

FROM VUCA TO BANI: GOVERNING DUAL-USE BIOTECHNOLOGIES THROUGH EU–NATO CIVIL-MILITARY INTEROPERABILITY

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Abstract: *This study examines the evolution of biotechnologies and their inherent dual-use risks within the context of the transformation of the security environment from VUCA to BANI. The paper applies a qualitative conceptual and policy-analysis approach based on literature review and the examination of EU and NATO strategic and regulatory frameworks. Particular emphasis is placed on advances in synthetic biology, genome editing, and automated bioengineering systems, which simultaneously catalyze innovation dynamics while exacerbating vulnerabilities in biosecurity and increasing the degree of systemic unpredictability. The study identifies key deficiencies in existing governance frameworks, including regulatory fragmentation, asymmetrical oversight, and limited coordination concerning dual-use research. It further analyzes the roles of NATO and the European Union as mutually complementary pillars of biosecurity—through operational coordination and civil-military resilience on the one hand, and through regulatory governance and scientific integration on the other. On this basis, strategic guidelines are formulated for EU–NATO coordination in the field of biosecurity, oriented toward the enhanced governance of dual-use biotechnologies through the strengthening of biosecurity mechanisms and the consolidation of interaction between civilian and defense institutional systems. The findings may contribute to scholarly and policy-oriented debates concerning the governance of technological risks under conditions of increasing systemic uncertainty.*

Keywords: biological security, biotechnology, dual use, civil-military collaboration

1. Introduction

Rapid advances in biotechnology and scientific discovery are forcing armed forces to transform their innovation models and approaches to capability development. This transformation encompasses both the establishment of strategic partnerships with the biotechnology sector and the integration of civilian research achievements, as well as the targeted enhancement of internal organizational and human resource capacities to effectively counter emerging biological threats and risks.

Biotechnologies constitute a key driver in the dynamics of scientific and technological development and global security. According to the conclusions articulated in the *Science & Technology Trends Report*

2023–2043, the next phase of technological transformation will be significantly shaped by advances in synthetic biology [1]. As a highly specialized domain within biotechnology, synthetic biology is defined as the design and construction of new biologically based parts, devices, and systems, as well as the redesign of existing natural biological systems for useful purposes [2].

As technological diffusion accelerates globally, biotechnologies are becoming a central domain of innovation and strategic competition. Their dual-use nature challenges traditional distinctions between civilian and military applications, thereby necessitating a fundamental reconsideration of existing regulatory and governance

approaches. A number of governments are formulating policies and developing science funding mechanisms specifically aimed at supporting synthetic biology [3]. Within the framework of NATO's strategic priorities, this encompasses not only the development of bioengineered materials, but also enhancement technologies, as well as the integration of related domains such as data infrastructures and biosensor systems. Concurrently, the transformation of the security environment can be conceptualized

through the transition from the classical VUCA model (volatility, uncertainty, complexity, and ambiguity) to the emerging BANI paradigm (brittleness, anxiety, nonlinearity, and incomprehensibility) [4]. This shift reflects a broader transformation in how uncertainty is understood — from manageable risk toward systemic unpredictability, at the center of which biotechnologies are prominently situated as illustrated in Figure 1.

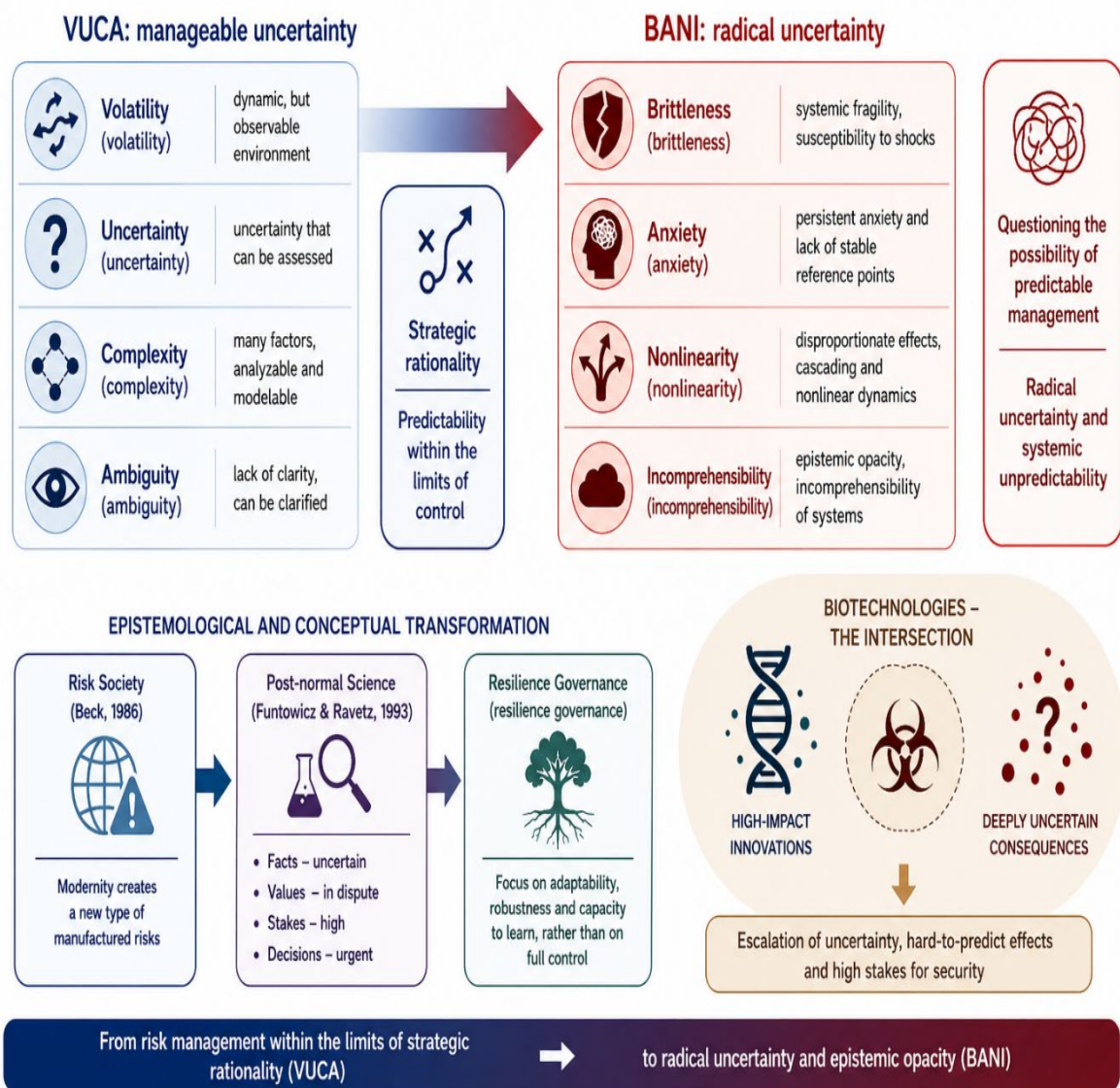


Figure 1: From manageable risk to radical uncertainty: epistemological and conceptual foundations

The theoretical framework of the present study integrates three mutually reinforcing analytical perspectives: Risk Society theory

[5], according to which modernity generates a new category of manufactured risks; the concept of post-normal science, which

underscores the role of high uncertainty and elevated stakes in decision-making processes; and resilience governance approaches, which emphasize system adaptability rather than complete control. Biotechnologies embody the defining characteristics of all three perspectives, as they simultaneously generate systemic risks, operate under conditions of epistemic uncertainty, and require flexible and adaptive governance mechanisms.

The aim of the present study is to synthesize the principal trends in the development of biotechnology, with particular emphasis on dual-use programs, and to formulate recommendations for governments on strengthening monitoring and governance mechanisms.

2. Methodology

This paper employs a qualitative interdisciplinary approach based on conceptual analysis, literature review, and policy analysis. It examines the transformation of biosecurity governance in the context of emerging dual-use biotechnologies and the transition from the VUCA to the BANI security environment.

The analysis draws on academic literature, NATO strategic assessments, and European Union regulatory documents related to synthetic biology, genome editing, resilience governance, and dual-use research. Particular attention is given to existing governance gaps, including regulatory fragmentation, asymmetrical oversight, and insufficient civil–military coordination.

The research is exploratory and analytical in nature. Its objective is to provide a policy-oriented synthesis of the principal technological and governance challenges associated with contemporary biosecurity risks.

3. Biotechnological Transformations, Dual-Use, and Civil–Military Convergence

Contemporary biotechnology is shaped by trends that both expand innovation potential

and increase security complexity. Synthetic biology enables the design of biological systems and the *de novo* synthesis of genetic material [6], marking a transition from modification toward the creation of novel structures. In parallel, genome-editing technologies such as CRISPR broaden access to genetic engineering by lowering barriers to entry and diversifying the range of actors beyond traditional scientific institutions [7, 8].

The integration of artificial intelligence and bioinformatics accelerates the analysis and modeling of biological data, including the discovery of new pharmaceutical compounds. In combination with the globalization of research and transnational supply chains, this enhances knowledge exchange while increasing regulatory complexity and systemic vulnerabilities.

In this context, dual-use biotechnologies generate a governance dilemma between innovation and security. Technological convergence and digitalization blur the boundaries between civilian and military domains and elevate the risk of misuse. Biotechnologies are critical for healthcare, agriculture, and sustainable industries, yet they simultaneously create opportunities for the development of agents with increased virulence, resistance, or targeted effects [9]. Civil–military convergence facilitates knowledge transfer between scientific, industrial, and governmental actors, but also complicates oversight and control. Digitalization, alongside the growing role of biodata and artificial intelligence, introduces additional vulnerabilities related to cyber-biosecurity and access to sensitive information [10].

In this regard, traditional regulatory approaches are becoming increasingly inadequate, necessitating adaptive, cross-sectoral frameworks that incorporate research security, responsible scientific practices, and international cooperation. Within this process, the European Union and NATO perform complementary roles: the EU through regulatory mechanisms

such as Regulation (EU) 2021/821 [11], and NATO through the development of innovation and defense capabilities.

In summary, biotechnologies are emerging as a strategic domain in which scientific and economic potential is inextricably linked with growing security and governance challenges.

4. Paradigmatic Transformation of Biosecurity in the Context of the VUCA–BANI Model

4.1. From Manageable Risk to Radical Uncertainty: Epistemological and Conceptual Foundations

Biosecurity risks associated with contemporary biotechnologies are shaped not only by technological developments, but also by changing governance and epistemological paradigms. The transition from an environment characterized by the VUCA model to the BANI framework reflects a profound structural transformation in the ways uncertainty, risk, and knowledge are conceptualized and managed. Whereas the VUCA model assumes that uncertainty can still be managed strategically, BANI conditions call into question the very possibility of predictable governance, introducing systemic fragility, epistemic opacity, and nonlinear escalation [4].

From a theoretical perspective, this transition corresponds to broader debates within security studies and Science and Technology Studies (STS), particularly the shift from the concept of the “risk society” [5] toward conditions of radical uncertainty and post-normal science, in which facts are uncertain, values are contested, stakes are high, and decisions are urgent [9]. Biotechnologies constitute an emblematic case of this transformation, as they operate at the intersection of high-impact innovation and profoundly uncertain consequences.

4.2. Systemic Fragility and Infrastructural Vulnerability of Bio-Innovation Ecosystems

Within the BANI context, biosecurity is increasingly affected by the fragility of global bio-innovation infrastructures. The COVID-19 pandemic constitutes a paradigmatic example, demonstrating how highly interconnected systems - global supply chains, vaccine production networks, and public health infrastructures - may collapse in a cascading manner [12]. From the perspective of resilience theory, such systems are characterized by high efficiency but limited buffer capacity, rendering them particularly vulnerable to disruption.

A related dimension concerns dependence on contemporary biological defense infrastructures. Programs supported by agencies such as the Defense Advanced Research Projects Agency (DARPA) stimulate innovation in fields including synthetic biology, biosurveillance, and vaccine development. While these initiatives enhance preparedness and response capacity, they simultaneously illustrate the dual-use dilemma: the same technological platforms may potentially be employed for offensive purposes or become targets of hostile exploitation [13].

4.3. Nonlinearity, Emergence, and Escalation Dynamics

In biotechnology, nonlinearity is not only a technical issue but also a defining feature of contemporary risk. The capacity of small-scale interventions to generate substantial effects calls into question traditional governance models grounded in proportionality and control. Gain-of-function research constitutes a particularly illustrative example: the debates surrounding experiments involving the H5N1 virus demonstrate how limited scientific interventions may give rise to disproportionately significant global security concerns [14].

Furthermore, synthetic biology enables the creation of systems exhibiting so-called emergent properties - that is, characteristics that cannot be predicted solely on the basis of their individual components, but instead

arise from the interactions among them. This substantially complicates the prediction and control of such systems' behavior. Within such an environment, causal relationships become increasingly ambiguous and nonlinear, while the risk of unintended consequences intensifies, thereby reinforcing the dynamics characteristic of the BANI paradigm.

4.4. Epistemic Opacity and Cognitive Limits

The increasing integration of artificial intelligence into biotechnology further intensifies epistemic challenges. AI-based models employed in protein folding, genomic analysis, and biological design operate at levels of complexity that exceed scientists' capacity for explanation and interpretation. This creates a form of epistemic asymmetry in which technological capabilities evolve faster than human understanding [13].

Such opacity carries significant implications for governance. Regulatory systems traditionally grounded in expert knowledge and risk assessment encounter growing difficulties in functioning effectively within an environment where knowledge itself is partial, uncertain, or dynamically evolving. As a consequence, decision-making processes become increasingly conditional, provisional, and frequently reactive.

4.5. Anxiety, Strategic Narratives, and Information Manipulation in Biosecurity

The dimension of anxiety within the BANI framework extends beyond the level of individual mental perception and encompasses broader societal and geopolitical processes. Biological threats are especially vulnerable to disinformation, strategic narratives, and politically motivated communication. A particularly illustrative example is the discourse surrounding the alleged "biolaboratories" in Ukraine. Interpretations ranging from legitimate international cooperation in the field of public health to allegations concerning covert biological weapons

programs have been strategically instrumentalized within geopolitical conflicts. These narratives demonstrate that biological risks possess not only a material but also a discursive dimension, shaped by political interests and information strategies.

Such processes further complicate the governance of biosecurity by undermining trust, skewing risk perception, and politicizing scientific cooperation. Under conditions characteristic of the BANI environment, the effective management of biological risks requires not only technical solutions, but also strategic communication capabilities and resilience against manipulative narratives.

4.6. Cyber–Biological Convergence

The convergence between cyberspace and the life sciences constitutes an emerging domain of risk. The digitalization of biotechnology introduces novel vulnerabilities, including opportunities for the manipulation of genomic databases, the sabotage of laboratory processes, and the compromise of bioinformatic systems [15].

This convergence challenges traditional security paradigms that treat cyber and biological threats as separate domains. In practice, their intertwinement gives rise to hybrid risks that are difficult to categorize, analyze, and regulate.

4.7. Limitations of Regulatory Frameworks

Existing biosecurity frameworks, including the Biological Weapons Convention, reflect a logic characteristic of the VUCA era, in which threats are relatively clearly identifiable and uncertainty is considered manageable. However, the conditions of BANI expose substantial limitations of these mechanisms. The absence of effective verification mechanisms, combined with rapid technological advancement, creates significant governance gaps.

Bio-defense programs further illustrate this tension. While they aim to enhance preparedness and deterrence capacity, they may also contribute to strategic ambiguity

and inter-state distrust. The dual-use nature of these technologies complicates transparency and undermines trust-building mechanisms.

4.8. Toward Adaptive and Reflexive Governance of Biosecurity

The effective management of biological risks within the VUCA–BANI context requires a transition toward adaptive and reflexive governance models. This requires a shift from static regulation toward adaptive systems capable of learning and proactive response.

A key role in this process is played by civil–military cooperation. Military institutions provide capacities for strategic planning, logistics, and crisis management, whereas civilian structures contribute scientific expertise and innovation. The integration of these domains enables more comprehensive and resilient responses to biological threats.

From a theoretical perspective, this approach aligns with concepts of resilience governance and complex adaptive systems, which emphasize flexibility, buffer capacity, and cross-sectoral integration. It also reflects the need to overcome epistemic

gaps between science, policy, and the security community under conditions of increasing complexity and uncertainty.

5. Strategic guidelines for EU-NATO coordination in the field of biological security

The growing convergence between biotechnology, security risks, and hybrid threats within the VUCA–BANI context places EU–NATO coordination at the center of the transatlantic agenda. Although the EU and NATO possess significant but distinct capabilities, fragmented mandates and different governance models continue to limit collective effectiveness and constitute a structural vulnerability to systemic biological risks.

The European Union and NATO perform complementary roles in biosecurity governance. The EU provides regulatory and public health instruments, while NATO contributes operational coordination and rapid-response capabilities. The absence of an integrated architecture reduces their strategic interoperability and responsiveness in the event of biological incidents as illustrated in Figure 2.

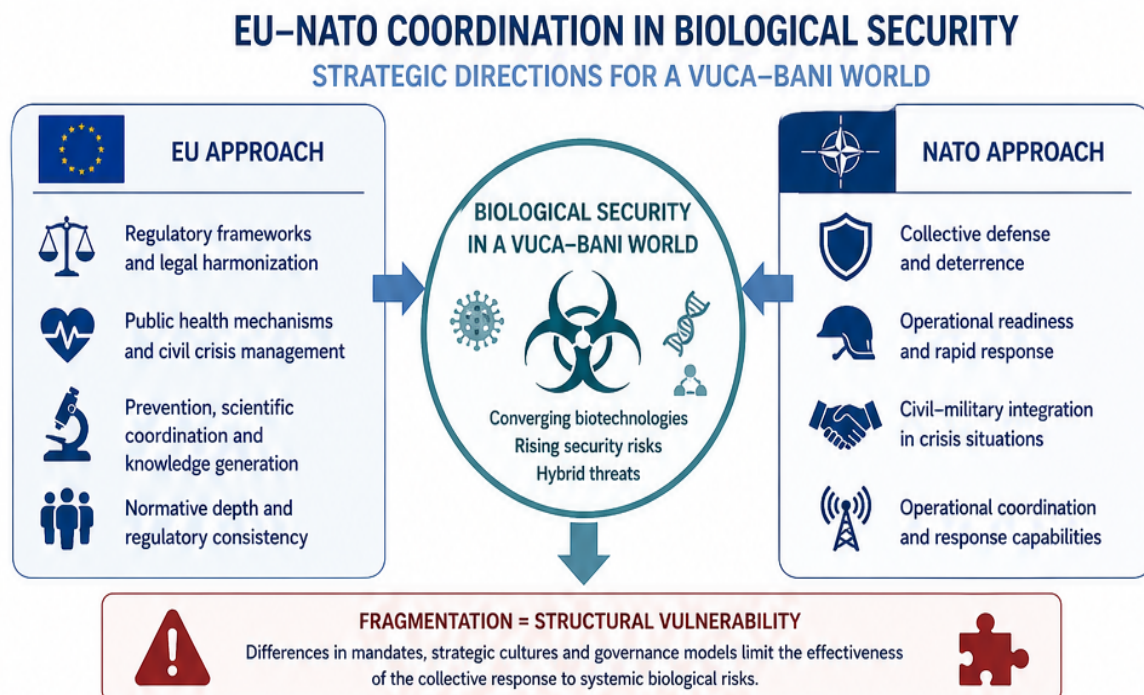


Figure 2: EU-NATO coordination in biological security

Based on the above, the following priority areas for effective and systematic coordination are outlined:

1. Institutionalized EU–NATO interface for systematic and timely exchange between public health surveillance systems, scientific networks, and defense intelligence structures, supported by interoperable data platforms and integrated situational awareness frameworks.
2. Coordinated governance framework for dual-use biotechnologies, including joint risk assessment methodologies, standardized protocols for high-risk research, and harmonized mechanisms for the control of transfers of sensitive technologies and knowledge, with the aim of reducing regulatory fragmentation without constraining innovation.
3. Transition toward a resilience-based paradigm grounded in the logic of complex adaptive systems, involving the development of redundancy in critical infrastructures, diversification of supply chains for countermeasures, and the establishment of adaptive, real-time crisis management mechanisms.
4. Strengthening coordination in civil preparedness and hybrid threat countermeasures through the integration of strategic communication capacities, analytical tools for disinformation detection, and mechanisms for assessing compound and cascading risks.
5. Balancing security imperatives with scientific autonomy through transparent regulatory procedures, ethical standards for dual-use research, and institutional safeguards for academic independence.
6. Joint capacity for strategic foresight

and horizon scanning of technological risks (synthetic biology, gene editing, AI-assisted bio-engineering) for early identification and preventive planning.

6. Conclusions

Biotechnology governance is entering a post-VUCA phase increasingly shaped by BANI dynamics, where traditional security paradigms appear insufficient to address systemic fragility, nonlinear escalation, and epistemic uncertainty. In this regard, civil–military cooperation emerges as an important mechanism for strengthening resilience, while NATO and the European Union function as complementary institutional pillars combining operational coordination, regulatory governance, and public health capacities.

The analysis suggests that conventional governance approaches based primarily on predictability and reactive risk management are becoming progressively less effective in the face of rapidly evolving dual-use biotechnologies. Instead, contemporary biosecurity governance requires adaptive, cross-sectoral, and resilience-oriented frameworks capable of operating under conditions of radical uncertainty.

The governance of dual-use biotechnology consequently represents a multidimensional transnational challenge requiring enhanced institutional coordination, interoperability, strategic foresight, and sustained cooperation between civilian and defense sectors. These dynamics are likely to play an increasingly important role in future debates concerning security governance, technological innovation, and resilience in complex risk environments.

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