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Biotechnology and Military Resilience: Operational Implications and Policy Priorities for India

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Abstract

Biotechnology is increasingly relevant to national security and defence preparedness, yet its most important military effects are likely to arise through resilience-building rather than overtly offensive use. This paper examines how emerging biotechnologies may strengthen military capability across three levels of operations: individual soldier performance, unit-level resilience, and theatre-level preparedness. It argues that advances in vaccines, diagnostics, biosensors, regenerative medicine, neurotechnology, and distributed biomanufacturing can improve force health outcomes, accelerate recovery, reduce logistical dependence, and enhance early warning against environmental and biological threats. Because much of this innovation is driven by civilian research ecosystems, defence institutions face a dual challenge: they must absorb useful technologies while also managing the governance risks associated with dual-use research. The paper proposes an analytical framework based on technology readiness, military adoptability, and strategic impact to help prioritise monitoring, investment, and transition. It concludes with policy implications for India, including the need to strengthen indigenous biotechnology capabilities, deepen defence–academia collaboration, and build integrated biodefence infrastructure. The paper contends that biotechnology should be treated as a strategic enabler whose near-term contribution to defence will lie primarily in improving resilience, preparedness, and operational endurance.

Keywords: biotechnology; military innovation; biodefence; biomanufacturing; resilience; India

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1. Introduction

Technological innovation has long shaped the conduct of war, not only through the development of offensive weapons but also through advances in defence, medicine, communications, and the logistical systems that sustain military operations. In the twenty-first century, biotechnology has emerged as a strategically significant field, primarily led by the civilian sector, but with increasing relevance for military operations. Recent NATO and U.S. Department of Defense (DoD) documents highlight biotechnology and biomanufacturing as areas with direct implications for security, resilience, and operational effectiveness, reflecting a wider recognition that advances in the life sciences are increasingly relevant to defence planning. (NATO 2024; Soare and Pothier 2021)

Biotechnology encompasses a broad and expanding set of capabilities for analysing, manipulating, and engineering biological systems. These include synthetic biology, gene-editing tools such as Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR), bioinformatics, neurotechnology, advanced diagnostics, and biomanufacturing platforms. As these capabilities mature, they are likely to affect military operations along at least three dimensions:

- first, by expanding the range of potentially harmful biological applications that could be used for offensive purposes;
- second, by strengthening defensive capacities such as disease surveillance, medical countermeasures, and force health protection; and
- third, by improving resilience through bio-based production of materials, fuels, and medical supplies.

The offensive dimension of biotechnology remains legally prohibited but strategically salient. The Biological Weapons Convention (BWC), opened for signature in 1972 and in force since 1975, prohibits the development, production, and stockpiling of biological and toxin weapons and requires the destruction or diversion to peaceful purposes of existing stockpiles. Yet the formal prohibition of biological weapons has not eliminated security concerns. On the contrary, contemporary advances in gene editing, synthetic biology, and related enabling technologies have intensified longstanding dual-use dilemmas, because techniques developed for beneficial civilian purposes may also be repurposed for harmful ends. (Ramanathan, 2022) Recent biosecurity literature and World Health Organization guidance accordingly stress that rapid progress in the life sciences requires governance frameworks capable of addressing misuse risks without unduly constraining legitimate research and innovation. (National Academies of Sciences, Engineering, and Medicine 2017; Trump et al. 2023; World Health Organization 2022)

At the same time, the same scientific advances that generate biosecurity risks have also improved the capacity of states to detect, characterise, and respond to biological threats. (Lentzos 2020) Progress in genomic sequencing, pathogen surveillance, computational biology, and vaccine platform technologies has strengthened public-health and biodefence capabilities. The COVID-19 pandemic illustrated this especially clearly; genomic surveillance was central to tracking viral evolution and the emergence of new variants, while platform-based vaccine development demonstrated the value of rapid biomedical innovation in crisis response. (Tosta 2023) For defence institutions, these developments underscore that biotechnology is relevant not only as a source of risk, but also as a foundation for biodefence, early warning, and resilience.

Biothreats and biodefence are thus two of the most direct outcomes of the use of biotechnology in the context of the military. It is no surprise then that scholarly literature on biotechnology and national security has mostly revolved around biological weapons, arms control, biodefense and the governance problems generated by dual-use research. More recent advances in biotechnology, however, have broadened this frame. Alongside questions of prohibition and biosecurity, it is becoming increasingly important to examine how biotechnology can enhance preparedness, force protection, medical support, and supply-chain resilience.

The recognition of this shift is visible in recent defence strategy documents, which place growing emphasis on diagnostics, medical countermeasures, biomanufacturing, and the ability to operate effectively in contested biological environments. (U.S. Department of Defense 2023) NATO's recent biotechnology strategy and the U.S. DoD's biomanufacturing strategy, both emphasise that the significance of biotechnology lies not only in disruptive applications, but also in its capacity to reshape preparedness, resilience, and supply systems. (Defense Industrial Base Consortium 2024) This paper focusses on this third aspect of biotechnology that drive operational resilience and performance by incrementally supplementing military operations.

A key feature of biotechnology advances that warrants analytical attention is that, unlike other military technologies, in many countries it is being driven primarily by civilian innovation ecosystems. There are three chief reasons to this:

- Usually, defence institutions have played a central role in technological innovation and standard setting for defence requirements. Technologies such as radar, jet engines, and the internet were initially developed through military research programs before diffusing into civilian sectors. By contrast, much contemporary innovation in diagnostics, vaccines, therapeutics, biomaterials, computational biology, and industrial biomanufacturing is led by universities, start-ups, and commercial biotechnology firms. This civilian orientation is rooted in three structural features of the contemporary biotechnology ecosystem: First, biotechnology innovation requires large-scale collaboration across multiple scientific disciplines including genomics, computational biology, chemistry, and medicine. These collaborative ecosystems are often centred in civilian research institutions rather than military laboratories.
- Second, civilian biotechnology markets, particularly pharmaceuticals, agricultural biotechnology, and industrial biomanufacturing, provide strong economic incentives for innovation.

- Third, the tools of biotechnology are becoming increasingly accessible, both in terms of cost and expertise required to operate. Advances in DNA sequencing, gene editing, and computational biology have reduced barriers to entry for biological research.

For defence establishments, this civilian-first model creates both opportunities and institutional challenges. On the one hand, armed forces can potentially draw on a far wider base of innovation than would be possible through military laboratories alone. On the other hand, the pace and direction of civilian biotechnology development may not align neatly with defence procurement cycles, operational requirements, or biosecurity priorities.

Effective defence planning therefore depends on the ability to monitor emerging technologies, cultivate relationships with civilian scientific communities, and establish pathways for technology transfer, adaptation, and evaluation. (Soare and Pothier 2021) In the aspects of biotechnology that may appear to be adjacent to core military functions, there might not be enough incentive for the military to prioritise resources for research and development. Yet, these supplementary inputs – cumulatively and in addition with other technological advancements – could be significant to military operations.

This paper focuses on this supporting dimension of biotechnology. It explores how emerging biotechnologies can enhance resilience across three levels of military operations:

1. Individual performance and health
2. Operational unit resilience
3. Theatre-level preparedness and biodefence

It also considers the policy implications of these developments for India, where a rapidly expanding biotechnology sector intersects with broader defence-modernisation goals. Indian armed forces operate across a wide range of demanding environments, including high-altitude zones, extreme heat, tropical disease ecologies, maritime settings, and remote border areas. Biotechnology could support these operational environments in distinct ways: improved physiological monitoring and nutrition for high-altitude troops, better vector-borne disease protection in tropical deployments, distributed energy and food systems in remote regions, and enhanced biodefence for both military bases and civilian populations.

The central argument advanced here is that the most immediate and policy-relevant impact of biotechnology on defence is likely to arise through incremental but consequential improvements rather than through dramatic transformations in human capability or overt offensive use. Realising these benefits, however, will depend on governance arrangements that can manage dual-use risks, sustained investment in research and translational infrastructure, and stronger institutional linkages between defence organisations and civilian scientific ecosystems.

This article is based on a review of recent scholarship on military medicine, biodefence, biomanufacturing, neurotechnology, and defence innovation, alongside selected policy and strategy documents from defence organisations and multilateral institutions. It does not seek to predict a single technological pathway and is only meant to illustrate an approach for biotechnology adoption for military operations. In doing so, it identifies the most plausible near- to medium-term channels through which biotechnology may affect military preparedness, resilience, and operational planning, but this is by no means an exhaustive list of options.

2. Biotechnology and Individual Soldier Performance

One of the most direct impacts of biotechnology on defence preparedness lies at the level of the individual soldier. Advances in biomedical science have the potential to significantly improve physical resilience, medical recovery and cognitive performance.

2.1 Improving Soldier Health and Disease Protection

One of the most profound impacts of emerging biotechnologies will be on early detection and protection from disease. Until World War I, infectious diseases, not battle-related injuries, were one of the main causes of morbidity and mortality among soldiers. (Smallman-Raynor 2004) For example, in the American civil war, two-thirds of the estimated 660,000 soldier deaths were caused by pneumonia, typhoid, dysentery, and malaria, and this death toll was one of the many factors that contributed to a 2-year extension of the war (Connolly 2002).

Although the threat of infectious diseases, including vector-borne diseases, persists today, advances in hygiene, sanitation, and medical interventions, particularly vaccines and antibiotics, have significantly reduced mortality rates. However, while deaths from disease have declined, illness continues to affect operational readiness among soldiers deployed in challenging environments.

Modern biotechnology offers the potential to further transform soldier health and disease preparedness. New vaccine platforms, including mRNA-based technologies, allow for the rapid design and development of vaccines against pathogens for which effective vaccines previously did not exist. (Pardi 2018) Advances in point-of-care diagnostic technologies further enhance these capabilities by enabling rapid identification of pathogens or other health conditions in field settings. Together, tools such as genomic surveillance, rapid diagnostics, and next-generation vaccine platforms can significantly improve the prevention, detection, and management of infectious diseases among military personnel.

In addition to disease prevention, biotechnology may also improve inherent individual health. Advances in genomics and genome editing are expanding scientific understanding of human health and disease mechanisms. This deeper knowledge may reveal new pathways for improving health and resilience among military personnel operating under exacting field conditions. In parallel, wearable biosensors and health-monitoring devices can provide real-time information on physiological parameters, enabling early detection of illness or abnormal conditions among deployed personnel. (Li 2017; Friedl 2018)

Biotechnology can also improve nutrition and physical resilience through innovations such as biofortified or genetically-improved crops and novel food processing technologies, which may help sustain adequate nutrient intake in challenging environments, including remote or operational settings. (Fallowfield 2025; Pfeiffer 2007; Ceasar 2024)

In this way, modern biotechnology has the potential to substantially improve soldier health while strengthening the overall resilience of military forces against biological threats. While this may reduce injury and illness incidence rate, it will not eliminate them. Recovery is another area where biotechnology may be of use.

2.2 Accelerating Recovery and Medical Treatment

Biotechnology is transforming trauma and regenerative medicine. Advances in wound-healing materials, tissue engineering, and biologically derived therapeutics can reduce recovery times following injuries. (Clark, 2023) Noting the importance of emerging technologies in improving recovery, the Department of Defence, academia and private sector collaborated to create the Armed Forces Institute of Regenerative Medicine (AFIRM) to develop technologies to meet the existing gaps in military trauma care. (Dean, 2011) New technologies such as stem-cell based technologies (Ude, 2018), tissue regeneration (Spear 2018) and biomaterials (Niculescu, 2022) are showing promising results in expediting soldier recovery from combat trauma.

Reduced recovery time could improve operational readiness and lower the logistical burden associated with long-term medical care for injured personnel. While health and recovery speak to physical resilience of an individual, biotechnologies are likely to have a significant impact also on mental performance.

2.3 Cognitive Performance and Neurotechnologies

Neurotechnologies represent an exciting frontier for military operations that are increasingly integrating automation and mechanisation in operations. Modern military personnel frequently operate complex platforms such as unmanned systems, advanced sensors, and networked command systems, placing significant cognitive demands on operators. The rate-limiting step for future military operations may be the human brain. As a result, defence research organisations have increasingly explored neurotechnology-based tools to monitor cognitive workload, improve cognitive performance, and integrate mind-machine operations.

One important area of research involves non-invasive neural monitoring technologies, such as electroencephalography (EEG) to track neural signals associated with attention, fatigue, and cognitive workload. For example, the U.S. Department of Defense has funded research to integrate EEG sensors into flight helmets in order to monitor pilot and aircrew fatigue and cognitive load during missions. These systems aim to identify early signs of cognitive degradation and enable real-time interventions to maintain operational performance. (SBIR n.d.)

Neurotechnologies are also being explored to improve threat detection and situational awareness. Programs such as the U.S. Defense Advanced Research Projects Agency's Cognitive Technology Threat Warning System integrate neural signals with sensor systems to help soldiers detect potential threats more rapidly in complex visual environments. By analysing brain signals associated with subconscious threat recognition, these systems can alert operators to potential hazards that might otherwise go unnoticed. (National Research Council 2009)

Prolonged missions often require personnel to function with limited sleep, leading to declines in cognitive performance, vigilance, and decision-making. Research programs such as DARPA's Alert WARfighter Enablement initiative aim to develop technologies capable of temporarily stimulating brain circuits to maintain alertness and cognitive performance during periods of sleep loss, without the side effects associated with traditional stimulants. (DARPA n.d.)

Taken together, these technologies could enhance situational awareness, decision-making speed, and resilience to fatigue—capabilities that are critical in modern high-tempo operational environments. In the future, where human-in-the-loop systems dominate warfare, the edge might not belong to those with the best hardware, but with the most responsive humans who control that hardware. This makes neuro-technologies an important area that requires scrutiny. Biosensors which sit at the intersection of humans, machines and the environment will be key enablers of this integration.

2.4 Environmental and Biological Sensing

Advances in biosensors could significantly improve how soldiers detect and respond to environmental hazards in the field. Recent research shows that portable and wearable biosensors are increasingly capable of rapid, on-site detection of pathogens, toxins, bioaerosols, and other environmental contaminants, often with advantages in sensitivity, portability, and turnaround time over conventional lab-dependent methods. (Pan 2024)

Reviews of pathogen-detection platforms describe electrochemical and optical biosensors as especially promising for point-of-care and field use because they support real-time or near-real-time analysis in compact formats. (Rasheed 2024) Parallel work in biodefense and airborne-threat sensing argues that such systems could function as early-warning tools against biological threats by identifying harmful agents in aerosols or contaminated environments before exposure escalates. (Behera 2026) That is particularly relevant for operations in unfamiliar environments, where laboratory infrastructure is absent and environmental uncertainty is high.

NATO research on physiological monitoring suggest that wearable biosensors can provide actionable information on heat strain, hydration-related risk, sleep and alertness, workload, and other markers relevant to readiness. (NATO Science and Technology Organization n.d.) Biosensor-enabled monitoring can improve cognitive and operational performance indirectly by helping track fatigue, stress, and biomarkers associated with readiness, although the evidence for fully integrated cognitive-readiness systems is still maturing. (Sipos 2025; de Vries 2025)

Such integrated systems with continuous monitoring could support earlier identification of conditions such as exertional heat illness, fatigue, and injury risk, enabling timelier intervention, more personalised training, and more targeted rehabilitation. Biosensors are therefore best understood not as a standalone enhancement, but as part of a holistic health and situational-awareness ecosystem that could reduce avoidable casualties, shorten some recovery timelines, and improve decision-making under stress. (Main 2023)

However, caution is warranted. Despite clear progress, many biosensor systems remain limited by issues such as specificity, environmental interference, validation in real-world settings, and the challenge of integrating raw sensor outputs into reliable operational decisions. Several recent reviews stress that field-ready military value depends not just on having sensors, but on validated algorithms, robust sampling workflows, and secure systems that convert measurements into actionable information.

Overall these technologies feed into improving health of individual soldiers and their constant monitoring and real-time communication. This augmented performance along with other technologies feeds into better unit resilience. The next section will cover other biotechnologies that can work in tandem with improved individual performance to boost unit-level resilience.

3. Unit-Level Resilience and Operational Sustainability

While individual capabilities are important, biotechnology may have an even greater impact at the level of operational units, by reducing logistical vulnerabilities and improving operational sustainability.

3.1 Reducing Supply Chain Dependence for Energy

One important dependence for military operations is the reliance on long and vulnerable supply chains for fuel. Localised biofuel production supports strategic autonomy. NATO's 2024 biotechnology strategy identifies biomanufacturing as a way to decrease strategic dependencies on competitors and adversaries, while recent European defence analysis argues that alternative and domestically-available fuels can strengthen resilience as conventional fuel infrastructure becomes more fragile or geographically exposed. (NATO 2024; EU Institute for Security Studies n.d.)

Localised biomanufacturing of biofuels could help military operations produce usable fuel closer to where forces actually operate. The importance of this is exemplified by the U.S. Department of Defense prioritising the adoption of more efficient and clean energy technologies that reduce logistics requirements in contested environments. (U.S. Department of Defense 2022) In the future, the DIU has projected that small, mobile systems producing synthetic drop-in fuels "at or near the point of need" could shift the fuel-resupply paradigm and reduce dependence on constrained supply lines. (Defense Innovation Unit n.d.)

Localised biomanufacturing can convert locally available biomass, waste streams, or other carbon inputs into liquid fuels, which may reduce the number of fuel convoys, lower exposure of logistics nodes to enemy targeting, and sustain operations when ports, pipelines, or fuel depots are disrupted. The ongoing conflict in West Asia is a testament to this vulnerability. Recent defence-facing work on distributed bio-industrial manufacturing explicitly frames biomanufacturing as a way to mitigate logistics bottlenecks in forward-operating environments, with some scholars noting a strong interest in "edge sustainment," where fuel is produced at the point of need. (Mittal 2024; Defense Industrial Base Consortium 2024)

A challenge to localised biomanufacturing is compatibility of the biofuel. Military organisations are especially interested in "drop-in" fuels that can meet existing performance requirements for diesel, petrol, or JP-8 (jet fuel) without redesigning vehicles or fuel systems. DARPA's Biofuels program, for example, was aimed at renewable jet fuel that meets or exceeds JP-8 performance metrics, and DIU's contested-environment fuel program likewise focused on synthetic drop-in jet fuel, diesel, and petrol.

If such drop-ins become available, localised biomanufacturing would become more attractive operationally than options that require new engines, separate infrastructure, or a parallel fuel architecture. However, the military usefulness of localised biomanufacturing will depend on scale, feedstock availability, fuel quality assurance, and whether forward systems can operate reliably under austere conditions.

3.2 Alternative Food Systems

Biotechnology may also strengthen military sustenance by enabling alternative food systems, particularly microbial proteins and engineered crops. Microbial proteins—produced from fungi, yeasts, algae, or bacteria in controlled fermentation systems—are increasingly viewed as a promising source of high-quality nutrition because they can be produced rapidly, with relatively low land use, and from flexible feedstocks. (Puljić 2025) This makes them relevant to defence contexts in which conventional agriculture or food resupply is constrained.

In parallel, advances in crop biotechnology, especially genome editing, are improving traits such as drought tolerance, salinity tolerance, and disease resistance, which could support more reliable food production in environmentally stressed settings. Together, these technologies broaden the range of food options available for military use and may improve the resilience of ration and supply systems.

Their relevance in remote, contested, or resource-constrained environments, where traditional food supply chains are costly, fragile, or difficult to maintain, is significant. Military nutrition research shows that operations in extreme environments place unusual demands on food systems: rations must be shelf-stable, lightweight, nutritionally adequate, and capable of sustaining physical and cognitive performance under stress. (Vidal et al. 2025)

Defence research agencies are beginning to address this problem directly. DARPA's *Cornucopia* program, for example, seeks deployable systems that can produce microbial-origin food from minimal inputs such as water, air, and electricity, explicitly to reduce the logistical burden of food transport in deployed operations and humanitarian settings. (DARPA n.d.) These efforts suggest that biotechnology-enabled food production may be most useful not as a wholesale replacement for conventional military rations, but as a resilience-enhancing complement where resupply is contested or infrastructure is limited.

3.3 Human–Machine Integration

Biotechnology may also contribute to military effectiveness through more advanced forms of human–machine integration, although this area remains at an early stage of development. The previous section covered how wearable biosensors, neurotechnology, and brain–computer interface (BCI) systems could improve the interaction between soldiers and increasingly autonomous military systems by enabling more continuous monitoring of physiological state, cognitive load, and user intent. (Billing 2021) DARPA's Next-Generation Nonsurgical Neurotechnology program, for example, was explicitly designed to explore high-performance, bidirectional brain–machine interfaces, for applications such as controlling unmanned systems and supporting complex multitasking in military missions. (DARPA n.d.)

At the unit level, BCI systems could integrate team-based planning, enable faster communications between team members and lead to more cohesive decision-making. There are two main challenges to this. First, technologies that could enable such team-based actions are still emerging. Second, the use of BCIs is currently being tested for disease alleviation, and their use for military purposes needs to be studied from an ethics point of view. Yet, alongside improvements in supply chain vulnerabilities, human-machine integration represents an important avenue through which biotechnology could enhance unit resilience and the effective use of advanced military systems.

The presence of stronger soldiers, along with improved logistical support and distributed manufacturing of key components will enhance operations at the unit level. As technologies advance, these improvements could even feed into changing the nature of theatres in which war is engaged in.

4. Theatre-level change

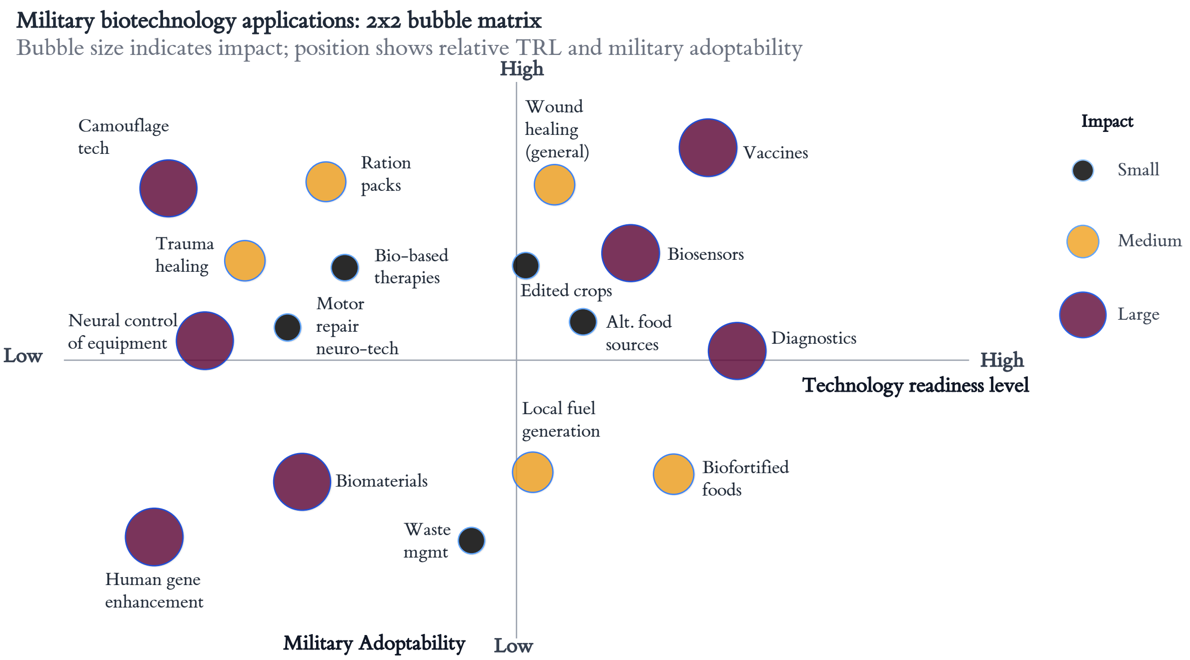
Enhancements in human health, endurance, cognition, and recovery could alter the geography of military operations by making some demanding environments more accessible to personnel and small units. In the near to medium term, the most plausible effects are incremental rather than transformative: improved physiological monitoring, medical countermeasures, nutrition, and rehabilitation may help sustain performance in settings such as remote or high-altitude environments, where hypoxia, cold, fatigue, and limited resupply place unusual strain on personnel.

Other advances in biotechnology also invite the rethinking of the environmental and operational limits within which military forces may be expected to function. For example, as humans are trained to enable long-term space travel, it is likely that space may become a new theatre for warfare.

5. A framework to assess the governance of new biotechnologies

Biotechnology innovation in the civilian sector is advancing rapidly, with several applications holding potential relevance for military operations. Some of these technologies may be suitable for direct adoption by the armed forces, while others will require targeted research, adaptation, and validation before they can meet military requirements. Given the breadth and pace of developments in this domain, continuous tracking of every biotechnology trend is neither practical nor efficient. A more useful approach is to apply a structured framework that helps defence planners identify which technologies warrant immediate attention, sustained monitoring, or strategic investment.

Figure 1. A framework for assessing military-relevant biotechnology applications by technology readiness, military adoptability, and strategic impact.



This paper proposes a 2x2 framework to support the assessment of emerging biotechnology applications. The framework is based on two policy-relevant parameters that are likely to shape the nature and urgency of a military response.

The first is technology readiness level (TRL). Since many biotechnology applications are being developed primarily for civilian use, TRL serves as an indicator of the maturity of a technology in the civilian domain. Technologies with higher readiness levels are more likely to deliver reliable outcomes and to be available for near-term transition.

The second is military adoptability. Civilian technologies are not always directly transferable to defence contexts. They may require modification, operational hardening, regulatory clearance, or mission-specific adaptation before they can be employed by the armed forces. This parameter therefore captures the likely speed and ease with which a civilian biotechnology application could be integrated into military use.

In addition to these two axes, biotechnology applications may also be assessed in terms of their likely effect on military operations. In the framework, this is represented through bubble size - the larger the bubble, the greater the anticipated strategic or operational impact.

A key strength of the framework is that it captures the fact that technological maturity in civilian markets does not automatically translate into military utility. A biotechnology product may be commercially available and scientifically validated, yet still be poorly suited to defence use because of durability constraints, regulatory barriers, cost, logistical incompatibility, or limited relevance to operational requirements. Conversely, some technologies with relatively low civilian maturity may warrant early military attention because they align closely with strategic needs or could become decisive in future operational environments.

The framework therefore helps prevent two common policy errors: assuming that all mature civilian technologies are immediately transferable to defence, and neglecting less mature technologies that could generate significant long-term strategic advantage. For example, civilian health wearables may be highly developed for fitness and wellness, but they may have limited defense utility if they are not secure, interoperable with military systems, or reliable in extreme environments. Conversely, portable synthetic biology-enabled biosensors for rapid detection of pathogens or toxins may not yet be fully commercialized, but could have clear defence relevance for battlefield surveillance and force protection.

The value of this framework therefore lies not merely in classifying biotechnology applications, but in helping defence institutions distinguish between different modes of state response. Emerging technologies do not all require the same policy treatment. Some are ready for procurement and deployment, others require targeted adaptation to military conditions, and still others merit only observation and early experimentation.

The addition of strategic impact as a third dimension further strengthens the framework by introducing a prioritisation logic. Not all technologies that are mature and adoptable will have equal consequences for military capability. Some may generate only marginal efficiencies, while others may reshape force protection, sustainment, or preparedness in more consequential ways. Representing impact through bubble size allows the framework to distinguish between technologies that are merely feasible and those that are strategically significant. This is especially important in resource-constrained policy environments, where defence institutions must choose not only which technologies to monitor, but which ones justify sustained funding, institutional reform, or dedicated procurement pathways. For example, the impact of biosensors on field operations may be disproportionately higher than that of alternative forms of nutrition.

Taken together, these three variables—technology readiness, adoptability, and impact—allow the framework to serve as a decision-support tool for defence innovation governance. Technologies in the high-readiness, high-adoptability quadrant should generally be candidates for rapid evaluation, piloting, and procurement. These are the applications most likely to produce near-term gains and may include diagnostics, biosensors, biofortified foods, or selected medical technologies. Their importance lies in the fact that they can generate visible operational benefits without requiring major institutional transformation. For defence planners, the relevant policy challenge here is less scientific uncertainty than bureaucratic speed: testing, acquisition, and integration mechanisms must be agile enough to absorb technologies before they become outdated.

By contrast, technologies with high readiness but lower adoptability require a different policy response. These are cases in which civilian biotechnology is already relatively advanced, but military use depends on additional adaptation, validation, or mission-specific redesign. Wound-healing technologies, distributed fuel-generation systems, and some human-machine interface applications may fall into this category. Here, the appropriate response is not immediate procurement, but an active role in bridging the gap between civilian innovation and military application. Defence institutions may need to fund translational R&D, articulate specific military use cases, support demonstration projects, or create incentives for private firms to tailor products to defence needs.

The lower-readiness quadrants are analytically important because they address the problem of anticipatory governance. Technologies that are still immature but could eventually have high military relevance cannot be ignored simply because they are not yet deployable. Rather, they require horizon scanning, early experimentation, and careful ethical and strategic assessment. This is particularly true for technologies such as advanced neurotechnology, human enhancement, or gene editing, whose eventual implications may be profound even if near-term operational application is limited. In such cases, the framework encourages defence planners to treat uncertainty not as a reason for inaction, but as a reason for selective monitoring and institutional preparedness.

Equally, the framework helps identify technologies that are currently low on both readiness and adoptability, and which may therefore warrant only limited policy attention in the short term. This is useful because defence policy may overinvest in highly speculative technologies at the expense of more immediate but less dramatic opportunities. The idea that gene editing technologies could be used to engineer a 'supersoldier' is an example of how emerging technologies can be over-hyped, and their real use can be misrepresented. By placing early-stage technologies in comparative perspective, the framework can reduce the risk of "narrative-driven" decision-making and encourage a more disciplined allocation of attention and resources.

From a governance perspective, the framework also underscores that biotechnology policy for defence goes beyond threat prevention or laboratory regulation with many relevant technologies emerging in sectors such as healthcare, agriculture, materials science, and industrial biomanufacturing. This wide spectrum of applications require defence institutions to set up institutional mechanisms for scanning and engagement across a range of stakeholders. This includes partnerships with universities, start-ups, hospitals, and industrial biotechnology firms; translational funding mechanisms; and specialised units capable of identifying which civilian advances are most relevant to military needs.

For India, the framework is particularly useful because it offers a way to connect a rapidly expanding civilian biotechnology base with defence-modernisation priorities. India's biotechnology ecosystem, now shepherded by the BioE3 policy, is growing across vaccines, diagnostics, agricultural biotechnology, biomanufacturing, and genomics, yet defence application remains fragmented. (Press Information Bureau, 2024) A structured framework can help identify which parts of this ecosystem are ready for near-term military use, which require adaptation and public support, and which should be monitored as part of longer-term strategic planning. In this sense, the framework is not only a classificatory device, but also a means of aligning industrial policy, defence planning, and national security strategy.

Ultimately, the framework suggests that the military significance of biotechnology will not be delivered through a single breakthrough application with a clear offensive or defensive purpose. Rather, it will arise through the selective accumulation of multiple innovations, some immediately usable, some requiring adaptation, and some still speculative, that together alter force health, logistics, preparedness, and resilience.

The framework's analytical value lies in enabling defence institutions to manage this diversity systematically. It encourages a shift from reactive engagement with biotechnology to a more strategic model of prioritisation. Its purpose is not to determine with certainty which biotechnology applications will become militarily decisive, but to help defence institutions allocate attention, funding, and institutional effort in a more systematic way. While the paper proposes a preliminary analysis of a few applications, this framework will be most useful, when applied by the armed forces for their specific contexts.

6. Policy Implications for India

The preceding analysis suggests that biotechnology should be treated not as a narrow subset of health or laboratory policy, but as a strategic enabling domain, with implications across defence preparedness, logistics, force health, and biodefence. For India, this raises an important policy challenge. Although the country possesses a rapidly growing biotechnology base and has articulated broader ambitions through recent industrial and bioeconomy policy, the integration of biotechnology into defence planning is limited and fragmented.

Where biotechnology does appear in the publicly available defence materials, it is largely through specific DRDO laboratories and task-based programmes, rather than as a clearly articulated cross-cutting defence priority. DRDO's technology-foresight architecture lists "Bio Defence", "Bio Remediation", and "Biomedical Engineering & Technologies" as a few categories, while its published "Bio Defence" tasks are relatively narrow, such as vector biosurveillance, insect-protection textiles, and related soldier-protection applications. Likewise, DRDO's Defence Institute of Bio-Defence Technologies is tasked with detection of food-borne pathogens and toxins of biodefence importance, along with military nutrition R&D, indicating that defence-biotech capacity exists but remains institutionally bounded, rather than integrated into a broader strategic doctrine.

A more systematic approach is useful if India is to translate civilian advances in biotechnology into military resilience and strategic capability. In practice, this means that biotechnology should be incorporated more explicitly into India's defence-technology planning frameworks, rather than being treated solely as a matter for civilian ministries or public-health institutions. Such recognition would help shift biotechnology from the margins of defence discourse to a more central place in long-term capability development.

6.1 Strengthening Indigenous Biotechnology Capabilities

The most immediate policy implication is the need to strengthen indigenous capability in biotechnology. India has achieved considerable success in vaccines, pharmaceuticals, diagnostics, and parts of agricultural biotechnology, but military-relevant biotechnology requires a broader capability base spanning genomics, synthetic biology, bioinformatics, microbial engineering, advanced biomaterials, and biomanufacturing. From a defence perspective, domestic capability is important for three reasons.

- First, indigenous capacity reduces dependence on foreign suppliers for critical technologies, biological inputs, and specialised materials. In a crisis, reliance on external supply chains may expose the armed forces to delays, export restrictions, or strategic coercion.
- Second, domestic capability enables more context-specific adaptation of biotechnology to Indian operational requirements, including high-altitude deployments, tropical disease environments, and long land and maritime supply lines.
- Third, investments in strategic biotechnology can generate spill overs across both civilian and military sectors, strengthening national resilience more broadly.

6.2 Expanding Defence–Academia–Industry Collaboration

A second policy implication concerns the institutional structure of innovation. As discussed earlier, much contemporary biotechnology innovation is occurring outside the military sphere, in universities, research hospitals, start-ups, and commercial biotechnology firms. This is especially true in India, where the biotechnology ecosystem is heavily civilian in orientation. As a result, defence institutions cannot rely solely on internal R&D structures such as DRDO if they wish to remain abreast of relevant developments.

India therefore needs more mechanisms that can enable defence–academia–industry collaboration in biotechnology. At present, interactions between these sectors are often episodic, project-based, or constrained by differences in institutional culture and timelines. Defence establishments tend to operate through long procurement cycles and narrow specifications, whereas biotechnology research evolves rapidly and often through exploratory collaboration. Bridging this gap requires intermediary mechanisms capable of translating defence needs into research problems and identifying civilian innovations with military relevance.

One option would be to create a dedicated platform or cell within the defence innovation system focused on biotechnology and biodefence. Such a mechanism need not replicate DARPA's Biological Technologies Office institutionally, but it should perform comparable functions: horizon scanning, coordination with research institutions, funding of translational projects, and identification of technologies that are close to military adoption. This would allow biotechnology to be treated as a continuing strategic portfolio rather than a series of isolated research efforts.

India would benefit from building domain awareness in biotechnology across the defence system. This could include specialised fellowships, secondments between defence and civilian research organisations, targeted training for military planners, and the inclusion of biotechnology in strategic studies and war-gaming exercises. Over time, such measures would help create a cadre of officials capable of evaluating biotechnology not simply as a technical issue, but as part of broader national-security planning.

6.3 Building an Integrated Biodefence Architecture

A third major implication concerns biodefence. Although this article emphasises the enabling and resilience-enhancing uses of biotechnology, these same technological developments also increase the importance of preparing for biological threats, whether naturally emerging, accidental, or deliberate. Biodefence cannot be understood solely as a military matter. Effective preparedness requires coordination across defence, public health, agriculture, environmental monitoring, disaster response, and law enforcement.

This points to the need for a more integrated national biodefence architecture. India is boosting capacity in surveillance, diagnostics, and vaccine production, but these capabilities are still dispersed across multiple ministries and agencies. In the event of a serious biological incident, fragmented institutional responsibilities can slow detection, attribution, and response. From a defence standpoint, this is especially important because military effectiveness depends on the continuity of civilian health and infrastructure systems as much as on internal force protection.

An integrated biodefence architecture would require at least three elements.

- First, stronger coordination mechanisms between defence institutions and civilian public-health agencies, particularly for surveillance, early warning, and crisis response.
- Second, expanded investment in genomic surveillance, microbial forensics, and rapid diagnostics, all of which are essential for timely detection and attribution.
- Third, regular joint exercises and planning processes that treat biological incidents as national-security contingencies rather than purely medical events. In effect, India needs to incorporate a whole-of-government approach in which defence institutions play an active but not isolated role.

6.4 Prioritising Translational and Field-Deployable Technologies

A fourth implication is that India should focus not only on high-end scientific research but also on translational technologies that can be deployed in operational settings. In the biotechnology domain, technology readiness does not automatically translate into military usefulness. Many technologies remain confined to laboratory or hospital settings and require substantial adaptation before they can operate reliably in field conditions.

For Indian defence planning, this suggests the importance of prioritising technologies that are portable, and operationally relevant. Examples include field-deployable diagnostics, wearable biosensors for health and readiness monitoring, portable biomanufacturing systems, and technologies for improved trauma care and rehabilitation. These may not always be the most scientifically novel applications, but they are more likely to deliver practical gains in the near to medium term.

6.5 Developing Ethical and Regulatory Preparedness

As biotechnology becomes more closely linked to defence, India will also need to strengthen ethical and regulatory capacity. Many biotechnology applications, particularly in areas such as human enhancement, neurotechnology, gene editing, and biological data collection, raise difficult questions about consent, privacy, long-term health effects, and dual-use risk. These issues are not unique to India, but they are likely to become more salient as the military begins to engage more deeply with biotechnology.

India should develop clearer frameworks for ethical review, biosafety, data protection, and military use of emerging biomedical technologies. This is especially important because military settings create unique pressures around hierarchy, voluntariness, and operational necessity. The objective should be to ensure that strategic adoption does not outpace ethical safeguards. In this sense, governance is not external to capability development; it is a condition of responsible and sustainable capability development.

7. Conclusion

Biotechnology will shape warfare less through exotic 'super-soldier' technologies and more through improvements in health protection, sensing, and distributed manufacturing. Biotechnology is poised to become a defining technological domain in national security and defence preparedness. Advances in biomedical science, synthetic biology, and bioinformatics are creating new opportunities to enhance soldier health, strengthen operational resilience, and improve biodefence capabilities.

However, realising these benefits requires strategic investments, institutional coordination, and robust governance frameworks. For India, integrating biotechnology into defence planning offers an opportunity to strengthen both national security and public health resilience. By building strong partnerships between defence institutions, scientific communities, and biotechnology industries, India can develop a comprehensive biodefence architecture capable of addressing the biological challenges of the future.

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