structures, as also concluded in the recent report of the US National Academies of Sciences, Engineering, and Medicine (NASEM).[51] As summarized elsewhere, "it doesn't matter what you do in the computer most of the time. What matters is how you translate it into a real, physical protein or small molecule"[50]. This also applies to the idea of designing alternative synthesis pathways for the known CWAs. Such an undertaking represents only an initial step in the entire process that does not replace the subsequent experimental procedure. Also, the predictive capabilities of AI models are limited by the availability of (curated) data used to train the models. Data quality is one of the known bottlenecks for AI in general, and would also impact attempts to misuse the information for malicious purposes. The obtained "recipes" for the synthesis of desired compounds are often incomplete, lacking essential information on required concentration, catalysts, yields, etc. Even more striking is the fact that AI models are known to 'hallucinate' – that is, to produce results that appear plausible at first glance but are in fact incorrect – meaning that

41 Hu H., Ooi H.K., Ghaemi M.S., et al. Machine learning for the prediction of safe and biologically active organophosphorus molecules., arXiv:2302.10952, (2023).
42 Lee S., Barron M.G. A mechanism-based 3D-QSAR approach for classification and prediction of acetylcholinesterase inhibitory potency of organophosphate and carbamate analogs. *J. Comput. Aided Mol. Des.* 30, 347–363, (2016).
43 Protein Data Bank https://www.rcsb.org/ (accessed 2026).
44 AlphaFold Protein Structure Database https://alphafold.ebi.ac.uk/ (accessed 2026).
45 Heikkilä M. DeepMind has predicted the structure of almost every protein known to science. MIT Technology Review https://www.technologyreview.com/2022/07/28/1056510/deepmind-predicted-the-structure-of almos -every-protein-known-to-science/ July, 2022 (accessed 2026).
46 Lin Z., Akin H., Rao R., et al. Evolutionary-scale prediction of atomic-level protein structure with a language model. *Science*. 379(6637), 1123-1130, (2023).
47 Callaway E. AlphaFold's new rival? Meta AI predicts shape of 600 million proteins. *Nature*. 611(7935), 211-212, (2022).
48 Callaway E. Could AI-designed proteins be weaponized? Scientists lay out safety guidelines. *Nature News*, 8. March 2024. https://www.nature.com/articles/d41586-024-00699-0 (accessed 2026).
49 Hattoh G., Ayensu J., Ofori N., et al. Can Large Language Models Design Biological Weapons? Evaluating Moremi Bio. 10.48550/arXiv.2505.17154 (2025).
50 Callaway E. AI can design viruses, toxins and other bioweapons. How worried should we be? *Nature* 653, 344-347 (2026)
51 National Academies of Sciences, Engineering, and Medicine. The Age of AI in the Life Sciences: Benefits and Biosecurity Considerations (National Academies Press, 2025).

extensive background knowledge and specialist expertise are required to identify such fabricated information in their outputs. Furthermore, the non-codable knowledge of laboratory procedures – known as 'tacit knowledge' – does not constitute a list of instructions that AI models could provide. These aspects raise questions about how successful amateur chemists would be in reality in their attempt not just to discover possible "promising" synthetic routes for the CWAs but also to carry them out experimentally (without poisoning themselves). Particularly when it comes to large-scale production of CWAs, amateur chemists are likely to reach the limits of their capabilities, as such an endeavour requires dedicated training in handling toxic substances as well as access to specialized equipment and consumables. Additionally, progress in S&T is not the only factor that matters in this discussion. The convergence of S&T makes access to multiple disciplines with diverse expertise and a solid scientific knowledge base essential. Non-state actors would find it very difficult to reconstruct this complex ecosystem by trying to identify and repurpose specific applications.

Another aspect is the computational search for novel CWAs. First and foremost, some experts argue that non-state actors would not necessarily seek novel CWAs, as the "existing ones are good enough"[40]. What's more: it's not just a question of old agents being 'good enough', but also of them being proven to work as intended, and being accessible and relatively easy to use. As pointed out by an expert in the field, this doesn't rule out terrorists' use of "unusual" (novel) agents, but they would probably not try to identify them in a vast chemical space comprising predicted chemical structures with predicted toxicity, but rather rely on established (empirical) chemical and toxicological findings from documented cases.[52]

In short, the sheer numbers of structures made available through AI tools may in fact be misleading when it comes to assessing the threat of chemical terrorism related to such tools. The discussion around the question of whether and how the computational solutions change the capabilities of malicious non-state actors in the CW realm needs therefore to be more nuanced. Such tools may, e.g., facilitate the first steps in the synthesis of the known CWAs from unregulated, accessible compounds —an application that is more likely to be used than searching for entirely novel toxic compounds without experimentally validated characteristics—but they still require a sound basic knowledge of chemistry, experience in carrying out experimental procedures, handling highly toxic substances, and effective delivery and dissemination methods, etc. As pointed out elsewhere, although LLMs can potentially improve the efficiency, accessibility, and scale of certain terrorist activities, "there remains limited evidence that they fundamentally alter the nature of terrorism or significantly enhance operational capability"[4]. However, even if it might not be the game changer (yet) regarding the possibility of producing CWAs, certain features of AI can certainly provide efficiency gains for terrorists, including chemical terrorists. These are, e.g., the spread of propaganda, disinformation, recruitment, or research on possible targets[4], exploration of vulnerabilities, cyberattacks on chemical facilities, etc.

b) Synthesis (and decontamination) strategies

As mentioned above, many of the known CWAs are organophosphorus compounds. This group encompasses a broad range of substances that serve peaceful purposes, such as pesticides and flame retardants. Traditionally, these agents have been manufactured using batch processes. Due to the high demand for these substances, novel, safer (so-called green) methods for their industrial synthesis have emerged over the years. These approaches are also applicable to the synthesis of CWAs as reference substances required in the verification procedures of the OPCW.[53] They utilize **continuous flow techniques**, which are often viewed as a paradigm shift from batch production,

[52] From personal discussion with Dr. Ralf Trapp (2026).

[53] Silva V.B., Santos Y.H., Hellinger R. et al. Organophosphorus chemical security from a peaceful perspective: Sustainable practices in its synthesis, decontamination and detection. *Green Chem.* 24, 585–613, (2022).

promising enhancements in efficiency and selectivity of the production process[54], and might even contribute to the discovery of new reactions.[55]

Flow technology is advantageous for managing different hazardous reactions and compounds,[56] as well as unstable or highly reactive compounds.[66] For instance, it allows the handling of chemicals "with limited exposure to the operator"[68]. This aspect is beneficial when working with toxic reagents and products in the synthesis process of organophosphorus compounds. The reactions generally occur in microreactors, which facilitate a controlled reaction environment.[57] Flow processes also allow for better optimization of parameters such as temperature and reaction time.[58] Furthermore, batch and continuous flow chemistry can be integrated with automation and robotics for the (multistep) synthesis of chemicals in an automated manner.[59] Several platforms aimed at streamlining laboratory workflows have been reported recently.[60,61,62]

The advancements in flow chemistry were highlighted during the 38th Session of the SAB.[32] Among other discussions, the potential of combining continuous processes with light sources to drive photochemical reactions was emphasized. The benefit of photocatalysis, for example, is the rapid synthesis of a broad range of chemicals, including pharmaceuticals, agrochemicals, and fine chemicals.[63] The possibility of automating this process has also been discussed. Thus, a robotic platform, RoboChem, has been shown to facilitate the optimization, intensification, and scaling up of the reactions performed, with minimal human intervention required, making the technology accessible to users with limited expertise.[64] However, the democratization of science can be exploited by malicious actors. Moreover, it has been noted that, alongside its undeniable advantages, "flow chemistry also stimulates lots of concerns when it comes with the potential production of CWAs for chemical terrorism"[68]. Additionally, advances in microfluidic setups might encourage the development of libraries of unlisted compounds related to known CWAs.[68] The International Union of Pure and Applied Chemistry (IUPAC) also highlights in one of its Technical Reports[65] on the impact of scientific developments on the CWC the importance of monitoring developments in the field of flow reactors. Particular emphasis is placed on microreactors, which "have the potential to be used in military or terrorist applications"[66].

The applicability of microreactor technology in the synthesis of classical CWAs has been evaluated by the Spiez Laboratory. According to the published results, the technology does not yield "benefits when compared to the conventional batch procedure, as many reactions produce a solid, the main

54 Bálint E., Tajti Á., Keglevich G. Application of the Microwave Technique in Continuous Flow Processing of Organophosphorus Chemical Reactions. *Materials*. 12(5), 788, 1-15, (2019).
55 Alfano A.I., García-Lacuna J., Griffiths O.M. et al. Continuous flow synthesis enabling reaction discovery. *Chem Sci.* 28;15(13), 4618-4630, (2024).
56 Mleczko L., Zhao D. Technology for Continuous Production of Fine Chemicals. A Case Study for Low Temperature Lithiation Reactions. *ACS Symposium Series* Vol. 1181, 403-440, (2014).
57 Porta R., Benaglia M., Puglisi A. Flow Chemistry: Recent Developments in the Synthesis of Pharmaceutical Products. *Org. Process Res. Dev.* 20(1),2-25, (2015).
58 Plutschack M.B., Pieber B., Gilmore K., et al. The Hitchhiker's Guide to Flow Chemistry. *Chem Rev.* 117(18), 11796-11893, (2017).
59 Clayton A.D., Recent developmets in reaction automation for multistep chemical synthesis. *Chem. Methods* 3, 1-12, (2023).
60 Adamo A., Beingessner R.L., Behnam M., et al. On-demand continuous-flow production of pharmaceuticals in a compact, reconfigurable system. *Science* 352(6281), 61-67, (2016).
61 Bédard A.C., Adamo A., Aroh K.C., et al. Reconfigurable system for automated optimization of diverse chemical reactions. *Science* 361(6408),1220-1225, (2018).
62 Coley C.W., Thomas D.A.III., Lummiss J.A.M, refd4erlöet al. A robotic platform for flow synthesis of organic compounds informed by AI planning. Science, 365(6453):eaax1566, (2019).
63 Noël T., Zysman-Colman E. The promise and pitfalls of photocatalysis for organic synthesis. *Chem Catalysis.* 2. 468-476. (2022).
64 Slattery A., Wen Z., Tenblad P., et al. Automated self-optimization, intensification, and scale-up of photocatalysis in flow. *Science*. 1-13, (2024)
65 Smallwood K., Trapp R., Mathews R., et al. Impact of scientific developments on the Chemical Weapons Convention (IUPAC Technical Report) *Pure Appl. Chem.* 85(4), 851-881, (2013)
66 Holger L., Hessel V., Mueller A. Microreactors – Prospects Already Achieved and Possible Misuse. *Pure Appl. Chem.* 74(12), 2271-2276, (2002).

criterion excluding microreactor technology"[66]. However, nowadays, the limitation of solid products can be addressed by various strategies that have been extensively reviewed elsewhere.[67] Numerous examples of advances in synthesizing organophosphorus compounds using continuous flow chemistry have been summarized in the dedicated review.[68] The ability to execute the workflow in an automated fashion with only limited human interaction is an important factor that may render the technology appealing to nefarious non-state actors. For example, SAB observes that microreactors could be misused "to reduce the footprint of a system that is making CWAs [...]However, traditional laboratory bench-scale chemical equipment (e.g. glassware) would also present a small footprint that could be concealed for preparing small amounts of material and the equipment later disassembled"[9].

There are additional methods for synthesizing chemical compounds of interest that exceed the scope of this manuscript. However, we will highlight certain aspects in the context of **metabolic engineering** for chemical production. This field incorporates strategies from systems biology, synthetic biology, computational biology, and genetic engineering to convert microorganisms into efficient bio-factories capable of producing a plethora of chemicals. Examples of these strategies include enzyme engineering, advanced genome-scale metabolic simulations, and even de novo design of metabolic pathways.[69] A key tool in designing metabolic pathways is the **directed evolution** of enzymes, which enhances and potentially diversifies their functional range. A recently developed robotic system can conduct a high-throughput virus-assisted (bacteriophage) continuous evolution of biomolecules[70] that "can be performed 1 billion times faster than traditional directed evolution experiments"[71]. Additionally, an automated design of synthetic metabolic pathways has been introduced, which may pave the way for fully automated biomanufacturing.[72]

Some advancements in metabolic engineering present a dual-use character, posing potential misuse risks by nefarious non-state actors to produce toxic compounds in various organisms. As noted in the Report by the Director-General of the OPCW from February 2023, the progress in this area "raises concerns regarding its potential to be used to produce toxic chemicals or their precursors"[73]. An illustrative example of this potential is the reported metabolic engineering of yeast, which subsequently served as a platform for synthesizing opioids from glucose.[74] Here, a non-regulated starting component (glucose) was employed for the synthesis of a regulated product (hydrocodone). However, the technological challenges inherent in experimental procedures should not be underestimated. In the case of metabolically engineered yeast for opioid production (vide supra), the reported success resulted from "the result of ten years of work, involves the artificial expression of 23 genes originating from yeast, plants, and rats"[74].

There are also several examples of using metabolic engineering to degrade organophosphorus compounds (see below). As mentioned by SAB reports of the OPCW (April 2018), "the development of microorganisms capable of hydrolysing and therefore inactivating organophosphates opens the possibility of also catalyzing the reverse reaction (e.g., their formation)"[9]. However, enzymes do not

[67] Hayes H., Mallia C. Continuous Flow Chemistry with Solids: A Review. *Org. Process Res. Dev.* 28(5) (2024).
[68] Morodo R., Bianchi P, Monbaliu J.C.M., Continuous flow organophosphorus chemistry. *Eur. J. Org. Chem*. 2020(33), 5236–5277, (2020).
[69] Ko Y.-S., Kim J. W., Lee J. A. et al. Tools and strategies of systems metabolic engineering for the development of microbial cell factories for chemical production. *Chem. Soc. Rev.*, 49, 4615-4636, (2020).
[70] DeBenedictis E.A., Chory E.J., Gretton D.W. et al. Systematic molecular evolution enables robust biomolecule discovery. *Nat Methods* 19, 55–64 (2022).
[71] Trafton A. Speeding up directed evolution of molecules in the lab, MIT News, December 30, 2021, https://news.mit.edu/2021/robotic-directed-evolution-molecules-1230 (accessed 2026).
[72] Otero-Muras I., Carbonell P. Automated engineering of synthetic metabolic pathways for efficient biomanufacturing. *Metab. Eng.* 63, 61-80, (2021).
[73] OPCW. Report by the Director-General, RC-5/DG.1, p.4 , 22. February 2023, https://www.opcw.org/sites/default/files/documents/2023/02/rc5dg02%28e%29.pdf (accessed 2026)
[74] Höhne M., Kabisch J. Brewing Painkillers: A Yeast Cell Factory for the Production of Opioids from Sugar *Angew. Chem. Int. Ed.* 55(4), 1248-1250, (2016).

alter the chemical equilibrium of a reaction; instead, they lower the activation energy.[75] Enzymatic reactions might not be reversible if the equilibrium lies in favor of the products. Therefore, reversing the hydrolysis of organophosphorus compounds might be challenging.[9]

The SAB report further points out that "no known examples of the production of Schedule 1 chemical warfare agents (CWAs), such as nerve agents or blister agents, or their chemical precursors, through biological means"[9] are currently available, which does not apply to some other (toxic) chemicals. As further stated, metabolic engineering "might permit in the future the manufacture of toxic compounds that could potentially be weaponized"[9]. Ricin, for instance, can be obtained from natural sources (castor beans). Due to the complexity of toxins like ricin (a proteinaceous toxin) it appears much simpler to acquire it from natural sources than through biotechnology. In contrast, obtaining several grams of the toxin saxitoxin from its natural sources (certain freshwater algae) is more challenging and requires substantial amounts of raw material ("tons of affected clams") for processing.[10,76] This might be circumvented through the advances in metabolic engineering and synthetic biology. For instance, the expression of the *sxtA* gene, which codes for an enzyme essential for saxitoxin biosynthesis, has been reported in *E. coli.*[77]

However, here again it should be emphasized that misuse of any technological advances by nefarious non-state actors requires certain skills and technological know-how. Continuous-flow systems can improve process control and safety, but they also introduce engineering requirements involving precise control of flow, temperature, pressure, residence time, and material compatibility. Similarly, metabolic engineering relies on sophisticated genetic, biochemical, and cultivation capabilities in complex biological systems. Moreover, the synthesis of any hazardous compounds presents significant challenges in containment, purification, characterization, storage, and handling of these compounds. Consequently, while technological advances may lower certain barriers to chemical synthesis, they do not eliminate the considerable technical, infrastructural, safety, and analytical barriers. In addition, advances in science and technology should not be evaluated solely on their potential for misuse by malicious non-state actors. Instead, their potential to improve the effectiveness of countermeasures during a chemical terrorist attack should also be considered. For instance, AI tools can facilitate the development of new vaccines, therapeutics, and diagnostic methods. Computational tools can also be used for comprehensive multiparametric risk analysis, which can guide future regulations and policies to prevent chemical terrorist attacks. For instance, a computational approach to analyze the risk of chemical terrorist attacks and support policymaking has been published.[78] Flow chemistry and metabolic engineering can also serve as a countermeasure in the event of an attack involving, for instance, organophosphorus CWAs. Several flow chemistry setups for the chemical neutralization of pesticides and analogously CWAs have been reported.[68,79] These setups also include mobile systems suitable for the on-site neutralization of organophosphorus compounds. [68] Possible scenarios for applications of such systems include processing/demilitarization options of stored agents, or agents that can be drained from weapons rather than field decontamination of soil, equipment, personnel, etc. Advances in metabolic engineering and the directed evolution of enzymes can also be applied, e.g., to decontaminate some of the known CWAs. Below, a few examples of the degradation of specific organophosphorus compounds (sarin, soman, tabun, VX) using naturally isolated or genetically modified enzymes will

[75] Cooper G.M. The Cell: A Molecular Approach. 2nd edition. Sunderland (MA): Sinauer Associates; The Central Role of Enzymes as Biological Catalysts. (2000).

[76] Tucker J. B. The convergence of biology and chemistry: Implications for arms control verification. Bull. At. Sci. 66(6):56–66, (2016).

[77] Soeriyadi A. H., Mazmouz R., et al. Heterologous Expression of an Unusual Ketosynthase, SxtA, Leads to Production of Saxitoxin Intermediates in *Escherichia coli*. *ChemBioChem*, 22, 845, (2021).

[78] Zhu R., Hu X., Li X. et al., A Personalized and Practical Method for Analyzing the Risk of Chemical Terrorist Attacks, *IEEE Access*, 8, 81711-81723, (2020).

[79] Jang Y.J., Kim K., Tsay O.G., et al. Update 1 of: Destruction and Detection of Chemical Warfare Agents. Chem Rev. 115(24), 1-76, (2015).

be provided. Note that this summary is not exhaustive. For further information, readers are referred to several detailed reports.[80,81]

Enzymatic degradation of organophosphorus compounds has advantages compared to "classical methods" such as neutralization, incineration, and the use of explosive systems, which may be inefficient and can produce toxic byproducts when applied.[53,80] Other advantages include the fact that the reactions tend to be "soft," allowing them to be employed to decontaminate sensitive instruments, clothing, etc. The most widely studied enzyme for the degradation of organophosphorus compounds is the so-called organophosphorus hydrolase (OPH) found in some species of soil bacteria.[82] These enzymes are capable of hydrolyzing a variety of nerve agents, including soman, sarin, cyclosarin, tabun, and VX.[53,82] Another class of enzymes that are more efficient at degrading the G-nerve agents (such as sarin, soman, cyclosarin, and tabun) compared to OPH is the organophosphate acid anhydrase (OPAA) derived from specific marine bacteria.[81,83] Additionally, the squid enzyme diisopropylfluorophosphatase (DFPase) can hydrolyze the G-type nerve agents (but not the V-type agents).[81,84,85] Interestingly, an enzyme called paraoxonase (PON1), present in human serum, can hydrolyze organophosphorus CWAs in the human body.[81,86] Prophylactic gene therapy with a recombinant variant of PON1 has shown promising results in mice regarding its protective capability against G-type nerve agents.[87]

Various bioengineering approaches have been utilized to enhance the stability, stereoselectivity, catalytic activity, and expression levels of some of these enzymes.[81] Thus, the detoxification rate of phosphodiesterase (PTE) against VX has been increased by 5000-fold compared to the wild-type enzyme using an integrated computational and experimental approach.[88] Furthermore, organophosphorus CWAs are chiral molecules and exist as a pair of so-called enantiomers (non-superimposable mirror images of each other), which possess identical chemical and physical properties but can exhibit differences in, e.g., toxicity, pharmacokinetics, etc.[89] Concerning organophosphorus CWAs, their enantiomers differ in toxicity. Notably, wild-type forms of the aforementioned enzymes prefer the less toxic enantiomer as a substrate. This stereoselectivity can be reversed with enzyme engineering based on rational design.[90]

[80] Chen J., Guo Z., Xin Y., et al. Effective remediation and decontamination of organophosphorus compounds using enzymes: From rational design to potential applications. *Sci. Total Environ.* 867, 1-17, (2023).

[81] Singh B.K., Walker A., Microbial degradation of organophosphorus compounds, *FEMS Microbiol.Rev.*, 30(3), 428–471, (2006).

[82] Theriot C.M., Grunden A.M. Hydrolysis of organophosphorus compounds by microbial enzymes. *Appl. Microbiol. Biotechnol.* 89, 35–43 (2011).

[83] Cheng T., Liu L., Wang B., et al. Nucleotide sequence of a gene encoding an organophosphorus nerve agent degrading enzyme from Alteromonas haloplanktis. *J. Ind. Microbiol. Biotechnol*. 18(1), 49-55, (1997).

[84] Soares F.V., De Castro A.A., Pereira A.F., et al. Theoretical Studies Applied to the Evaluation of the DFPase Bioremediation Potential against Chemical Warfare Agents Intoxication. *Int. J. Mol. Sci*. 19(4):1257, (2018).

[85] Blum M.M., Timperley C.M., Williams G.R., et al. Inhibitory potency against human acetylcholinesterase and enzymatic hydrolysis of fluorogenic nerve agent mimics by human paraoxonase 1 and squid diisopropyl fluorophosphatase. *Biochemistry*. 47(18), 5216-5224, (2008).

[86] Cowan J., Sinton C.M., Varley A.W., et al. Gene therapy to prevent organophosphate intoxication. *Toxicol. Appl. Pharmacol.* 173(1), 1-6, (2001).

[87] Betapudi V., Goswami R., Silayeva L., et al. Gene therapy delivering a paraoxonase 1 variant offers long-term prophylactic protection against nerve agents in mice. *Sci. Transl. Med.* 12(527):eaay0356, (2020).

[88] Cherny I., Greisen P. Jr., Ashani Y., Engineering V-type nerve agents detoxifying enzymes using computationally focused libraries. *ACS. Chem Biol.* 8(11), 2394-2403, (2013).

[89] Coelho M.M., Fernandes C., Remião F., et al. Enantioselectivity in Drug Pharmacokinetics and Toxicity: Pharmacological Relevance and Analytical Methods. *Molecules*. 26(11):3113, (2021).

[90] Melzer M., Chen J.C., Heidenreich A., et al. Reversed enantioselectivity of diisopropyl fluorophosphatase against organophosphorus nerve agents by rational design. *J Am Chem Soc.* 131(47), 17226-17232, (2009).

c) Impact from other converging disciplines

Developing a functional chemical weapon by any (state or non-state) actor requires a combination of approaches and techniques due to the complexity of this multi-step process. Designed and synthesized chemical agents need to be disseminated. Terrorists would most likely make use of improvised devices, made, e.g., "from PlayStation controllers, rope, fertilizer, and explosive material"[91] for these purposes. Furthermore, the impact of **agricultural drones** on the threat of chemical terrorism[92] remains a long-standing issue, as they can be equipped with payloads of chemicals that can be sprayed over large areas. This concern was also addressed in the discussion agenda of the 38th SAB Session regarding "the implication of this technology for malicious use" and "existing regulation of large agricultural drone sales and ease of access to the technology"[32].

Another aspect is the so-called **digital fabrication technologies** (such as 3D manufacturing) used to produce laboratory equipment. The availability of these services can undoubtedly draw the attention of nefarious actors as they provide cost-effective and more clandestine means to acquire necessary laboratory utensils. The assembly of laboratory equipment and specific devices utilizing 3D printers has transitioned from prototyping to practical applications in everyday life. Recently, a modular system has been developed for the 3D printing of various laboratory equipment at a fraction of their retail costs.[93] Equipment can be designed using software for computer-aided design. Printable equipment examples are highly versatile, including centrifuges, micropipettes, and gel electrophoresis units, to name a few. One example in this context is the Jubilee project, an open-source hardware machine with automated tool changing, capable of 3D printing with diverse materials and even automatically handling liquids.[94] This platform for multi-tool fabrication has received considerable support from the scientific community. However, such devices "could be misused by malicious actors, who are often inventive in repurposing technology for harmful purposes", as noticed by SAB in its recent report.[95]

In addition to the laboratory equipment, spraying equipment and other delivery devices can also be produced with 3D printers.[9] For example, in a notable case, a PhD student used additive manufacturing to create a "kamikaze drone" intended to deliver a warhead or chemical weapons by terrorists.[96] This issue warrants careful consideration in the present discussion, though it is only one piece of a larger puzzle. Other methods of obtaining necessary materials and devices, such as the second-hand market within national borders or the EU, should also be taken into account.

Lately, the "face" of life sciences has changed tremendously, partly due to substantial investments in research and medicine. High-throughput laboratory systems, improvements in data storage and processing, and an increasing wealth of knowledge in natural sciences and engineering constitute just a few brushstrokes in this complex picture. Other important developments include the rapidly expanding **DIY community**, the emergence of **self-driving labs**,[97] and the acceleration of "the synthesis and fabrication of molecules and materials"[97] using robotics and machine-learning algorithms. In addition, the "diffusion of science" is continually increasing in both geographical reach and the growing number of stakeholders involved (research institutions, private sector), making it even harder to evaluate current S&T developments and their potential implications in the CW domain.

[91] Peterfi C.-T. Are the improvised chemical weapons as efficient as media claims they are? Case study: the Syrian war. The Scientific Research Centre for National, European and Euro-Atlantic Security. National Defence University "Carol I" (2021).
[92] Kallenborn Z. Why cheap drones pose a significant chemical terrorism threat. *Bull. At. Sci.* (2023)
[93] McNair M.C., Cocioba S.C., Pietrzyk P., et al. Toward an open-source 3D-printable laboratory. *Appl Plant Sci.* 12(1):e11562, (2024).
[94] Dunn K., Feng C., Peek N. Jubilee: A Case Study of Distributed Manufacturing in an Open Source Hardware Project. *J Open Hardw.* 7. (2023).
[95] Report of the Scientific Advisory Board at its thirty-eighth session, 4 April, SAB 39/1, (2025).
[96] Murray J. Birmingham PhD student guilty of using 3D printer to build "kamikaze" drone. The Guardian 28. Sep. (2023).
[97] Abolhasani, M., Kumacheva, E. The rise of self-driving labs in chemical and materials sciences. *Nat. Synth* 2, 483–492, (2023).

3. Governance

The described recent advances in areas relevant to chemical research and production, such as AI, additive manufacturing, flow chemistry, laboratory automation, and metabolic engineering, are only part of a bigger picture of relevant new and emerging technologies. They all contribute to the fact that approaches for the synthesis of known and new products become refined, accelerated, or sometimes change fundamentally. Progress is occurring simultaneously across multiple disciplines, marked by rapid vertical growth (new capabilities) and horizontal growth (greater accessibility). While these developments create economic and security opportunities, they also pose risks, including risks relevant to chemical terrorism (see Section 2). The existing normative framework may therefore not be flexible or comprehensive enough to effectively cover all of these developments. The question is how governance activities, here understood as the entirety of formal and informal multilevel approaches to tackle a specific field, could respond to this rapid growth and transformation in S&T[98].

This challenge is widely discussed in the literature[99]. Yet a clear solution remains elusive. It cannot be codified in a single norm, nor provided by a single stakeholder. This paper does not propose a definitive answer either, but briefly highlights governance challenges at different levels and reviews the potential of existing approaches. In doing so, it is important to be more specific about the gaps that are at stake. In the present context, the most relevant gaps are not a general absence of rules, but rather the difficulty of addressing: (i) intangible transfers of knowledge and capability; (ii) emerging technologies that lower the threshold for synthesis, modification, or dissemination; (iii) small-scale or distributed activities that may fall below existing declaration or control thresholds; and (iv) the limited ability of current systems to connect technical developments with terrorist acquisition pathways.

However, one can also manage a situation by doing nothing and simply letting things take their course. This was the radical approach of some Silicon Valley leaders who have recently called for a 10-year moratorium on the regulation of one of the technologies in question, namely AI[100] in all its aspects, and to societally accept all kinds of risks associated with the technology—this would hence include the making of chemical weapons. Historically speaking, this would mark a departure from past practice, as moratoriums have generally been applied in the opposite way: when risks were not yet fully understood, temporary restrictions were imposed to buy time and allow standards to evolve further. Examples from the neighboring field of biology include the Asilomar Conference on recombinant DNA in 1975 and the U.S. moratorium on gain-of-function research introduced by the Obama Administration in 2014.

Formally, no such moratorium was implemented, but what we currently see is basically the implementation of the demands of those who oppose regulation, though endeavors to regulate auxiliary technologies, such as AI, remain very limited. The reason is not necessarily that decision makers do not recognize that there is a problem—there are countless examples of critical AI developers, national security agencies, and international disarmament bodies who repeatedly warn that AI tools lower the barrier to creating chemical and biological weapons[101]. Rather, the challenge lies in the complexity of stakeholders and fields of application, the pace of development, the ubiquitarian use, the lack of oversight, and the subsequent fact that there is no single point at which one could simply set the lever for regulating the field.

Apart from AI, the complexity of converging technologies is further heightened by the fact that the technologies in question are often not individually distinguishable, but their combinations create

[98] Hooghe L., Marks G., Types of Multi-Level Governance. European Integration online Papers (EIoP), Vol. 5, No. 11, October 12, (2001).

[99] Brackmann M, Gemünden M, Invernizzi C et al. Assessing emerging technologies from an arms control perspective. *Front. Res. Metr. Anal.* 7:1012355. doi: 10.3389/frma.2022.1012355, (2022).

[100] https://www.washingtonpost.com/technology/2025/07/01/ai-moratorium-defeat-senate-silicon-valley/

[101] International AI Safety Report 2026 https://internationalaisafetyreport.org/publication/international-ai-safety-report-2026 (accessed 2026).

governance challenges spanning academic research and industrial application. Nevertheless, lacking governance might neither help to implement the beneficial sides of the development nor to prevent misuse, above all weaponization. Within the scope of this manuscript, we therefore focus primarily on the objectives, objects, and tools when we address the aspect of governance. This is based on approaches to understanding governance that emphasize, first, that governance applies to a wide variety of stakeholders (state, private, civil society, etc.) at different levels (from local to multilateral, and from informal to formal), and, second, that it can be arranged around objectives, context, and means of governance activities.[102]

In the following, we will have a closer look at the following questions in the context of this manuscript:

- What exactly is the goal of governance?
- What exactly is the object of governance?
- What are the appropriate tools for governance?

Two remarks are in order at the outset. First, in the area of chemical weapons, arms control cannot be effectively implemented over the long term through the existing normative framework alone. Convergence with emerging technologies governed under separate regulatory frameworks, where it occurs, can generally be addressed through the General Purpose Criterion of the CWC, but it cannot be adequately contextualized by the existing body of norms governing other technological fields. Indeed, it is not even straightforward to identify or develop an appropriate set of principles for risk mitigation. Can the precautionary principle be applied in a field in which the potential risks are not yet fully understood? This question is particularly relevant in the context of chemical terrorism, where governance must address not only the control of chemical agents and facilities, but also the pathways through which knowledge, tools, and services can be repurposed for hostile purposes.

Second, we would like to clarify the relationship between the two concepts of (global) governance and multinormativity. Global governance refers to an established body of theories that conceptualize political problems—including global ones—as being addressed at multiple levels, both within and beyond formal regulatory mechanisms. In addition to states acting in their various capacities, including collectively at the international level as well as individually through their external and internal functions, actors from the private sector and civil society are also involved. We understand the totality of these activities as governance. Multinormativity is a closely related concept that focuses on the diverse material and immaterial norms that emerge within and through these governance activities.

a) Goal of governance

The primary aim of governance in this context is to prevent new technologies from creating new opportunities for misuse that could undermine security. Ideally, the behavior of stakeholders—particularly developers and users—would ensure that such risks do not materialize in the first place, although this can never be guaranteed completely. At present, there is no reliable basis for estimating the likelihood that any actor, whether state or non-state, might seek to develop or use weapons by exploiting these technologies. A particular concern is the potential misuse of emerging technologies by terrorists. As a general rule, terrorists stand to benefit disproportionately from technologies that become easier to use and more accessible, as this can broaden the range of weapons technologies available to them and increase the unpredictability of potential attacks. At the same time, factors such as remaining technological barriers, knowledge and expertise

[102] Pierre J. and Peters B. G. Advanced introduction to governance. Cheltenham, UK: Edward Elgar Publishing, (2021).

requirements, and the availability of resources and facilities continue to shape the feasibility of such misuse.

In the context of chemical terrorism, the objective of governance is therefore not only to prevent state programs or large-scale prohibited activities, but also to reduce the likelihood that non-state actors can exploit technological change to acquire, produce, modify, conceal, or disseminate toxic substances. At a minimum, governance should promote transparency, support responsible development and use, and provide regulatory and preventive mechanisms that make misuse more difficult and more readily detectable. The objective is not to eliminate all risk—which would be unrealistic—but rather to reduce opportunities for misuse, raise barriers to exploitation, facilitate early detection, and strengthen the resilience of the overall system.

b) Objects of governance

Once the objective of regulation has been defined, the question of its scope arises. In the field of chemical weapons, this could mean regulating either the agents themselves (i.e., chemicals), the technologies used to produce them, or both. Focusing on agents is practical because they are the direct source of harm. However, emerging technologies make it increasingly possible to design and synthesize novel substances with slightly modified chemical compositions but similar effects. Such compounds may not be explicitly identified in existing regulatory frameworks, creating practical challenges for the implementation of the prohibition. The development of Novichok-type agents illustrates this gap[103]: although these agents have no legitimate peaceful applications and are clearly covered by the General Purpose Criterion (GPC), they were not initially listed in the CWC Schedules. It should be emphasized, however, that such substances are covered by the catch-all provisions of the Convention and by relevant export control regimes.

Alternatively, regulation could target the technologies that enable the production of chemical agents. This approach might make it easier to monitor capabilities than stockpiles of substances or their transfer. In practice, however, such an approach is hardly feasible. Technologies are inherently difficult to regulate, particularly once they have become widely available across jurisdictions and among a broad range of users. Moreover, regulating enabling technologies would require entirely new and internationally coordinated legal frameworks. Artificial intelligence (AI) aptly illustrates this dilemma. It is only one of many converging technologies that are collectively reshaping the emerging, technology-driven threat landscape. These developments are also unfolding at a pace that surpasses that of previous technological transformations, with the result that policymakers have yet to define clearly what, precisely, should be subject to regulation, even as new and potentially transformative applications emerge on an almost daily basis.

Some of the challenges involved in regulating converging technologies such as AI are discussed in greater detail in the following section. However, the discussion should not be framed solely in terms of agents versus technologies. A third potential object of governance is actor behavior. This is particularly relevant in the context of terrorism, where the central variables are not only capability but also intent and opportunity. While intent itself cannot be directly regulated as a preventive matter, governance can influence behavior through awareness-raising, professional norms, screening, training, and institutional safeguards. Neither actors nor technologies, therefore, appear to be sufficient as sole objects of regulation. A more realistic approach is to regulate chemical agents where feasible, oversee enabling technologies where necessary, and shape actor behavior through legal, regulatory, and preventive measures.

[103] Costanzi S. and Koblentz G. D. Strengthening controls on Novichoks: a family-based approach to covering A-series agents and precursors under the chemical-weapons nonproliferation regime. The Nonproliferation Review Volume 28, Issu 1-3 https://www.tandfonline.com/doi/full/10.1080/10736700.2021.2020010?journalCode=rnpr20, (2021).

c) Tools of governance

Technologies must be understood as embedded in social and political contexts that shape both their legitimate applications and their potential misuse. Governance mechanisms for mitigating risks associated with chemistry have existed since the emergence of the first treaties banning chemical weapons[104]. Over time, these mechanisms have multiplied and expanded in scope, ranging today from local safety regulations to comprehensive multilateral treaties such as the CWC. The legal framework encompasses national laws, regional regulations (e.g., within the EU), and international treaties. It is complemented by industrial standards, codes of conduct, ethical guidelines, and voluntary forms of self-restraint within scientific and private-sector communities.

Historically, this system has demonstrated a considerable capacity for adaptation—for example, through the integration of the debate on dual-use research of concern (DURC) and the updating of the CWC Schedules. Today, however, there is growing uncertainty as to whether these adaptive mechanisms will remain sufficient, or whether fundamentally new governance tools will be required—and, if so, who would be responsible for developing and implementing them. This reflects the multinormative character of the field, which is examined in greater detail in other publications by members of CBWNet[105]. The following paragraphs provide an overview of the legal and non-legal norms operating at different levels of governance in this field.

International legal tools for governance

The CWC and the OPCW: The CWC of 1997 is the central legal instrument prohibiting chemical weapons and established the OPCW, whose responsibilities include verification and scientific and technological (S&T) review. Following the destruction of all declared chemical weapons stockpiles[106], the verification regime remains engaged in investigating the possible use of chemical weapons and, where appropriate, attributing responsibility for such use outside the context of declared arsenals[107]. At the same time, the focus is increasingly shifting towards what might be described as "preventive verification": measures aimed at detecting and deterring the emergence of new chemical weapons programs and production capabilities. Routine inspections may not be sufficient for this purpose, suggesting that new mechanisms may need to be developed. The CWC Schedules of Chemicals have functioned as relatively stable but not static instruments. However, they have only rarely been updated to reflect technological and scientific developments[108]. The adaptation of the Schedules also faces clear limitations when it comes to novel compounds and technologies that enable the creation of new toxic agents or facilitate their misuse in small-scale scenarios. The convergence of chemistry and biology further amplifies these challenges. New synthesis methods expand the possibilities for producing toxic substances, while bioregulators—peptides and proteins that regulate homeostasis in organisms—may eventually need to be considered for inclusion in the Schedules. The OPCW, however, is not only the verification organization of the CWC; it also has the SAB, which serves as a central mechanism for translating scientific knowledge about new and emerging technologies into information that can inform the evolution of the regime[109]. This function is a prerequisite for bringing new technological

[104] Jefferson C. Origins of the norm against chemical weapons**.** International Affairs (Royal Institute of International Affairs 1944-) 90(3):647-661 https://www.jstor.org/stable/24538513, (2014).
[105] E.g. Chemical and Biological Weapons. The Interconnectivity of Norms. 2025. International Humanitarian Law Series, Band: 76.
[106] https://www.opcw.org/media-centre/news/2023/07/opcw-confirms-all-declared-chemical-weapons-stockpiles-verified
[107] https://opcw.org/about/technical-secretariat/divisions/verification
[108] The limited representation of Novichok derivates led, however, to contrains after the salisbury case. See: da Fonseca Carvalho L. M. Novichok (s) a challenge to the chemical weapons convention. *Port. J. Mil. Sci. (Rev. Ciências Mil.)*, 9(2):39-62, (2021).
[109] Scientific Advisory Board. Keeping pace with scientific and technological change https://www.opcw.org/about/subsidiary-bodies/scientific-advisory-board (accessed 2026).

developments onto the agenda of the regime and enabling their consideration within its institutional framework.

The BWC: The neighboring Biological Weapons Convention (BWC) of 1975 is meanwhile engaged in ongoing negotiations on strengthening its institutional framework. Among the issues under discussion is the establishment of a SAB Advisory Board, which could help identify and assess the types of threats that may arise from different actors and technological developments[110]. While the details are beyond the scope of this paper, overlaps between the CWC and BWC are increasing. Bioregulators may, in the coming years, constitute another category of agents falling within the scope of both conventions, alongside toxins, which are already covered by both regimes. Should the BWC eventually establish its own S&T review board and verification mechanism, interaction—and potentially competition—in the interpretation of situations, the assessment of risks associated with emerging technologies, and related matters could become an issue for the two regimes. Ideally, both treaty regimes would take these potential interactions into account already during the negotiation phase.

Both treaties base their core prohibitions on the General Purpose Criterion (GPC), which was designed to ensure that the treaties would remain relevant in the face of technological developments that, while foreseeable in principle, could not be predicted in detail. Early Review Conferences within both treaty regimes affirmed that the definitions of "chemical/biological weapons" and "chemical/biological weapons production facility" were sufficiently broad to cover relevant advances in science and technology. [111] This approach has proven effective thus far, but it is now being tested by the rapid development of AI and other converging technologies.

The OPCW's Scientific Advisory Board (SAB) has recently established a temporary working group on AI. At its inaugural meeting in April 2025, the Director of Verification emphasized that new technologies could lower the barriers to producing chemical warfare agents, potentially even below current declaration thresholds. This development challenges the foundations of the schedule-based approach, which currently forms the backbone of the verification system. As a possible response, the Secretariat has begun exploring a shift towards a more risk-based system. It is also investigating how open-source data and blockchain technology could support elements of the declaration process.[112]

UNSCR 1540: UN Security Council Resolution 1540, which has been extended until 2032[113],, obliges all states to implement domestic measures to prevent the proliferation of weapons of mass destruction (WMD). The 1540 Committee, which also monitors compliance[114], primarily serves as a forum for coordination and outreach to states. In this context, it also conducts research and publishes contributions from Committee members and external experts, including through its journal *1540 Compass*. With regard to the issues discussed here, de Silva et al. have highlighted the significant new governance challenges posed by emerging technologies. [115] Given its broad scope, however, the 1540 Committee establishes only general obligations rather than detailed pathways for implementation. Its governance approach therefore relies primarily on strengthening awareness and national capacities. The activities of the 1540 regime are not designed to exert direct influence over individual stakeholders.

[110] Final Document of the Ninth [BWC] Review Conference, 22 December 2022 (accessed 2026).
[111] BWC Second Review Conference. Final Document BWC/CONF.II/13 and *Political Declaration* & *Review Document*, First CWC Review Conference RC-1/3
[112] Summary of the first Meeting of the Scientific Advisory Board's Temporary Working Group on Artificial Intelligence SAB-40/WP.1 11 April 2025 https://www.opcw.org/sites/default/files/documents/2025/06/sab-40-wp01%28e%29.pdf (accessed 2026).
[113] UNSCR Resolution 2663(2022), https://docs.un.org/en/s/res/2663(2022) (accessed 2026).
[114] https://www.un.org/en/sc/1540/faq.shtml
[115] De Silva K., Perera R., Martinez I. S. Overview of Emerging Technologies with an Impact on Chemical Disarmament and Non-Proliferation Regimes, 1540 Compass, Issue 2, 64-101, (2024).

Export Control Regimes: In the field of chemical weapons, the Australia Group and the Wassenaar Arrangement remain key actors in preventive arms control governance. Although they are not based on formal treaties or universal mandates, both are membership-based arrangements whose decisions on controlled items are translated into binding national legislation. Their control lists cover both dual-use materials and enabling technologies. Importantly, the term "technology" in this context refers not only to hardware but also to intangible transfers, including those facilitated through information technology, publications, or human expertise.[116] Governing such intangible flows has long been challenging, and the emergence of cloud laboratories and AI-driven research makes this challenge increasingly acute, particularly because many technology providers operate outside these export control arrangements.

From the perspective of chemical terrorism, export controls are most effective where access to precursors, equipment, dissemination devices, or specialized know-how can be constrained. Their effectiveness is more limited, however, when relevant capabilities can be acquired through open-source platforms or broadly accessible digital services.

The example of AI as a converging technology

In the following, we take a closer look at the complexity of regulating a converging technology such as AI at the international, national, and regional levels, involving a range of different stakeholders. AI is, of course, only one of many technologies relevant to the present discussion. The difficulties surrounding its regulation at multiple levels nevertheless illustrate the broader challenges involved in governing technologies whose characteristics and potential applications are still evolving. The risks posed by AI in the CBRNE domain have already become a national security priority in many countries. The U.S. National AI Action Plan (2024), for instance, warns that "powerful AI systems may pose novel national security risks in the near future in areas such as cyberattacks and the development" of CBRNE weapons, and that AI "could create new pathways for malicious actors to synthesize harmful pathogens and other biomolecules." [117] The plan proposes a "multitiered approach designed to screen for malicious actors, along with new tools and infrastructure for more effective screening."[118]

Risks arise when AI can be used to design, enable, or accelerate prohibited activities, for example through synthesis planning or the automation of other R&D processes that lower barriers for malicious actors. AI, however, is more than just another tool within existing R&D processes. A widespread concern is that it could open entirely new pathways for misuse, raising the question of whether existing arms control treaties sufficiently cover the use of AI in this context, or whether the diversity and rapidly evolving capabilities of AI systems may ultimately require dedicated governance mechanisms. In the context of chemical terrorism, the practical significance of these risks lies primarily in the possibility that AI could support procurement planning, route selection, the avoidance of controlled substances, or the identification of more accessible alternatives. It remains an open question, however, whether terrorist actors would possess the organizational capabilities, tacit knowledge, and infrastructure required to translate such outputs into operational capabilities. For this reason, AI should be understood less as an autonomous threat than as an enabling technology that may become relevant to technically capable actors seeking to reduce barriers and improve efficiency.

A multilateral response in the form of a treaty or other binding agreement is not yet in sight. Although the "Global Dialogue on AI Governance" [119] provides a forum for discussion at the UN

[116] Brockmann K. and Héau L. December 2025 Stockholm SIPRI https://doi.org/10.55163/ILLU2609 (accessed 2026)
[117] Joint-NGO statement for the CSP29 in 2024: https://www.opcw.org/sites/default/files/documents/2024/11/CSP29%20NGO%20Statement%20AI%20Converging%20Tech.pdf
[118] O'Brien E. The AI Action Plan for Defense The AI Action Plan for Defense (accessed 2026).
[119] Global Dialogue on AI Governance https://www.un.org/global-dialogue-ai-governance/en (accessed 2026).

level, agreement on a comprehensive framework for the governance and ethics of AI remains distant.[120] Some expectations have been placed on the EU AI Act of 2024[121], which establishes a risk-based framework classifying AI systems according to different levels of risk, from low to unacceptable, and provides corresponding regulatory requirements for different applications. Upon closer examination, however, the EU AI Act primarily addresses risks associated with AI itself, including issues such as data protection, fundamental rights, and safety, rather than the specific risks that AI may pose in the context of chemical weapons. It therefore currently offers only limited tools for mitigating CW-related risks. Given the transnational and potentially extraterritorial nature of AI services, the development of extraterritorial jurisdiction, as seen in the field of data protection, may nevertheless offer a model that could be applied to AI-related CW risks in the future.[122]

National and regional legal norms

National implementation remains a core requirement of multilateral arms control treaties. Beyond this, states may adopt additional measures—such as export licensing, research funding restrictions, or domestic safety rules—to address emerging risks. Yet, with technologies like AI, states face serious limitations: defining the object of regulation, prohibiting misuse, and ensuring enforceability remain difficult, if not impossible. The number of dedicated national laws for the regulation of AI is limited worldwide. With a presidential Executive Order (EO), the US has withdrawn President Biden's EO "for the Safe, Secure, and Trustworthy Development and Use of AI"; the consequences of the Trump administration's "America's AI Action Plan" remain uncertain[123], while the EO is clearly not based on a risk-based approach. Recently, President Trump issued an executive order that directed the attorney general to create a task force to challenge state laws that are more than "minimally burdensome" and directed the Commerce Department to draw up a list of problematic regulations.[124] This is not coined on CW-related risks, but might give an idea about the future direction for (de-) regulation.

A list of "AI laws around the world" [125] suggests a field with fast-developing legal regulation. Upon closer inspection, however, it becomes apparent that these are mostly not dedicated regulatory norms, but rather unspecific national AI strategies, funding rules, etc. The call for more regulation in this area, both at the national and international levels, will therefore continue to be heard for some times, as there have been few significant developments and there is a lack of clarity regarding how desired AI tools and applications should be demarcated against undesired AI (the latter a well-known phenomenon for all dual-use technologies), and how this could become subject to regulation.

Epistemic community

Scientific communities are central drivers of innovation. Their work in academic and industrial research environments leads to the accelerated development of new applications that often shape how science translates into technology. Ideally, scientists are aware of risk potentials already in the set-up of research designs. The debate about DURC is, however, much more established in the field of biology than in chemistry. Yet, in chemistry, security concerns are still centered around industrial production, while there is little literature and debate about security challenges that might become visible already during the research phase. Although the Hague Ethical Guidelines[126] apply to all "chemistry practitioners," it might only become apparent with increasing convergence to

[120] United Nations News. 193 countries adopt first-ever global agreement on the Ethics of Artificial Intelligence, November 2021, https://news.un.org/en/story/2021/11/1106612 (accessed 2026).
[121] Artificial Intelligence Act (Regulation (EU) 2024/1689)
[122] https://www.edpb.europa.eu/system/files/2024-10/edpb_20240417_report_extraterritorial_enforcement_gdpr_en.pdf
[123] AI Watch: Global regulatory tracker - United States https://www.whitecase.com/insight-our-thinking/ai-watch-global-regulatory-tracker-united-states (accessed 2026).
[124] https://abcnews.com/US/wireStory/trump-block-state-ai-regulations-states-forging-ahead-133859386
[125] AIPRM AI Laws Around the World. https://www.aiprm.com/ai-laws-around-the-world/ (accessed 2026).
[126] The Hague Ethical Guidelines: https://www.opcw.org/hague-ethical-guidelines https://www.opcw.org/sites/default/files/documents/2025/08/OPCW_Hague_Ethical_Guidelines.pdf (accessed 2026).

biology that early phases of technology development should be assessed in terms of their dual-use potentials. For chemical terrorism, this is relevant because epistemic communities can either amplify risk by normalizing the open dissemination of operationally relevant knowledge, or reduce it through screening, review, and responsible communication.

Private stakeholders

Science developments become technologies and leave the academic ivory tower of science when they are mature enough to enter large-scale and/or global use in industry[127], which transfers an equivalent share of the responsibility for secure use and further development to these commercial users. Companies, professional associations, industry organizations, such as ICCA or CEFIC, and IUPAC have an important role in balancing economic freedom with security concerns. In practical terms, this can be facilitated through a variety of tools which could become important governance tools for the private sector, including codes of conduct, ethical guidelines, and professional/industry standards. This is particularly important in the context of technologies that may be misused for toxic chemical production, detection avoidance, or dissemination support. Private-sector actors are often best placed to detect unusual purchasing patterns, misuse indicators, or suspicious requests for services, and can therefore complement state regulation.

Civil society

Civil society has historically played a significant role in the efforts to reduce the threat of chemical weapons.[128] However, this is rather true for e.g. human rights and humanitarian actors —the engagement with developers and users of emerging technologies remains limited. As the challenges of converging technologies become more pressing, broader societal awareness and engagement may be necessary to reinforce norms, transparency, and accountability. In relation to chemical terrorism, civil society is particularly relevant for awareness-raising, risk communication, and the promotion of public resilience, rather than for direct control of agents or technologies.

Obviously, efforts could and should be made at various levels to establish different types of norms aimed at mitigating the risks associated with chemical weapons posed by new and emerging technologies. Auxiliary complex technologies have a rapidly growing share in the risk landscape, making governance in this area highly challenging. A common or encompassing solution is not in sight and may not be achievable. What does appear feasible, however, is a more layered and targeted approach: schedule-based control where possible, technology-sensitive oversight where necessary, and behavioral and institutional measures where the legal framework alone cannot reach. For chemical terrorism, this suggests that governance should be assessed not only by whether it can eliminate all risk, but by whether it can raise the threshold for misuse, strengthen detection, and make hostile adaptation more difficult.

4. Conclusions

The current CW-related S&T landscape is evolving rapidly, leading to larger risks and shifts in threat perceptions regarding the potential misuse of these advances in future terrorism attacks. It is not easy, though, to quantify risks or to judge which perception mirrors reality. It is not a new (and a rather obvious) insight that emerging technologies are likely to have a profound impact on armament risks (including non-state actors to an unknown/hardly predictable level). However, treaty regimes will always struggle to respond to threats posed by non-state actors, as the norms and implementation mechanisms of these regimes (e.g., verification and compliance systems, where they exist at all) apply to the states parties rather than to non-state actors, whose activities are subject to national criminal law.

[127] Jonas, H. Das Prinzip Verantwortung. Versuch einer Ethik für die technologische Zivilisation“ (1979)

[128] Crowley M., Dando M., Shang L. (Hg.). *Preventing chemical weapons: arms control and disarmament as the sciences converge*. Royal Society of Chemistry, Chapter 1, (2018).

None of the technologies listed in the course of this manuscript is per se a game changer in itself, but a combination of developments in analytical and synthetic chemistry, biochemistry, rational drug design driven by advancements in computational tools (including AI), and robotics defines the frames for the discussion around applications with possible misuse potential in the CW realm. In this context, it is vital to stay informed about current and upcoming scientific and technological developments. However, identifying a specific research area or application that might be particularly relevant to chemical terrorism remains difficult. When it comes to the threat of chemical terrorism, the numerous "unknowns" make it difficult to understand the true threat landscape, especially given the rapid changes in geopolitical, technological, and social contexts. The possibility of a future attack is like an equation with many unknowns, one being the intent behind such actions, which is ungovernable and often hardly predictable.

What we can describe scientifically are the technological developments and the patchy governance landscape, which has far more gaps than planks at all levels – to stay with the metaphor: There aren't even any frames, just the idea that we need to build something that floats. In a few (!) places, people have begun to draw sketches for parts of the ship, but whether these will ever form a ship capable of coping with the new dangerous currents is impossible to predict.

Hence, what has to be done in the first place (and it is somewhat tiresome to have to repeat this with every new technological development we experience) is to create risk awareness among all stakeholders – many of them feel quite comfortable with the situation, recognizing the chances of these new waters, but not the cliffs. There is hardly an automatism that the availability of a technology directly leads to misuse. We have no evidence that the famous saying that every invention is used for bad sooner or later is wrong. But misuse still needs intention and opportunity.

Still, there is no good idea of what to do about the new situation. The platitude "effective governance measures" does not mirror the complexity of the issue at hand. We have understood governance as the totality of pathways to organize policies. Effective governance will require responsibility in both the development and use of technology, complemented by preventive and behavioral arms control (concepts that will be elaborated on in subsequent papers). Some of the long-time gold standards, such as the schedule-based CWC verification system, or export controls in the actual format, might not be sufficient as stand-alone instruments any longer. Stakeholders have to be creative in the set-up of measures, some of which have to be of a new kind – which, and that might be the main pitfall, means that they have to be aware and willing to become active in this way.

The CBW network for the comprehensive strengthening of norms against chemical and biological weapons (CBWNet)

The research project CBWNet is carried out jointly by the Berlin office of the Institute for Peace Research and Security Policy at the University of Hamburg (IFSH), the Chair for Public Law and International Law at the University of Gießen, the Peace Research Institute Frankfurt (PRIF) and the Carl Friedrich Weizsäcker-Centre for Science and Peace Research (ZNF) at the University of Hamburg. The joint project aims to identify options to comprehensively strengthen the norms against chemical and biological weapons (CBW).

These norms have increasingly been challenged in recent years, *inter alia* by the repeated use of chemical weapons in Syria. The project scrutinizes the forms and consequences of norm contestations within the CBW prohibition regimes from an interdisciplinary perspective. This includes a comprehensive analysis of the normative order of the regimes as well as an investigation of the possible consequences which technological developments, international security dynamics or terrorist threats might yield for the CBW prohibition regimes. Wherever research results point to challenges for or a weakening of CBW norms, the project partners will develop options and proposals to uphold or strengthen these norms and to enhance their resilience.

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