Biotechnology and Synthetic Biology; Biosecurity Risk

Fatima Javed[1,*], Muqaddas Yaseen[2], Ali Raza[1], Muhammad Usama Gulzar[1], Sufyan Maqsood[3], Shoaib Ahmad[1], Qadeer Nazir[3], Isra Naveed[3] and Naila Afzal[4]

[1]Institute of Microbiology, Government College University, Faisalabad, Pakistan
[2]Department of Allied health Sciences, College of rehabilitation Sciences, Government College University Faisalabad, Pakistan
[3]Department of Medical Laboratory Technology, Ripah International University, Faisalabad, Pakistan
[4] Institute of Microbiology, Agriculture University, Faisalabad, Pakistan
*Corresponding author: fatimajaved179@gmail.com

Abstract

Biotechnology and synthetic biology are groundbreaking fields that have made major strides in agriculture and medicine. But as these technologies advance, they present intricate biosecurity threats that need to be properly controlled. Synthetic biology entails the design and construction of new biological parts, devices, and systems, and Biotechnology uses biological systems and organisms for practical purposes both have enormous potential but also present risks associated with Bioterrorism and misuse of engineered organisms which can cause unintended ecological effects. This chapter examines the potential and consequences of pathogenic organisms. It also highlights how these risks are currently being monitored, controlled, and mitigated, highlighting the value of a strong governance framework and International Cooperation. Proactive steps are needed for innovations in these domains to ensure safe and responsible development in synthetic biology and biotechnology along with reducing any potential biosecurity risk. Building trust and promoting well-informed decision-making can be achieved through open and honest communication about the advantages and risks of innovation. In the end, protecting both human advancement and the environment in a globalized world will require a balanced strategy that prioritizes biosecurity while encouraging innovation.

Keywords: Biotechnology, Biosecurity, Synthetic Biology, Bioterrorism, Biohackers

Cite this Article as: Javed F, Yaseen M, Raza A, Gulzar MU, Maqsood S, Ahmad S, Nazir Q, Naveed I and Afzal N 2025. Biotechnology and synthetic biology; biosecurity risk. In: Farooqi SH, Kholik K and Zaman MA (eds), One Health Horizons: Integrating Biodiversity, Biosecurity, and Sustainable Practices. Unique Scientific Publishers, Faisalabad, Pakistan, pp: 138-147. https://doi.org/10.47278/book.HH/2025.119

A Publication of Unique Scientific Publishers	**Chapter No:** 25-019	**Received:** 22-Feb-2025 **Revised:** 09-March-2025 **Accepted:** 25-Apr-2025

Introduction

The origins of biotechnology can be found in the ancient communities of Egypt, Greece, Rome, India, China, and other places. These societies produced beverages like wine and beer, exploited microorganisms for fermentation, tamed animals for livestock, and applied plant-based balms and herbal medicines for wounds. Illnesses are some of the first examples of biotechnology (Khan, 2020). Over the past 20 years, the term "Biotechnology" has gained immense importance and relevance, which is unheard of. The likelihood and potential for this level of interest in biotechnology may stem from its boundless capacity to assist and advance humankind. The cure of illnesses and the genetic alteration of organisms to enhance human life are the main concerns of modern biotechnology, whereas early biotechnology concentrated on useful uses like agriculture and medicine (Verma et al., 2011). As per the unified definition developed by European experts, "Synthetic biology is the engineering of biology: the creation of complex, biologically based systems that display functions that do not exist in nature."

Biosecurity

Originally, the term "biosecurity" was largely utilized by defense addressing the management of biological weapons. Biosecurity encompasses all actions taken to stop infections from entering the body i.e. bio-exclusion and stops them from spreading i.e. bio-containment (Saegerman et al., 2023)

In a broader sense, a country's capacity to effectively respond to biological threats and other elements is referred to as "biosafety" or "biosecurity" (Laith et al., 2022). A country must uphold and defend its own security and interests in order to do this. Among these requirements are the avoidance and management of major infectious disease outbreaks, defensive measures against attacks using biological weapons, preventing bioterrorism, restricting misuse of biotechnology, stability of clinical biosafety, isolating particular resources sustainably, and preventing invasion by invading organisms (Zhou et al., 2019).

Biotechnology

Biotechnology is an interdisciplinary branch that has a significant impact on contemporary societies. The technology, which uses cellular nuclei along compounds crafted from cells for a plethora of reasons, has been around for years. Diagnostics and treatments have been transformed and the biggest hazards to human health have been the lethal viral pandemics, such as bird influenza, typhus, Ebola, h1n1/h5n1 pneumonia, SARS, and the most recent hanta or zika virus has been reduced infect almost diminished (Gupta et al., 2017).

Historical Context of Biotechnology

Plant culture and animal training, especially domestication, are the most archaic forms of biotechnology. Since our ancestors began keeping plants as a dependable food source more than 10,000 years ago, animals have been domesticated. Barley, wheat, and rice are the first instances of such domesticated plants. Additionally, wild animals were tamed to generate meat or milk. There are additional reports of the ancient use of microorganisms to produce bread, cheese, and yogurt. The discovery of fermentation at this time led to the development of a variety of alcoholic beverages, including wine and beer (Bhatia et al., 2018). Nowadays, biotechnology is employed in many fields, such as agriculture, energy production, and bioremediation. Forensics frequently uses DNA fingerprinting.

Louis Pasteur provided the first scientific description of fermentation in the last decade of nineteenth century. He stated a theory called "germ theory" by illustrating the survival and subsequent impact of microorganisms in the fermentation process (Gul et al., 2023).

Table 1: A few key events that formed the basis of modern biotechnology

YEAR	SPECIFIC EVENTS	References
1950-1980	• DNA's structure, known as the double helix was introduced by Watson and Crick. • Messenger RNA (mRNA), restriction enzymes, and southern blotting were discovered. • Numerous techniques like the use of DNA ligase, the first artificial chromosome and test-tube baby, genetic fingerprinting, and PCR technique were developed.	(Glick et al., 2022)
1981-2000	• First genetic therapy was executed safely. • Genetic testing of in vitro embryos. • Crude map of all 23 human chromosome pairs. • Investigated BRCA1 as first breast cancer gene. • Gene chip, a breakthrough in DNA sequencing was created.	(Ma., 2024)
2001-2010	• Human Genome Project successfully topped. • Cloning of an adult sheep was managed to accomplish. • Genomes of chimpanzees, mice, dogs, and hundreds of other species were successfully sequenced. • Venter advanced the creation of first living artificial organism in history, by fully replicating the bacterium's genetic material.	(Amarakoon et al., 2024)

Advancements in Biotechnology

1. Gene Circuits

Advances in biotechnology have led to the engineering of genetic circuits that are specific to particular biological activities. In response to particular input signals, these circuits are made to control the timing and level of gene expression (Stone et al., 2024).

Genetic circuits imitate the structure of a silicon-based electronic system by combining different logic gates as; AND where the output is high when all inputs are high, NAND where the output is low when all inputs are low, and NOR where the output is low when any input is high. Gene circuits either control the direction of gene expression or activate gene expression by external factors (Ngo et al., 2024)

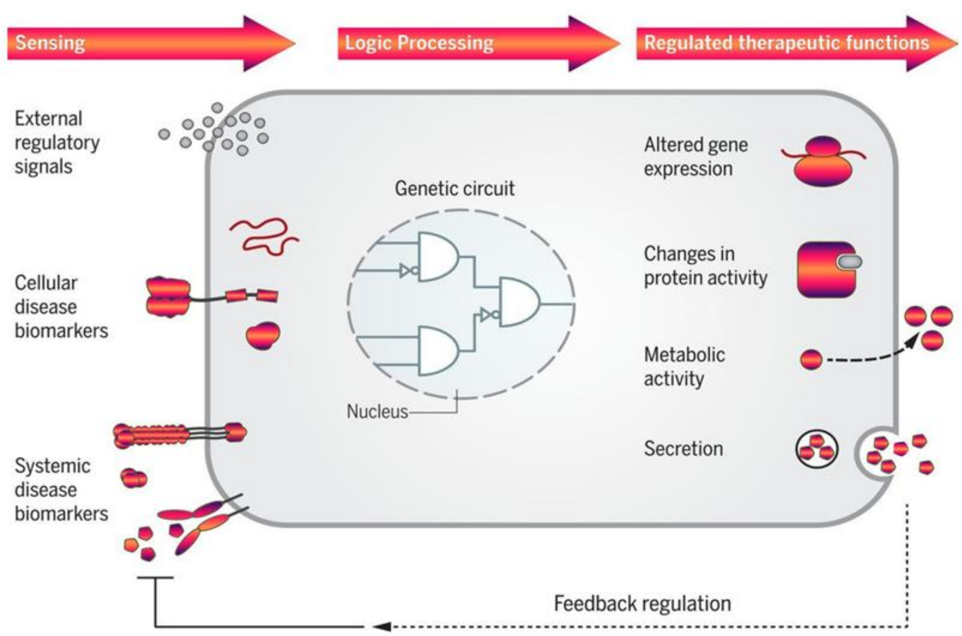

Fig. 1: Genetic circuits demonstrating programming in living therapies (Adobe Photoshop)

Enzymes involved in gene switching include tyrosine recombinases as well as serine integrases. In general, genes encoding enzymes that induce unidirectional recombination have been employed to build circuits that sustain gene expression following the switch event (Zhang et al., 2024).

Gene Switches

The notion that genes may be turned on and off was groundbreaking just 40 years ago. The fundamental process was established by parallel studies on the lambda bacteriophage, which produced many of the same findings. Eukaryotic cells are subject to many of the same rules. However, the incredibly intricate gene regulation of higher species, together with the way their DNA is packaged into chromatin, presents unique control options as well as unique obstacles (Alberts et al., 2002).

Gene X is a gene whose expression is controlled by both external signals (like environmental conditions) and internal factors (like transcription factors). The term "heteroregulated" suggests that this gene may be controlled by a variety of positive and negative processes, potentially involving various pathways or regulators. A person's Gene X can turn "ON" or "OFF" based on these variables. Factor of transcription A protein called Y attaches itself to the promoter or enhancer regions of Gene X, aiding in transcription and raising Gene X expression. This transcription factor is regarded as "positive" since it raises or activates gene expression, hence turning the gene "ON" (Mansouri et al., 2024).

Environmental factors are external signals or situations (such as temperature fluctuations, stress, nutrition availability, toxins, etc.) that can affect the stability of Gene X's protein or mRNA. These elements may cause the gene product (mRNA or protein) to degrade, which would lower or stop Gene X expression. Numerous processes, including RNA interference and the ubiquitin-proteasome system, can cause degradation. Here, Gene X is generally regulated by the positive transcription factor Y, which increases its expression. However, the presence of certain environmental conditions might cause degradation of either the mRNA or the protein generated by Gene X, lowering or terminating expression. This results in a dynamic system in which Gene X is positively regulated by Y but is also susceptible to outside influences that may degrade it and prevent it from expressing itself (Ngo et al., 2024).

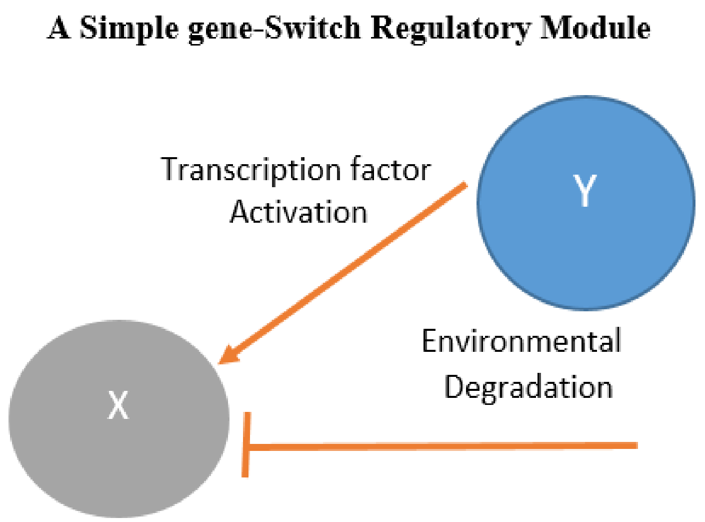

Fig. 2: The hetero-regulated gene X, its positive transcription factor Y, and environmental factors that cause degradation are shown in this straightforward gene switch model (Adobe Photoshop).

Dual-use Dilemma

Rapid advances in biotechnology have transformed several industries and raised important questions for global biosecurity. In many areas, such as healthcare, agriculture, and environmental sustainability, biotechnology has shown promise as a game-changer for the benefit of humanity (Aggarwal et al., 2024). However, it also presents serious concerns about global biosecurity, such as the possibility of biological warfare, bioterrorism, and the unintentional or intentional introduction of genetically modified organisms (GMOs).

Bioterrorism

Bioterrorism is defined with a slightly different standpoint which is the intended exposure of viruses, bacteria, or toxins to harm humans, livestock, or crops. Whether in the form of microbiological agents or toxic compounds produced from organic sources like plants or animals or inorganic like minerals or vapors, biological terrorism has been one of the strategies employed by ancient civilizations to subjugate others in both wartime and non-war situations. Since ancient times, toxicology and bioterrorism have been studied and examined (Eslami et al., 2024). Between 1600 and 1180 BC, an ancient Anatolian group known as the Hittites founded an empire in what is now Turkey. Historical records indicate that the Hittites were the first to use bioterrorism. The Hittites used deadly bacteria against their enemy for the first time. Among the first people to study bioterrorism and toxicity were the Egyptian, pharaoh, Menes, the Persian ruler Attalus III, and the Roman emperor Nero.

The four important components of bioterrorism are explained below (Hwang, 2024).

I. **Biological Agents**

Toxins, viruses, and bacteria are examples of biological agents used in bioterrorism that can cause serious disease or even death. Botulinum toxin, smallpox (variola virus), and anthrax (Bacillus anthracis) are a few examples. These agents are chosen based on their potential for spreading, ease of manufacture, and lethality (Danese et al., 2015).

II. Weaponizing

The process of altering biological agents to increase its potency and make delivery feasible is known as weaponization. This entails enhancing agent's stability in environment, creating fine particles that can be aerosolized or incorporating the agent into specialized dispersal apparatus. The quality of dispensability can be enhanced by turning liquid into gas or in dry powder which facilitates distribution over a longer and wider area (Halpin, 2016).

III. The Delivery System of a Biological Agent

A delivery system is a mean by which the agent is dispersed throughout the target population. Usually, it works with two different strategies:

i- Point source

This strategy releases agent from a single point like a building ventilation system.

ii- Line source

This method disperses agents along paths like a line such as by a moving car.

IV. Weather Conditions for Biological Attack

A biological attack's effectiveness is greatly impacted by the weather. The biological agent's potency and dissemination can be impacted by variables like temperature, humidity, and wind direction and speed. High winds, for instance, may spread the agent across a larger region but may also reduce its concentration. On the other hand, steady, windy weather conditions could keep the agent in the aimed region for a long time.

Table 2: Bio Weaponization dissemination and mitigation

Dissemination mechanism	Agent	Precaution	References
Air Borne	Infection transmitted by particles Example corona virus	Hand Hygiene Gloves Glasses for Eye protection N95 mask Negative pressure private room for isolation	(Argyropoulos et al., 2023)
Droplet	Viral hemorrhagic fevers Pneumonic plague Influenza	All PPEs	(Ijaz et al., 2023)
Contact	Category B agents that spread by infected or direct contact with virus	All PPEs	(Comunian et al., 2020)

The Sverdlovsk Case

Sverdlovsk, in the former Union of Soviet Socialist Republics, witnessed a sudden outbreak of an unidentified sickness in early April 1979 led to the deaths of numerous people. Most of the deaths from this outbreak were represented by few necropsies' cases, which regularly showed pathologic abnormalities which were indicative of inhalational anthrax (Kelley, 2024).

The official reports did not acknowledge the genuine cause, which was the unintentional release of anthrax, but instead claimed that the deaths were due to tainted meat. Eventually, it was discovered that the anthrax spores had accidentally been released when the facility was operating in its entirety. The surrounding areas became contaminated as a result of the spores escaping into the atmosphere due to a filtration system failure (Kelley, 2024).

Table 3: Ancient roots of bioterrorism

Civilization	Bioterrorism Agent	References
Mesopotamian	• Animals e.g., snakes, scorpions, spiders • Poisonous plants • Babylonians: (microbes)	(Eslami et al., 2024)
Romans and Greeks	• Microbes • Cyanide • Deadly nightshade • Poisonous mushrooms	(Ashiq et al., 2023)
American Indians	• Monkshood • Poisonous frog	(Chrystal, 2023)
Egyptians	• Cyanide • Arsenic • Monkshood • Opium • Mandragora officinarum,	(Ashiq et al., 2023)
Japanese	• Venoms • Clostridium tetani • Burning mercury • Puffer fish	(Ferreira et al., 2023)
Melanesians	Clostridium tetani	(Chrystal, 2023)

Legal Framework

Global biosecurity issues of biotechnology are largely addressed by international accords and conventions including the International Health Regulations, the Cartagena

I. Cartagena Protocol on Biosafety

The very first multinational pact with binding legality about contemporary biotechnology is the Cartagena Protocol on Biosafety (CPB).

Adopted under the framework of the Convention on Biological Diversity (CBD), The cross-border immigration of genetically modified organisms (GMOs) is its primary focus. which the Protocol refers to as LMOs "living modified organisms" (Pereira, 2022). The Advance Informed Agreement process, which involves prior notification and authorization for the import and export of LMOs, is its essential component.

The Proto-col's Overarching Goal is:

"To help ensure a sufficient level of protection in the area of the safe transfer, handling, and use of living modified organisms resulting from modern biotechnology that may have negative effects on the conservation and sustainable use of biological diversity, while also taking into account risks to human health and with a particular focus on transboundary movements" (Kinderlerer, 2008).

II. Biological Weapons Convention

With the potential to have a more profound and catastrophic impact on human populations than another weapons, including chemical and nuclear ones. Given these difficulties, the Biological Weapons Convention is regarded as a pillar of the multilateral disarmament regime and a crucial political and legal tool that upholds the universal denunciation of biological weapons (Ait, 2023).

The BW Convention forbids the creation, manufacture, storage, acquisition, having control of weapons, tools, or means of delivery designed to use such agents or toxins in violent actions or armed confrontations, as well as the preservation of microbiological or biological agents, or poisons (Millet, 2010).

Synthetic Biology

The phrase biotechnology refers to the use of biological elements or processes for human benefit, whereas "synthetic biology" refers specifically to the collection of ideas, methods, and instruments used in biotechnology. Synthetic biology is a narrow term that essentially seeks to enhance genetically modified procedures. The construction of ever-more sophisticated biological entities for new uses through engineering is involved (National Academy of Science, 2019).

Designing and building systems is a part of synthetic biology. Prompted by developments in artificial gene network layout, de novo DNA synthesis, and the engineering of proteins every component has unique requirements and inputs. In the end, synthetic biology will produce new biological entities with enhanced capabilities (Bibi et al., 2020).

Evolution of Synthetic Biology

Synthetic biology has come a long way in the past 20 years to establish itself as an established engineering field. For the following reasons, designing life along certain engineering traits is a feasible and somewhat promising goal:

I. Looking For Replaceable Components: DNA

According to the 52-year-old Watson and Crick model, DNA is made up of two antiparallel strands that are made up of nucleotide building blocks, which are made up of nucleobases, phosphates, and sugars. The basic principles of base pairing (A with T, G with C) are substantially responsible for the stability of the DNA duplex and can effectively direct DNA design (Lins et al., 2024). Although there are more intricate structures like Z-DNA and catalytic RNA, most molecular biology tasks do not often require them. The Watson-Crick model's elegance has made it popular, but it can occasionally mask the complexity of other chemical systems, such as proteins, whose behavior is more difficult to predict from their parts (Hargittai, 2024).

II. Standardized Cloning

The most significant fabrication technique in synthetic biology today is conventional cloning. An existing DNA fragment is modified for a new use using common, usually PCR-based technologies, and then put into one of a wide variety of cloning vectors following the requirements of the multi-cloning site (Raimbault et al., 2016).

- ***Gateway Cloning***

Invitrogen's Gateway recombinational cloning technology uses an advanced form of the bacteriophage site-specific recombination mechanism. Two virtually identical but incompatible forms of the recombination site are used in the Gateway cloning technology to preserve the cloned DNA's helix by using vector swaps (Bryant et al., 2024).

- ***Clontech Cloning***

Clontech uses two enzyme methods to collect PCR results and transfer gene expression clones using genes via parental clones. A proprietary enzyme is used by Clontech for the capture reaction. Clontech In-Fusion, which uses brief segments of sequence homology to facilitate DNA cloning (Wang et al., 2019)

- ***Univector Cloning***

The Univector cloning technique, developed by Stephen Elledge's group at Baylor College of Medicine, is similar to the Clontech Creator. Invitrogen offers this system under the name "Echo Cloning System." The Univector cloning approach involves combining an expression vector with a master clone (a plasmid) to create a single, cointegrated expression plasmid through in vitro Cre-loxP-mediated recombination (Zhou et al., 2019).

Engineering of Artificial Gene Network

MAGE gene

MAGE gene was recognized as a gene that encodes a tumor-specific antigen. This gene has since been determined to be a member of a group of 12 hMAGE-A genes located in the X chromosomes q28 locus (Makise et al., 2016). Male germ cells and, in the case of some, the placenta are the only tissues in which they aresilent (Gee et al., 2020). Some are expressed in tumor cells of different histological kinds, and they encode antigens that cytolytic T lymphocytes can recognize. Antitumor immunotherapy is particularly interested in these antigens due to their unique expression on tumor cells.

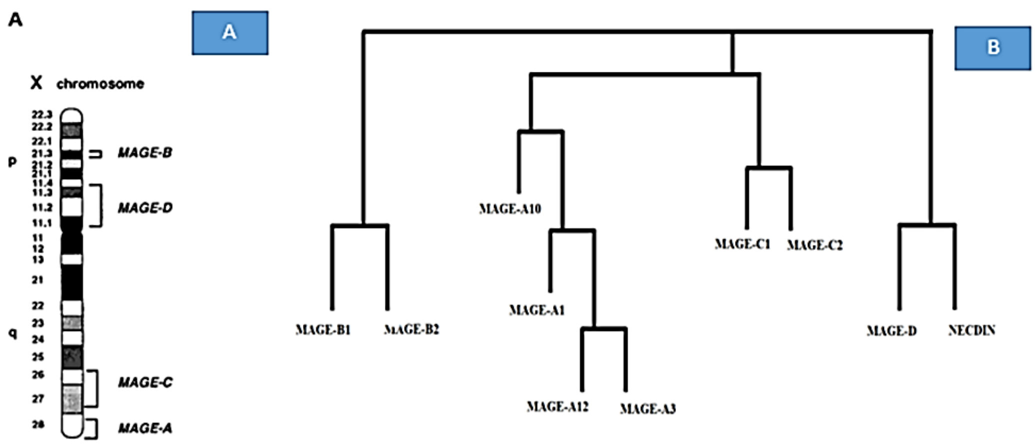

Fig. 3: (A) position of the MAGE gene on X chromosome (B) dendrogram of the connections between MAGE and necdin proteins (Adobe Photoshop).

(CRISPR)/Cas9

CRISPR loci and the associated CRISPR-associated (cas) genes encode complex RNA-guided adaptive immune systems seen in most bacteria and most archaea. Acquired immunity against phage infection and plasmid transfer is provided by these systems (Godfery et al., 2024). It easily turns genes on or off in cells and organisms as well as fix mistakes in the genome. With its programmable and heritable manipulation of gene expression, CRISPR-Cas offers a versatile and adjustable method of modifying phenotypes and producing elite traits without altering protein-coding sequences. It frequently has pleiotropic effects or is even deadly (Zhu et al., 2020).

Chimeric Antigen Receptor T-cells (CAR-T)

Implanted T cells are used therapeutically to eradicate cancerous cells in effective adoptive T cell therapy (ACT). One of the main ACT tactics is the use of chimeric antigen receptor (CAR) T cells. CAR T cells promote MHC-unrestricted tumor cell killing by enabling T cells to bind to target antigens found on cell surfaces through a single-chain variant fragment (scFv) recognizing motif (Benmebarek et al., 2019).

Directed Evolution of Enzymes

Laccases

Laccases are usually Exterior Glycoprotein Monomers that are members of the blue multicopper oxidase family (Mate et al., 2011). Laccases are thought to be highly biotechnologically promising green catalysts. This has sparked a lot of interest in creating laccases à la carte with improved stability or activity catered to certain circumstances for various application domains. These enzymes have numerous applications due to their oxidative diversity and minimal catalytic needs. They consume oxygen from the air and only produce water as a byproduct (Mateljak et al., 2020).

Many attempts have been made over the past 20 years to build these oxidases and comprehend their reaction processes using site-directed mutagenesis, and more recently, through the use of directed evolution techniques and computational computations (Pardo et al., 2015).

Beneficial Vs. Malicious Applications

2018 He Jiankui Controversy

In 2018, the "He Jiankui Scandal" occurred (Macintosh, 2021). To produce twin girls' embryos resistant to HIV, a Chinese biophysicist named He Jiankui used CRISPR in a gene-editing experiment. Global indignation resulted from his actions, which were carried out without the consent of ethical boards or adequate scientific supervision. He was not a biohacker in the conventional sense, but his acts demonstrated a severe kind of unapproved biohacking in the field of biotechnology. Later, for engaging in unlawful medical procedures, he received a three-year prison sentence.

Biohackers

These genetic biohackers have a variety of frequently intricate reasons, some of which are unrelated to professional biology knowledge. It seems that normative views of a "right to do science" are what drive some people. Others value creative expression or bodily autonomy highly, including the freedom to experiment on one or use genome editing for artistic purposes (Zettler et al., 2019). Some believe that traditional scientific organizations are slow and overly complicated, or that they are inadequate regulators of themselves. Since genome editing is now much simpler, quicker, less expensive, and more effective than ever before (similar to changing a computer article), it benefits scientists from a variety of scientific domains as well as a threat like "He Jiankui Scandal". The fourth generation of gene editing, CRISPR-Cas9, can edit new programmers in people, animals, plants, germs, and viruses (Fattolahi et al., 2023).

CRISPR-Cas9 "Gene Drive" Concern

CRISPR a recently developed Clustered, Regularly Interspaced, Short Palindromic Repeat that could be misused to create biological weapons. Genetic "engineers" seek to change future generations' DNA to meet an idealistic set of standards, but the development of this technology has resulted in abuse. (Alsmani, 2024). In the post-COVID-19 era, gene editing with CRISPR technology and its variations raises grave concerns and has the potential to become a major threat (Ben et al., 2024).

The American Medical Association (AMA), the preeminent organization of licensed medical professionals in the US, is in favor of CRISPR adoption, but only under certain rules and guidelines. According to the AMA's Lisa Lehmann's 4-S Framework (Chokshi et al., 2024), the physician must explain the safety of CRISPR and the uncertainty surrounding its risks, demonstrate the importance of preventing harm, advise the patient of the unknown effects of CRISPR on progeny and future generations, and talk about the social ramifications of CRISPR.

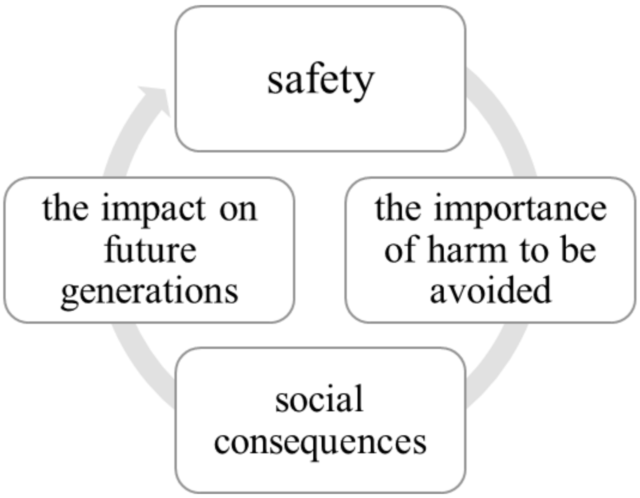

Fig. 5: Lisa Lehmann's 4-S Framework (Word)

Bioterrorism and Bioweapons

More than 2,000 years ago, before the scientific understanding of bacteria, toxins, or viruses was established, biological agents were used as weapons. COVID-19 also showed the potential of biological weapons to upend societies and cause significant economic harm (Brussel, 2024). The pandemic exposed the state's or its competitors' susceptibility to diseases, as well as an incapacity to efficiently address and manage such medical conditions.

Biosecurity Paradigm Shift

The term "biosecurity paradigm shift" describes a substantial shift in how biosecurity issues are viewed, handled, or dealt with. It entails a shift in knowledge, regulations, and tactics about safeguarding people, animals, plants, and ecosystems against dangerous biological agents, including bacteria, viruses, invading species, and genetically modified organisms (MacIntyre, 2015). This change usually results from new scientific discoveries, developments in technology, or shifting global conditions that call for more all-encompassing or flexible approaches to biosecurity.

Table 4: Here are some events with detailed pathogen description

DATE	EVENT	PATHOGEN	REFERENCES
1984	Rajneeshee Cult Bioterror Attack	Salmonella	(Neill et al., 2024)
	Aum Shinrikyo's Attempted Bioterror Attack	Anthrax	(Ordeanu et al., 2022)
2001	Anthrax Attacks (Amerithrax)	Bacillus Anthracis	(Ordeanu et al., 2022)
2004	Sarin Gas Attack (Aum Shinrikyo)	Sarin	(Shay, 2024)
2013	Ricindum Poisoning Threat in White Powder	Ricin	(Santhosh et al., 2024)
2019	COVID-19 Pandemic	SARC-cov2	(Koblentz et al., 2024)

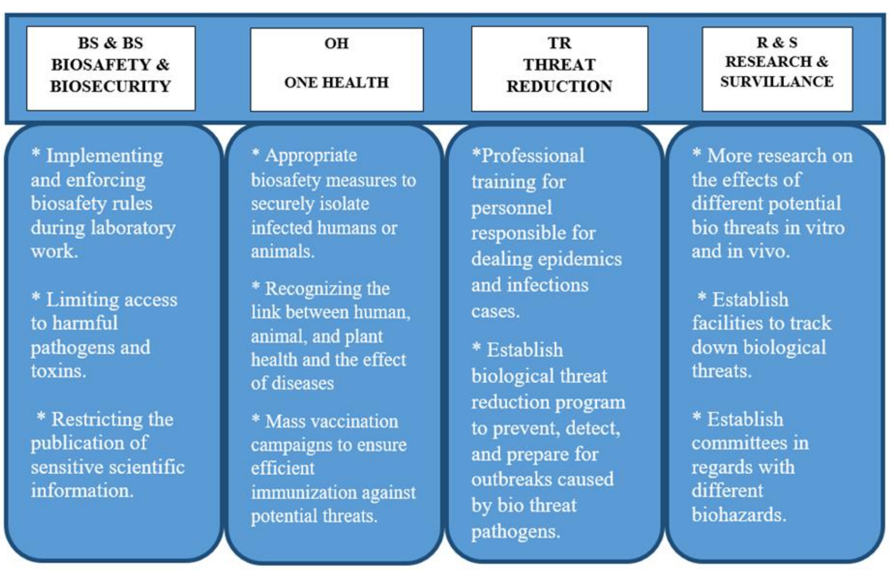

Fig. 6: Actions that nations should take to lessen the effects of biological threats and epidemics and to raise knowledge, comprehension, and readiness (Adobe Photoshop)

When evaluating the risks posed by biological threats and creating mitigation plans, biosecurity brings up many significant issues.

First of all, it is very challenging to predict the probability and effects of the majority of biological threats. The threats are uncommon, except for infectious diseases like HIV/AIDS that occur naturally. There are very few instances of states, terrorists, or criminals using biological weapons, mass casualty laboratory accidents, or influenza pandemics (Mauroni, A. (2022).Many analysts resort to categorizing uncertain but feared threats, like bioterrorism or an influenza pandemic, as "low probability, high consequence" when faced with this degree of uncertainty.

Third, the perception of risk will still be crucial in determining how to react to it, even if the likelihood and consequences of these risks could be accurately measured (Godfery et al., 2024).

There Can Never be Zero Risk of use

There is a common argument that, even if biology is pursued as a science, there is always a chance that it will be used as a weapon because practically every aspect of contemporary biology has the potential to be abused for negative purposes. Therefore, there is nothing we can do to eliminate risk unless we completely halt our scientific endeavor. Therefore, no matter what we do, there will never be a perfect regime that completely solves the issue (Idir, 2023). Instead, we've had to switch to a risk management strategy that uses a wide range of instruments and methods to bring the risk down to a manageable level.

Conclusion

In the quickly changing world of today, striking a balance between biosecurity and innovation is a crucial task. Innovation in industries like biotechnology and medicine has the potential to significantly enhance environmental sustainability and human health, but it also carries a higher risk. Without proper regulation and oversight, new technologies may unintentionally result in biosecurity risks including the unintentional release of genetically modified organisms, improper use of synthetic biology, or the spread of novel infections. Establishing strong regulatory frameworks that encourage responsible innovation is crucial to finding a balance. This entails taking preventative steps to avoid the misuse of new technologies in addition to making sure they are extensively evaluated for safety and effectiveness. To make sure that innovation is informed by moral principles and in line with the long-term welfare of society, cooperation between scientists, legislators, business executives, and biosecurity specialists is essential. Building trust and promoting well-informed decision-making can be achieved through open and honest communication about the advantages and risks of innovation. In the end, protecting both human advancement and the environment in a globalized world will require a balanced strategy that prioritizes biosecurity while encouraging innovation.

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