

1. Introduction

When the character Alice passes through the mirror, she enters a different world, where everything seems familiar but works in reverse; where mirror images are not superimposable, and where dangers are hidden beneath an appearance of similarity.

The choice of this introductory paragraph is not accidental, as advances in synthetic biology are currently at a turning point that require careful reflection, due to their potential impact on security and defense, on the scope and implications of advancing research by taking advantage of the property of chirality¹.

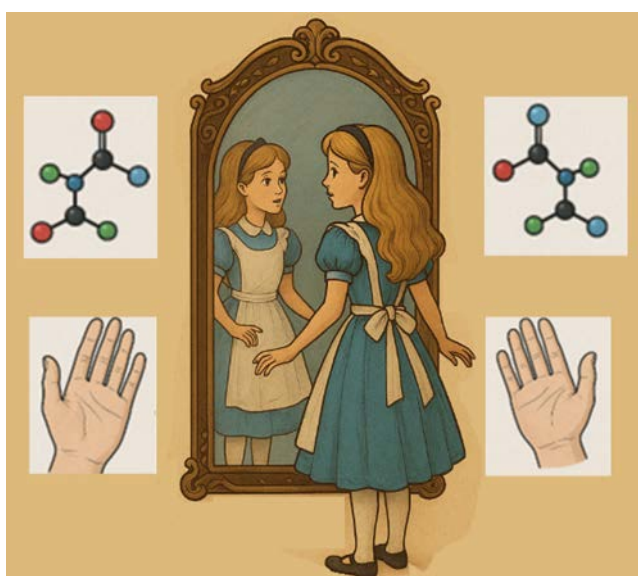


Figure 1: Mirror images associated with chirality

This property, fundamental in both chemistry and biology, refers to the characteristic of certain objects or biomolecules—called enantiomers—that prevents them from being superimposed on their mirror image; in other words, they are not identical to their reflection. A clear example is the hands of the person reading these lines: they are almost the same, but it is impossible to place the right hand over the left and make them match perfectly. These enantiomers are pairs of chiral molecules that are mirror images of each

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¹Chirality is a geometric property of certain molecules that are not superimposable on their mirror image; that is, they exist in two «mirror» forms, called enantiomers (like the right and left hand), or in other words, they are two versions oriented in space as reflections of each other. These forms may have the same general chemical properties, but they differ in how they interact with other chiral systems, such as proteins or other biomolecules. In biology, this is important because many processes (such as the action of enzymes or drugs) recognize only one enantiomer and not the other, due to the specific three-dimensional shape of the molecules

other but cannot be superimposed, and although they have the same chemical formula and composition, the different spatial arrangement of their atoms gives them different biochemical activity (Figure 1).

This property has important implications in pharmacology, especially because some molecules possess it, which influences how they interact with other molecules and within the organism. A well-known example is the ill-fated thalidomide: one enantiomer of this drug alleviated nausea symptoms in pregnant women (the R form), while the other caused teratogenic effects in babies (the S form) ^{2,3,4}.

If chirality is a key property in chemistry, it is no less important in biology, since many metabolic processes recognize only one enantiomer and not the other. In other words, our organism (like that of all living beings) is «programmed» to recognize and respond to only one of the two versions. In fact, most biomolecules—such as amino acids and sugars essential for life—exhibit specific chiral forms; that is, they are «homochiral» meaning that all chiral biomolecules follow the same configuration, which determines their molecular compatibility and functionality in living organisms.

The origin of this marked chiral preference is one of the most enigmatic and fundamental features of the development of life on our planet as we know it. Consequently, nucleic acids, depending on the sugars that compose them, have a right-handed (dextrorotatory) structure, since the sugars in DNA and RNA (deoxyribose and ribose, respectively) adopted this configuration, a circumstance that affects how they are metabolized and recognized in biochemical pathways.

On the other hand, the amino acids that make up proteins are exclusively left-handed (levorotatory). This molecular asymmetry, established in the early stages of biochemical evolution, defined the structural and functional foundations of all existing organisms. However, from a theoretical perspective, nothing would have prevented life from following the opposite path: a «mirror» biological world in which nucleic acids were left-handed and

2 MCBRIDE, W. G. Thalidomide and congenital abnormalities. *The Lancet*, 1961;278(7216):1358. doi [https://doi.org/10.1016/S0140-6736\(61\)90927-8](https://doi.org/10.1016/S0140-6736(61)90927-8)

3 ZAFRA ANTA, M., & GARCÍA NIETO, V. M. Síndrome de la Talidomida: Descubrimiento, tragedia y enseñanzas. *Pediatría Integral*, 2022;XXVI(4):259.e1-259.e9. Available at: https://www.pediatriaintegral.es/wp-content/uploads/2022/06/Pediatria-Integral-XXVI-4_WEB.pdf

4 MARTÍNEZ-FRÍAS, M. L. Talidomida: 50 años después. *Medicina Clínica* 2012;139(2):25-32. Doi <https://doi.org/10.1016/j.medcli.2011.10.011>

amino acids right-handed^{5,6}.

The choice of this leftward path—that is, a «mirror biology» with L-sugars and D-amino acids—could have developed an equally coherent and functional biochemistry, albeit completely incompatible with our own. The initial selection of one molecular configuration over another, likely the result of chance but amplified by self-organization mechanisms, sealed the fate of life as we know it, reminding us of that life, in its essence, could have been radically different had primordial chirality taken the opposite direction^{7,8,9}.

2. Synthetic Biology and Chirality

Advances in chemical sciences, particularly in the field of asymmetric catalysis (such as stoichiometric asymmetric reductions) and the development of separation techniques like chiral chromatography, have enabled the production of enantiomerically pure compounds with unprecedented precision¹⁰.

These advancements have revolutionized the synthesis of pharmaceuticals, agrochemicals, and functional materials, making it possible to design molecules with specific biological activity and greater efficacy. Examples range from organochlorine insecticides like alpha-HCH (alpha-hexachlorocyclohexane) to key antibiotics such as carbapenems or levofloxacin¹¹. However, the use of chiral compounds with a single enantiomeric configuration is not without risk: minimal differences in the spatial orientation of molecules can translate into opposite or even toxic biological effects. This was seen in the case of thalidomide or, regarding glyphosate and certain pyrethroids, where some

5 CLINE, D. B. On the physical origin of the homochirality of life. *European Review*, 2005;13(Supp. No. 2):49–59. doi: <https://doi.org/10.1017/S1062798705000657>

6 Weller, M. G. The Mystery of Homochirality on Earth. *Life* 2004;14:341-353. doi: <https://doi.org/10.3390/life14030341>

7 DEVINSKY, F. Chirality and the Origin of Life. *Symmetry*. 2021;13:2277-2293. doi: <https://doi.org/10.3390/sym13122277>

8 GLOBUS, N., & BLANDFORD, R. D. The Chiral Puzzle Of Life. *The Astrophysical Journal Letters*, 2020;895(L11). doi: <https://doi.org/10.3847/2041-8213/ab8dc6>

9 CHIN, M. Origin of life favors one 'hand' of chemical building blocks? UCLA [pág. web] 21 de noviembre de 2024. Disponible en: <https://newsroom.ucla.edu/releases/origin-of-life-favors-one-hand-of-chemical-building-blocks>

10 NOYORI, R., OHKUMA, T., KITAMURA, M., TAKAYA, H., SAYO, N., KUMOBAYASHI, H., & AKUTAGAWA, S. (1987). Asymmetric hydrogenation of .beta.-keto carboxylic esters. A practical, purely chemical access to .beta.-hydroxy esters in high enantiomeric purity. *Journal of the American Chemical Society*, 109(19), 5855-5856. doi:<https://doi.org/10.1021/ja00253a051>

11 NOYORI, R. Asymmetric Catalysis: Science and Opportunities (Nobel Lecture). *Angewandte Chemie*, 2002;41(12):2008-2022. doi: [https://doi.org/10.1002/1521-3773\(20020617\)41:12<2008::AID-ANIE2008>3.0.CO;2-4](https://doi.org/10.1002/1521-3773(20020617)41:12<2008::AID-ANIE2008>3.0.CO;2-4)

enantiomers exhibit toxicity and environmental persistence different from their counterparts, accumulating in non-target organisms and causing serious environmental impact^{12,13}.

Biological sciences are also undergoing this revolution. Specifically, synthetic biology has emerged as a field that seeks to go beyond traditional chemistry to create and manipulate artificial biological systems. Within this area, «mirror biology» has surfaced, exploring the possibility of designing «inverted» microorganisms or molecules—mirrored versions of those existing in nature. This concept could allow for the manufacture of synthetic cells composed of components opposite to those of life as we know it¹⁴.

Mirror biology aims to use molecular tools to build biomolecules and microorganisms composed of D-amino acids and L-sugars—the reverse of natural chirality—opening the door to exploring the possibility of life based on opposite chirality. In addition to helping understand why life chose a specific configuration, this will open new opportunities in biotechnology, medicine, agriculture, livestock, and even astrobiology—whether by optimizing metabolic processes, improving the degradation of pollutants, or creating «mirror» systems resistant to pathogens^{15,16,17}.

Taking another approach as Alice discovers that the world behind the looking glass holds hidden dangers beneath a similar appearance, the development of this discipline demands prudent reflection. It raises profound ethical, security, and biosafety questions,

12 BOLTES ESPÍNOLA, A. K. La quiralidad de los fármacos en sistemas biológicos de depuración, un problema más que abordar. Madridblogs [website] June 22, 2018. Available at: <https://www.madrimasd.org/blogs/remtavares/2018/06/22/133669>

13 BUSER, H. R., MÜLLER, M. D., POIGER, T., & BALMER, M. E. (2002). Environmental Behavior of the Chiral Acetamide Pesticide Metalaxyl: Enantioselective Degradation and Chiral Stability in Soil. *Environ. Sci. Technol.*, 36(2), 221–226. doi:<https://doi.org/10.1021/es010134s>

14 FRIESEN, S. "Mirror Life" is Still a Hypothetical. Here's Why it Should Probably Stay That Way. Health University of Utah [website] December 12, 2024. Available at: <https://healthcare.utah.edu/newsroom/news/2024/12/mirror-life-still-hypothetical-heres-why-it-should-probably-stay-way>

15 HANDLEY, T. Biología espejo: la ciencia que crea moléculas en reverso y divide a la comunidad científica. gizmodo [website] December 12, 2024. Available at: <https://es.gizmodo.com/biologia-espejo-la-ciencia-que-crea-moleculas-en-reverso-y-divide-a-la-comunidad-cientifica-2000193750>

16 FRANCO-RODRÍGUEZ, F. C., GONZÁLEZ-MORALES, H., HEREDIA-BARBERO, A., MONTOYA, L., & REYES-MEDINA, Y. Quiralidad en las ciencias naturales: Un acercamiento a distintas escalas. *La Granja: Revista de Ciencias de la Vida*, 37(1):8-22. doi: <http://doi.org/10.17163/lgr.n37.2023.01>

17 RELMAN, D., & PARKINSON, J. Understanding the Serious Risks, Potential Benefits Around the Mirror Life Concept. ContagionLive [website] August 3, 2025. Available at: <https://www.contagionlive.com/view/understanding-the-serious-risks-potential-benefits-around-the-mirror-life-concept>

as one of its goals is to create parallel life forms. This ambition is not free from risks and threats, as noted in December 2024 by thirty-eight researchers from nine countries. They published the article Facing the risks of mirror life in the journal Science, warning society of the dangers to all life on Earth associated with the creation of «specular» life forms before their risks are fully understood.

This warning places us in a potential scenario where, due to the democratization of knowledge, falling costs, and process optimization, we face new challenges in biosafety, as well as in security and defense.

For example, if current techniques are optimized, a minimal structural investment could transform an innocuous substance into a potentially dangerous one, capable of altering its biological behavior or escaping natural control mechanisms. In this sense, the advanced synthesis of chiral molecules poses ethical dilemmas in the context of dual-use research for illegitimate purposes. This could involve the development of specific chemical weapons that selectively interfere with human biochemical pathways or, in synthetic biology, the manipulation of chirality in amino acids or sugars to alter microorganisms for uncertain ends¹⁸.

The problem is that with the development of «mirror biology» it is technically feasible to modify this configuration in organisms such as bacteria. This could cause these «new» organisms to behave differently, effectively turning them into bacteria that maintain their «shape» but totally change their behavior in nature. This possibility has caused alarms in the scientific community, leading to a call for public attention regarding the risks and threats associated with this new branch of biology^{19,20}.

Nevertheless, despite the aforementioned points, integrating these new biomolecules—should they be obtained—into a functional cell will require the reassembly of all

18 VICIOSA, M. “Paren los experimentos”: el peligro (y los posibles usos) de las bacterias espejo. Newtral [website] December 23, 2024. Available at: <https://www.newtral.es/bacterias-espejo-peligros-quiralidad/20241223/>

19 ROMERO, S. Bacterias espejo: qué son y por qué representan una amenaza para la humanidad. National Geographic España (website) December 28, 2024. Available at: https://www.nationalgeographic.com.es/ciencia/bacterias-espejo-que-son-y-por-que-representan-amenaza-para-humanidad_23945

20 SANJURJO, B. Qué es la biología espejo y cómo podría revolucionar los tratamientos del futuro. Infobae [pág. web] 22 de septiembre de 2025. Disponible en: <https://www.infobae.com/salud/2025/09/22/que-es-la-biologia-espejo-y-como-podria-revolucionar-los-tratamientos-del-futuro/>

components for effective integration. This includes the entire metabolic system and the cytoskeleton, ensuring it is viable and can be considered a living cell in the literal sense; that is, possessing the capacity for development and growth.

3. Risks and Threats of Mirror Biology

The primary risk of so-called «mirror bacteria», once existing technical barriers are overcome, is that these ex novo synthesized microorganisms could evade the immune systems of living beings, as the latter are adapted to «normal» spatial conformations. Furthermore, these bacteria could be resistant to, or unrecognized by, their natural enemies (e.g., bacteriophages). This could lead to environmental persistence, the displacement of natural species, and the disruption of ecosystems, ultimately affecting agriculture and livestock since no effective treatments would exist against them^{21,22}.

From a security and defense perspective, these risks and threats may intensify if research is directed toward spurious ends in covert biological programs. Such programs could exploit dual-use research to develop undetectable biological agents with high environmental persistence, or for which there are no available treatments or vaccines. Consequently, it is essential to analyze and mitigate the risk factors associated with the development of mirror biology to establish potential mitigation and control measures, given the significant scientific potential of this new discipline²³.

3.1. Accelerated Technological Advancement in an Environment Lacking International Governance

Given the magnitude of the risk, it is emphasized that scientific progress alone is not enough to guarantee safety. It must be complemented by regulatory frameworks and

21 FERNÁNDEZ AGUILAR, E. M. Estos organismos sintéticos podrían poner en riesgo la vida tal como la conocemos: se llaman "bacterias espejo" y no pueden existir de forma natural. Muy Interesante [website] December 13, 2024.: <https://www.muyinteresante.com/ciencia/peligro-bacterias-espejo.html>

22 RADIO CANADÁ INTERNATIONAL. Advierten que crear "células espejales" podría destruir la vida en la Tierra. Radio Canadá Internacional [website] January 7, 2025.: <https://ici.radio-canada.ca/rci/es/noticia/2131173/advierten-que-crear-celulas-espejales-podria-destruir-la-vida-en-la-tierra>

23 INGESSON, T., CHATTOPADHYAY, S., & GISSELSSON, D. Large-Scale Nightmare or Precision Tool for Covert Operations? An Assessment of the Risks of Genetic Technology in the Near Future. *International Journal of Intelligence and Counterintelligence*, 2025;1, 1-30. doi: <https://doi.org/10.1080/08850607.2025.2531921>

preventive measures, including international regulations and potential moratoria, as is the case in the field of Artificial Intelligence²⁴.

To this end, a public and interdisciplinary dialogue must be promoted—incorporating ethical, political, social, and scientific dimensions—ensuring total transparency regarding projects related to mirror biomolecules and microorganisms. This must happen before «mirror life» becomes technically feasible, while we are still within the 10-year window that could make «mirror life» possible, leading to the birth of a new tree of life as proposed by Adamala in the previously cited interview for Radio Canada International.

International regulation is essential, as legal differences between countries can compromise the «precautionary and prevention principles». Existing frameworks may prove insufficient or ineffective in counteracting the risks we would face because of the aforementioned factors^{25,26}.

To mitigate these risks, the following actions are considered advisable:

- Establish regulatory frameworks for mirror biology inspired by the Asilomar Accords and complementary to instruments such as the Tianjin Guidelines. This includes establishing codes of conduct for scientists to halt or pause research lines aimed at creating «mirror bacteria» favoring scientific transparency and collaboration while preventing advances in synthetic biology from occurring in unsupervised environments^{27,28}.

24 PAYO A. La vida especular plantea riesgos invisibles para el equilibrio biológico. SINC [website] August 10, 2025. Available at: <https://www.agenciasinc.es/Reportajes/La-vida-especular-plantea-riesgos-invisibles-para-el-equilibrio-biologico>

25 LANDA, C. La Constitución y los Principios Ambientales de Precaución y Prevención. Enfoque Derecho (digital edition). May 25, 2017 Available at: <https://enfoguederecho.com/la-constitucion-y-los-principios-ambientales-de-precaucion-y-prevencion/>

26 ORF, D. 38 científicos advierten que crear vida especular (o vida espejo) podría desatar una pandemia global y poner en peligro toda la humanidad. Squire [website] December 21, 2024. [pág. web] 21 de diciembre de 2024. Available at: <https://www.esquire.com/es/ciencia/a63233416/celulas-espejo-podrian-ascabar-vida-tierra/>

27 UNITED NATIONS. Revised report of the 2020 Meeting of Experts on the Review of Developments in the Field of Science and Technology Related to the Convention (BWC/MSP/2020/MX.2/2/Rev.1). [website] November 26, 2021. n (BWC/MSP/2020/MX.2/2/Rev.1). United Nations [website] November 26, 2021. Available at: <https://docs.un.org/es/BWC/MSP/2020/MX.2/2/Rev.1>

28 EDITORIAL TEAM SDG 3. Warnings rise over mirror life: Synthetic biology's new frontier and its global risks. Global Society World News [website] May 21, 2025. Available at:

The key aspects of the Tianjin Guidelines include²⁹:

- Ethical and Legal Standards: Responsible use of bioscience and respect for international prohibitions to avoid malicious use. It is fundamental to know and comply with national and international laws on biological research, including the prohibition of biological weapons.
 - Responsible Research Management: Strengthening the scientific integrity of researchers, primarily regarding the prevention of abuse by fostering scientific integrity and preventing misconduct.
 - Training and Outreach: Continuous training and balanced dissemination of results to minimize the risks of misuse.
 - International Involvement and Cooperation: Scientists must foster public understanding of bioscience and collaborate internationally to share best practices and mitigate risks. The goal is to prevent both intentional misuse and unintentional harm in biological research.
- Derived from these regulatory frameworks and/or codes of conduct, establish a moratorium to paralyze experiments seeking to create self-replicating «mirror life» organisms without complete risk assessments and global scientific consensus.

This moratorium would include:

- Risk assessments and biosafety improvements, including physical containment and transport protocols adapted for this new risk category.
- Promotion of best practices and biological containment, preventing these organisms from using non-transmissible vectors that only proliferate in specific hosts.
- Prohibition of cloning mirror structures, especially in pathogens, and of large-scale experiments; permitted experiments should use organism's

<https://www.globalsociety.earth/post/warnings-rise-over-mirror-life-synthetic-biology-s-new-frontier-and-its-global-risks>

²⁹ IAP SCIENCE, HEALTH, POLICY. Directrices de Tianjin en materia de biocustodia para códigos de conducta de los científicos. IAP Science, Health, Policy [website] July 2021. Available at: <https://www.interacademies.org/sites/default/files/2021-12/2021%20TIANJIN%20BIOSECURITY%20GUIDELINES-Spanish.pdf>

incapable of surviving in natural environments. All of this should occur within the context of strengthening biosecurity measures^{30,31}.

- Cost-benefit evaluation by public and private entities supporting this research, with the ability to suspend funding if risks outweigh benefits³².
- A ban on creating complete organisms based on mirror biomolecules until their risks are fully understood, though this would not affect research into mirror biomolecules for therapeutic purposes or materials that do not involve self-replication.
- Mandatory declaration and evaluation of progress if research is not halted, if a regulated framework is not established at both national and international levels to guarantee trust between governments, society, and the scientific community.
- Strengthen international instruments such as the Cartagena Protocol and the Biological Weapons Convention through effective verification and control mechanisms, as well as updating criminal codes to penalize prohibited activities.

Finally, it is a priority for investors to apply the precautionary principle when risks outweigh benefits, promoting global collaboration to ensure universal control and avoid regulatory gaps, while simultaneously informing society about the associated risks and threats.

3.2. Environmental Release Risks and Technical Detection Difficulties

Faced with the possible «accidental or deliberate release» of uncontrolled chiral compounds or systems, it is necessary to develop specific detection and containment technologies for these types of mirror-image compounds or systems. This involves anticipating the potential harm they could cause to «target» living beings, whether by evading immune mechanisms or by altering traditional ecological controls.

30 LARRIÓN, J. Historia de las reuniones de Asilomar. Éxitos y fracasos de la autorregulación en las comunidades tecnocientíficas. *Sociología y tecnociencia*. Revista digital de sociología del sistema tecnocientífico 2011;1(1):63-82.

31 BATTIFOGLIA, E. Del ADN a la IA, la necesidad de una ciencia autorregulada. ANSA Latina [website] February 22, 2025. Available at: https://www.ansalatina.com/americalatina/noticia/ciencia_y_tecnologia/2025/02/22/ansa-del-adn-a-la-ia-necesidad-de-ciencia-autorregulada_2d020046-fa4d-4f7c-aa00-2a563665d161.html

32 YANES, J. Los científicos abandonan el sueño de crear 'vida espejo', que podría convertirse en pesadilla. *Diario El País* (digital edition). March 4, 2025. Available at: <https://elpais.com/ciencia/2025-03-04/los-cientificos-abandonan-el-sueno-de-crear-vida-espejo-que-podria-convertirse-en-pesadilla.html>

This potential scenario establishes the need to enhance the detection and identification capabilities for these types of agents or substances, as well as to establish collaborative networks for information sharing. In fact, it is important to highlight that the detection, identification, and monitoring, as well as the quantification of enantiomers in mixtures (racemic or otherwise), involve high associated costs. This limits early response capacity and environmental surveillance. Furthermore, these processes require highly demanding technical training, a circumstance that must be taken into account as it favors biosecurity³³.

Should these detection and identification techniques be available, it would be advisable to develop environmental monitoring programs to detect potential toxic enantiomers or uncontrolled chiral compounds that have been released accidentally or intentionally due to a breach of the previously described mitigation measures.

The above determines the necessity to:

- Integrate these advanced systems for the detection and identification of mirror biomolecules into biosafety infrastructures and reference laboratories, as well as—if deemed appropriate—establish environmental monitoring programs to detect potential toxic enantiomers.
- Ensure that current biosafety systems (laboratory containment, organism transport protocols) are adapted or reformulated for this new category of risk.
- Establish international collaborative networks to share information and technical standards.
- Fund research into technologies for the rapid detection and quantification of enantiomers in racemic or non-racemic mixtures.

3.3. Ethical Training and Biosecurity Culture Deficit

Insufficient ethical and biosecurity training among research personnel constitutes a factor that exacerbates the risk and threat of misuse or negligence; driven by competitiveness

33 GOVERNMENT OFFICE OF THE SCIENCE. Research and analysis Mirror life. GovUK [website] July 16, 2025. Available at: <https://www.gov.uk/government/publications/mirror-life/mirror-life?utm>

or personal interests, they may minimize the consequences of their actions or even work without supervision in unsafe environments.

This lack of ethical grounding in the deontological aspects of their profession may lead, from a self-centered drive to advance knowledge and achieve recognition by reaching an unprecedented milestone in mirror biology, to overlooking or minimizing the consequences of their actions. This is without disregarding those individuals who, driven by ulterior motives, conduct research in this new field without any form of control.

Motivated by competitiveness or personal interests, some researchers may downplay the consequences of their actions or work without supervision in unsafe environments. Hence the importance of defining clear boundaries in research involving mirror biomolecules, distinguishing—as proposed in this work—between studies for therapeutic or material purposes (considered low risk) and the creation of self-replicating living organisms (high risk)³⁴.

The proposed mitigation measures include:

- To reduce these potential situations, it is essential to strengthen the ethical training of research personnel, with the aim of discouraging participation in dual-use research lines. Promoting strong research ethics is key to reducing both risks and threats associated with work conducted in unsafe or uncontrolled environments. This training should begin at the earliest stages of education.
- From a complementary perspective, it is necessary to train research and technical staff in the risks associated with chiral research.
- Integrating education in bioethics and biosecurity into the curricula of research and technical personnel, to promote a global culture of safety and responsibility, including content on the risks associated with dual-use research and scientific responsibility in the field of chiral research.
- Such training in bioethics and biosecurity will, in turn, foster international

34 UNDHEIM, T. A. The whack-a-mole governance challenge for AI-enabled synthetic biology: literature review and emerging frameworks. arXiv. Feb. 1, 2024. Available at: <https://arxiv.org/pdf/2402.00312>

transparency and scientific cooperation as pillars of trust and oversight^{35,36}.

4. Conclusion

Advances in the synthesis and analysis of chiral compounds have opened unprecedented opportunities in pharmacology, agroindustry, and nanotechnology. However, these advances also entail health, environmental, and ethical risks—ultimately, risks to security—that, if not properly managed, may result in significant harm.

Research in the field of chirality, while essential for scientific progress, involves risks and threats that extend beyond chemistry and synthetic biology. Historical examples show that lack of knowledge and insufficient control can lead to health crises and irreversible environmental damage. Advances in the production and manipulation of chiral compounds must be accompanied by responsible management, robust regulatory frameworks, and international oversight to ensure that progress does not become a threat, through a preventive and collaborative approach.

Mirror biology opens a horizon of great promise, but also of unprecedented dangers. Although it offers valuable therapeutic and scientific applications, its potential to evade biological defenses and disrupt ecosystems makes it imperative to act with caution. Science and governments must collaborate proactively to prevent the scientific frontier from becoming an existential threat. International cooperation and proactive regulation are essential to prevent this scientific advancement from becoming a global threat. Indeed, the boundary between innovation and threat will become increasingly blurred without proper governance.

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35 SAMPLE, I. 'Unprecedented risk' to life on Earth: Scientists call for halt on 'mirror life' microbe research. The Guardian (online version). Dec. 12, 2024. Available at: <https://www.theguardian.com/science/2024/dec/12/unprecedented-risk-to-life-on-earth-scientists-call-for-halt-on-mirror-life-microbe-research>

36 PIPER, K. A whole new thing that could end the world. Vox [web site] Jan. 3, 2025. Available at: <https://www.vox.com/future-perfect/393048/mirror-life-mirror-bacteria-existential-risk-science-biology-apocalypse>