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Natural Science in an Age of Planetary Change

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EDITORIAL INFORMATION

ALLATRA Natural Science Review is a curated quarterly publication that transforms natural science into a credible, accessible context for institutions, decision-makers, and informed publics. It is grounded in evidence, free from political partisanship, visually compelling, and readable for both specialists and informed non-specialists.

The purpose of the Review is to convene a substantive, evidence-based conversation about what science means for society.

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Contents

A Letter from the Editor

ISSUE NO. 1, 2026

John Ahn,

Ph.D., MBA, Chief Scientist and Chair, ALLATRA Global Research Center

With this inaugural issue, the ALLATRA Global Research Center launches the *ALLATRA Natural Science Review*, a quarterly, editorially reviewed publication dedicated to advancing understanding of the natural sciences and their implications for society and public policy.

The Review was launched in response to a growing gap between the pace of scientific discovery and the public conversation surrounding it. Findings that are important to public health, disaster preparedness, and environmental policy often remain confined to specialized journals, while critical discussions continue and decisions are made without the benefit of this knowledge. The Review aims to help close that gap by providing clear, accurate, and evidence-based scientific analysis for scientists, researchers, engineers, clinicians, educators, and decision-makers whose work depends on it.

The Review brings together contributions from scientists at the ALLATRA Global Research Center and invited researchers and specialists from the broader scientific community. It is a non-commercial editorial publication that carries no advertising or sponsored content, and authors pay no publication fees.

Several principles guide our editorial approach. We strive to make complex science accessible while preserving its essential nuance. We welcome careful interpretation and thoughtful disagreement, provided both remain grounded in evidence and stay free of political partisanship.

The contents of this inaugural issue reflect four broad areas of scientific inquiry.

The first part explores micro- and nanoplastics (MNPs) and the growing recognition that they are not only an environmental issue but also a matter of human exposure and health. Professor Antonio Ragusa, who first identified microplastics in human placental tissue, examines one of the earliest environments of human development. Dr. Jeffrey Long, a radiation oncologist, considers the clinical dimensions of MNP exposure. Beyond human health, José Antonio Muñoz examines how micro- and nanoplastics affect the brain: a study of seabird chicks documents neurological changes that parallel those observed in human disease, while an analysis of advanced diamond-based sensing technologies explores how far detection methods must advance before particles at this scale can be reliably detected and characterized.

The second part examines natural hazards and the planetary systems that produce them. In June 2026, northern Venezuela experienced an unusual earthquake consisting of two shocks separated by thirty-nine seconds. Although its classification remains debated, the earthquake came at a significant human cost while revealing important scientific insights: how ruptures jump from one fault to another, and why its human consequences depend more on where and how people build than on magnitude alone. The section then turns to an assessment of heat accumulation in the Pacific Ocean and the forecasts warning of a potentially severe El Niño, before concluding with the 2025 Kamchatka mega-earthquake in its global context.

The third part considers the foundations of science and the methods and instruments that expand scientific understanding. A deceptively simple question, why plastics hold an electrical charge when wood does not, still lacks a complete physical explanation. Another article explores how the thymus, a small and long-overlooked organ, trains the immune system across the lifespan. A further contribution demonstrates how scientific knowledge is built in practice by examining the growing role of neural networks as tools of scientific research.

The fourth part gives the ocean the final word through an extended conversation with Dr. Sylvia Earle about the state of the seas and the science behind their protection.

The issue closes with a chronicle of the Center's recent scientific activities.

With each quarterly issue, we aim to strengthen the ALLATRA Natural Science Review and broaden the community of authors it brings together. We warmly invite scientists, researchers, and other subject-matter experts who share this commitment to rigorous, evidence-based scientific communication to contribute to future issues.

John Ahn, Ph.D., MBA
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The First Environment: Microplastics, Nanoplastics, Pregnancy, and the Future of Human Health

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Dr. Antonio Ragusa earned his medical degree from the University of Milan and completed his residency in Obstetrics and Gynecology at the same institution. He collaborates with the Institute of Atmospheric Pollution Research of the Italian National Research Council as a senior researcher, studying the effects of environmental pollution during prenatal and perinatal development. He is currently Director of the Department of Obstetrics and Gynecology at Sassuolo Hospital in Italy.

In 2010, following the earthquake in Haiti, he worked at Saint Damien Hospital in Port-au-Prince, where he helped establish the delivery room and obstetric unit. In 2013, he served aboard the San Marco hospital ship during Operation Mare Nostrum, providing initial medical care to people rescued in the Mediterranean by the Italian Navy.

He served as President of the Fondazione Confalonieri Ragonese until 2024, coordinating national recommendations issued by the main Italian scientific societies in obstetrics and gynecology. Since 2024, he has chaired the AOGOI Ethics Committee. He has served as a scientific consultant to the Italian Ministry of Health and has authored more than 150 scientific papers and 22 books or book chapters. His current research focuses on perinatal medicine, strategies to reduce unnecessary cesarean sections, and the effects of plastic pollution on fetal, neonatal, and human health. He led the first study reporting microplastics in human placental tissue.

1. The First Environment

For most of modern medicine, environmental exposure was assumed to begin at birth. The fetus was generally considered protected within a privileged biological environment, shielded from many of the hazards present in the outside world. The placenta, often described as a selective barrier, was viewed as an efficient interface capable of regulating exchanges between mother and child while protecting the developing fetus from potentially harmful agents.

Over the past decade, however, this assumption has been profoundly challenged.

A growing body of evidence suggests that microplastics and nanoplastics (MNPs) —microscopic particles and fragments generated by the degradation of synthetic materials and industrial products, are capable of reaching human tissues previously considered inaccessible. These particles have been detected in blood, lungs, liver, kidneys, the human brain, and, most importantly, within the maternal-fetal unit itself.

In 2020, our research group reported the first evidence of microplastics in human placental tissue, a finding that challenged long-standing assumptions regarding the isolation of the intrauterine environment and contributed to opening an entirely new field of investigation. The discovery attracted international attention because it suggested that synthetic particles generated by human activities could reach one of the most protected biological interfaces in human development.

Recent studies have identified MNPs in placental tissue, amniotic fluid, umbilical cord blood, and human breast milk, indicating that exposure to anthropogenic particles may begin long before birth [1-9].

This discovery represents more than a toxicological concern. It challenges one of the most fundamental concepts in medicine: the notion that the intrauterine environment is largely insulated from the ecological conditions surrounding the mother.

The implications are profound. If synthetic particles are capable of crossing biological barriers and reaching the earliest stages of human development, then pregnancy becomes not merely a reproductive process but the first frontier of environmental health.

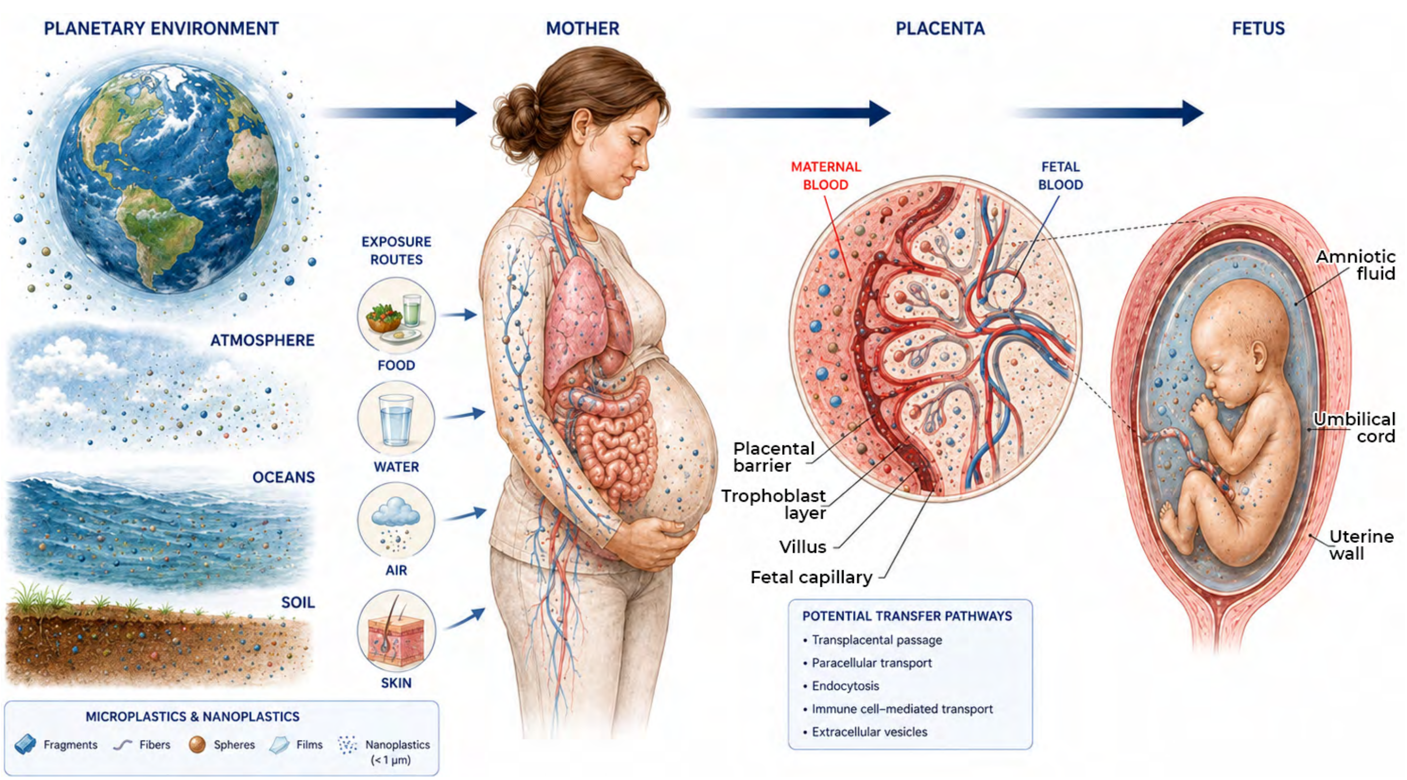

Figure 1. The First Environment.

Conceptual representation of the continuum linking planetary ecosystems, maternal exposure, placental biology, and fetal development. Emerging evidence suggests that environmental contaminants, including microplastics and nanoplastics, may reach the maternal-fetal interface, indicating that environmental exposure can begin before birth.

From this perspective, the fetus can no longer be regarded as an isolated biological entity. Rather, it becomes part of a complex continuum linking planetary systems, environmental contamination, maternal physiology, placental function, and lifelong health trajectories (Figure 1).

The emerging science of microplastics invites us to reconsider a simple but powerful question: when does environmental exposure truly begin? Increasingly, the answer appears to be: before birth.

2. How MNPs Enter the Human Body

Few materials have transformed human society as profoundly as plastic.

Since large scale industrial production began in the middle of the twentieth century, plastics have revolutionized medicine, food preservation, transportation, communication technologies, and countless aspects of everyday life. Lightweight, durable, versatile, and inexpensive, synthetic polymers became one of the defining materials of the modern age. Global plastic production increased from approximately 2 million metric tons annually in 1950 to more than 400 million metric tons per year today, with cumulative production exceeding 8 billion metric tons [10-11].

Plastic is perhaps the most successful mimic ever created by humans. It can imitate wood, glass, ivory, leather, cotton, silk, stone, and countless other natural materials.

The same characteristics that made plastics economically successful also created an unprecedented environmental challenge. Most conventional plastics do not readily biodegrade. Instead, they gradually fragment under the influence of sunlight, mechanical abrasion, temperature fluctuations, and biological processes. Over time, larger plastic objects are transformed into increasingly smaller particles known as microplastics (typically defined as particles smaller than 5 mm) and nanoplastics, commonly defined as plastic particles smaller than 1 μm, although definitions and analytical thresholds remain under discussion [12-13].

These particles are now found in virtually every environmental compartment that has been investigated. They have been detected in oceans, rivers, lakes, agricultural soils, atmospheric dust, polar ice, deep ocean sediments, and remote mountain ecosystems [14-17]. Their global distribution demonstrates that plastic pollution is no longer a local waste management problem but a planetary phenomenon.

As environmental contamination has expanded, so too have opportunities for human exposure.

Humans encounter microplastics through multiple pathways. Food and drinking water represent important sources of exposure. Microplastic particles have been identified in seafood, table salt, fruits, vegetables, bottled water, and tap water [18-21]. Airborne particles represent an additional and often underestimated route (Figure 2). Synthetic fibers released from textiles, household materials, industrial activities, and urban environments can be inhaled and deposited in the respiratory tract. Dermal exposure is also possible, although evidence for systemic absorption through intact skin remains limited [22-23].

Recent estimates suggest that humans may ingest or inhale tens of thousands of plastic particles each year, although precise exposure levels remain difficult to quantify because analytical methods are still evolving [18-19]. The challenge becomes even greater when considering nanoplastics, whose extremely small size may facilitate interactions with biological tissues that are not possible for larger particles.

For many years, scientists assumed that these particles would remain largely confined to the gastrointestinal tract and be eliminated from the body. Emerging evidence suggests that this assumption may have been overly optimistic. Studies performed during the past decade have demonstrated the presence of microplastic and nanoplastic particles in human blood, lungs, liver, and other human tissues [22-27]. Plastic particles have become biological as well as environmental contaminants.

The question is therefore no longer whether humans are exposed to microplastics. The evidence strongly indicates that they are. The more pressing scientific question has become: what happens after these particles enter the human body?

The extraordinary success of plastic materials was driven by genuine technological advantages. Plastics reduced costs, simplified transportation, improved food preservation, and enabled countless innovations. Yet the same economic forces that accelerated their adoption also contributed to the rapid displacement of more inert materials such as glass, metal, and natural fibers.

As a result, decisions that profoundly altered environmental exposure patterns for billions of people were often driven primarily by market efficiency rather than by long-term biological evidence.

This observation should not be interpreted as an accusation against industry, nor as a rejection of technological progress. It is simply a reminder that economic success and public health are not always identical objectives.

When uncertainty exists regarding potential risks to future generations, precaution should not be viewed as an obstacle to innovation. Rather, it should be considered one of the responsibilities of a mature society.

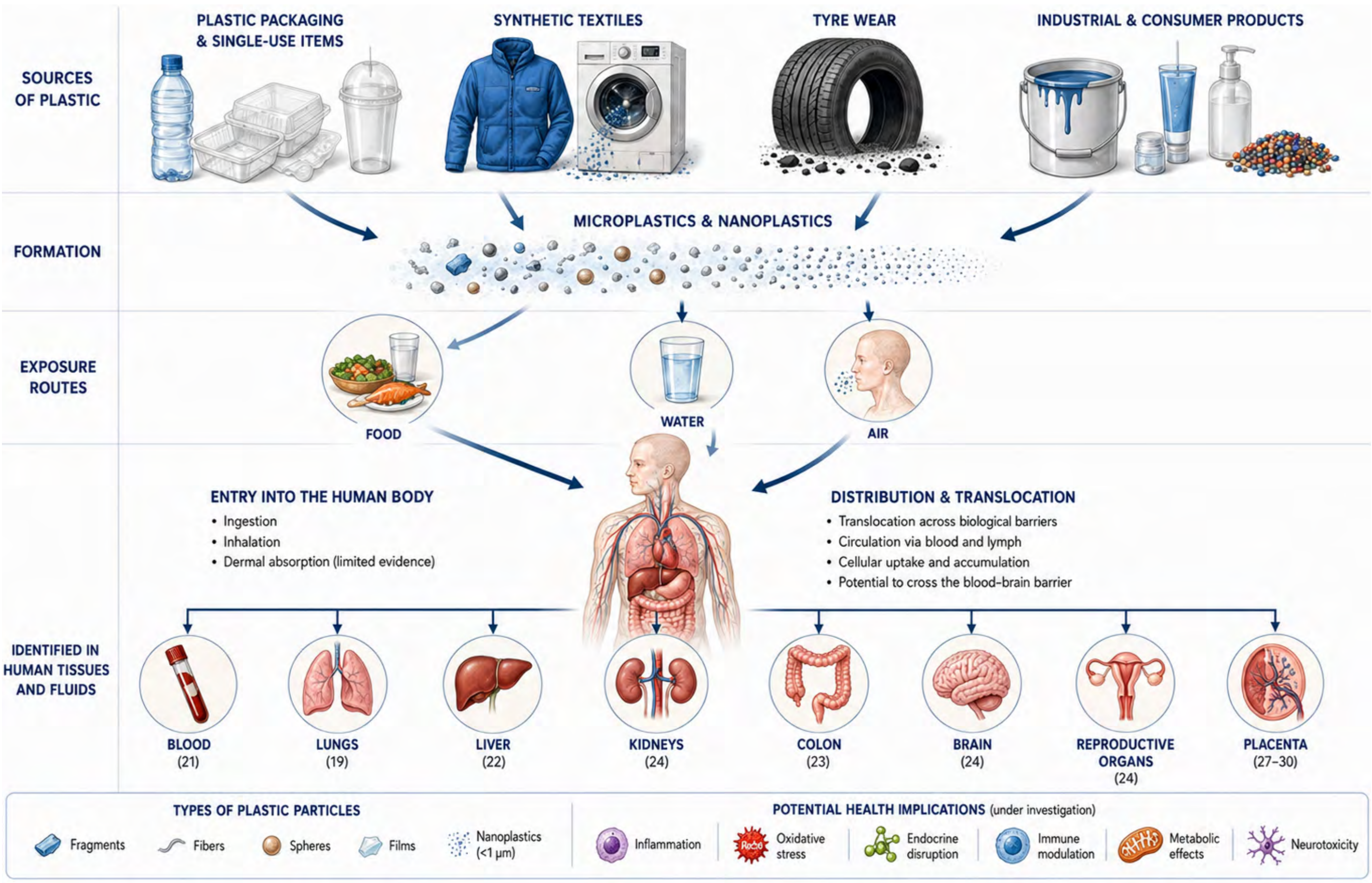

Figure 2. From Plastic Production to Human Exposure.

Plastic materials released from packaging, textiles, transportation, and consumer products undergo environmental fragmentation into microplastics and nanoplastics. Human exposure occurs primarily through food, water, and air, allowing particles to enter biological systems and potentially accumulate in multiple tissues. This figure illustrates the continuum linking industrial plastic production, environmental contamination, human exposure, and the emerging investigation of potential health effects.

3. The Maternal-Fetal Connection

Among all the recent discoveries concerning microplastics and human health, perhaps none has been more surprising than their detection within the maternal-fetal environment.

For decades, the placenta was viewed primarily as a highly selective biological interface. Although it was never considered an absolute barrier, it was generally assumed to provide substantial protection against many environmental contaminants. This assumption remains broadly valid. The placenta performs remarkable physiological functions, regulating the exchange of oxygen, nutrients, hormones, immune signals, and waste products between mother and fetus. However, recent evidence suggests that some anthropogenic particles may also traverse or accumulate within this complex organ. [1-7]

The placenta is not the only compartment in which microplastics have been identified. Investigators have subsequently reported the presence of plastic particles in human amniotic fluid, umbilical cord blood, meconium, and breast milk [4-9]. These findings collectively indicate that environmental exposure may begin during fetal life and continue throughout the earliest stages of postnatal development (Figure 3) [9].

This observation represents a profound conceptual shift. Traditionally, environmental health has focused largely on exposures occurring after birth. Air pollution, contaminated water, occupational hazards, dietary contaminants, and lifestyle factors have generally been evaluated within postnatal frameworks. The emerging evidence on microplastics suggests that exposure histories may begin considerably earlier.

Nevertheless, developmental biology teaches an important lesson: early life stages are uniquely sensitive to environmental influences. During fetal development, organs are forming, cellular differentiation is occurring at extraordinary speed, and physiological systems are establishing the foundations that will support health throughout life. Small perturbations occurring during these critical windows may have disproportionately large consequences compared with similar exposures occurring in adulthood [28-29].

Experimental studies have begun to explore possible mechanisms through which microplastic and nanoplastic particles might influence biological systems. Proposed pathways include oxidative stress, inflammatory responses, endocrine disruption, altered cellular signaling, and interactions with the immune system [30-33].

The maternal-fetal environment occupies a unique position in this debate. It represents the earliest stage at which environmental contamination can intersect with human biology. For this reason, pregnancy may become one of the most important settings in which to investigate the long-term implications of microplastic exposure.

The question is no longer whether synthetic particles can reach the maternal-fetal environment. Multiple studies indicate that they can. The extent to which different particles reach fetal tissues and the biological significance of this exposure remain under investigation.

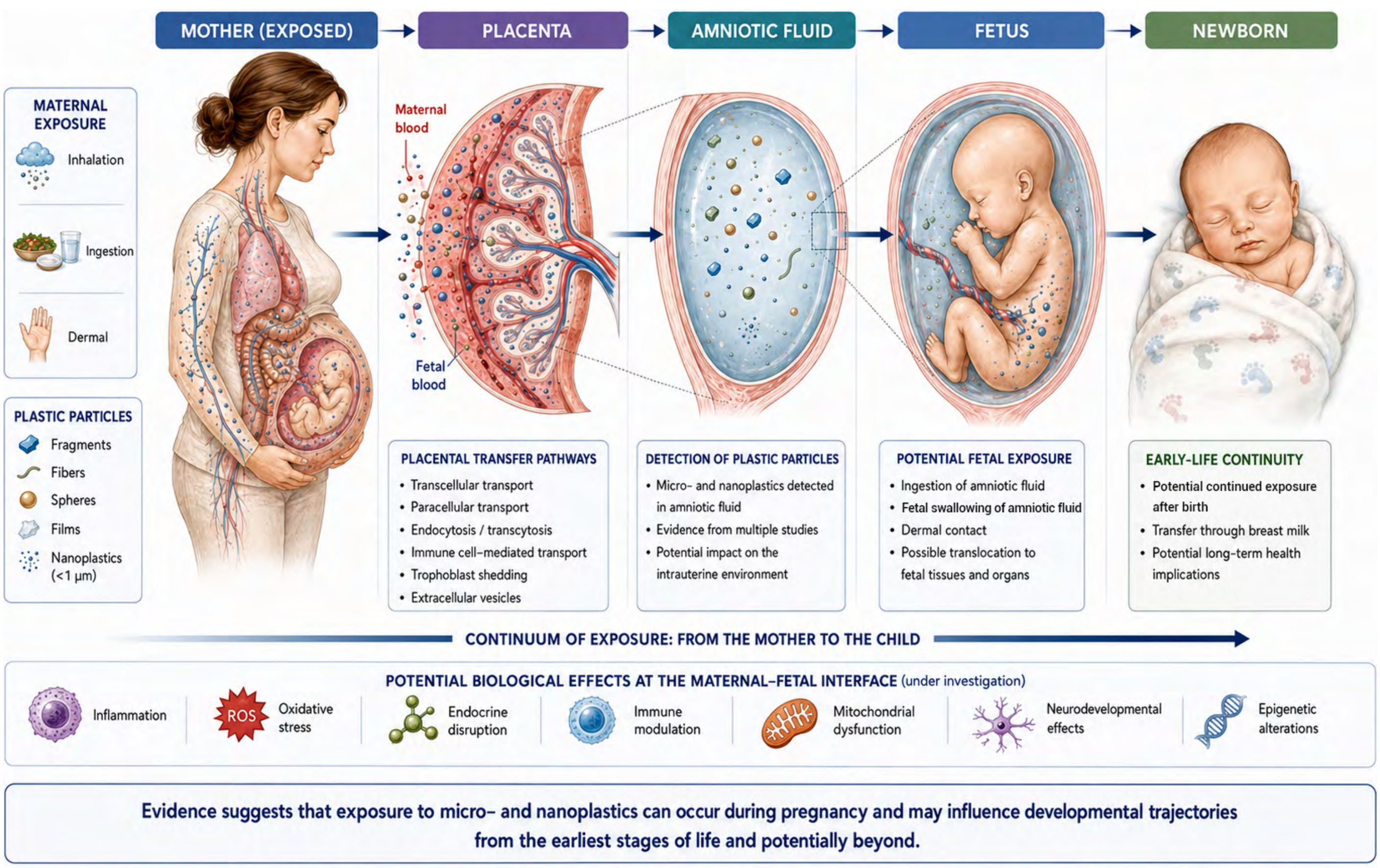

Figure 3. The Maternal-Fetal Connection.

The maternal-fetal unit represents the earliest biological interface between environmental contamination and human development. Microplastics and nanoplastics originating from food, water, air, and dermal exposure may reach the maternal circulation and have been identified in placental tissue, amniotic fluid, umbilical cord blood, and breast milk. This continuum suggests that environmental exposure can begin before birth and may extend across critical developmental windows, from fetal life to infancy and beyond. The figure illustrates the concept that pregnancy is not only a reproductive process but also a key stage in environmental health.

4. Metabolism and the Obesogen Hypothesis

For decades, rising rates of obesity have been attributed primarily to excess caloric intake, reduced physical activity, and genetic susceptibility. While these factors undoubtedly remain central, researchers have increasingly explored the possibility that environmental contaminants may also contribute to metabolic dysfunction. Among these, certain plastic-associated chemicals have attracted particular attention because of their ability to interfere with endocrine and metabolic pathways.

The role of endocrine disrupting chemicals in metabolic disease is no longer considered a purely speculative hypothesis. A substantial body of experimental and epidemiological evidence indicates that several plastic associated compounds can interfere with hormonal regulation, adipocyte differentiation, appetite control, insulin sensitivity, and energy metabolism. While obesity remains a multifactorial condition driven primarily by nutrition, physical activity, genetics, and social determinants, environmental contaminants are increasingly recognized as potential contributors to the global metabolic crisis. Antimony compounds are widely used as catalysts in PET manufacture and may migrate from PET containers under certain storage conditions. Their possible endocrine and metabolic implications remain under investigation [34].

Compounds such as bisphenols, phthalates, and other plastic-related substances have been described as potential "obesogens" because experimental studies suggest that they may influence adipocyte development, energy balance, insulin sensitivity, and hormonal regulation [35-38]. More specifically, a 2022 study by Molonia et al. demonstrated that the PET-related compounds terephthalic acid (TPA) and dimethyl terephthalate (DMT), the starting monomers used to synthesize PET, induced significant lipid accumulation in murine 3T3-L1 preadipocytes at nanomolar concentrations (10 nM) comparable to levels found in water from PET packaging, activating key adipogenic markers (PPAR-γ, C/EBPβ, FABP4, FASN) and the NF-κB inflammatory pathway via estrogen receptors [39]. More recently, attention has expanded toward microplastics and nanoplastics themselves, although evidence remains preliminary and many mechanistic questions are still unresolved.

The history of food and beverage packaging illustrates how rapidly environmental exposure can change. During much of the twentieth century, water, milk, wine, and soft drinks were predominantly stored in glass containers.

The transition from glass to modern plastic packaging did not occur primarily because of demonstrated health advantages. Rather, it was driven by economic efficiency, reduced transportation costs, lower breakage rates, and the logistical benefits associated with lightweight materials.

Glass and earlier plastic containers and packaging systems (PVC) were progressively replaced by polyethylene terephthalate (PET), which offered additional economic and industrial advantages. As a result, billions of people shifted within a few decades from predominantly glass-based food and beverage storage to continuous exposure to synthetic polymers.

One generation effectively modified the exposure profile of the next without the possibility of evaluating long-term biological consequences beforehand. While PET undoubtedly contributed to the global availability of food and beverages, its widespread adoption illustrates how economic priorities can reshape human exposure patterns on a planetary scale.

The question is therefore not whether PET brought benefits. Clearly it did. The question is whether economic convenience alone should be sufficient justification for environmental transitions whose biological implications may only become apparent decades later.

This transition undoubtedly brought important economic and logistical advantages. Yet it also created an unprecedented situation in human history: billions of individuals now experience daily and lifelong contact between food, beverages, and synthetic polymers.

A substantial body of evidence indicates that several plastic-associated chemicals can interfere with endocrine regulation and energy metabolism. Some substances used in, or potentially released from, PET production and packaging have therefore attracted increasing scientific attention.

The long-term biological implications of this transformation remain incompletely understood. From a public health perspective, the replacement of traditional inert materials with plastic packaging may represent one of the largest uncontrolled environmental exposure experiments ever conducted on the human population. Unlike conventional scientific experiments, however, the participants never provided informed consent, the duration was measured in generations rather than years, and the biological outcomes are still being investigated.

Never before in human history had entire populations experienced continuous, lifelong contact between food and beverages and synthetic polymer materials on such a scale. It is reasonable to acknowledge that society adopted these materials long before the long-term biological implications of chronic exposure could be fully evaluated.

5. What We Know, What We Suspect, and What We Still Do Not Know

The discovery of MNPs within human tissues has generated understandable concern. Whenever a previously unrecognized contaminant is found in blood, organs, or the maternal-fetal environment, a fundamental question immediately arises: what does this mean for human health?

This statement should not be interpreted as a sign of ignorance or scientific failure. Rather, it reflects the reality of how science progresses. Detection is often the first stage of discovery. Understanding biological consequences requires years, and sometimes decades, of additional research. Several facts, however, are already well established. First, human exposure is real and widespread. MNPs have been identified in environmental systems across the globe and have been detected in multiple human tissues [14-27]. The question is no longer whether exposure occurs, but how much exposure occurs and what its consequences may be. Second, the smallest particles appear biologically relevant. Nanoplastics, because of their dimensions, may interact with cells, biological membranes, and intracellular structures in ways that larger particles cannot. Experimental studies have shown that these particles can induce oxidative stress, inflammatory responses, altered cellular signaling, and disturbances of normal physiological processes [30-33]. Third, vulnerability is unlikely to be uniform across the human lifespan. Early developmental stages, including fetal life, infancy, and childhood, may represent periods of increased susceptibility. During these critical windows, even subtle environmental influences can shape biological systems in ways that persist long after the original exposure has ended [28-29].

Certain plastic-associated chemicals, including bisphenols, phthalates, and related compounds, have been described as potential environmental obesogens because they can interfere with hormonal signaling, adipocyte differentiation, insulin regulation, and energy metabolism [35-38].

This discussion acquires additional relevance when considered in the context of modern food packaging. As noted above, the replacement of glass by PET was not simply a technological innovation; it represented a global change in patterns of human exposure. Billions of people moved from occasional contact with plastics to continuous, lifelong interaction with synthetic polymers. Such a profound environmental transition occurred largely for economic and logistical reasons, long before its biological consequences could be adequately evaluated.

The challenge facing contemporary science is therefore not merely to identify microplastics, but to determine whether their presence is biologically meaningful, under what circumstances, and for whom.

Many scientific questions remain.

Yet perhaps the most important question is not biological but societal.

How much evidence should be required before preventive action is justified when future generations are potentially involved?

History teaches that waiting for absolute certainty has often delayed responses to environmental threats. The challenge is therefore not only to understand microplastics, but also to decide how societies should respond to uncertainty when the earliest stages of human life may be affected (Figure 4).

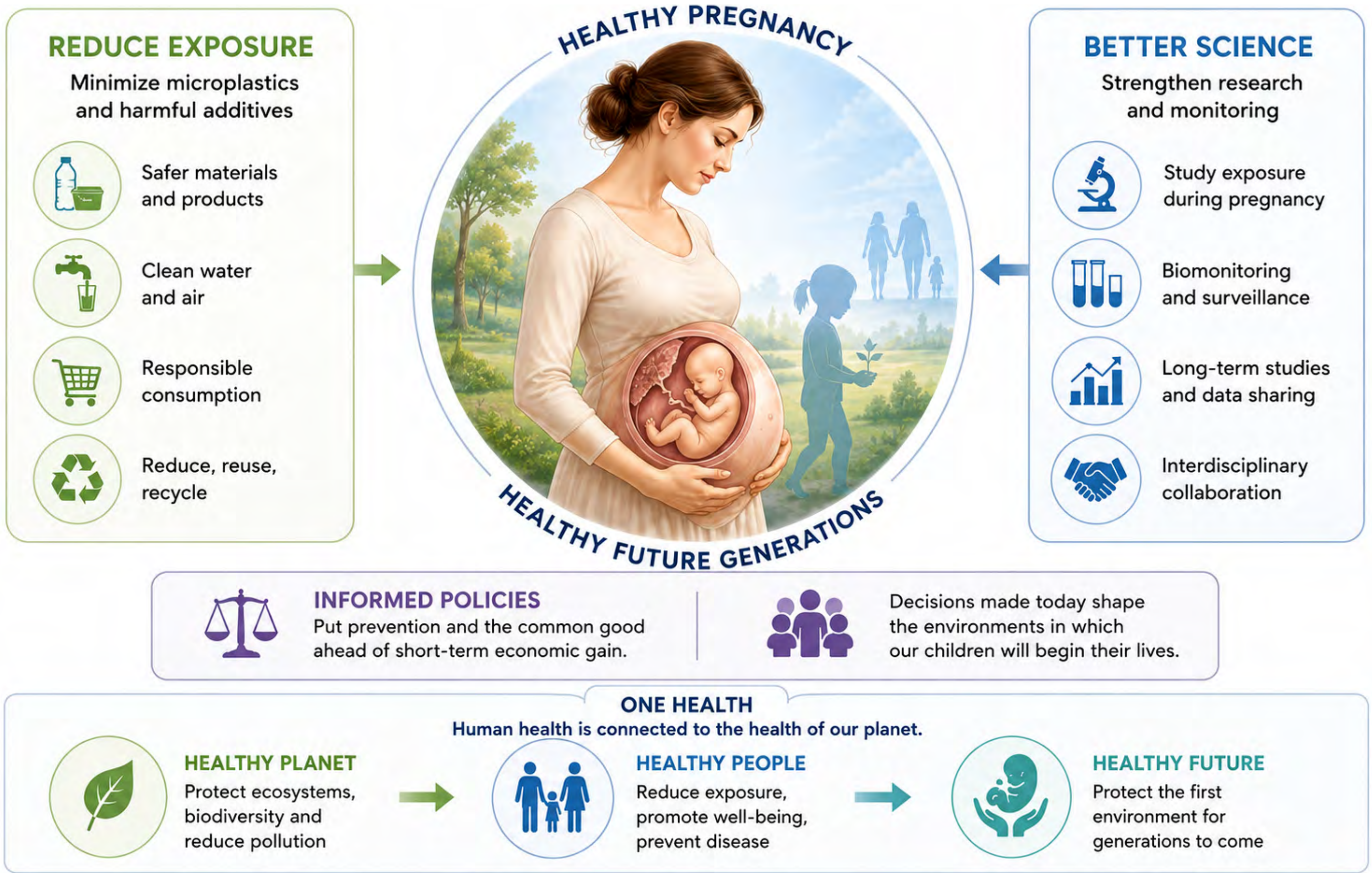

Figure 4. Protecting the First Environment.

The health of future generations begins long before birth. This figure illustrates the concept that protecting pregnancy means protecting the first human environment. Through responsible environmental stewardship, scientific research, informed public policies, and a One Health approach, societies can reduce harmful exposures and promote healthier developmental trajectories for children yet to be born.

6. Why Pregnancy Should Become a Priority in Environmental Health

The emerging science of microplastics invites a broader reconsideration of environmental health priorities.

For much of modern public health, prevention has focused on individuals who are already born. Efforts have concentrated on reducing exposure to pollutants in workplaces, homes, schools, and communities. While these interventions remain essential, growing evidence suggests that the origins of health and disease may begin much earlier than previously recognized [28-29].

Pregnancy occupies a unique position at the intersection of human biology and the environment. The maternal-fetal unit represents a highly dynamic system in which maternal physiology, nutrition, environmental exposures, and placental function interact continuously. For this reason, pregnancy may serve not only as a critical developmental window but also as a sensitive indicator of broader environmental conditions.

Historically, some of the most important public health advances emerged from recognizing the vulnerability of early life. Improvements in maternal nutrition, reduction of tobacco exposure, folic acid supplementation, vaccination programs, and safer obstetric care have all demonstrated that protecting mothers and infants generates benefits that extend far beyond pregnancy itself [40-43].

The emerging evidence on MNPs suggests that environmental protection may require a similarly long-term perspective. If exposure begins before birth, then prevention strategies cannot start in adulthood.

They must begin earlier, potentially even before conception.

Importantly, this does not imply fear, alarmism, or unrealistic expectations. Plastic materials have brought undeniable benefits to medicine, food preservation, sanitation, transportation, and modern life. The challenge is not to demonize a material, but to understand how to use it responsibly while minimizing unintended consequences.

This perspective aligns closely with the principles of One Health, which recognize that human health, animal health, and environmental health are inseparably connected. Microplastics illustrate this interconnectedness with unusual clarity. Particles released into oceans, rivers, soils, and the atmosphere do not remain confined to those environments. They move through ecosystems, food chains, biological systems, and ultimately human bodies [44].

For this reason, the question of microplastics is not merely a toxicological issue. It is also a question of stewardship.

What kind of environment are we creating for future generations?

What forms of exposure are we willing to accept in exchange for consumer convenience and economic efficiency? The central question is not whether plastics have improved modern life. They clearly have. The question is whether societies are willing to evaluate their long term biological costs with the same rigor used to measure their economic benefits.

How should societies act when scientific uncertainty exists but credible reasons for concern are emerging?

These questions extend beyond laboratories and academic journals. They belong equally to policymakers, educators, healthcare professionals, industry leaders, and citizens.

Political decisions should be guided by scientific evidence and long term public health considerations rather than by short term economic convenience alone.

Science alone cannot answer all of them. What science can do is provide increasingly accurate evidence regarding the pathways through which environmental change influences human biology. The role of society is to determine how that knowledge should guide action.

One of the central questions raised by plastic pollution is not merely scientific but societal. The economic benefits of plastic production are often immediate and concentrated, whereas the environmental and potential health costs are delayed, diffuse, and frequently borne by populations that did not participate in the original decisions. Understanding this imbalance is essential for designing sustainable policies capable of protecting both present and future generations.

Remarkably, recent analyses suggest that a relatively small number of large consumer-goods producers account for a disproportionate share of the plastic waste that can be traced to its source. Just as striking, roughly half of all plastic waste found in the environment carries no identifiable branding at all, a gap that itself raises pressing questions about corporate accountability and the transparency of how plastics are produced and disposed of [45].

A few may profit from plastic, but its environmental and health costs are shared by everyone — especially by mothers and future generations.

The story of MNPs in pregnancy is therefore about far more than plastic itself. It is about how human societies shape the environments in which future generations begin their lives. It is about recognizing that environmental protection is not only an ecological responsibility but also a form of intergenerational care. And it is about a simple but profound realization: The first environment experienced by every human being is not the world outside the womb, but the world carried into the womb itself. The future of environmental health may ultimately depend on how seriously we choose to protect the smallest and most vulnerable ecosystem on Earth: the developing human being.

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The Particles Within

A RADIATION ONCOLOGIST ON MICRO- AND NANOPLASTICS IN THE HUMAN BODY.

This article is based on the inaugural conversation in the ALLATRA Global Research Center's podcast series. It brought together Jeffrey Long, M.D., a physician and radiation oncologist with many years of clinical experience in cancer care, and the host, John Ahn, Ph.D., Chief Scientist and Chair of the ALLATRA Global Research Center. Opening the series, the conversation drew a wide audience, gathering over 1.5 million views on X. What follows is drawn from Dr. Long's remarks.

Dr. Jeffrey Long came to the subject of micro- and nanoplastics not through a single sensational headline but through an accumulation of evidence. "I first became aware of micro- and nanoplastics the way a lot of clinicians do," he says, "not from a single headline, but from a gradual accumulation of credible findings that started to feel impossible to ignore." For years, he regarded reports of plastic in seafood and bottled water as an environmental issue. That changed when the particles were detected closer to home. "The data began to move from out there to in here," Dr. Long says, "with detection of these particles in the human stool, lung, blood, and even in the placenta tissue. That shifts matters, because it reframes this from a distant environmental problem to a direct human exposure question."

Dr. Long points to two properties at once: how widespread the particles are, and how biologically plausible their effects might be. "Plastic is not simply inert," he notes. Plastic products carry additives, plasticizers, stabilizers, flame retardants and pigments, and can adsorb other chemicals on their surfaces. At the micro- and nanoscale, their surface area, and consequently their reactivity, increases sharply. On the extent of exposure, Dr. Long is unequivocal: "This affects all people regardless of where they live, what they eat, or what their occupation is. You're not going to find a human on earth that has not been exposed to nanoplastics." For a physician, he adds, such an exposure raises a standard question: "What are the long-term consequences, and what can we do to understand and hopefully reduce harm?"

> *“You’re not going to find a human on earth that has not been exposed to nanoplastics.”*
>
> *— Dr. Jeffrey Long*

Why did medicine take so long to notice? The first reason, for Dr. Long, is measurement. "For decades routine environmental and biomedical testing simply wasn’t designed to detect particles at these tiny sizes," he says, and results still vary by method. "When measurement is hard, recognition is slow." Plastics were also assumed to be inert, so concern centered on visible pollution such as bags, bottles and ocean debris. And the relevant expertise was divided. "The science has been siloed," Dr. Long says: environmental scientists, chemists, toxicologists, clinicians and epidemiologists have each held a different piece of the puzzle, and connecting them takes time and sustained funding.

Size, Dr. Long explains, is not a technicality: "It changes how these particles behave in the body." Larger microplastics can be swallowed or inhaled and are often cleared, though some lodge in the mucus membranes, airways or gut. Nanoplastics, often only tens to hundreds of nanometers across, behave differently. At that scale cells can absorb them through endocytosis, and, "in principle, they may cross biological barriers more easily": the blood-brain barrier, the placental barrier, the alveolar-capillary barrier of the lung. Because they are so difficult to measure, Dr. Long cautions, "we may be shockingly underestimating our exposure to them," and their small size lets them act "at the level where disease begins": oxidative stress, inflammation, mitochondrial disruption, and possible effects on DNA integrity and cell signaling.

On cancer, his own specialty, Dr. Long stresses the limits of the current evidence. Plastic particles have been found in human tissue, and in some studies within tumors. "Finding particles in cancer tumors doesn’t prove that they caused the tumor," he says. "Tumors are biologically unusual environments. They can have leaky vasculature, altered lymphatics, and high metabolic activity. So it’s also possible that these cancers preferentially accumulate circulating particles." The hypothesis that plastics contribute to cancer risk is, in his words, "absolutely biologically plausible," though the proof is not yet in hand. Asked which cancers, Dr. Long replies: "we just can’t quantify that at this time."

As a radiation oncologist, Dr. Long describes possible mechanisms and emphasizes that they remain unproven: "the word here is plausible." Chronic inflammation from any source might, in theory, alter how tumors and healthy tissue respond to radiation, chemotherapy or immunotherapy. Dr. Long also points to the slow aftermath of treatment. "It’s not that microplastics would change the physics of radiation therapy," he says, "but they could certainly influence the biology of how tissues heal after treatment," referring to the fibrosis and inflammatory cascades that can unfold months or years later. For patients, his advice is limited to low-cost measures: avoid heating food in plastic, reduce single-use plastic, and attend to water and air filtration.

In Dr. Long’s words, it is "an absolutely legitimate but emerging public health concern that… deserves attention." The priorities he sets out are methodical: standard definitions and methods, reliable measures of exposure, and long-term studies that follow people for years. "The goal here is not to panic," he says. "The goal here is… risk reduction based on evidence… and common sense."

> *“I just hope we don’t find out 20 years from now that we should have thought about nanoplastics a lot more seriously today.”*
>
> *— Dr. Jeffrey Long*

Watch the full episode, “Oncologist Warns About Nanoplastics in the Human Body | Dr. Long | ALLATRA Global Research Center,” on YouTube:

https://youtu.be/C3gtFQVSQFs

An open invitation to the podcast

This conversation opened the ALLATRA Global Research Center’s podcast series, and the invitation is open. We are looking for thoughtful voices from across the sciences: physicists, geologists, mathematicians, astronomers, chemists, climate and Earth scientists, and anyone doing serious work on the questions that shape our world.

If you would like to join us on the podcast, to share your research, test an idea in open dialogue, or propose a topic, write to us at: *grc@allatra.org*

How Do Micro- and Nanoplastics Affect the Brain? New Evidence

Dr. José Antonio Muñoz

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Dr. José Antonio Muñoz is a distinguished pediatric neurologist who was awarded the title of Professor Honoris Causa by the Faculty of Education Sciences at Universidad Mayor de San Andrés (UMSA). He also serves as Director of the Institute for Child Neurodevelopment (INDI) in Bolivia.

His work focuses on child neurodevelopment, particularly the maturation of the brain and nervous system during early childhood, as well as the clinical assessment, diagnosis, and treatment of neurodevelopmental disorders.

Dr. Muñoz is widely recognized for his expertise in Autism Spectrum Disorder (ASD), where he combines clinical practice with public awareness and educational initiatives aimed at promoting early diagnosis and improving understanding of the condition across Bolivia. As Director of INDI, he leads a specialized center dedicated to the early assessment, ongoing clinical follow-up, and comprehensive care of children's neurological development.

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ABOUT THE AUTHOR

**Specialist Degree in Geology and Geography,
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Anna Kotlyar (Israel) is a data analyst with a background in environmental research and interdisciplinary expertise spanning ecology, gemology, and analytics. A graduate of the Faculty of Geology and Geography at Southern Federal University, where she specialized in Geoecology, she focuses her research on environmental pollution, ecological risks, and the impact of emerging pollutants on ecosystems and human health. Combining environmental research with data-analysis expertise and experience in medical technologies and infection control, she applies scientific methods and digital technologies to uncover patterns and provide data-driven insights for decision-making across complex environmental and public-health questions.

It is difficult to imagine that an organism only a few months old could already exhibit signs of processes resembling Alzheimer's disease.

Yet that is precisely the unexpected conclusion reached by researchers studying young seabirds that were still preparing to leave the nest and embark on their first long migration across the ocean.

In the spring of 2025, Science Advances published the article **"Seabirds in Crisis: Plastic Ingestion Induces Proteomic Signatures of Multiorgan Failure and Neurodegeneration,"** which examined shearwater chicks on Lord Howe Island in the Tasman Sea. The researchers investigated the consequences of plastic ingestion after adult birds mistakenly ingested plastic debris, mistaking it for food. Unable to distinguish plastic fragments from natural prey, the parent birds are not only exposed to plastic pollution themselves but also inadvertently feed plastic to their chicks. As a result, plastic begins to accumulate in chicks' bodies from the very first months of life [1].

The study's findings were so unexpected and alarming that they quickly drew the attention of researchers around the world. Even chicks that appeared outwardly healthy showed evidence of serious dysfunction affecting multiple internal organs and the nervous system.

The chicks whose stomachs contained hundreds of plastic fragments exhibited signs of impaired liver, kidney, gastrointestinal, and, most concerningly, brain function.

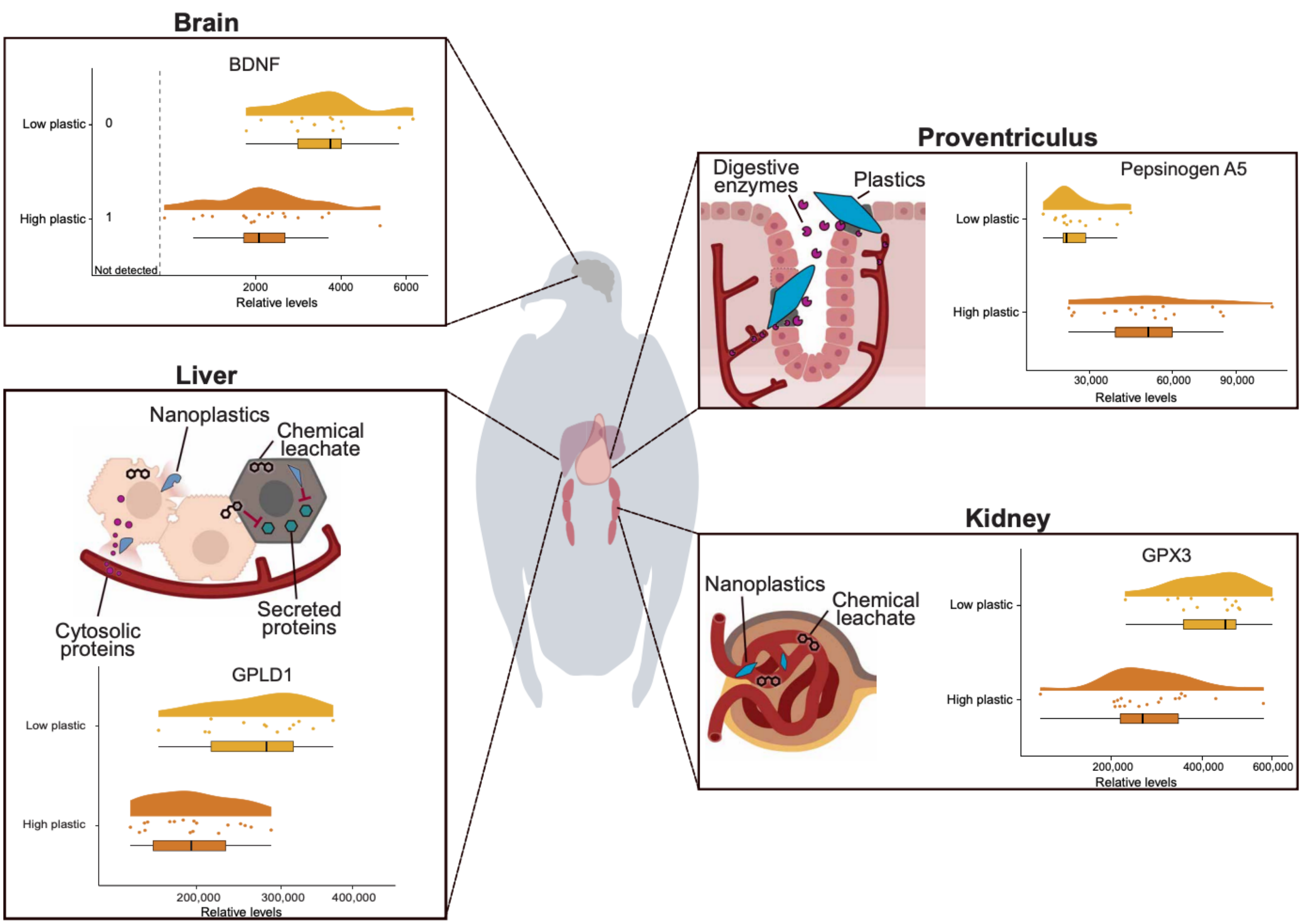

Figure 1.
Schematic illustration of changes in the proteomic profile of shearwater chicks with a high plastic burden, showing signatures associated with impaired brain, liver, kidney, and stomach function.
Source: [1]. License: CC BY 4.0.

Analysis of the blood proteome revealed signatures of biological processes commonly associated with neurodegeneration in humans. Remarkably, these changes were detected in birds that were not yet three months old.

This does not mean that the birds were developing Alzheimer's disease. Rather, it indicates similarities in the underlying molecular and cellular mechanisms [1].

The Brain Is Emerging as a New Target of Plastic Pollution

Until recently, scientists viewed plastic primarily as a physical hazard. It was widely believed that its harmful effects stemmed mainly from the ingestion of plastic fragments, which accumulate in the digestive tract and interfere with normal feeding. Today, however, it is increasingly clear that plastic can also affect the body at the cellular level due to its unique physicochemical properties. A comprehensive analysis of these mechanisms is presented in the ALLATRA scientific and analytical report *Nanoplastics: A Systematic Risk Analysis for Human Health, Ecosystems, and the Environment* [2].

Researchers are increasingly detecting micro- and nanoplastics in nervous system tissues, including the brain. Animal studies have shown that these particles can cross the blood-brain barrier, the body's highly specialized protective system that separates the brain from the bloodstream. Under normal conditions, this barrier prevents toxins, pathogens, and other potentially harmful substances from entering the brain [3-5].

Nanoplastic particles, however, are so small and possess physicochemical properties, including surface electrical charge, that enable them to penetrate this protective barrier and accumulate in brain tissue [2-5].

A review article published in Frontiers in Neuroscience, *"From Environment to Brain: The Role of Microplastics in Neurobehavioral Disorders,"* synthesized findings from numerous studies on the effects of micro- and nanoplastics on the nervous system. The authors concluded that these particles can induce neuroinflammation, oxidative stress, neuronal damage, and disruption of neurotransmitter systems. Animal experiments have further shown that such effects may be accompanied by impaired memory and learning, increased anxiety-like behavior, and deficits in motor function [3].

What Happens Inside the Brain?

When micro- and nanoplastics enter nervous tissue, they can trigger a range of biological processes that may interfere with normal brain cell function.

One of the primary mechanisms is **oxidative stress**.

Neurons are particularly vulnerable to reactive oxygen species, highly reactive molecules that, when produced in excess, can damage cell membranes, proteins, and DNA. Numerous studies have shown that micro- and nanoplastics can increase the production of these molecules, disrupting normal cellular function [2-5].

Another important mechanism is **neuroinflammation**.

The brain has its own immune defense system, in which specialized cells called microglia play a central role. Under normal conditions, microglia help maintain the health of nervous tissue by removing cellular debris and responding to potential threats.

However, prolonged activation, including that induced by micro- and nanoplastics, causes microglia to release pro-inflammatory molecules that sustain chronic inflammation. The problem is compounded by the fact that the body lacks effective mechanisms to break down and eliminate most plastic particles. Once they enter brain tissue, micro- and nanoplastics can persist within cells for extended periods. Macrophages and microglia attempt to remove these foreign particles by phagocytosis, but are unable to completely degrade them. As a result, plastic accumulates within these cells, leading to cellular dysfunction, cellular stress, and, in some cases, cell death. This persistent accumulation helps maintain chronic inflammation and creates conditions that are unfavorable for the normal function and survival of neurons [2-5].

Today, chronic neuroinflammation is widely recognized as one of the factors associated with the deterioration of nervous tissue and age-related cognitive decline.

Another potential mechanism involves disruption of neuronal communication.

Animal studies, including experiments in fish and mice, have shown that exposure to micro- and nanoplastics can alter the levels of dopamine, serotonin, and acetylcholine. These neurotransmitters play essential roles in learning and memory, regulate mood, and help control movement [3-5].

Studies also point to another potential mechanism involving mitochondrial dysfunction. Mitochondria serve as the cell's "powerhouses," generating the energy required for normal cellular function. Because the brain is one of the body's most energy-demanding organs, even subtle impairments in mitochondrial function can have significant consequences for nervous tissue.

Interestingly, many of the proposed mechanisms by which micro- and nanoplastics influence the brain resemble processes observed in age-related neurodegenerative disorders, including Alzheimer's disease and Parkinson's disease [2-5].

Additional evidence comes from the study *"Exposure to Polystyrene Microplastics Impairs Hippocampus-Dependent Learning and Memory in Mice,"* whose findings suggest possible damage to the hippocampus, a brain structure often referred to as the brain's "memory center." The hippocampus plays a critical role in learning, the consolidation of new information into long-term memory, and spatial navigation. In experiments with mice, microplastic particles were detected directly within this region of the brain. Their presence was associated with increased inflammation, impaired neuronal function, and deficits in learning and memory [6].

Researchers at the Chinese Research Academy of Environmental Sciences also provided important new evidence in their study *"Microplastics in the Bloodstream Can Induce Cerebral Thrombosis by Causing Cell Obstruction and Lead to Neurobehavioral Abnormalities,"* in which they observed the movement of micro- and nanoplastics through the cerebral blood vessels of mice in real time [7].

The researchers found that blood cells which had engulfed the particles could become lodged in small blood vessels, partially obstructing normal blood flow. These accumulations resembled microscopic "traffic jams" within the brain's vascular network. In the exposed animals, these changes were accompanied by neurological and behavioral abnormalities, including reduced motor activity [7].

Even more concerning is that similar processes are being observed not only in animals.

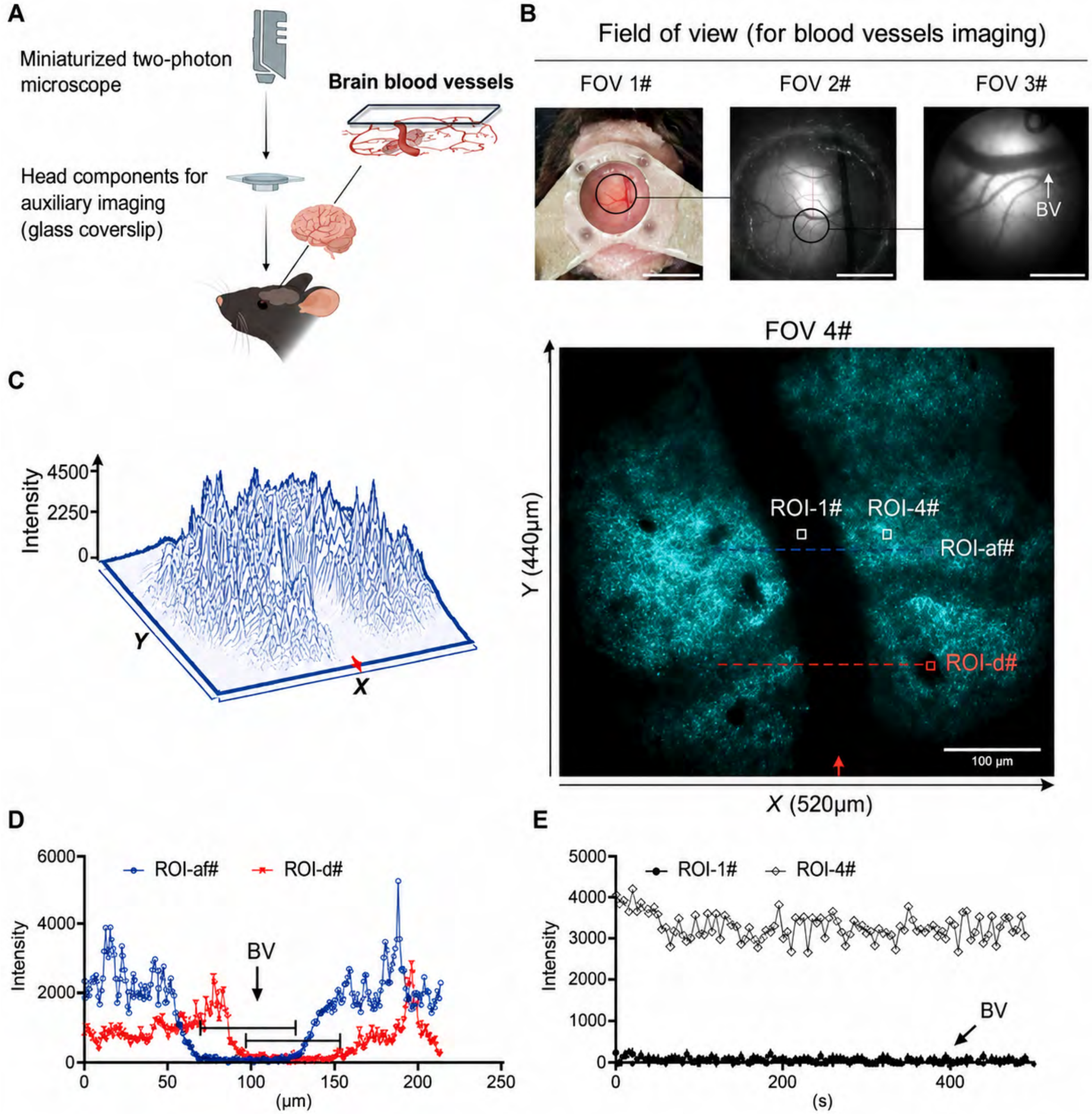

Figure 2.
Visualization of the cerebral blood vessels in a living mouse using two-photon fluorescence microscopy, the technique employed to investigate the circulation of microplastics within the brain's vasculature. Source: [7]. License: CC BY-NC 4.0.

Researchers Have Detected Micro- and Nanoplastics in Human Brain Tissue

In a study published in Nature Medicine, researchers analyzed postmortem samples of human brain, liver, and kidney tissue. They found that the concentration of plastic particles in the brain was 7 to 30 times higher than in the other organs examined [8].

Of particular interest was the observation that brain samples from patients with confirmed dementia contained higher levels of detected plastic particles [8].

The authors emphasize that their findings do not establish a causal relationship between plastic accumulation and the development of dementia. Nevertheless, the discovery of such high concentrations of plastic particles in the brain, along with their elevated levels in individuals with dementia, has become one of the most widely discussed findings in this field in recent years.

Following its publication, the study sparked considerable scientific debate. Some researchers raised concerns about potential limitations of the Py-GC/MS method used to quantify micro- and nanoplastics in brain tissue. The study's authors disagreed with these criticisms. As a result, although the presence of micro- and nanoplastics in human tissues has been confirmed, questions regarding their precise concentration in the brain and their clinical significance remain the subject of ongoing research [5, 8].

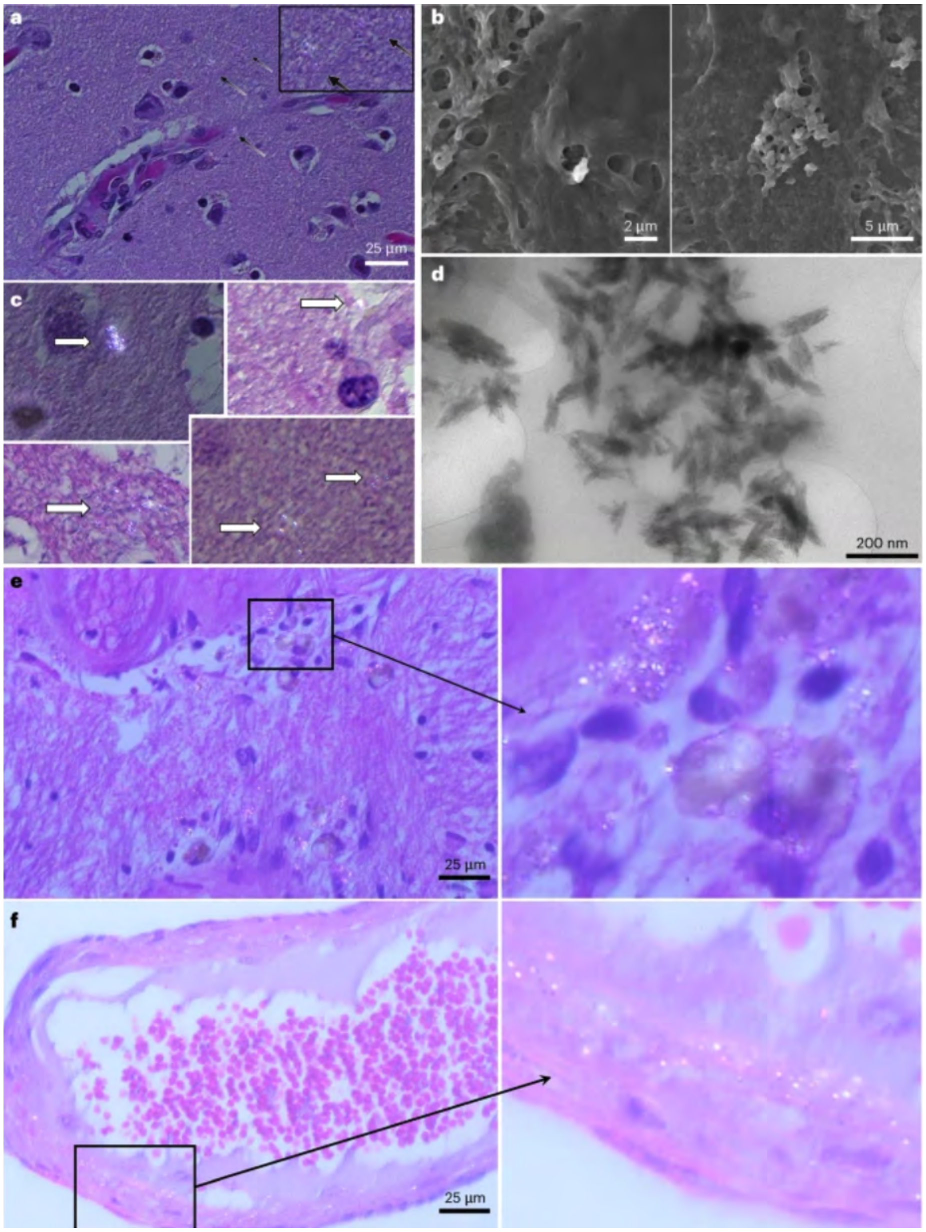

Figure 3.
Visualization of suspected micro- and nanoplastic particles in human brain tissue using light microscopy, scanning electron microscopy, and transmission electron microscopy. Source: [6]. License: CC BY-NC-ND 4.0.

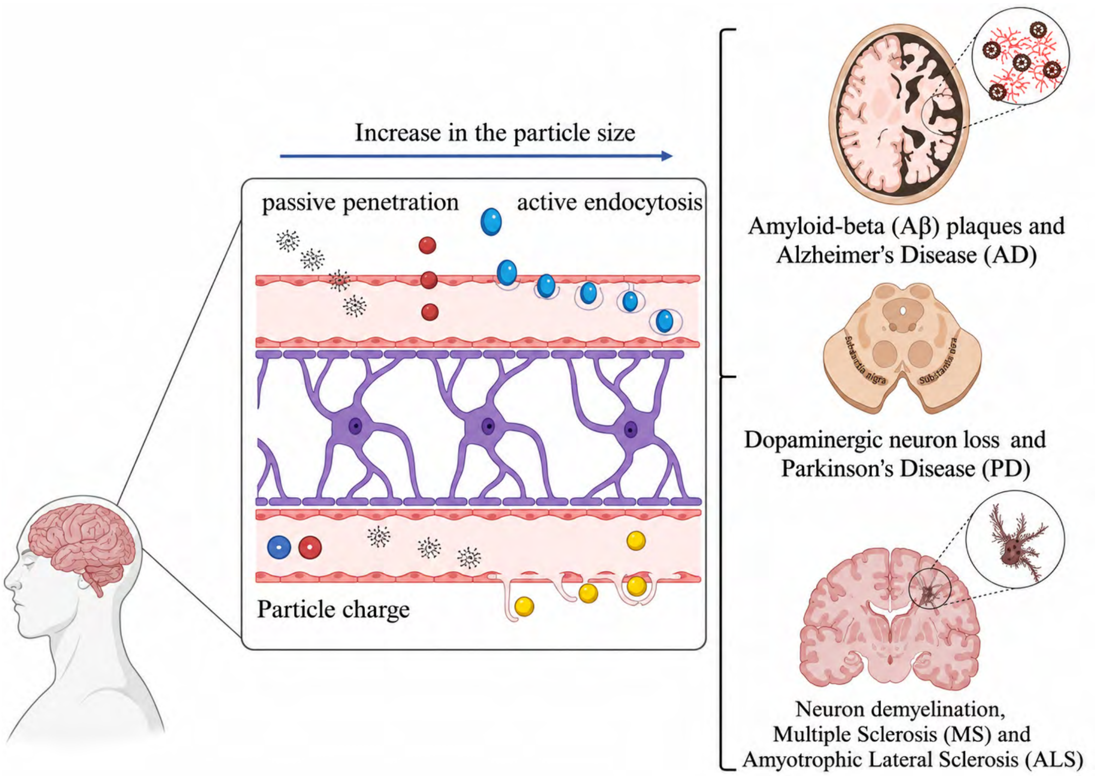

Figure 4.
Schematic illustration of the proposed mechanisms by which micro- and nanoplastics may cross the blood-brain barrier and their potential role in processes associated with Alzheimer's disease, Parkinson's disease, multiple sclerosis, and amyotrophic lateral sclerosis (ALS).
Source: [5]. License: CC BY 3.0.

From Animal Observations to Human Health Risks

Returning to the shearwater chicks, it is important to recognize that seabirds are often regarded by scientists as an early warning system. They are among the first to experience the consequences of ocean pollution, providing valuable insight into emerging environmental threats long before their effects become apparent in other species and ecosystems.

For this reason, the discovery of biological changes resembling neurodegenerative processes in chicks only three months old has raised serious concern within the scientific community. The implications extend far beyond the well-being of a single seabird species. Taken together, the findings of these studies suggest that micro- and nanoplastics may interfere with fundamental cellular mechanisms that support nervous system function across a wide range of living organisms [1–8].

Many important questions remain unanswered. Nevertheless, it is already becoming clear that plastic pollution is far more than an environmental issue. It has the potential to affect the biological processes that underpin the health of both animals and humans.

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Light from the Crystal's Darkness: When Diamonds Trace Invisible Plastics

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Tatiana Károvà holds a degree in Nuclear and Subnuclear Physics from Charles University in Prague, earned in 2006. During her studies, she focused primarily on neutrino physics.

She currently works as a physics and mathematics educator and serves as a mentor in the Hejny method, an innovative approach to developing students' logical and conceptual thinking.

She has re-engaged in scientific research through the ALLATRA platform, with a focus on bridging the gap between complex research and the general public. Her work focuses on nanoplastics, including their physical properties and potential impact on global climate stability, as presented within the ALLATRA framework. By combining her background in physics with her pedagogical experience, she strives to foster public understanding of these urgent challenges. Her goal is to communicate complex climate dynamics as accessible knowledge, helping a broader audience understand the physical realities facing our world today.

Micro- and nanoplastic pollution is a major environmental concern and a growing subject of health research. Yet particles below 100 nanometers are difficult to detect and chemically characterize, especially in complex biological and environmental samples. This article examines whether nitrogen-vacancy (NV) centers in synthetic diamond could contribute to future nanoplastic sensing. We explain the principles of optically detected magnetic resonance and nanoscale nuclear magnetic resonance (nano-NMR), the production of near-surface NV centers, and the limitations imposed by surface noise. Existing studies have separately demonstrated nanoscale NMR, long-term tracking of model polymer particles with fluorescent nanodiamonds, and quantum sensing of free radicals in cells. Their combination into a direct, chemically specific nanoplastic detector, however, remains a future research goal. We conclude by discussing the engineering steps required for integrated and potentially field-deployable quantum sensing systems.

Finding and accurately identifying a plastic particle that is a thousand times thinner than a human hair, and located deep within living tissue or a natural water source, is a monumental challenge for contemporary science. Conventional optical methods commonly used in laboratories have rigid physical boundaries (Fig. 1). Quite simply, light cannot scatter properly on objects of such minuscule dimensions. Other analytical methods can identify the chemical composition of plastics, but they irreversibly destroy the sample in the process. Consequently, tracking the transport of nanoplastics in real time inside a living organism has long been exceptionally difficult. Surprisingly, a promising—though still largely experimental—solution is now emerging from the realm of quantum physics, utilizing technology hidden within laboratory-grown diamonds.

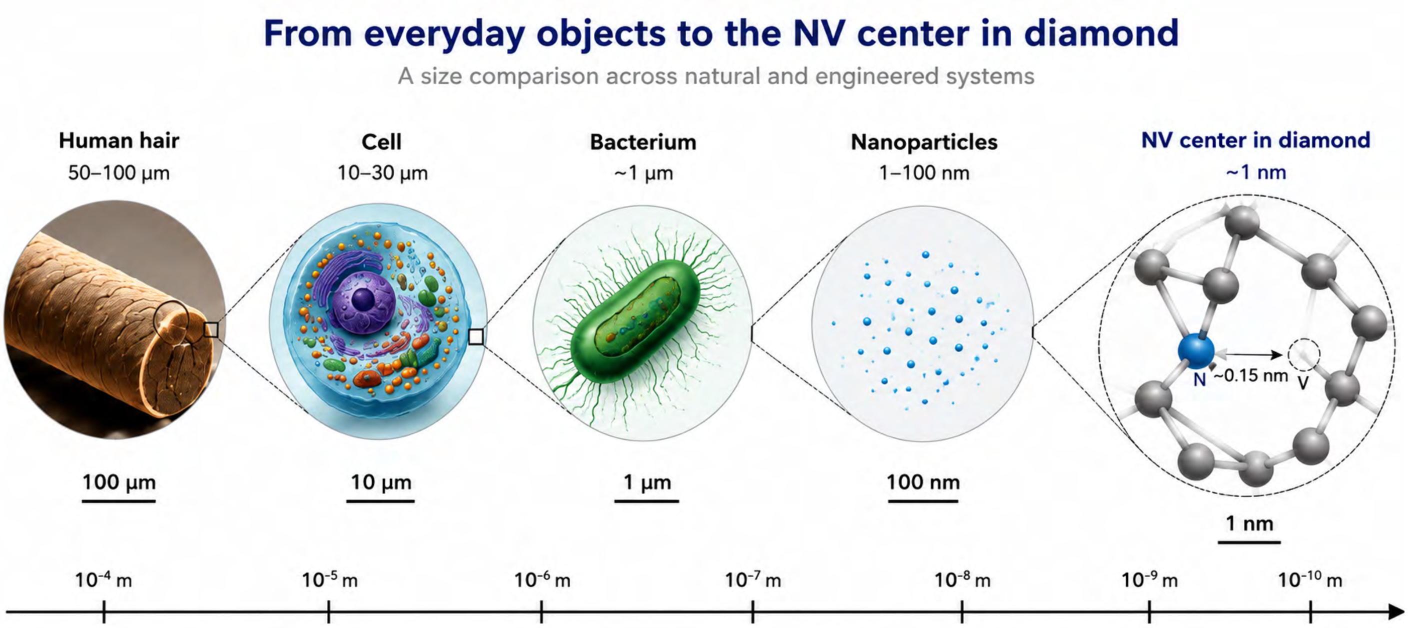

Figure 1.
The scale of nanoplastics compared to a human hair, a cell, and a bacterium. Particles smaller than 100 nm are beyond the capabilities of many traditional optical methods.

The Current State of Nanoplastic Detection and the Historical Context of NV Centers

The demand for reliable nanoplastic analysis is increasing. Clean laboratory conditions are no longer sufficient; scientists need to monitor pollution directly in ecosystems, and physicians are interested in observing how these tiny particles behave inside cells and organs [1]. However, once a plastic particle drops below the 100-nanometer threshold, conventional laboratory instruments essentially go blind.

Conventional Detection Technologies: Advantages and Limitations

Nanoplastic research uses a broad range of analytical approaches. Two methods that demonstrate current limitations and trade-offs are Raman spectroscopy and pyrolysis gas chromatography-mass spectrometry (Py-GC-MS) (Fig. 2).

- **Raman spectroscopy** works by illuminating a sample with a laser, causing the polymer molecules to vibrate. The scattered light carries their unique chemical fingerprint. The main advantage is that this method is non-destructive. However, conventional microscopes hit a fundamental limit called the diffraction limit: because of its wavelength, ordinary light cannot clearly resolve objects smaller than a few hundred nanometers. For nanoplastics, the signal drops off rapidly as the particles get smaller, meaning it practically vanishes for the tiniest fragments. Moreover, in biological samples, this weak signal is entirely drowned out by the natural autofluorescence of the surrounding tissue [1].

- **Pyrolysis-GC-MS** takes a different approach. The sample is literally vaporized at extreme temperatures in an oxygen-free environment, and the instrument analyzes the mass of the resulting molecular fragments. The advantage lies in its extreme sensitivity, which can detect trace amounts of a specific polymer. The overarching disadvantage, however, is its destructive nature. Because the material is permanently destroyed, its original size, shape, and biological context are completely lost, and the same particle cannot be followed over time [1].

Scientists are therefore exploring complementary approaches, and one promising possibility involves nitrogen-vacancy centers in diamond.

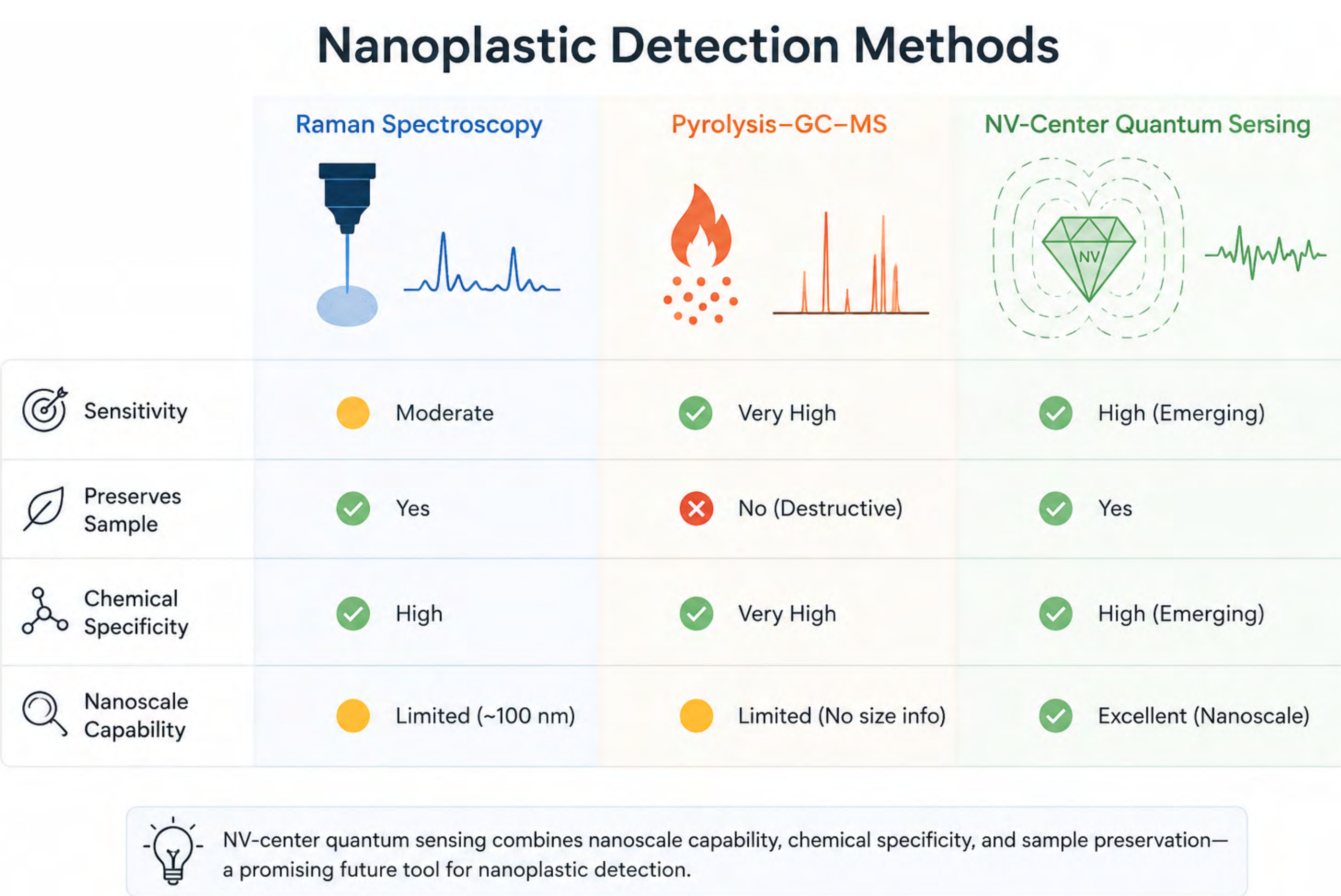

Figure 2.
Comparison of Raman spectroscopy, pyrolysis–GC–MS, and emerging NV-center quantum sensing for nanoplastic detection. The methods differ in sensitivity, preservation of the sample, chemical specificity, and suitability for nanoscale analysis.

A Brief History of NV Centers

The history of nitrogen-vacancy centers dates back to the 1960s, when researchers began investigating the unusual optical properties of radiation-damaged diamonds. A major breakthrough occurred in 1997, when a team at Chemnitz University of Technology demonstrated that the spin state of a single isolated defect could be detected at room temperature using confocal optical microscopy [2]. This milestone helped establish NV centers as a platform for quantum sensing and metrology. Around

2008, researchers demonstrated that individual NV centers could function as nanoscale magnetic-field sensors (Fig. 2). Several years later, NV centers were also developed into nanoscale thermometers [3]. More broadly, the possible use of quantum sensing to detect microplastics has recently begun to attract attention, although it remains an exploratory research direction [4].

The Physical Principles of NV Centers and Quantum Nanoplastic Sensing

The Quantum Structure of an "Artificial Atom"

What exactly is an NV center? It is a point defect in the crystalline carbon lattice of a diamond. It forms when a single carbon atom is replaced by a nitrogen atom, and an immediately adjacent site in the lattice is left empty—creating a vacancy [5]. This system behaves like an isolated atom locked within a solid-state diamond matrix. It possesses its own distinct energy levels and its own atomic magnetic moment, known as spin, which can be easily initialized and read using ordinary light [3, 5] (Fig. 3).

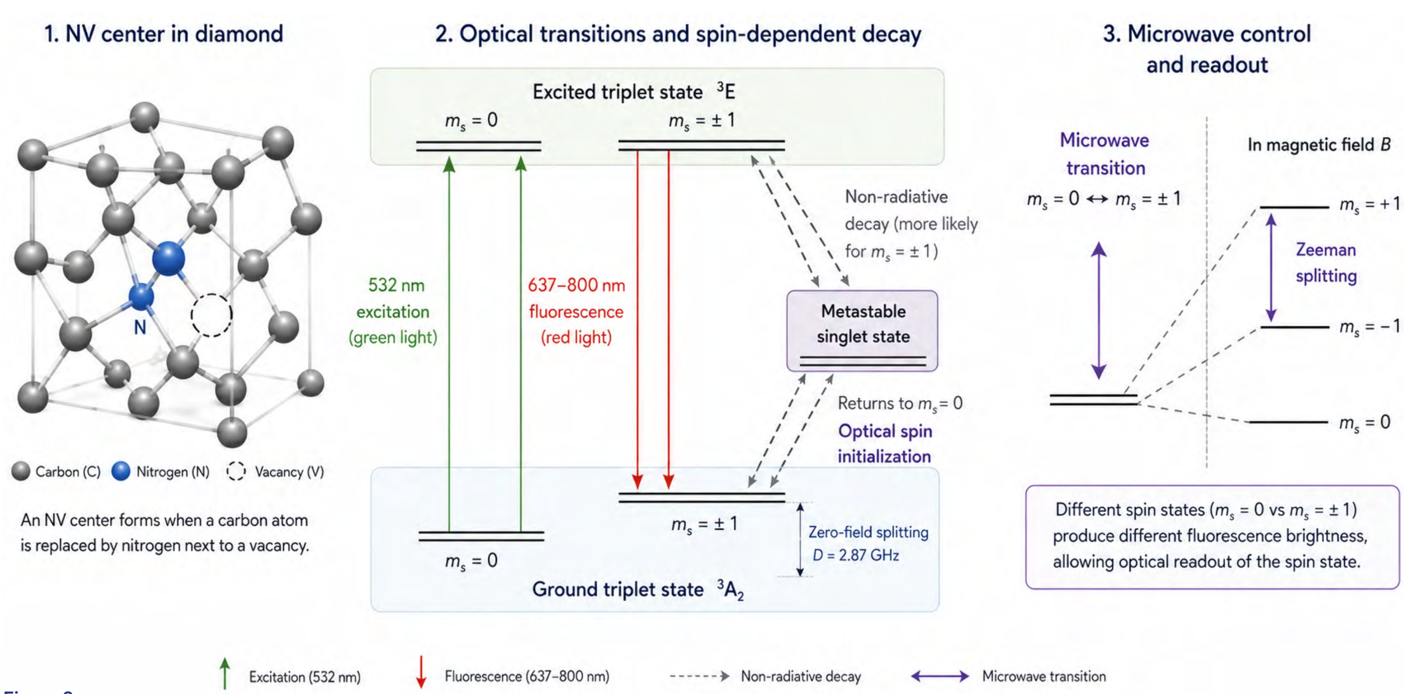

Figure 3.

How a nitrogen-vacancy center in diamond works. An NV center forms when a nitrogen atom replaces one carbon atom in the diamond lattice and a neighboring site remains empty. Green laser light excites the center, which responds by emitting red fluorescence. Microwaves and magnetic fields change the electron spin and, as a result, the brightness of this fluorescence, allowing the NV center to act as an extremely small magnetic-field sensor.

Communicating with the Quantum World: The Principle of ODMR

The remarkable feature of NV centers is that their quantum spin state can be manipulated and read using ordinary light at room temperature. When the diamond is illuminated with a green laser, the electrons within the defect are excited to a higher energy state. As they relax back to the ground state, they emit red photoluminescence, which can be easily measured.

The core principle relies on the NV center's atomic spin. To interact with this spin, the diamond must be prompted not only by the laser but also by invisible microwave radiation (similar to the frequencies used by mobile networks, but at a fraction of the power) [3, 5]. This microwave excitation acts like a fine radio tuner: it sweeps across frequencies to interact with the spins and prepare them for the measurement.

When an external magnetic field is applied, it shifts the spin energy levels of the NV centers within the diamond sensor. When the system is scanned with microwaves at this shifted resonance frequency, the electron spins are flipped, forcing them to relax through an alternative energy route that bypasses the direct path, causing the red light to dim slightly [2, 3, 5] (Fig. 4).

The magnitude of this fluorescence decrease depends strongly on the experimental setup. Early measurements on a small ensemble of NV centers showed a decrease of about 10% [2], whereas the optical contrast between the spin states of a single NV center can approach 30% [3]. This method of reading the magnetic state of the environment through changes in fluorescence intensity and tuned microwaves is called optically detected magnetic resonance (ODMR) [3, 5]. By precisely measuring how the microwave resonance frequencies shift in response to an external magnetic field, scientists can determine the field's strength with high sensitivity.

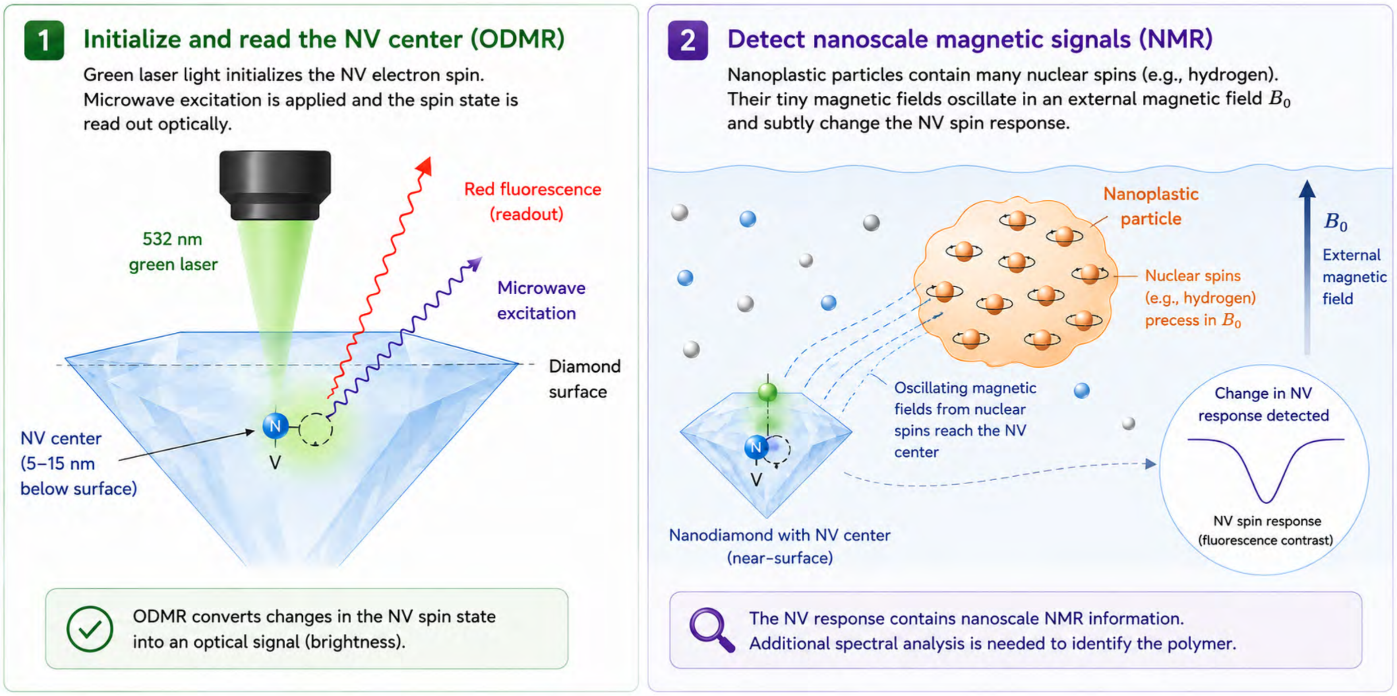

Figure 4.
How an NV center could probe nanoplastic-related signals. Green laser light and microwaves prepare and control the electron spin of an NV center in diamond, while changes in its red fluorescence provide an optical readout. In a liquid sample, nuclear spins in a nearby nanoplastic particle produce tiny oscillating magnetic fields that alter the NV response, providing nanoscale NMR information. Because hydrogen nuclei are also abundant in water and biological material, additional spectral analysis is required to identify the polymer.

Nanoscale NMR: A Chemical Fingerprint

This principle of brightness dips also extends to the detection of specific polymers. Common plastics, such as polystyrene and polyethylene, contain large numbers of hydrogen atoms. The nuclei of these atoms possess their own tiny nuclear spin and precess like microscopic spinning tops at a characteristic frequency (known as the Larmor frequency) when exposed to a magnetic field.

When a nanoplastic particle approaches the diamond surface within a distance of less than 20 nanometers, the rotating magnetic field of the plastic's hydrogen nuclei gently perturbs the spin of the nearby NV center [3, 6]. By applying rapid sequences of microwave pulses, scientists can filter out the chaotic environmental noise and isolate only the spin changes that match the specific precession frequency of hydrogen. By monitoring the resulting light dips of the diamond, researchers can perform nuclear magnetic resonance (nano-NMR) on a volume of just a few cubic nanometers. However, because hydrogen is found in almost all organic matter—including living cells—a simple hydrogen signal is not enough. Distinguishing a plastic particle from the surrounding tissue requires analyzing additional atomic details, meaning that a direct, live-ready nanoplastic detector is still a future research goal [6, 7] (Fig. 4).

Growing Quantum-Grade Diamonds

To ensure predictable results, researchers avoid unpredictable natural diamonds. Instead, high-purity synthetic crystals are grown in laboratories using Chemical Vapor Deposition (CVD) [5]. A vacuum chamber is filled with a mixture of hydrogen and methane gases, and microwave energy ignites a brilliant, high-temperature plasma. Carbon atoms precipitate from this plasma and deposit onto a substrate layer by layer. To eliminate background magnetic noise from the lattice itself, isotopically pure methane containing exclusively carbon-12 is used, as carbon-12 possesses no nuclear spin [3]. In the final stage of growth, trace amounts of nitrogen are introduced, and the crystal is subsequently irradiated with electrons and annealed to create a controlled distribution of stable NV centers localized just a few nanometers beneath the surface [5].

Current Bottlenecks and Outstanding Questions

Despite its immense promise, the technology faces significant hurdles. For an NV center to capture the incredibly weak magnetic fields of a nanoplastic particle, it often needs to lie only about 5 to 15 nanometers below the surface. However, the diamond surface is inherently unstable, plagued by dangling chemical bonds and surface contaminants that generate severe electrical and magnetic noise. This noise severely shortens the coherence time—the duration during which the NV center can maintain its quantum information—and limits the sensor's overall sensitivity [8].

Furthermore, the scientific community is currently grappling with conflicting experimental data.

Different surface treatments—including oxygen-, fluorine-, hydrogen-, and nitrogen-based terminations—can affect the charge stability and coherence of shallow NV centers in different ways. Their performance depends on the crystal surface, preparation procedure, and sensing conditions, so no single treatment is universally optimal [7, 8].

Liquid samples introduce additional complications at the complex diamond-water interface, where localized electrostatic fluctuations and ion adsorption can unexpectedly shift the resonance frequencies of shallow NV centers. Untangling these environmental effects from the actual plastic signal requires rigorous calibration and blank measurements, and remains a critical area for further investigation [6, 7, 8, 9].

From Living Cells to Field Microchips: Biological Challenges and Technological Visions

Detecting nanoplastics directly within the human body remains an urgent frontier for modern science. Due to their unique physicochemical properties and surface charges, experimental studies suggest that these minute particles can interact with biological barriers and, under certain conditions, may cross them—including the intestinal, placental, and blood-brain barriers, though the exact extent of this in humans is still being mapped [10, 11].

To study how nanoplastic particles influence cell processes, researchers synthesize model polymer particles with fluorescent nanodiamonds (FNDs) embedded directly inside them [10]. While the plastic matrix mimics the pollutant, the embedded diamonds serve as a tracer, showing so far low cytotoxicity, allowing scientists to reliably measure the cell's genuine response to the plastic itself without signal degradation [10].

Furthermore, the internalization of plastics often triggers a cellular immune response accompanied by a massive surge of free radicals, a state known as oxidative stress [12]. Because these radicals possess unpaired electrons, they behave like highly reactive miniature magnets, creating a localized magnetic unrest that nearby NV centers can detect. Since magnetic fields decay rapidly with distance, this sensing relies on nanodiamonds located at the particle's outermost boundary or those gradually exposed as the polymer matrix undergoes cellular weathering. In a healthy, undisturbed cell, the NV center retains its quantum state for a relatively long period. While NV centers have been used to measure free radicals in human cells, and plastics are known to cause oxidative stress, combining these two steps into a single experiment has not yet been demonstrated. If successful, this method would provide an indirect but highly valuable indicator of cellular distress, helping toxicologists observe how cells react to plastic pollution [11, 12].

Moving this technology out of the controlled environment of a laboratory microscope and into natural water bodies or wastewater facilities introduces severe engineering complications. Natural water is highly heterogeneous, filled with background noise from dissolved iron or manganese ions and organic detritus that would completely blind a basic quantum sensor. To bypass this issue, the diamond sensor must be paired with dynamic decoupling protocols. By applying microwave pulses in a meticulously timed rhythm, the sensor acts as a temporal sieve. The slow, chaotic magnetic fluctuations of the environmental noise are actively canceled out, while the rapid, coherent precession of the hydrogen nuclei within the nanoplastics is amplified and isolated [6, 7]. Even with this quantum filtering, a sensor placed directly into a river or wastewater plant cannot do the job alone. Real-world analysis will still require traditional sample preparation, such as pre-filtering and calibration, to protect the diamond from fouling and ensure reliable measurements [3, 9].

Real environmental samples rarely contain a single pure polymer. They include mixtures of polyethylene, polystyrene, nylon, additives, natural organic matter, and weathered particles whose spectra may overlap. Vibrational-spectroscopy studies have therefore begun combining spectral measurements with machine-learning methods, including convolutional neural networks, to classify polymers and estimate weathering [1]. Similar computational tools might eventually assist in interpreting quantum-sensing data, but this remains a forward-looking proposal rather than a demonstrated nanoplastic application.

A further challenge is miniaturizing the optical, microwave, fluidic, and detection components. Current research has demonstrated microfluidic quantum-sensing platforms and NV measurements in flowing microdroplets [9]. Integrated light sources, microwave structures, and photodetectors are also being developed for diamond quantum technologies, but a portable, nanoplastic-specific quantum system-on-a-chip has not yet been demonstrated. A realistic intermediate step may be a stationary, automated instrument operating in a controlled laboratory or water-treatment workflow. Large-scale environmental mapping with such systems remains a long-term technological vision [4] (Fig. 5).

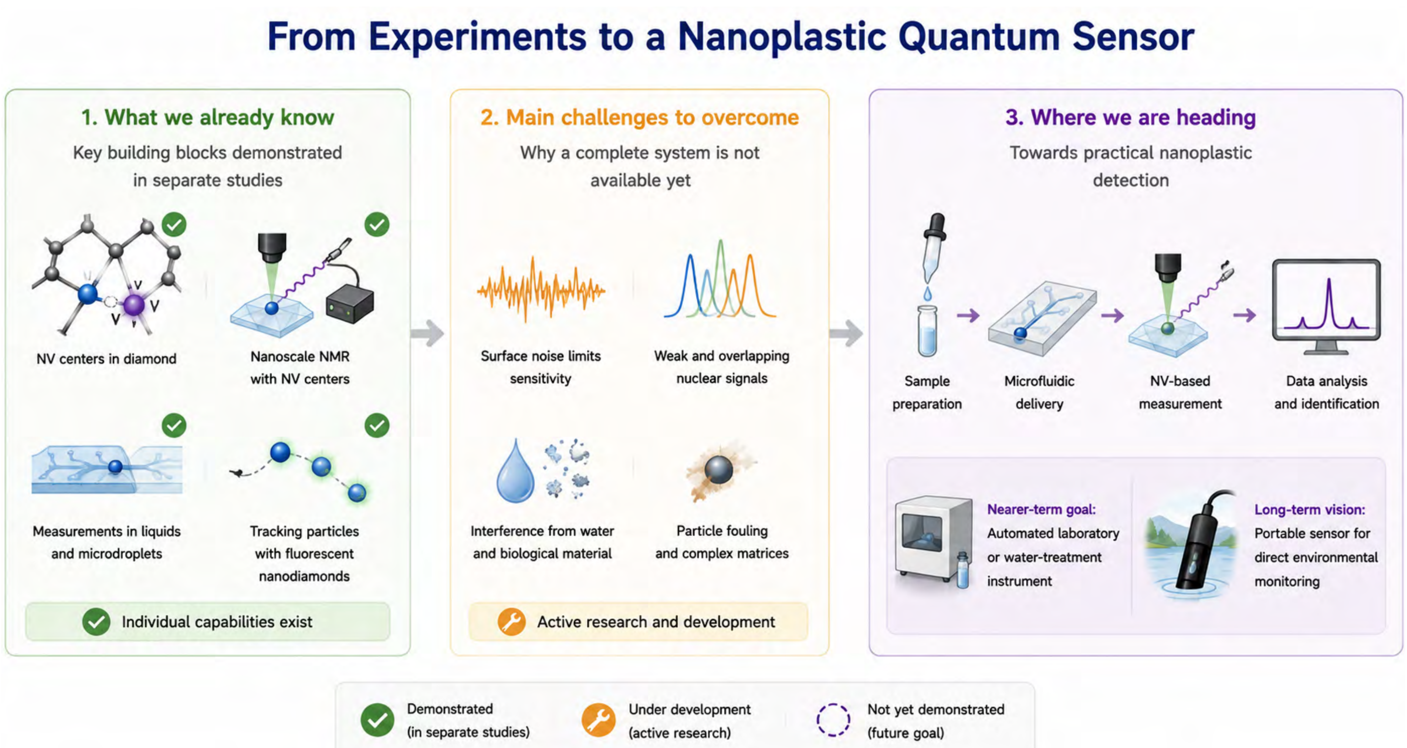

Figure 5.

Roadmap from demonstrated quantum-sensing methods to a future nanoplastic detector. Existing components include NV-center sensing, nanoscale NMR, liquid measurements, and particle tracking. Key challenges remain surface noise, complex samples, and signal overlap. Their integration into an automated laboratory instrument—and eventually a portable field sensor—has not yet been demonstrated.

Quantum metrology leveraging nitrogen-vacancy centers in diamond offers a compelling technological perspective on how science might eventually probe the otherwise invisible domain of nanoplastics. While still largely in the developmental and laboratory stages, this approach highlights a potential pathway to bypass the diffraction limits of conventional optics and to gather indirect data from within complex environments such as living cells or fluid dynamics. Individual parts of this puzzle—like nano-NMR or cellular radical sensing—have already been proven to work separately. What hasn't been done yet is combining them into a single, direct, and ready-to-use plastic detector. If current engineering and surface noise challenges are successfully overcome, this fusion of quantum tech and computer science will eventually complement—not replace—conventional methods, giving us a powerful tool to study these elusive pollutants in targeted environmental and medical research.

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Thirty-Nine Seconds: Insights from the 2026 Venezuela Earthquake

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His multidisciplinary background in engineering, physical sciences, and data-driven research, together with extensive experience leading interdisciplinary scientific collaborations, enables him to bridge fundamental scientific inquiry with practical approaches to understanding large-scale Earth systems.

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On June 24, 2026, two powerful seismic pulses struck northern Venezuela, separated by less than 40 seconds. The United States Geological Survey (USGS) estimated their magnitudes at 7.2 and 7.5. The ongoing debate among seismologists regarding whether these were two distinct earthquakes or a single complex rupture raises critical questions for seismic hazard assessment. Addressing these questions is essential to reevaluating current seismic hazard assessment methodologies.

On the evening of June 24, 2026, at 6:04 p.m. local time (22:04 UTC), the coast of northern Venezuela was shaken by a powerful initial pulse whose moment magnitude (Mw) USGS seismologists later estimated at 7.2. Less than 40 seconds later, the ground shook again: the USGS estimated the second pulse at magnitude 7.5. The two shocks, separated by less than a minute, occurred in nearly the same area near the town of Yumare in Yaracuy State. They resulted in the country's worst natural disaster in more than a century. Immediately after the shocks, the USGS PAGER rapid assessment system issued a red alert, indicating a high probability of very large losses [1]. The death toll rose as rubble was cleared: by mid-July, authorities had confirmed more than 5,000 deaths, over 16,700 injuries, and approximately 17,800 people left homeless [2]. UN agencies (UNDRR and UN OCHA) estimated direct damage to buildings and infrastructure at approximately $37 billion [3]. A tsunami warning was issued as far away as Puerto Rico and the U.S. Virgin Islands; the shaking was felt in Bogotá, northern Brazil, and the Dominican Republic; and the country's main airport was closed. La Guaira State and the capital, Caracas, were hit hardest, with dozens of buildings collapsing, including multistory apartment buildings.

Search-and-rescue operations in La Guaira, Venezuela, June 28, 2026. Photo: U.S. Marine Corps / Cpl. Daniel Garcia. Public domain.

Beyond the scale of the disaster, these events became the focus of significant scientific debate. The unusual pattern of the earthquake sequence continues to challenge physical interpretation. Understanding this requires an examination of the region's geology. Northern Venezuela is situated within a complex boundary zone between the Caribbean and South American lithospheric plates. These plates move relative to each other at approximately 18–20 millimeters per year, with deformation distributed among several major right-lateral strike-slip faults, primarily the Boconó, San Sebastián, and El Pilar faults (Fig. 1) [4, 5]. While a major earthquake in this zone is not geologically unexpected, such events are rare in the historical record. According to the British Geological Survey, only seven earthquakes of magnitude 6 or greater have occurred in the region over the past century [5]. The last event of comparable strength was the 1967 Caracas earthquake, which had a magnitude of approximately 6.6 and resulted in about 240 fatalities [5]. The mainshock of June 24, 2026, was the strongest earthquake in Venezuela since approximately 1900, making it the most powerful of the entire instrumental era [6]. However, the rarity of large earthquakes does not imply a low long-term hazard, as stress accumulates along these faults for decades before eventual release.

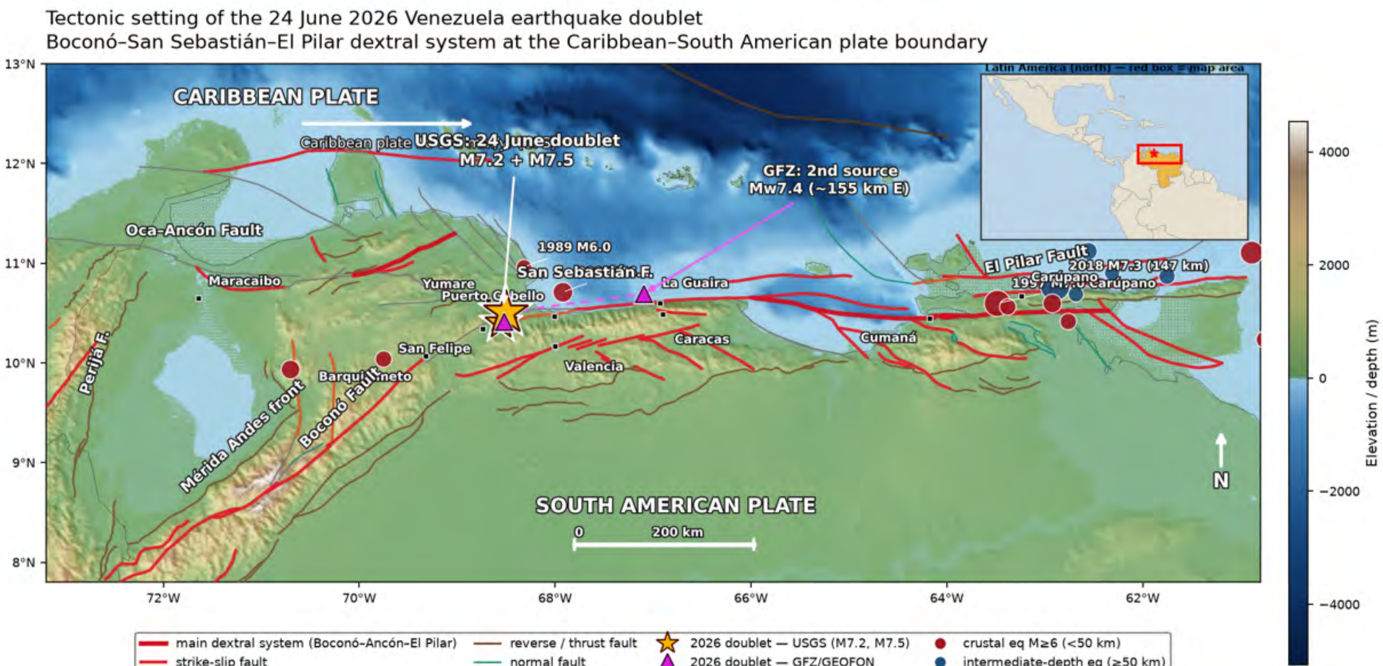

Figure 1.

Tectonic setting of the June 24, 2026, Venezuela doublet: the right-lateral Boconó–San Sebastián–El Pilar strike-slip system along the boundary between the Caribbean and South American plates. Stars indicate the epicenters of the doublet as estimated by the USGS (M7.2 and M7.5); triangles indicate the alternative GFZ/GEOFON solution, which places the second shock approximately 160 km farther east, toward Caracas; circles indicate historical earthquakes of magnitude 6 and above (USGS/ComCat). The background shows land topography and seafloor bathymetry (ETOPO1). Sources and licenses: topography, ETOPO1, NOAA NCEI (public domain); active faults, GEM Global Active Faults Database (Styron & Pagani, 2020), licensed under CC BY-SA 4.0; epicenters and historical earthquakes, USGS/ComCat catalogs (public domain) and GFZ/GEOFON; land boundaries, Natural Earth (public domain). This figure is published under a CC BY-SA 4.0 license.

This pair of earthquakes, what seismologists call a doublet, became the focus of the scientific debate. A doublet is a descriptive term for two events of comparable magnitude that occur close together in time and space, but it is not a strict classification with a single threshold. Typically, the events in a doublet are usually separated by minutes, hours, or even days. In this case, less than 40 seconds elapsed [5].

The difference in magnitude is also telling. Båth's law describes a statistical average: the strongest aftershock is generally about 1.2 magnitude units weaker than the mainshock. In Venezuela, the difference was only 0.3 units (M7.5 versus M7.2), an unusually small gap for a conventional mainshock-and-aftershock sequence. This alone does not prove that the sequence comprised two independent mainshocks, but it clearly departs from the typical pattern. Estimates of the source locations also diverge. The USGS places the two events relatively close together, whereas Germany's national geoscience centre (GFZ) locates the onset of the second subrupture approximately 160 kilometers farther east, closer to Caracas [4]. Until these differences are reconciled, it is premature to conclude that the rupture zones overlap almost completely. The historical parallel is likewise tentative but revealing. Modern researchers reconstruct the events of March 26, 1812, which destroyed Caracas, as two subevents: an approximately M7.4 earthquake on the Boconó fault in the Barquisimeto–San Felipe area, followed tens of minutes later by an approximately M7.1 earthquake on the San Sebastián fault closer to the capital [7]. This demonstrates the region's capacity for cascading ruptures, although it does not establish doublets as a signature feature of any particular fault.

Parameter	Event 1	Event 2
Magnitude (USGS) [1]	7.2	7.5
Magnitude (GFZ) [4]	7.3	7.4
Time (UTC)	22:04:33	22:05:12
Interval	—	39 seconds
Depth	21.9 km	10.0 km
Mechanism	right-lateral strike-slip	right-lateral strike-slip

This raises a central question: were these two earthquakes or a single complex rupture? Rupture during an M7.2 event lasts approximately 30 seconds, so the first rupture might still have been underway when the second shock began less than 40 seconds later. The USGS maintains two separate catalog events and retrospectively identifies the first as a foreshock and the second as the mainshock [8]. The GFZ emphasizes [4] that this division is useful for cataloging purposes, but the sequence may physically have represented a nearly continuous rupture consisting of two subevents.

The European centers INGV (Italy's National Geophysics Institute) and GEOSCOPE (French global seismic network) also favored interpreting the sequence as a single complex rupture of magnitude 7.6–7.8. Similarly, the Global Centroid Moment Tensor (GCMT) catalog recorded the Venezuela doublet as a single event (Mw 7.52). Because the signals overlapped, different agencies obtained substantially different estimates of magnitude and location. Karen Lythgoe, a research fellow at the University of Edinburgh, explicitly considers it possible that this was a single complex event of magnitude 7.6–7.7 rather than two separate events [5]. Seismologist Judith Hubbard of Cornell University is more cautious: a final determination requires “more scientific data” [9].

Several researchers have focused on the physics of the second shock’s almost instantaneous triggering. The most likely general explanation is stress redistribution: slip on the first segment altered the stress state of neighboring segments, and if one was already close to failure, the additional stress change may have been sufficient to initiate the second rupture. Given the extremely short interval, two mechanisms may have operated simultaneously: static Coulomb stress transfer to a neighboring fault and dynamic triggering by passing seismic waves [5]. As Mark Quigley of the University of Melbourne notes, those waves could have “shaken loose” a neighboring segment already under stress [10]. Harold Tobin, director of the Pacific Northwest Seismic Network at the University of Washington, also considers it highly likely that the first earthquake triggered the second [11]. Without a detailed rupture model, however, the sequence cannot yet be attributed to any single mechanism; these remain working hypotheses.

The overlap of two nearly simultaneous ruptures also complicated real-time analysis. The signals from the two subevents became superimposed, different centers obtained different estimates of magnitude and location, and automated systems initially overestimated the magnitude. Disentangling the two sources ultimately required manual and model-based analysis [4, 11]. Preliminary data indicate that the rupture propagated eastward toward Caracas, concentrating energy in that direction. This rupture-directivity effect probably amplified ground motion toward the capital, although it was not the only cause of the destruction.

Rupture directivity also helps explain one of the disaster’s most notable paradoxes: La Guaira, approximately 170 kilometers from the epicenter, experienced more severe damage than Barquisimeto, which is only about 100 kilometers away. The epicenter marks only the initiation point of a rupture. More significant factors include the distance to the entire rupture plane, the direction of rupture propagation, local ground conditions, and building vulnerability. Barquisimeto is located opposite the direction of rupture propagation and is built on hard rock; the observed effects there corresponded to moderate macroseismic intensity levels V–VI on the Mercalli scale.

The Mercalli Scale

The Modified Mercalli Intensity Scale (MMI), developed in 1931 from Giuseppe Mercalli’s original 1902 scale, measures macroseismic intensity, meaning the observed effects of an earthquake at a particular location on Earth’s surface. This differs from magnitude, which characterizes the energy released during the earthquake.

The scale comprises 12 intensity levels, from I to XII:

· I–III: Shaking is not felt or is barely perceptible; only a few observers detect it, primarily on the upper floors of buildings.

· IV–V: Weak shaking is felt by most of the population; furniture and dishes typically vibrate.

· VI–VII: Moderate intensity may compromise structural integrity; masonry can crack and plaster can flake.

· VIII: Significant damage and partial collapse of buildings with low load-bearing capacity.

· IX–X: Severe destruction, including deformation of soil and rock masses.

· XI–XII: Complete destruction of infrastructure, with seismic waves visible at the surface.

Source: USGS Earthquake Hazards Program, Modified Mercalli Intensity Scale

Caracas, despite its greater distance, was situated in the path of eastward rupture directivity, and the soft sedimentary deposits in its valley amplified shaking at certain frequencies. Intensity in Caracas is estimated at level VIII. La Guaira was both near the eastern part of the rupture zone and characterized by particularly vulnerable construction; the observed destruction corresponds to intensity levels IX–X [5]. Mercalli intensity measures observed effects and damage, rather than the energy released by an earthquake. Extreme structural vulnerability exacerbated the physical effects: older buildings constructed under outdated codes, informal housing lacking engineering oversight, and soft-story ground floors used for parking. The combination of rupture directivity, soft soils, and fragile structures ultimately determined the scale of the tragedy.

The sequence had another unusual feature: what did not happen. During the first day, global catalogs showed unusually few moderate aftershocks. By June 26, the German GFZ center had recorded only one event above magnitude 4, although several would normally be expected after an event above magnitude 7 [4].

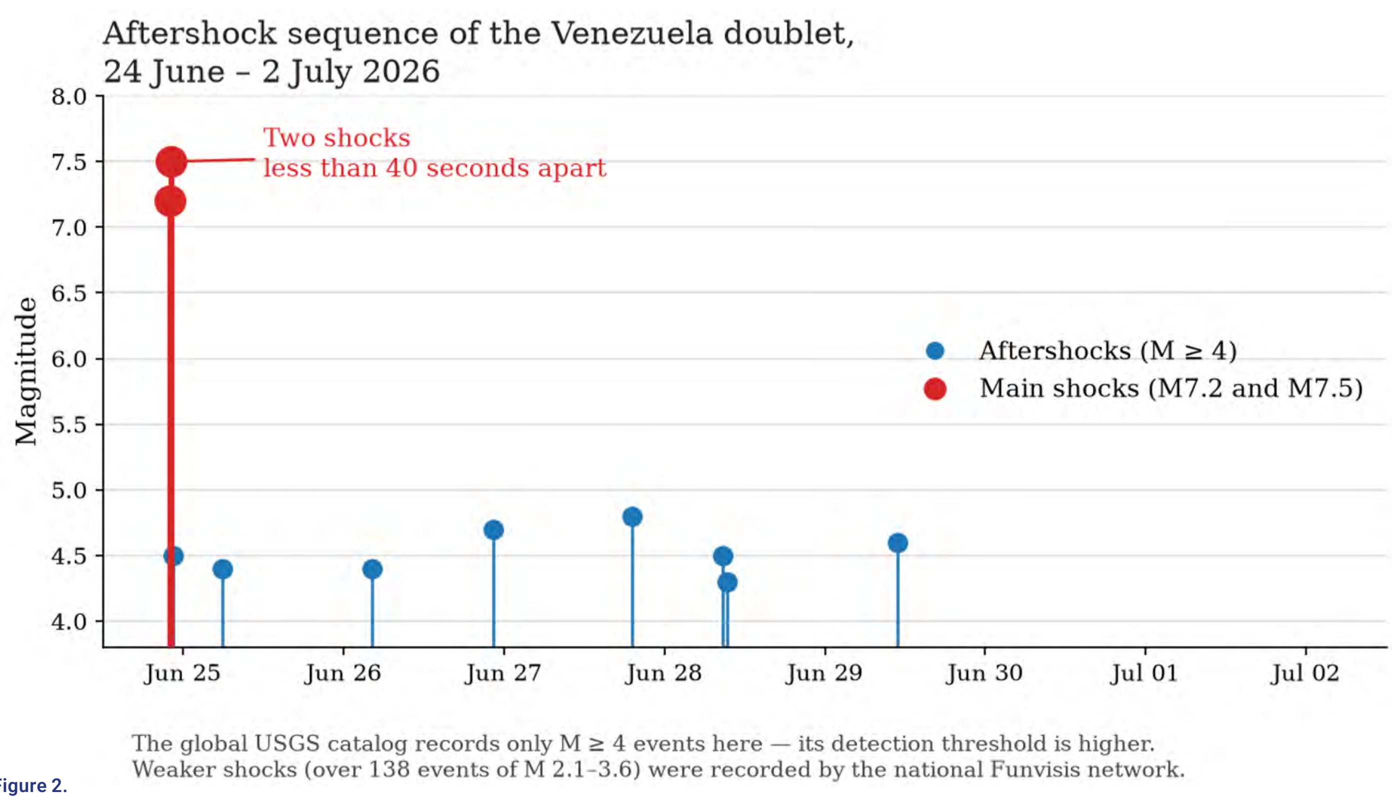

Figure 2.

Aftershock sequence in the global USGS catalog for June 24–July 2, 2026: the two mainshocks and eight aftershocks (M ≥ 4) within a radius of approximately 250 km. Smaller earthquakes recorded by the national Funvisis network (more than 138 events with M2.1–3.6) were absent from the global catalog due to its higher detection threshold.

This was an early observation, not a definitive conclusion that there was an "aftershock deficit." The denser national network Funvisis (Venezuela's national seismological service) recorded many smaller events, more than 138 earthquakes of magnitude 2.1–3.6 by the same date, that global networks may simply have been unable to locate because of their higher detection thresholds [4]. During the first week, the global USGS catalog contained only eight aftershocks of magnitude 4 or greater within a radius of approximately 250 kilometers (Fig. 2), and only three within 100 kilometers of the source. Even moderate aftershocks remained dangerous: they could collapse already damaged buildings, dislodge rubble, and trigger landslides.

These specific anomalies point to a broader, more sobering conclusion. The Venezuela sequence demonstrates that earthquakes can cascade from one fault to another, while, as paleoseismologist Chris Goldfinger of Oregon State University notes, seismic hazard models often consider rupture scenarios involving only a single segment [12]. A classic example of a multifault event is the 2016 Kaikōura earthquake in New Zealand (M7.8). Hamling and colleagues report that the rupture propagated along at least 12 faults over more than 170 kilometers, making it one of the most complex ruptures ever recorded [13]. Contemporary models are beginning to incorporate such cascades. It is therefore more accurate to state that some regional assessments may underestimate the probability and maximum scale of multifault events, rather than exclude them entirely. The Venezuelan case raises a specific question: Has the potential linkage among the Boconó, San Sebastián, and El Pilar faults been adequately considered?

The story also has a global context that has generated considerable speculation. The Venezuela doublet occurred over several days, during which a series of notable earthquakes struck around the world. The sequence began nearly seven hours before the Venezuela event: at 15:10 UTC on June 24, an M5.6 earthquake struck Northern California near Redwood Valley. It was the region's strongest earthquake in decades, but caused no serious damage [1]. The Venezuela doublet followed. Just 26 minutes later, at 22:30 UTC, an earthquake struck off Japan's Iwate Prefecture. The USGS estimated its magnitude at Mw 6.9 [14], while the Japan Meteorological Agency (JMA) assigned it Mj 7.2. These are different magnitude estimates produced by different agencies and methods. Two days later, on June 26, an M6.5 earthquake struck near Sarangani, Philippines. On June 27, a deep M6.1 earthquake at approximately 200 km depth struck the Hindu Kush Mountains of northern Afghanistan and was felt in Kabul and across much of Pakistan [15] (Fig. 3).

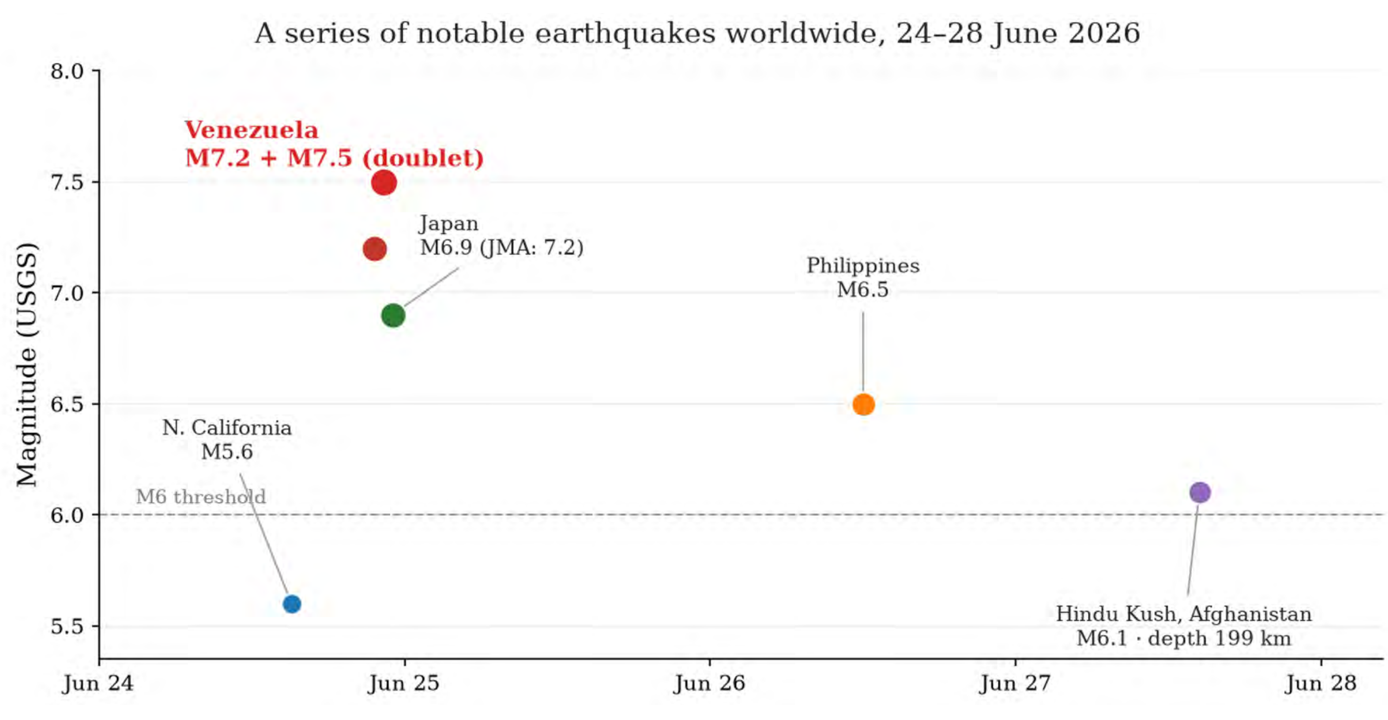

Figure 3.
A series of notable earthquakes worldwide from June 24 to 28, 2026: six felt events on five different tectonic boundaries within five days. Their temporal proximity is striking, but the earthquakes occurred thousands of kilometers apart on different fault systems.

On June 24 alone, three earthquakes of approximately magnitude 7 or greater occurred worldwide, and social media users immediately began discussing a supposed global “awakening” of Earth. But the actual record lets us be precise. Since 1964, the global USGS catalog has never recorded a single day with more than three earthquakes of magnitude 6.9 or greater—and even three earthquakes of this magnitude in a single day have occurred only nine times in more than sixty years. June 24, 2026, marked the ninth such occurrence (Fig. 4).

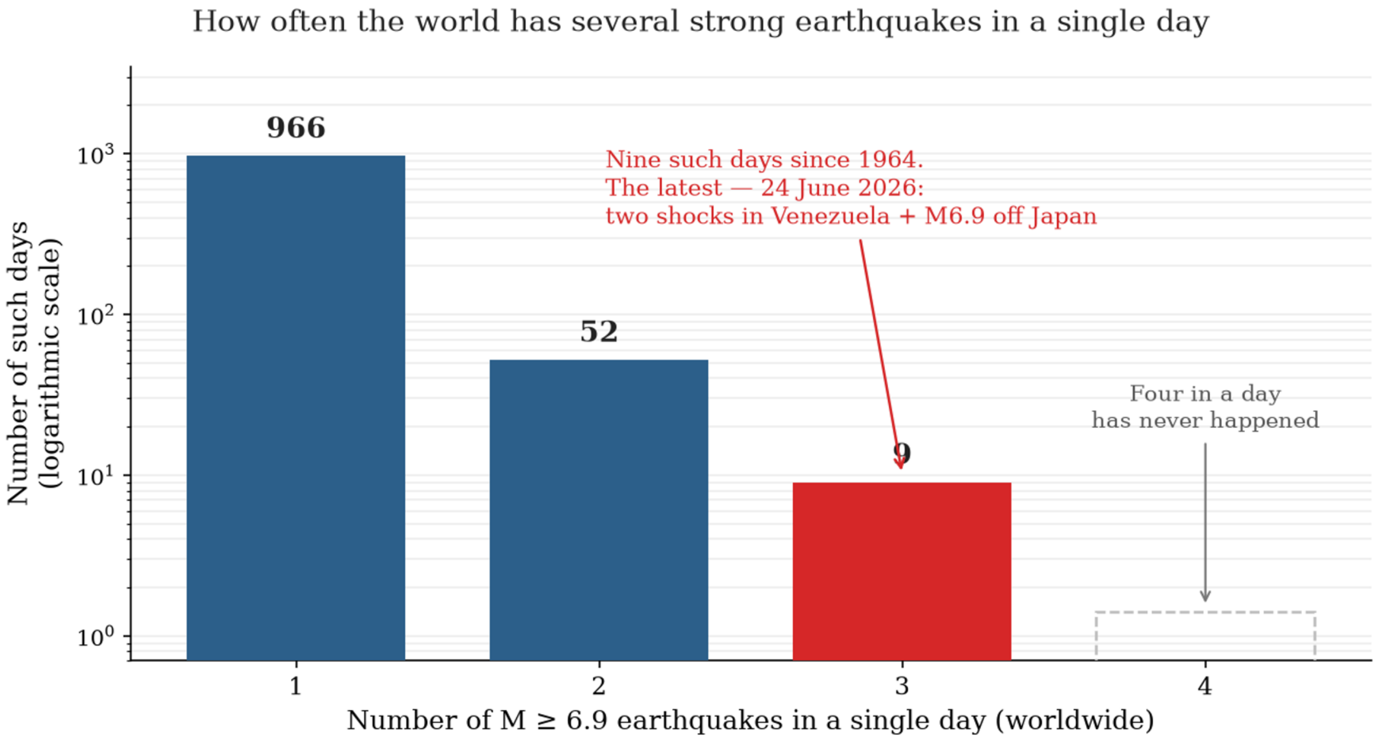

Figure 4.

Frequency of multiple major earthquakes worldwide within a single day. According to the global USGS/ComCat catalog, since 1964, there have been 52 days with two earthquakes of magnitude 6.9 or greater and only 9 days with three; no day has had four. June 24, 2026, was the ninth “triple” day in 62 years of observations. The vertical axis uses a logarithmic scale.

What distinguishes June 24, 2026, is that these three earthquakes above magnitude 6.9 were not part of a single aftershock cascade. Two of them were the Venezuela doublet; the third struck off Japan 26 minutes later, on a different plate boundary thousands of kilometers away (Fig. 5).

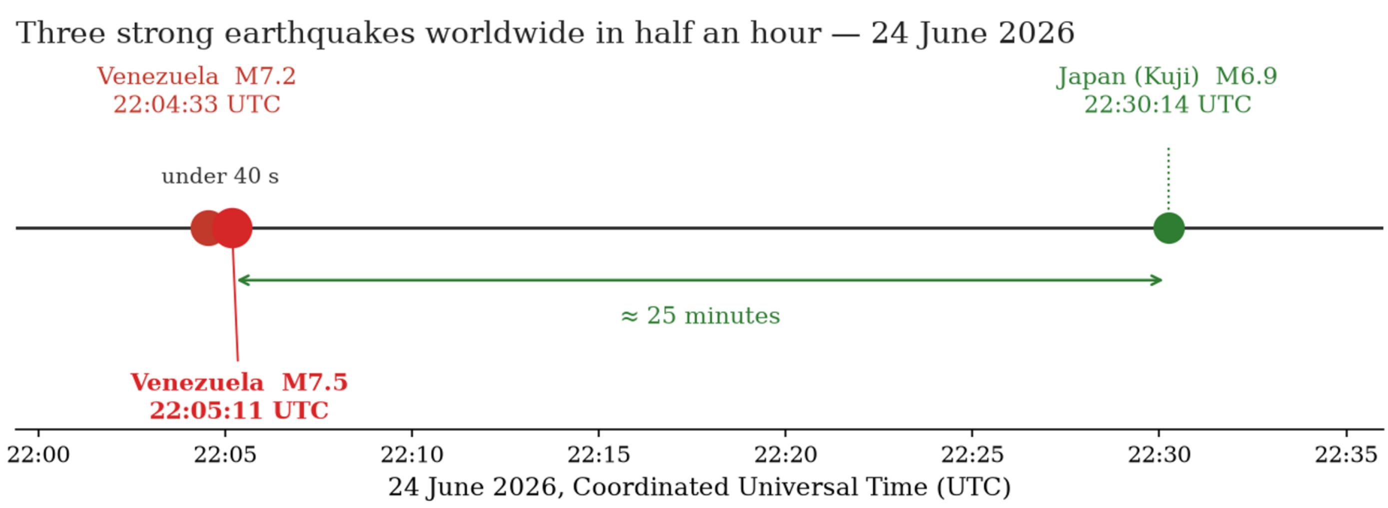

Figure 5.

Three major earthquakes occurred worldwide within half an hour on June 24, 2026: the two earthquakes of the Venezuela doublet were separated by less than 40 seconds, and an M6.9 earthquake struck off Japan 26 minutes after the first Venezuelan shock.

The more important point is that this was a statistical rarity, not evidence of a common physical process. William Barnhart of the USGS Earthquake Hazards Program described the near-simultaneous earthquakes in California, Japan, and Venezuela as a random coincidence [14, 16]. According to Martin Hudson of the University of California, Los Angeles, a century of observations has not established any causal connection between earthquakes separated by such great distances [16].

The distinction between the two mechanisms is fundamental. Static Coulomb stress changes decay rapidly with distance and are significant only near a rupture, whereas surface waves can, in theory, trigger distant earthquakes dynamically. Temporal coincidence alone, however, does not demonstrate such triggering. Judith Hubbard of Cornell University noted that surface waves from the M7.5 Venezuela earthquake could have physically reached Japan before the Japanese earthquake began, making this scenario theoretically possible. She emphasized, however, that the Iwate region was already under elevated stress following an M7.5 earthquake in December 2025, and the Japanese M6.9 event fits logically within its own regional sequence [8, 9].

The exceptional nature of the Venezuela doublet becomes clear only when it is compared with global statistics. By three independent measures, it lies near the extremes of the relevant distributions. The first measure is temporal proximity. We compiled a catalog of 60 doublets of magnitude 7 or greater from 1970 through 2026, selecting pairs with a magnitude difference of no more than 1.0, a separation of less than 150 kilometers, and an interval of less than 30 days. Against this background, the Venezuelan shocks, separated by less than 40 seconds, have the shortest interval in the entire sample. The next-shortest case, recorded near the South Sandwich Islands, had an interval of 2.4 minutes, four times longer. Earthquakes in a typical M7+ doublet are separated by hours. Depending on how a doublet is defined, the median interval is approximately half a day (about 14–20 hours). Venezuela's 39-second interval is thousands of times shorter (Fig. 6).

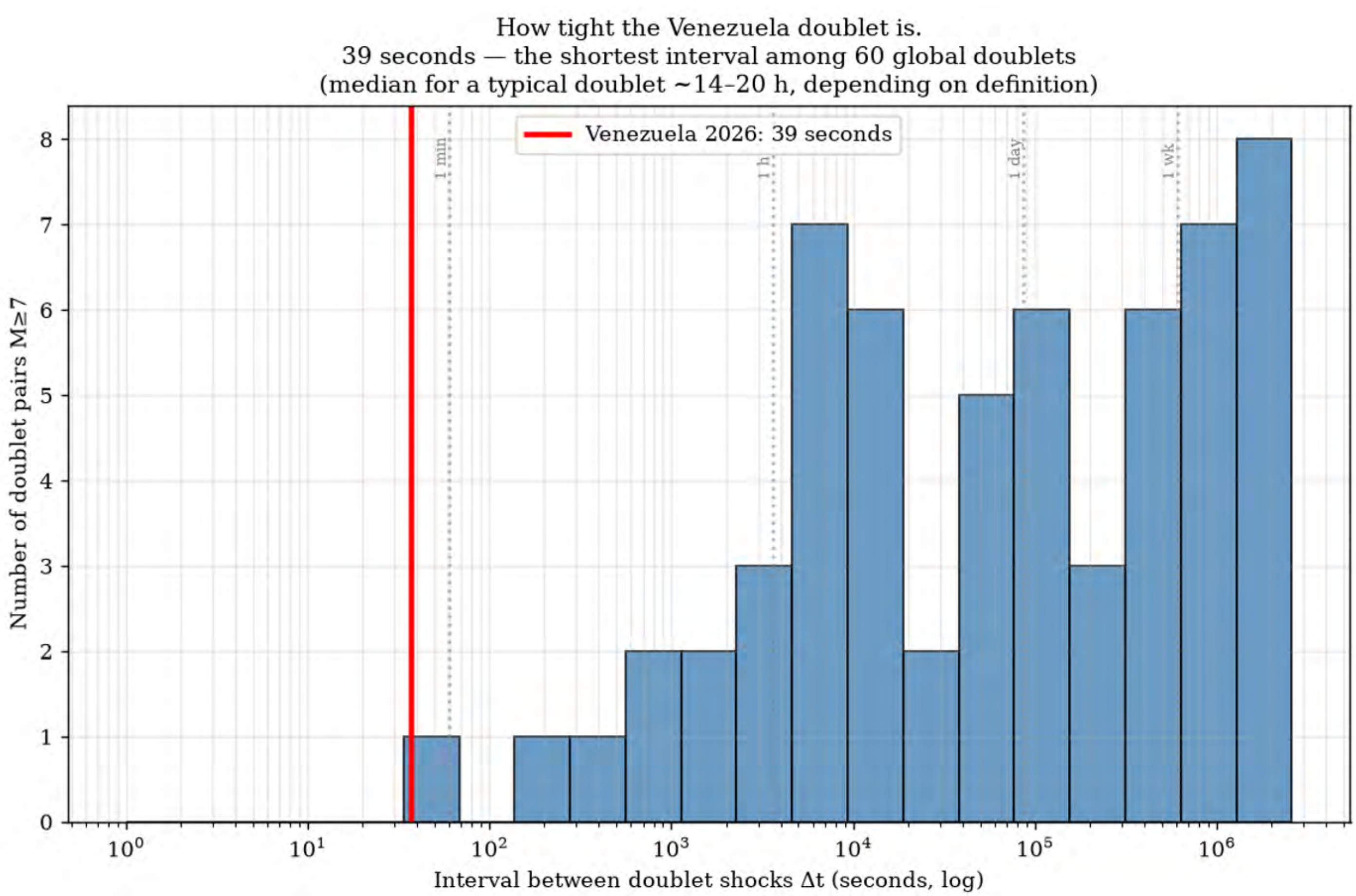

Figure 6.

Distribution of intervals between the two earthquakes in global doublets of magnitude 7 or greater from 1970 through 2026 (60 pairs). The Venezuela interval, shown by the red line, is the shortest in the entire sample; the next-shortest interval was four times longer.

The second measure is the unusual quiet that followed the mainshocks. A major earthquake is usually followed by a swarm of aftershocks; sequences that produce more aftershocks are considered more "productive." To compare events consistently, seismologists apply a common criterion: the number of aftershocks of magnitude 4.5 or greater that occur during the first week within a spatial window approximately one rupture length across. The Venezuela pair produced only one such earthquake, an exceptionally low number. Among comparable strike-slip earthquakes of magnitude 7.2–7.8, most produce far more aftershocks, averaging approximately 14. Thrust earthquakes average approximately 29. Venezuela ranks near the bottom of this distribution: only about one-fifth of comparable events (approximately 18–22%) produce as few aftershocks or fewer (Fig. 7). Some of this quiet can be explained. During the first hours, the national station network operated intermittently, and strike-slip ruptures generally produce fewer aftershocks. Even so, an observational gap alone cannot explain the complete absence of earthquakes of magnitude 4 or greater near the rupture zone during the first day after an M7.5 event.

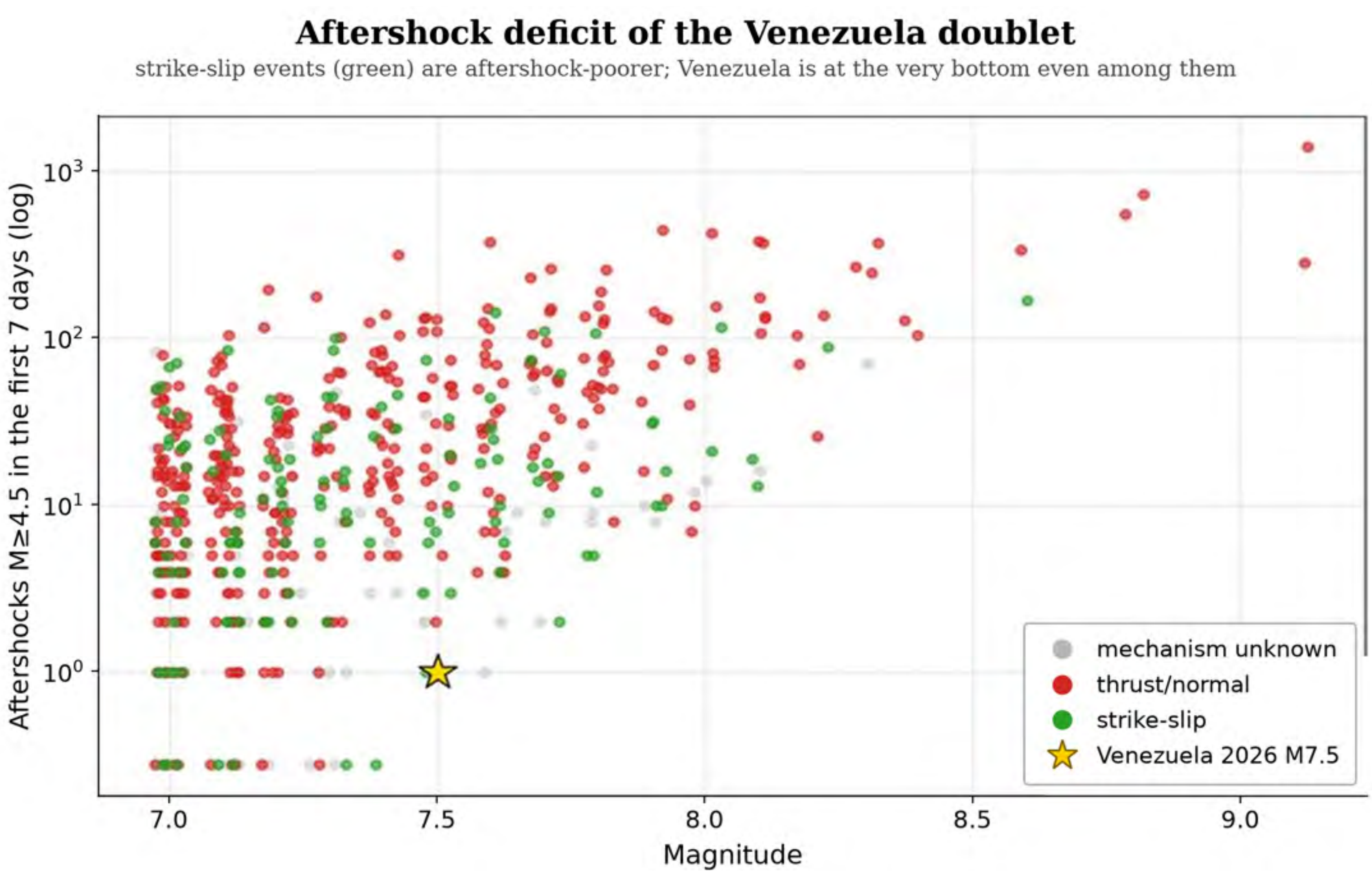

Figure 7.

Aftershock productivity, defined as the number of earthquakes of magnitude 4.5 or greater during the first week within a spatial window approximately one rupture length across, plotted against mainshock magnitude; color indicates focal mechanism. The Venezuela doublet, marked by a gold star, lies in the lower portion of the distribution at approximately the 20th percentile, or the lowest fifth of the sample.

The third measure is the unusually large magnitude gap between the mainshock and its strongest aftershock. Seismologists use a simple empirical rule, Båth's law: the strongest aftershock is usually about 1.2 magnitude units weaker than the mainshock. For Venezuela, if the second mainshock is excluded and the strongest of the smaller subsequent events (M4.5) is used, the gap is 3.0. In other words, the strongest aftershock was not merely weaker than usual but anomalously weak. Such a large gap is extremely rare: among earthquakes of magnitude 7 or greater, only about 1% have a value this large or larger (Fig. 8). Taken together, the three measures indicate that the Venezuela sequence behaved not like a conventional mainshock-and-aftershock sequence, but like two nearly equal primary shocks followed by almost no conventional aftershock sequence.

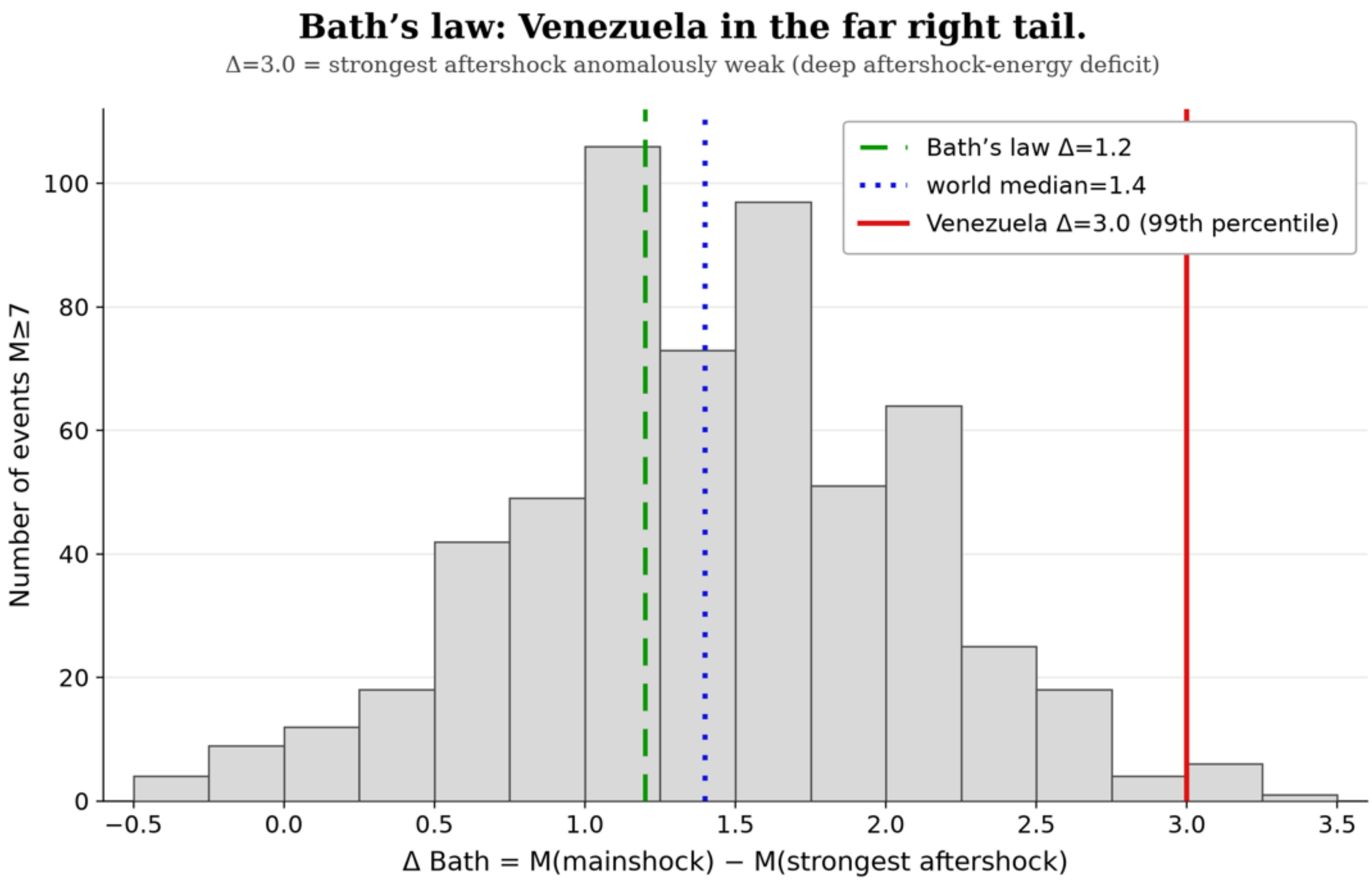

Figure 8.
Distribution of the Båth's-law magnitude gap, defined as the difference between the mainshock magnitude and the magnitude of the strongest aftershock, for earthquakes of magnitude 7 or greater. The Venezuela value of 3.0 lies in the extreme right tail of the distribution and corresponds to the 99th percentile.

Ultimately, the most sobering lesson of the Venezuela disaster lies not in tectonics but in human vulnerability. Strong ground motion became catastrophic where high population density, old or structurally weak buildings, unstable soils, and limited response capacity coincided. It would be inaccurate to describe the country as entirely "scientifically blind": the Funvisis network continued to record earthquakes and provided a more detailed local catalog. Questions remained, however, about the condition of some equipment, the accessibility of data, and the speed of public alerts. A significant portion of the housing stock was constructed before earthquake-resistant building practices became standard, while the recent economic crisis limited inspections and retrofitting of older buildings. As Goldfinger notes, many buildings around the world were constructed before modern plate tectonics was understood, and retrofitting the building stock of entire cities for seismic resilience remains an extraordinarily difficult task [12].

The official address to the nation came more than two hours after the earthquakes. Timely public communication was hindered by a disrupted communications infrastructure and the closure of hundreds of local media outlets in the preceding years. Moreover, buildings had been designed for expected ground-motion parameters, while a shallow earthquake with a rupture directed toward the capital exceeded the design basis of a significant portion of the building stock.

The primary conclusion from the 39 seconds on June 24 is the significant impact of vulnerability. This disaster offers insights with relevance beyond national boundaries. As observed in Venezuela, the Earth does not always release accumulated stress through a single, discrete shock; instead, stress may be released through an interconnected cascade of ruptures that is difficult to classify in real time and does not conform to conventional hazard models. While seismologists continue to debate whether this was one event or two, the mechanism that triggered the second shock, and the scarcity of moderate aftershocks, the practical implications remain unchanged.

Seismic risk maps should incorporate scenarios in which rupture propagates from one segment to another and from one fault to another. The maintenance and density of monitoring networks, as well as the open availability of their data, are essential. Buildings in seismically hazardous areas should be designed and retrofitted to withstand earthquakes that have not occurred in recent history. Although science cannot yet predict the exact time, location, or magnitude of an earthquake, it is increasingly capable of explaining where and why cities collapse. This understanding provides the most effective means of reducing the toll of future disasters, whose countdown is always measured in seconds.

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The Ocean Is Storing Heat: Why 2026 Could Bring One of the Strongest El Niños on Record

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Anastasiya Pashigreva, Ph.D., is a chemist and interdisciplinary researcher with expertise in sustainable technologies, environmental systems, and climate science. Throughout her career, she has worked at internationally recognized institutions, including the University of Oxford, the Technical University of Munich, DuPont, and Bayer contributing to the development of innovative technologies that advance industrial sustainability and reduce environmental impact.

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Weather agencies are warning that by winter the Pacific could unleash an extreme El Niño. Here is what the phenomenon is, why such events are intensifying, and what the last one, in 2023/24, resulted in.

An Official Advisory

In the summer of 2026, the U.S. National Weather Service did something it does only rarely: it issued an official El Niño Advisory [1]. El Niño is developing in the tropical Pacific and, according to the forecast, "is predicted to intensify to a moderate or strong level this fall." In its July 9, 2026, outlook, NOAA placed the probability of a "very strong" El Niño at its October–December peak at 81%, confirming expectations and pointing to one of the largest events since 1950 [2]. So what exactly is this phenomenon?

What El Niño Is

El Niño (Spanish for “boy”) is the warm phase of a large-scale climate “pendulum” in the Pacific that scientists call the El Niño–Southern Oscillation, or ENSO. In ordinary years, the trade winds drive sun-warmed water westward along the equator toward Indonesia, while off the coast of South America cold deep water rises to take its place—an upward motion known as upwelling. During El Niño the trade winds weaken, the warm water spreads back toward the east, and an enormous pool of anomalously warm water forms over the central and eastern equatorial Pacific. The opposite, cold phase is called La Niña (Spanish for “girl”): the trade winds strengthen, upwelling off South America intensifies, and the eastern Pacific becomes markedly cooler than usual. El Niño and La Niña are the two poles of this single “pendulum” oscillation.

This regular alternation of warm and cold phases stands out clearly across the half-century record of the Oceanic Niño Index (ONI) [3] (Fig. 1). This index measures an event’s strength: it is the averaged departure of sea surface temperature in a reference region from the climatological norm. A value of +0.5 °C or higher signals El Niño, and the threshold for a “very strong” event is taken to be +2.0 °C.

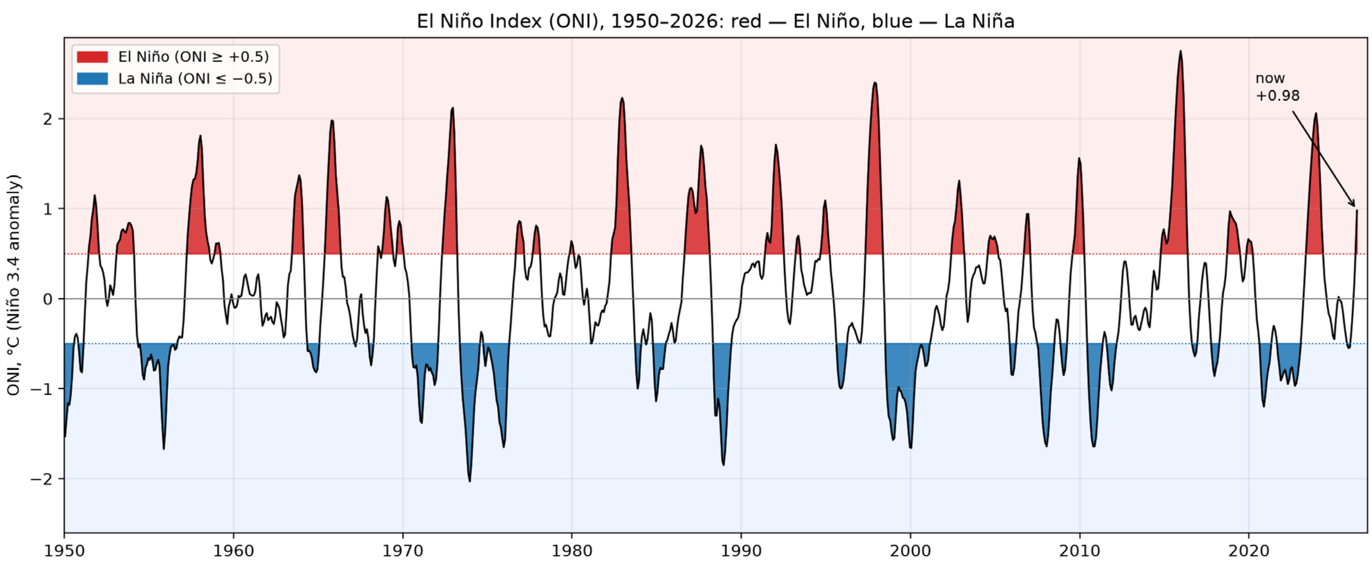

Figure 1.
The El Niño index (ONI) from 1950 to 2026: red indicates El Niño phases, and blue indicates La Niña. The ENSO “pendulum,” the regular alternation of warm and cold phases, is clearly visible (computed from NOAA CPC data).

In broad strokes, the mechanism of this “pendulum” works as follows. In neutral years the trade winds push warm water toward the western Pacific. When the trade winds weaken or briefly reverse (episodes called westerly wind bursts), a slow internal wave known as a Kelvin wave begins to travel eastward across the ocean. It deepens the thermocline, the thin boundary between the warm surface layer and cold deep water, and off the coast of South America the cold water stops rising to the surface. The warm water spreads eastward and reaches the surface, and the zone of heavy thunderstorms shifts along with it. The more heat stored beneath the surface and the farther east it travels, the stronger the event. This is how every El Niño works; in strong years, such as the current one, what is unusual is not the mechanics themselves but the scale of the subsurface anomaly and how far east the region of extreme warmth reaches. That is why it is necessary to examine not only the ocean surface but also the heat stored at depth (Fig. 2).

The event may seem local, yet its consequences are global. The zone of powerful tropical convection moves eastward with the warm water. These are the same heavy thunderstorms that transfer colossal amounts of energy into the atmosphere. When the convection shifts, jet streams reorganize across the planet, changing weather patterns: droughts arrive in some places, floods in others. That is precisely why El Niño is felt on every continent, and not only off the coast of Peru.

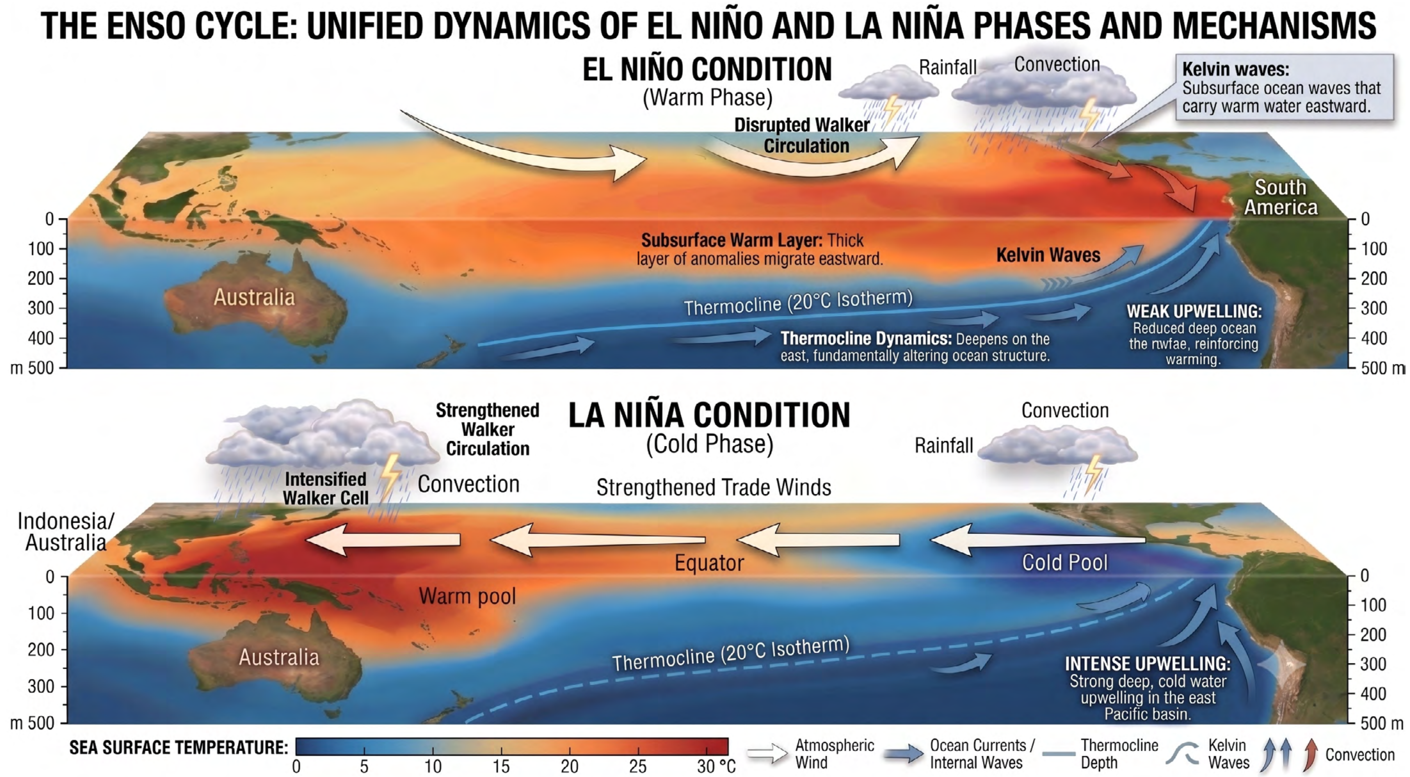

Figure 2.

Simplified conceptual scheme of the ENSO cycle: a cross-section of the upper Pacific Ocean along the equator, with Indonesia and Australia to the west and South America to the east. The top panel shows the El Niño (warm) phase, in which the trade winds weaken, warm water and convection shift eastward, the 20 °C isotherm (thermocline) deepens and flattens, and upwelling off South America is suppressed. The bottom panel shows the La Niña (cold) phase, in which the trade winds strengthen, the warm pool is confined to the west, a cold tongue and intense upwelling develop in the east, and the thermocline in the east is raised. Colour indicates water temperature on a schematic scale of roughly 5–30 °C, where red denotes warm water and blue denotes cold. The diagram illustrates the mechanism rather than real proportions: depths, distances and the placement of features are schematic and not to scale, and no specific temperature or anomaly values are implied.

Why the Current El Niño Could Become So Strong

The extent of the current El Niño will become clear by autumn. But the initial conditions are already unusual, and here is why. First, a strong event is forming only two years after the previous extreme El Niño of 2023/24 and immediately following the rare "triple" La Niña of 2020–2023, when the cold phase of ENSO persisted for three winters in a row instead of the usual one or two [3] (Fig. 3). The ocean swung from the cold phase into the warm one unusually fast. Second, this time, international models are unusually consistent in indicating that the event will be at least strong.

Climatologist Daniel Swain, author of the popular science blog Weather West, gave his June 11, 2026, analysis the blunt title: "Rising odds of a strong-to-historic El Niño event in 2026." In his words, the latest results from international model ensembles are "depicting at least a 'strong' event, and the majority indicating a top-tier, very strong-to-historic event" [4]. In other words, this is not an ordinary fluctuation but a potentially record-setting phenomenon.

It is the combination of the rapid transition between El Niño and La Niña and the consistency of model forecasts that is raising concern among meteorologists.

Early observations are already confirming these concerns. On individual days in early July 2026, the daily temperature anomaly in the Niño-3.4 region, according to OISSTv2.1 data, approached +2.0 °C. This had never happened so early in the satellite era: even in the powerful year of 1997 the anomaly held at only about +1.0 °C by early July, and that El Niño did not reach the +2.0 °C threshold until September. In terms of its strength this early in the year, the present warming is unprecedented; the central Pacific is now warmer than has ever been observed for this time of year. Here it is worth distinguishing between metrics. The official ONI index, averaged over three months, remains at the threshold of the moderate category (+0.98 °C, the upper bound of the weak El Niño category), while NOAA forecasters place the "very strong" event threshold of +2.0 °C at the winter peak, so July values above +2.0 °C reflect daily spikes

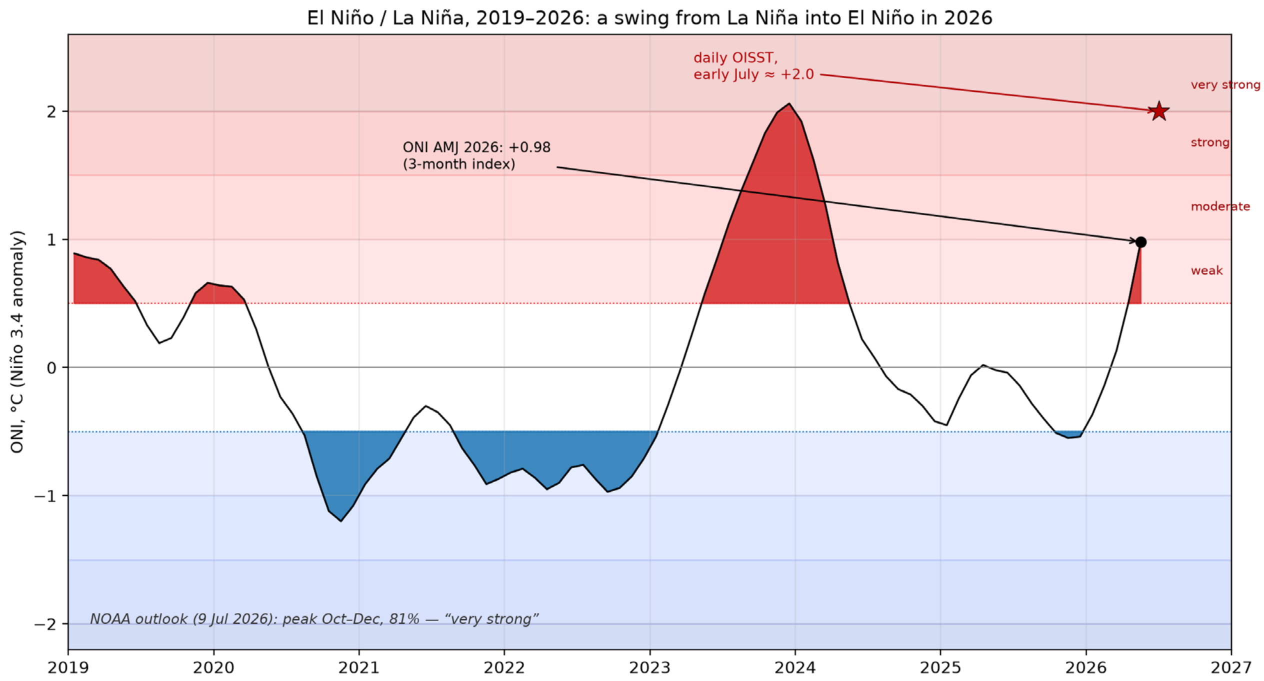

Figure 3.
The El Niño index (ONI) in 2019–2026. Red indicates El Niño phases, and blue indicates La Niña. After the triple La Niña of 2020–2023 and the strong El Niño of 2023/24, the ONI is rising again in 2026: the ocean is once more shifting into its warm phase (NOAA CPC data).

rather than a seasonal category. Even so, the changes are visible to the naked eye: the cold tongue off the coast of South America has almost disappeared, and the pool of water warmer than 30 °C has migrated eastward of the International Date Line, consistent with observations by Eric Webb and Paul Roundy [5]. On the graph itself this is immediately apparent: the bold 2026 line runs above the cloud of prior years for almost the entire season and stays near its upper edge, whereas in ordinary years the water is already noticeably cooler by July (Fig. 4).

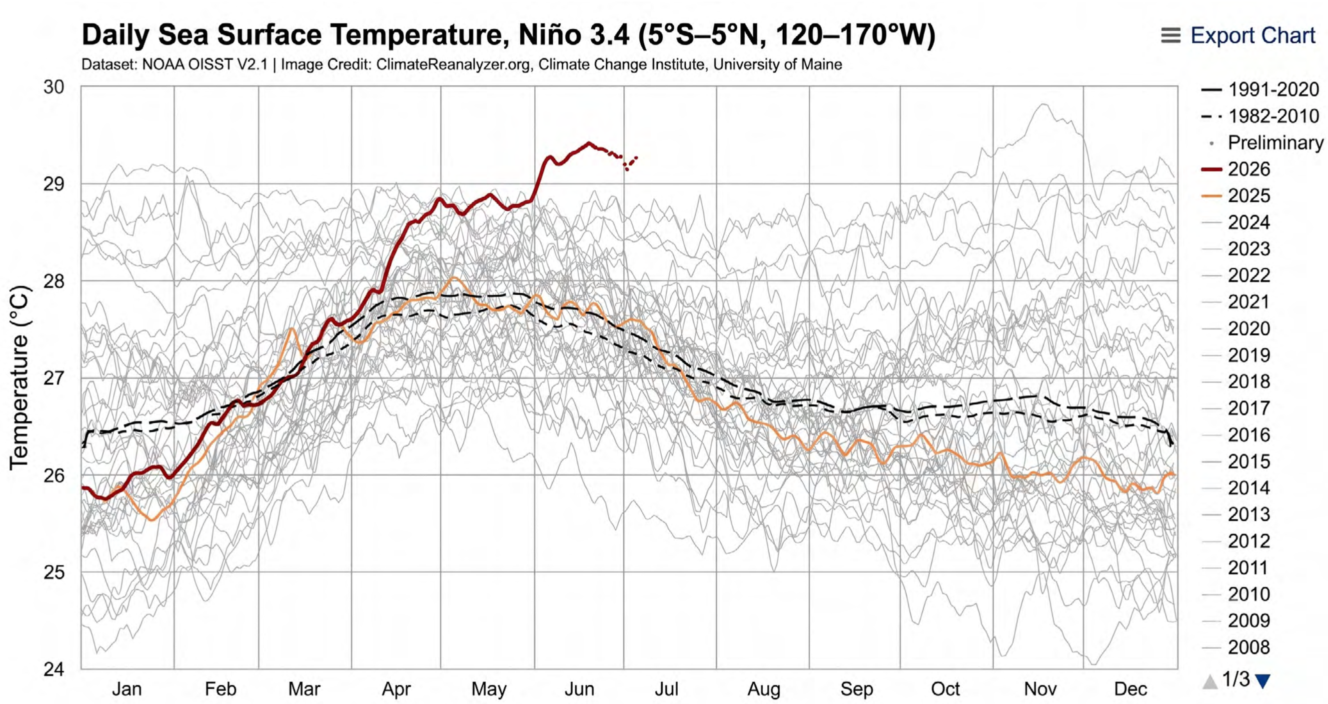

Figure 4.
Daily sea surface temperature in the Niño-3.4 region (5°S–5°N, 120–170°W). The bold line represents 2026 and runs above all previous years for this point in the season, indicating the unusually early and strong warming (NOAA OISSTv2.1 data; ClimateReanalyzer, Climate Change Institute, University of Maine; data as of late June 2026).

But the most important thing is unfolding beneath the ocean surface. Westerly wind bursts have generated a Kelvin wave, which has already pushed an enormous reservoir of warm water with anomalies of four to six degrees beneath the thermocline; a volume this large, lying this deep, has not been seen in several decades [2]. For now this heat is accumulating at depth in the eastern Pacific, and as it rises toward the surface, it feeds the strengthening El Niño.

Why Extreme El Niños Are Intensifying

El Niños occur on average once every three to four years. Over the past two decades, however, the character of El Niño events has begun to change: the most powerful, "extreme" events are becoming stronger. Our analysis of the official ONI record since 1950 [3] shows that the five strongest El Niños in the entire instrumental record, with peaks above +2.0 °C, are 1972/73, 1982/83, 1997/98, 2015/16, and 2023/24. Four of these five occurred within the last forty-odd years, and the two most intense of the entire record, 1997/98 and 2015/16, occurred during the era of pronounced global warming (Fig. 5).

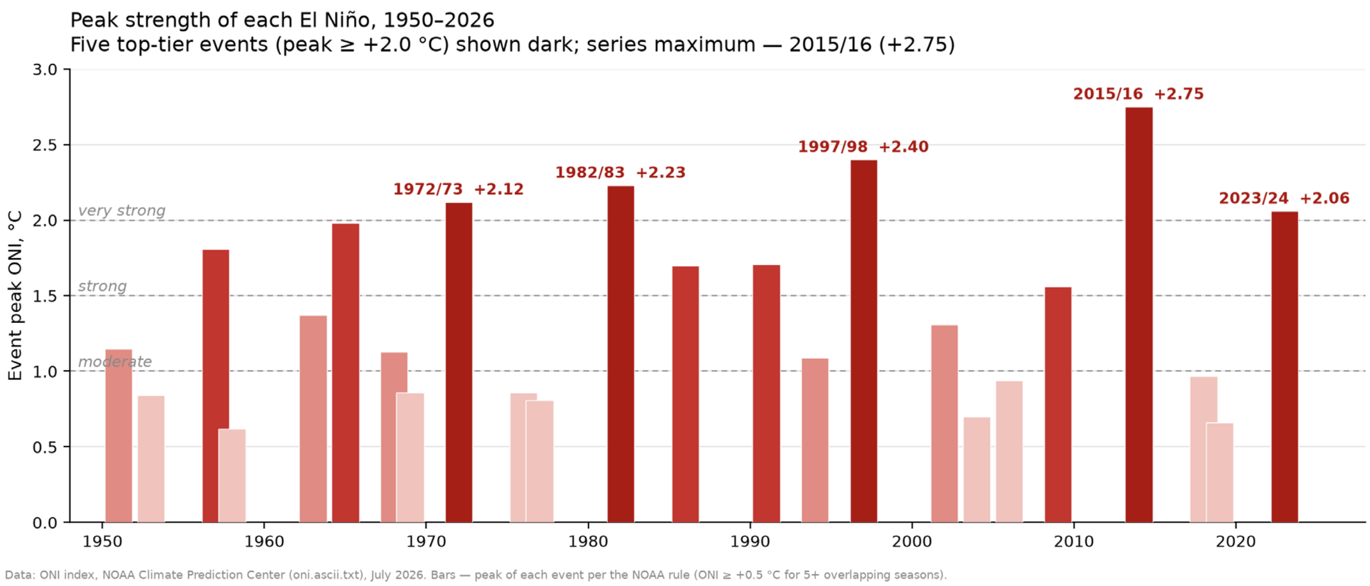

Figure 5.
The peak strength of each El Niño since 1950 by the ONI index. The five most powerful events (dark red, with peaks ≥ +2.0 °C) occurred in 1972/73, 1982/83, 1997/98, 2015/16, and 2023/24. The intensity of the extremes is increasing, not the frequency of El Niños themselves (computed from NOAA CPC data).

This is not only an observed pattern but also a theoretical projection. In 2014, Nature Climate Change published what has since become a landmark paper by Wenju Cai, a chief research scientist at CSIRO, and colleagues. The study concludes that the frequency of extreme El Niños will be "doubling in the occurrences in the future in response to greenhouse warming." The mechanism is not straightforward. It is not simply a matter of uniform warming, but of the fact that the eastern equatorial Pacific, according to model projections, warms faster than the surrounding waters, and this makes it easier to trigger that same powerful convection in the normally cold and dry eastern sector [6]. Put simply, a warmer ocean more readily "flips" into the extreme regime.

There is yet another reason today's extremes are breaking records: the current El Niño is unfolding against the backdrop of an already warmer ocean, whose heat content breaks records year after year (Fig. 6).

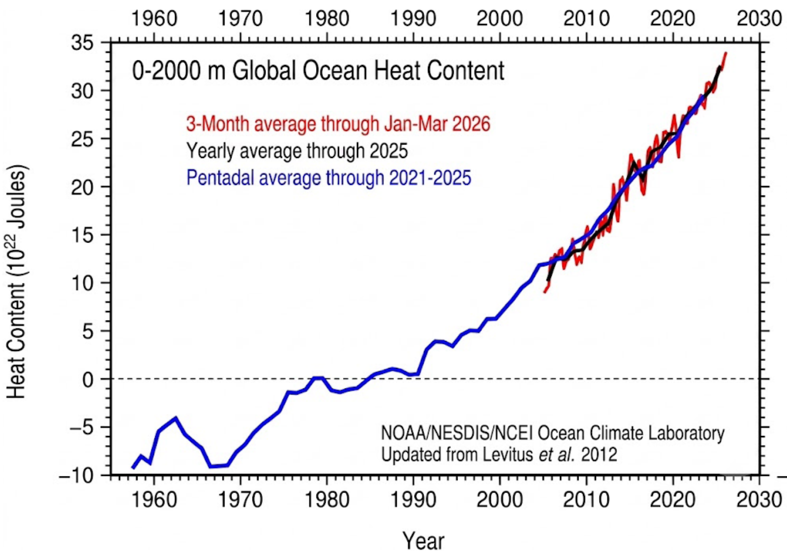

Figure 6.
The heat content of the upper global ocean (0–2,000 m) continues to rise: in 2025 it once again reached a record high. Shown are three-month, annual, and five-year averages beginning in 1955; the data run through early 2026. Source: NOAA/NESDIS/NCEI Ocean Climate Laboratory (public domain): https://www.ncei.noaa.gov/access/global-ocean-heat-content/.

The same +2.5 °C anomaly in 2026 means a higher absolute water temperature than the same anomaly in 1998, because it is superimposed on a warmer baseline than existed during the 1997/98 and 2015/16 events. By the estimate of the mathematician and climate analyst Eliot Jacobson, by July 2026 the sea surface temperature anomaly in the Niño-3.4 region had reached approximately 3.6 standard deviations above the 1991–2020 baseline—a magnitude virtually unattainable without greenhouse warming [7]. Here it's important to clearly distinguish between two metrics. The ONI index measures deviation from the norm, but the norm itself is rising year after year, so the same deviation today means warmer water than it did before. What is more, raising an already-warm ocean by the same number of degrees takes more energy, and warmer water gives that heat back to the atmosphere faster. As a result, an event with a formally more modest ONI peak — 2023/24 compared with 2015/16, for instance — can carry more energy than the index alone suggests.

A caveat about the indices is warranted. For this reason, in February 2026, NOAA shifted its official ENSO monitoring to a new index—RONI (the Relative Oceanic Niño Index) [8]: it subtracts the ocean's background warming from the measured temperature and therefore compares the strength of events from different decades more fairly. All the graphs in this article are built on the classic ONI, used consistently across the entire record since 1950; at the same time, NOAA's recent forecast of an 81% probability is already tied to the thresholds of the new index [9].

What the Last Extreme El Niño, 2023/24, Set in Motion

The significance of the current situation becomes clear when compared with the previous major El Niño event. The El Niño of 2023/24 was superimposed on long-term warming, resulting in record-breaking conditions. The Copernicus Climate Change Service (C3S) confirmed this: "2024 is confirmed by the Copernicus Climate Change Service (C3S) to be the warmest year on record globally, and the first calendar year that the average global temperature exceeded 1.5°C above its pre-industrial level" [10]. The World Meteorological Organization estimated the anomaly at about 1.55 °C [11]. Scientists emphasize that the primary driver was human-induced climate change, while El Niño temporarily amplified the warming and helped push temperatures to record levels against the background of the long-term trend [10].

These temperature records had tangible consequences. At the peak of the 2023/24 warmth, the fourth global coral bleaching event on record unfolded, and NOAA officially announced widespread bleaching across the planet's reefs [12]. By the time the event was declared over in 2025, bleaching-level heat stress had affected 84% of the world's coral reef area, across reefs in all three ocean basins that contain coral [13]. Bleaching happens when an overheated coral expels the algae living within it and, deprived of nourishment, risks dying.

But reef bleaching was only one of the consequences. In the Amazon, a prolonged drought led to record-low river levels: in October 2024, the level of the Rio Negro at Manaus fell to its lowest mark since measurements began in 1902, severely disrupting navigation on the Amazon's tributaries [14]. In southern Africa, the drought took on the scale of a humanitarian disaster: Zambia, Zimbabwe, and Malawi declared national emergencies, and tens of millions of people were at risk of food shortages [15]. In Canada, the 2023 wildfire season was record-breaking: according to a revised satellite estimate, the fires covered about 15 million hectares, more than double the previous maximum, set in 1989 [16]. The risk of such extreme events remains in 2026, as international meteorological organizations warn [17].

What El Niño Does Not Explain

But the story of 2023/24 has a second, far more mysterious side. The warmth of those years exceeded even what scientists expected after accounting for both the approaching El Niño and long-term warming. The climatologist Gavin Schmidt, director of the Goddard Institute for Space Studies (NASA GISS), stated this directly in the subtitle of a March 2024 article in Nature: "Taking into account all known factors, the planet warmed 0.2 °C more last year than climate scientists expected." In the article itself, he wrote: "It's humbling, and a bit worrying, to admit that no year has confounded climate scientists' predictive capabilities more than 2023 has" [18].

Later, Schmidt spoke even more candidly: "Warming in 2023 was head-and-shoulders above any other year, and 2024 will be as well. … I wish I knew why, but I don't. We're still in the process of assessing what happened and if we are seeing a shift in how the climate system operates" [19]. For a field grounded in predictive modeling, such an acknowledgment is especially significant.

The issue is not limited to El Niño or the tropical Pacific. John Abraham, a professor at the University of St. Thomas who studies ocean temperature, put it this way: "I do fear there may be something else going on that is causing a long-term change in sea surface temperatures we hadn't predicted" [20]. Record heat was observed far from El Niño's usual "domain": in the North Atlantic, the North Pacific, the Southern Ocean, and the Indian Ocean—and in different basins at different times. In the North Atlantic, the records began as early as March 2023, before the peak of El Niño, while the Niño-3 and Niño-3.4 indices themselves were not record-setting at all in 2023, even though global ocean temperature was breaking records [21-23].

Simple arithmetic shows the size of the gap. In the WMO report "State of the Global Climate 2024," Schmidt and climatologist Zeke Hausfather prepared a special assessment. They quantified the known external factors for 2023: the contribution of El Niño of about +0.01 °C, the shift to cleaner shipping fuel (that is, fewer reflective sulfates) of 0.03 to 0.08 °C, the eruption of Hunga Tonga of about −0.02 °C, and a small solar contribution. Even together, these standard factors still do not fully account for the anomaly [18, 24]. This indicates that part of the signal remains unexplained.

The leading candidate today for this missing link is the planet's reflectivity. Goessling and colleagues show that the known drivers, including ongoing warming and the onset of El Niño, cannot fully explain the jump of about 0.2 K, and identify record-low planetary albedo, driven primarily by a decrease in low cloud cover, as the factor that closes the gap [25]. But both the authors of that work and the authors of the "multi-basin" studies acknowledge the same limitation: a complete attribution has not yet been established.

Therefore, this gap in understanding is real, and leading climatologists themselves acknowledge it. Understanding what made 2023 a year of "El Niño plus something else," beyond both El Niño itself and the known factors, is today one of the most pressing open questions in climate science. As for the 2026 El Niño, NOAA forecasts its peak for autumn and early winter, and we will see whether the "very strong" scenario is borne out. We will return to this question when the ocean has its say.

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Kamchatka’s 2025 Mega-Earthquake in Global Context

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One of the ten strongest earthquakes in the history of instrumental observation occurred on the same fault segment as the giant 1952 event, and its aftershock sequence proved to be among the most prolific of the great megathrust earthquakes of the modern era. A numerical analysis can determine just how anomalous this sequence was.

On July 29, 2025, the seafloor off the eastern coast of the Kamchatka Peninsula shifted by more than nine meters, releasing one of the largest known pulses of seismic energy. The earthquake reached a moment magnitude (Mw) of 8.8, placing it among the ten strongest instrumentally recorded events in history and matching the scale of the great 2010 Chile earthquake [1]. The Kamchatka earthquake generated a relatively small tsunami that spread across the Pacific Ocean and briefly activated several Kamchatka volcanoes [2, 3]. However, the most remarkable feature of this event lies not so much in its absolute power as in the intensity and unusual temporal pattern with which the Earth’s crust continued to move in the following months.

In September 2025, a month and a half after the mainshock, two major aftershocks occurred within the rupture zone: Mw 7.4 on September 13 and Mw 7.8 on September 18. This delayed reactivation shows that the period of elevated seismic hazard was not limited to the first days after the main event. This has direct practical implications for coastal populations: an unusually prolonged and active sequence means that the threat of strong earthquakes and tsunamis may persist not for days, but for months.

Kamchatka lies along one of the most active tectonic boundaries on the planet. Here, the Pacific Plate meets the Okhotsk Plate along a megathrust, an extensive contact between two plates where the world's largest earthquakes occur [4]. Failure along such an interface ruptures segments hundreds of kilometers long, displaces the seafloor vertically by several meters, and radiates seismic waves that are recorded across the planet. On November 4, 1952, this same boundary produced the great magnitude 9.0 Kamchatka earthquake (Fig. 1) [5]. The resulting North Kuril tsunami reached heights of up to eighteen meters along the coast and traveled across the entire Pacific Ocean [6].

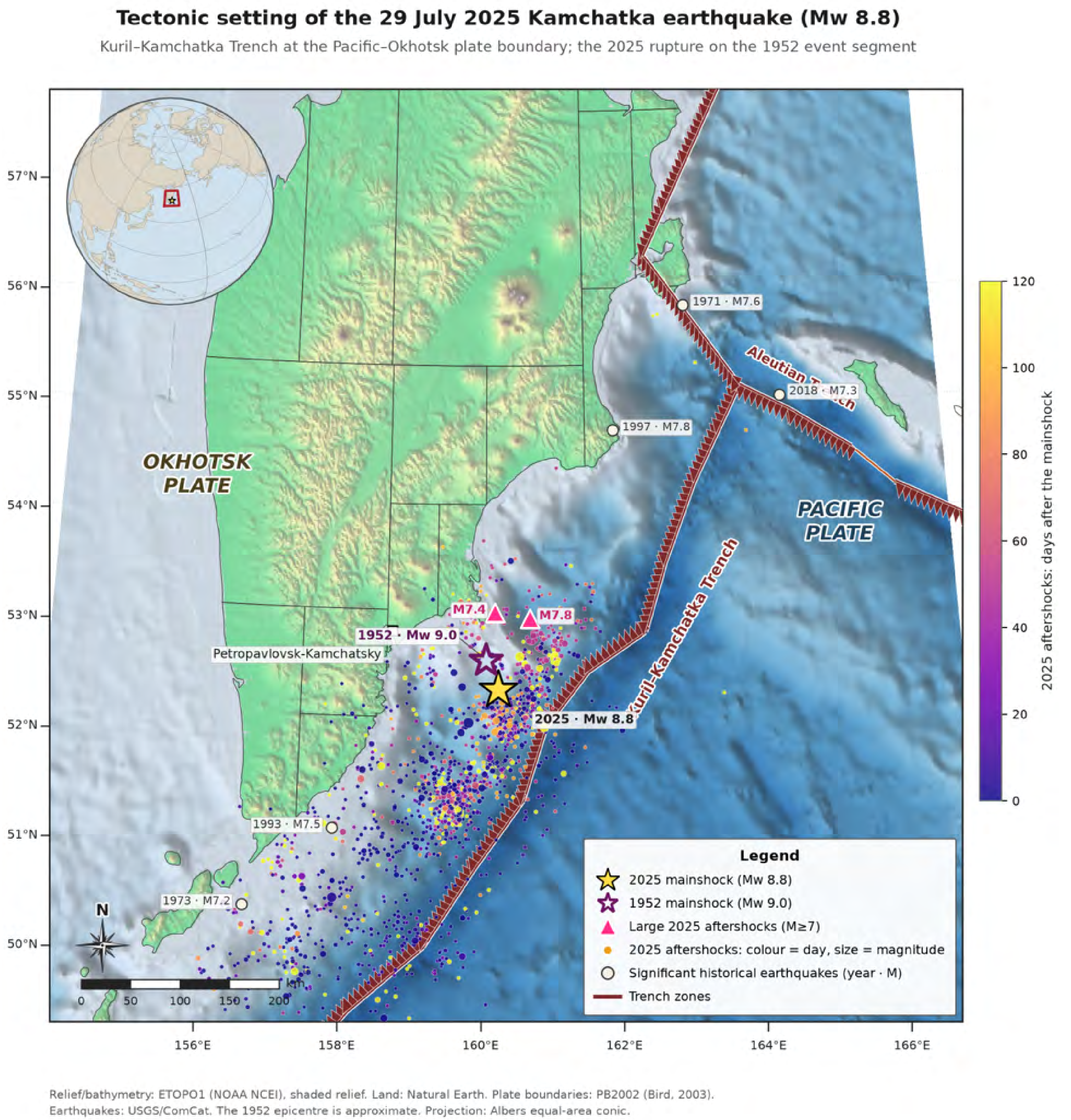

Figure 1.

Tectonic setting of the July 29, 2025 earthquake (Mw 8.8): eastern Kamchatka at the boundary between the Pacific and Okhotsk plates along the Kuril–Kamchatka Trench. The figure shows the 2025 (Mw 8.8) and 1952 (Mw 9.0) mainshocks, which occurred on the same segment of the plate boundary, the two strongest aftershocks of 2025 (M 7.4 and 7.8), and the aftershock sequence. Color indicates the number of days after the mainshock (the first 120 days), and symbol size indicates magnitude. Data: USGS/ComCat; ETOPO1 (NOAA NCEI) [10]; PB2002 plate boundaries (Bird, 2003) [11].

The 2025 rupture propagated unilaterally. It began near the hypocenter and spread southwestward along the Kuril–Kamchatka Trench, encompassing a segment several hundred kilometers long [3]. According to geodetic and seismological models, most of the slip was concentrated at depths of approximately 15 to 30 kilometers, where it reached about ten meters, while the rupture extended to the trench only in limited areas [7]. This distribution explains the moderate scale of the local tsunami. Runup heights along the southeastern coast of Kamchatka and the northern Kuril Islands were predominantly between 5 and 10 meters, reaching 10–16 meters only along a 100-kilometer stretch near Vestnik Bay and on Paramushir Island [8]. Thus, despite a magnitude comparable to that of the 1952 event, vertical seafloor displacement in shallow waters was substantially smaller, resulting in a weaker wave at the coast.

The 2025 Kamchatka event also has another, more profound distinguishing feature. Kamchatka is one of the few regions in the world where the largest earthquakes have long been considered within the framework of an official long-term seismic forecast [9]. The eventual occurrence of an extremely powerful event in this region was generally consistent with those expectations, but its timing was unexpected. The 2025 rupture occurred on the same fault segment as the 1952 event, only seventy-three years later. For megathrusts of this scale, this is an unusually short interval. According to the classical understanding, they release accumulated stress at intervals of centuries.

To determine whether the 2025 sequence truly stands out, it must be compared not only with the region's own past but also with the entire family of great megathrust earthquakes recorded worldwide during the modern era of comprehensive catalog coverage. Such a comparison under equivalent conditions is the focus of this analysis. The key step is to define the boundaries of the analysis carefully. For each event, a rectangular geographic window is selected and scaled to the rupture length using the empirical Wells and Coppersmith relationship [12]. The larger the earthquake, the larger the window. For events with magnitudes around 8.8, including those in Kamchatka and Chile, the window is approximately 600 kilometers. This relationship was derived from continental earthquakes and provides only an approximate scale for megathrust events. However, because it is applied uniformly to all events, the comparison remains valid. The window is selected to capture the aftershocks of the main rupture while excluding unrelated background earthquakes. Because the same rule is applied to every event and all regions are analyzed using the same open USGS catalog, differences among the sequences reflect the properties of the faults themselves rather than differences in data collection.

One of the most reliable ways to evaluate an aftershock sequence is to count the number of earthquakes that occurred after the mainshock within a defined area and over the same period of time. For such a comparison to be valid, only events above the magnitude threshold at which the catalog is considered sufficiently complete should be counted. Since approximately the 1990s, the global catalog maintained by the U.S. Geological Survey (USGS) has generally recorded earthquakes of magnitude 4.5 and above reliably in regions with well-developed seismic networks. However, catalog completeness still depends on focal depth and tectonic setting [13]. Therefore, M 4.5 is used here as a conservative lower threshold, and the comparison is limited to events from the modern era, beginning around 2004. This places all sequences under comparable conditions. The analysis includes the largest megathrust earthquakes of this period: Sumatra–Andaman (2004, Mw 9.1) [14], Nias (2005, Mw 8.6), Bengkulu (2007, Mw 8.4), Chile–Maule (2010, Mw 8.8), Tohoku (2011, Mw 9.1) [15], and Kamchatka (2025, Mw 8.8) [3].

By this measure, Kamchatka 2025 does indeed stand out, although it does not set an absolute record (Fig. 2). During the first eleven months after the mainshock, approximately 1,568 events of magnitude 4.5 and above were recorded in the Kamchatka region, with about nine out of ten (89%) occurring within the first five months. This is considerably more than the 1,081 events recorded after the 2010 Chile–Maule earthquake, which was of similar magnitude. In terms of the number of aftershocks, Kamchatka nearly matches the 2004 Sumatra–Andaman event, which produced 1,673 aftershocks, even though the main Sumatra earthquake had a magnitude of Mw 9.1 and released approximately three times as much seismic energy. Only the 2011 Tohoku earthquake (Mw 9.1) ranks substantially higher in this dataset, with approximately 3,264 aftershocks, about twice as many as Kamchatka 2025.

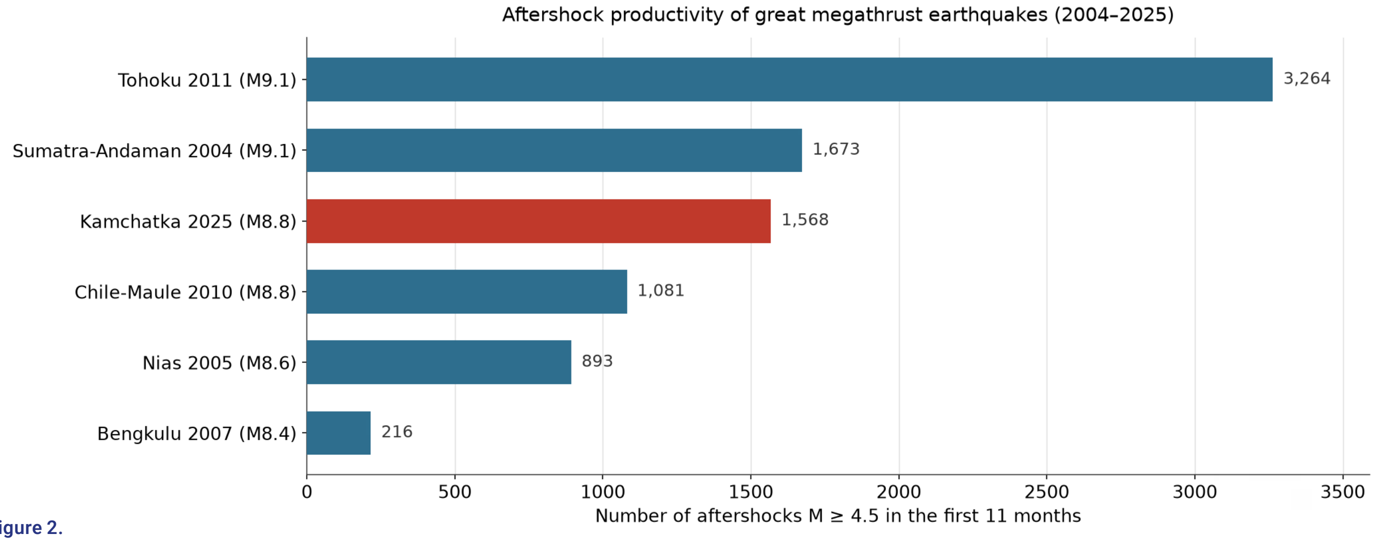

Figure 2.
Number of aftershocks of magnitude 4.5 and above during the first eleven months following each great megathrust earthquake (2004–2025). Kamchatka 2025 ranks among the most active sequences, nearly matching Sumatra 2004 (M 9.1) and surpassed by Tohoku 2011 (M 9.1). Data: USGS catalog, as of June 29, 2026.

This comparison leads to an important conclusion: by the number of aftershocks above magnitude 4.5, Kamchatka 2025 ranks among the most active sequences of the modern era. Within the dataset examined, it is substantially surpassed only by Tohoku 2011 (Mw 9.1), while it is nearly on par with Sumatra–Andaman 2004 (Mw 9.1). The significance of this comparison becomes clear from the nature of the magnitude scale itself. Because the scale is logarithmic, the difference of only 0.3 magnitude units between 8.8 and 9.1 represents not a small increase, but an approximately threefold difference in energy released. In energy terms, one magnitude 9.1 event is roughly equivalent to three Kamchatka earthquakes. It is therefore particularly striking that Kamchatka nearly matched Sumatra (Mw 9.1) in the number of aftershocks despite releasing approximately three times less energy. For an event of its size,

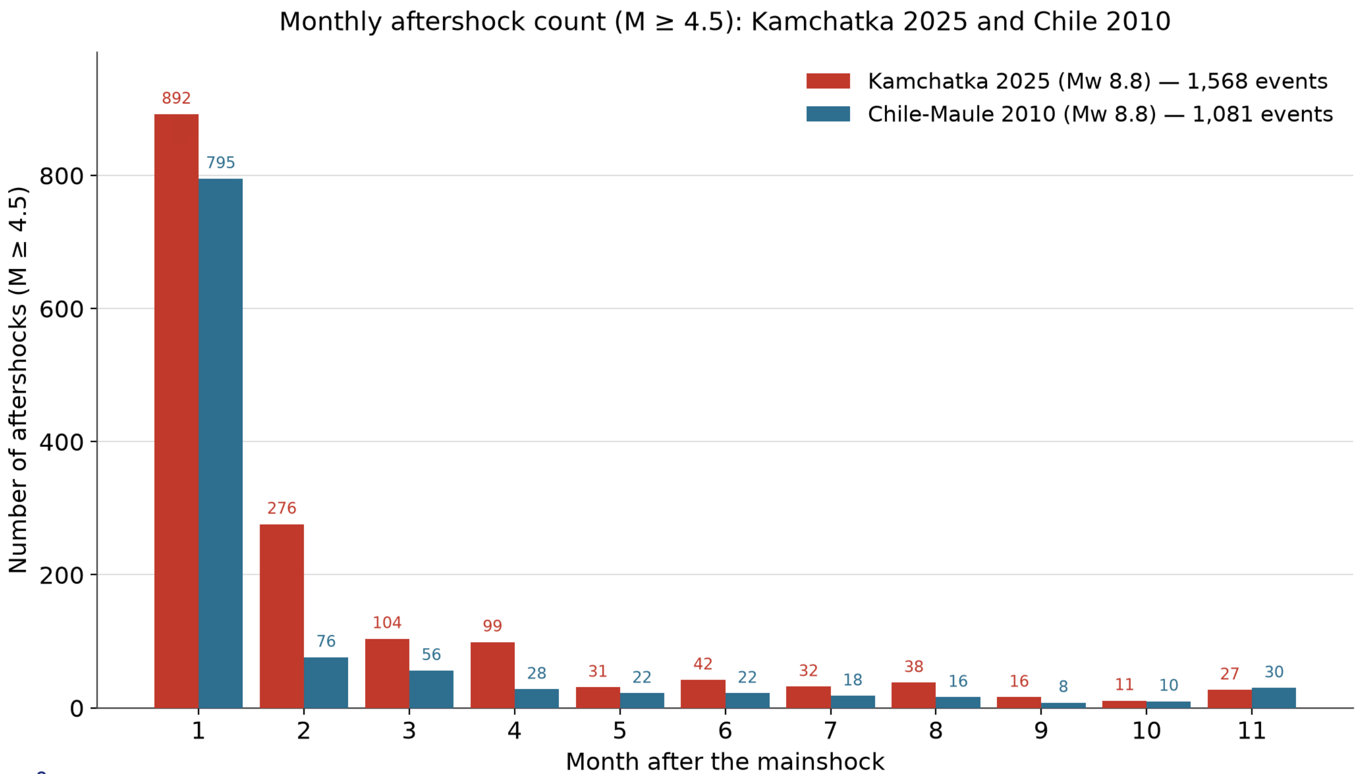

Figure 3.
Monthly number of earthquakes of magnitude 4.5 and above during the same first eleven months following each mainshock. Kamchatka (2025) remained above Chile (2010) in aftershock activity throughout the entire period, except for the final month, which was still incomplete as of the catalog cutoff date, producing 1,568 events compared with 1,081. Data: USGS earthquake catalog, as of June 29, 2026.

the 2025 Kamchatka sequence was extraordinarily rich in aftershocks.

The 2010 Chile–Maule earthquake [16] occurred in a different region, but its key parameters make it the closest analog to Kamchatka 2025: the same moment magnitude of Mw 8.8, a similar focal depth of more than 30 kilometers [17], and the same type of tectonic setting, a megathrust. The clearest comparison can therefore be made by aligning both sequences with the day of their respective mainshocks and calculating, under the same criteria and using the same catalog, the monthly number of aftershocks of magnitude 4.5 and above (Fig. 3). In both cases, the first month was highly active, with 892 events in Kamchatka compared with 795 in Chile. Both sequences then began to decay, as typically occurs after major earthquakes. However, Kamchatka remained above Chile month after month, with the most pronounced difference occurring during the second through fourth months. By then, the Chilean sequence had already declined to several dozen events per month, while hundreds of aftershocks were still being recorded in Kamchatka. During the same first eleven months following each mainshock, 1,568 earthquakes of magnitude 4.5 and above occurred in the Kamchatka region, compared with 1,081 in Chile. In other words, under comparable conditions, Kamchatka produced approximately one and a half times as many aftershocks. This is one of the principal observations concerning the 2025 sequence: what was unusual was not any single earthquake, but the overall duration and intensity of fault activity.

Why does the number of aftershocks matter? The practical significance of this measure lies in how long a region remains at elevated risk. For coastal populations in regions such as Kamchatka, a more prolific aftershock sequence means a longer period of danger. Strong aftershocks can be destructive in their own right and hinder rescue and recovery operations. Continued fault displacement also indicates further stress redistribution, the progression of which is difficult to predict. Therefore, a sequence with approximately one and a half times as many earthquakes as its closest analog is not merely a statistical distinction, but an important indicator of the duration of seismic hazard.

What makes the Kamchatka sequence particularly unusual is not only the total number of aftershocks or their magnitudes, but above all their temporal distribution. This feature becomes especially clear when viewed in the context of Omori's law, one of the classic empirical

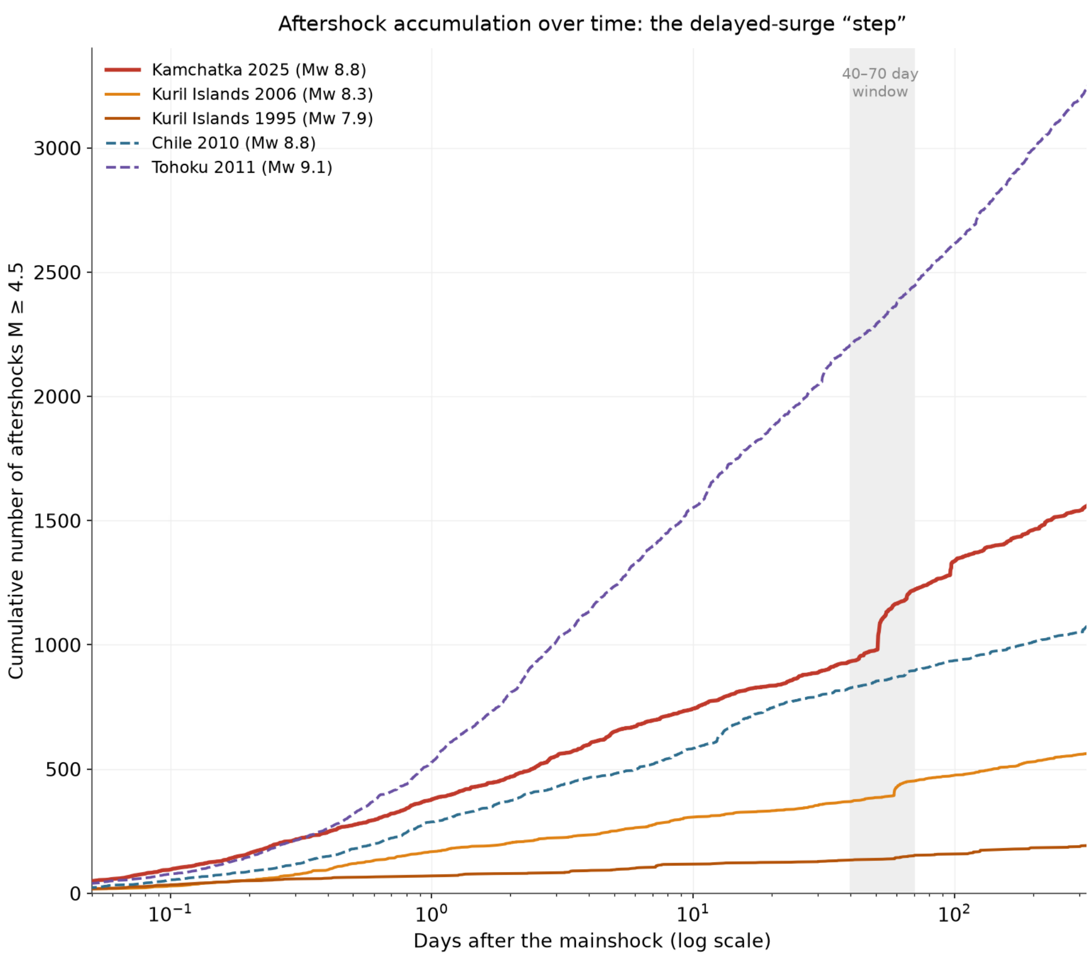

Figure 4.
Cumulative number of aftershocks of magnitude 4.5 and above over time, with days shown on a logarithmic scale. For Kamchatka 2025 and the Kuril Islands 2006, a “step” caused by a delayed surge is visible within the 40–70-day window, while the decline is smooth for Chile and Tohoku. Data: USGS catalog.

laws of seismology, according to which the frequency of aftershocks decreases approximately in inverse proportion to the time elapsed since the mainshock [18, 19]. In a typical aftershock sequence, this produces a rapid increase in the cumulative number of events during the first few days, followed by a gradual flattening of the cumulative curve. In the case of Kamchatka 2025, after the expected decline during the first few weeks, a pronounced secondary surge in activity emerged (Fig. 4). Approximately 46 and 51 days after the mainshock, two major aftershocks of magnitude 7.4 and 7.8 occurred, each accompanied by its own secondary sequence. As a result, the slope of the cumulative curve increased sharply again during the very interval when, under ordinary Omori decay, it should already have begun to flatten markedly. Importantly, such a delayed peak in aftershock activity is not unique to the 2025 Kamchatka sequence but is also observed in other modern events along the Kuril–Kamchatka Arc. Following the November 15, 2006, Simushir earthquake (Mw 8.3), the strongest aftershock, with a magnitude of 8.1, did not occur until day 59. In the 1995 Kuril earthquake sequence, the strongest aftershock occurred on day 66. Some of these delayed strong aftershocks are outer-rise events, which are sometimes regarded as independent earthquakes rather than aftershocks. However, this does not negate the systematic delay in the peak. By comparison, following the 2010 Chile earthquake and the 2011 Tohoku earthquake, the strongest aftershocks occurred within the first few hours after the mainshock, consistent with the general pattern observed for most major earthquakes worldwide. A comparison of mainshock magnitude and the time of the strongest aftershock in the global catalog shows that, in most sequences, the strongest aftershock occurs within the first few days, although the variation is wide and individual events deviate in both directions (Fig. 5). Against this background, modern events along the Kuril–Kamchatka Arc stand out because their strongest aftershocks occurred several weeks later: on day 51 for Kamchatka 2025, day 59 for the 2006 Kuril Islands event (the Simushir earthquake), and day 66 for the 1995 Kuril Islands event.

The distinction between a mainshock and an aftershock is not inherent in the nature of the event itself, but is determined by the declustering algorithm. It should therefore be noted

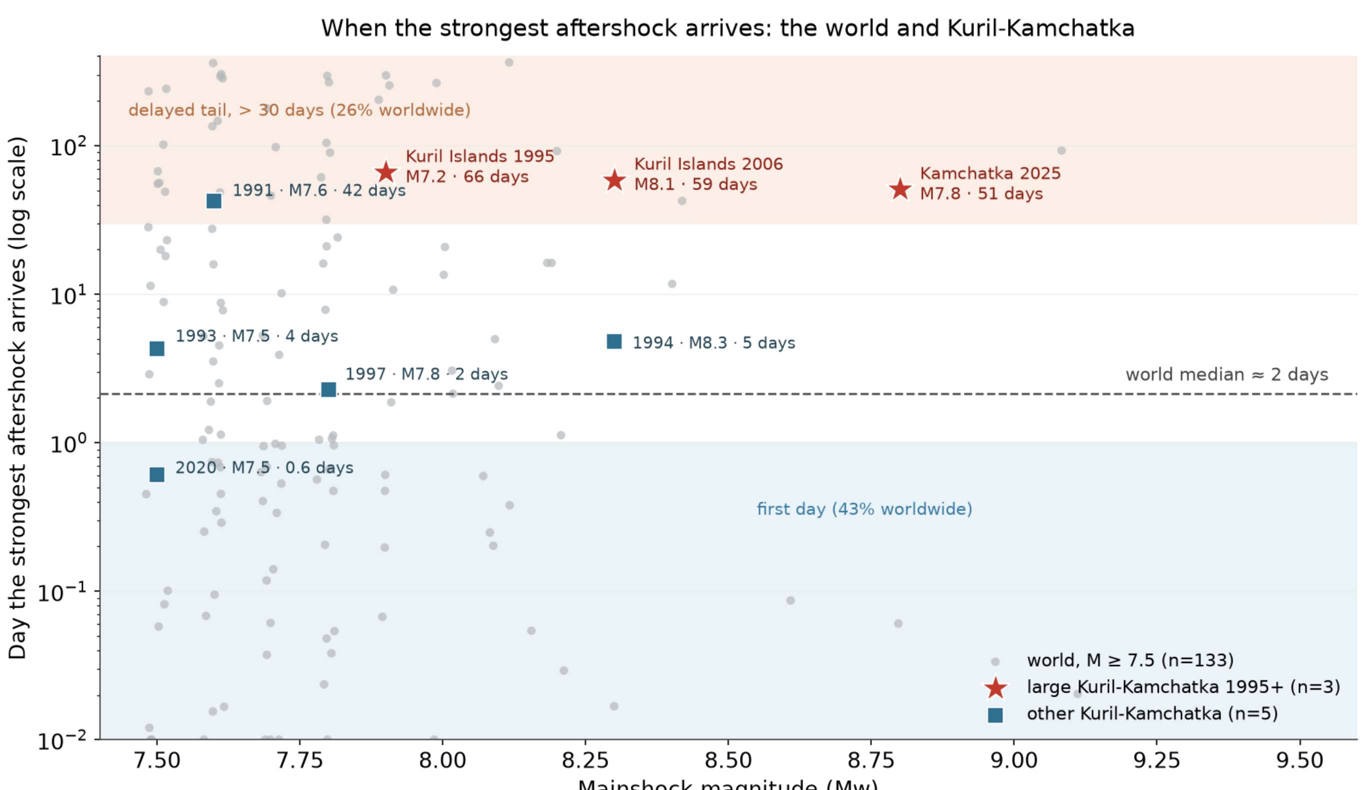

Figure 5.

Day of occurrence of the strongest aftershock as a function of mainshock magnitude. Gray dots represent all mainshocks worldwide with M ≥ 7.5 since 1990, following declustering, with the strongest aftershock of M ≥ 5.0 identified within 12 months using a uniform framework (n = 133). Globally, the strongest aftershock usually occurs early: the median is approximately 2 days, and 43% occur within the first 24 hours. However, there is also a delayed zone, with 26% of events occurring more than 30 days later. Three modern events along the Kuril–Kamchatka Arc, the 1995 Kuril Islands event (66 days), the 2006 Kuril Islands event (59 days), and Kamchatka 2025 (51 days), fall within the delayed zone (red stars). This group is distinguished by the delay duration rather than by the mainshock magnitude. The larger 1994 Shikotan earthquake (Mw 8.3) is not included because its strongest aftershock occurred on day 5. The remaining regional events (blue squares) had early aftershocks, with one exception: the 1991 event (Mw 7.6), for which the delay was 42 days, also placing it within the delayed zone. The labels next to the red stars indicate the magnitude of the strongest aftershock, while those next to the blue squares indicate the mainshock magnitude. Declustering was performed using Gardner–Knopoff windows and the USGS/ComCat catalog. Under other reasonable rule variants, the number of mainshocks in the dataset ranges from 149 to 177, while the median delay and the percentages reported above remain unchanged. Data: USGS catalog, as of June 29, 2026.

that applying the Gardner–Knopoff windows preserves the delays for seven of the eight events. The exception is the 2006 event, for which the M 8.1 aftershock of January 2007 is classified as an independent earthquake under the stricter scheme, forming the 2006–2007 Simushir doublet. Formally, the magnitude 8.1 aftershock occurred 104 kilometers from the mainshock, while the window threshold is 102.5 kilometers, placing it approximately one and a half kilometers beyond the window boundary. Thus, the delayed timing observed for Kamchatka 2025 and the 1995 Kuril Islands event is robust across methods, whereas the result for the 2006 Kuril Islands event depends on how the 2007 earthquake is classified.

Year	Mainshock	Main Event Mw	Strongest Aftershock	Interval
1991	1991-12-22 08:43	7.6	1992-02-02 17:43 · M 5.8	42 days
1993	1993-06-08 13:03	7.5	1993-06-12 20:33 · M 6.3	4 days
1994 · Shikotan	1994-10-04 13:22	8.3	1994-10-09 07:55 · M 7.3	5 days
1995	1995-12-03 18:01	7.9	1996-02-07 21:36 · M 7.2	66 days
1997 · Kronotsky	1997-12-05 11:26	7.8	1997-12-07 17:56 · M 6.2	2 days
2006 · Simushir	2006-11-15 11:14	8.3	2007-01-13 04:23 · M 8.1	59 days
2020 · Paramushir	2020-03-25 02:49	7.5	2020-03-25 17:21 · M 5.1	0.6 days
2025	2025-07-29 23:24	8.8	2025-09-18 18:58 · M 7.8	51 days

What could account for such a delay in major aftershocks? Branching-process models, such as the Epidemic-Type Aftershock Sequence (ETAS) model, provide the most cautious framework for describing this phenomenon. In these models, each earthquake can generate its own subsequence [20]. Within this framework, a strongly cascading sequence can become self-exciting after a period of quiescence and produce a major delayed aftershock.

In addition to its productivity, the 2025 Kamchatka earthquake sequence exhibited two other features that should be noted specifically as observations. The first concerns timing. According to the available data, the strong seismic activity in 1952 was primarily associated with aftershocks following the main event. In 2025, strong earthquakes began before the main rupture. On July 20, a cluster of powerful foreshocks occurred, including a magnitude 7.4 event initially mistaken for the main rupture, as well as three more earthquakes, two of magnitude 6.6 and one of magnitude 6.5. The magnitude 8.8 earthquake itself occurred only nine days later, on July 29, 2025.

This cascade was preceded by a prolonged period of relative quiescence. Beginning around mid-2003, a persistent deficit of events of magnitude 5.0 and above was recorded within a 100-kilometer radius of the future hypocenter. This deficit lasted approximately twenty years and was abruptly replaced by renewed activity beginning with the magnitude 7.4 foreshock on July 20, 2025 [21]. Earlier still, in August 2024, a magnitude 7.0 earthquake occurred approximately fifty kilometers from the future hypocenter. The combination of a multiyear deficit in low-magnitude seismicity followed by abrupt activation is regarded as an indication that this segment of the plate boundary remained strongly locked until it ruptured.

However, strong foreshocks are not unprecedented among great megathrust earthquakes. The 2011 Tohoku earthquake was preceded by a magnitude 7.3 foreshock only two days before the mainshock. Kamchatka's foreshock activity should therefore be regarded as striking, but not unique.

The second feature concerns the largest aftershocks. In September 2025, the Kamchatka fault produced two very strong aftershocks: Mw 7.4 on September 13 and Mw 7.8

on September 18. A well-known empirical relationship, Båth's law, states that the largest aftershock is, on average, approximately 1.2 magnitude units smaller than the mainshock [22]. For a magnitude 8.8 event, this would yield an expected maximum of approximately 7.6. The magnitude 7.8 aftershock on September 18 exceeded this level. However, examining the entire dataset places this observation in context. The deficit of the largest aftershock based on its events ranges from approximately 1.0 to 1.7, close to the classical value of 1.2. Kamchatka, with a difference of 1.0, does lie on the large-aftershock side of the distribution but remains within the normal range of variation. By contrast, the 2004 Sumatra earthquake and its largest subsequent event, the 2005 Nias earthquake (Mw 8.6), yield a far more extreme difference of approximately 0.5, although Nias is often regarded as a separate great earthquake. In other words, Kamchatka's large aftershock is notable, but not unique.

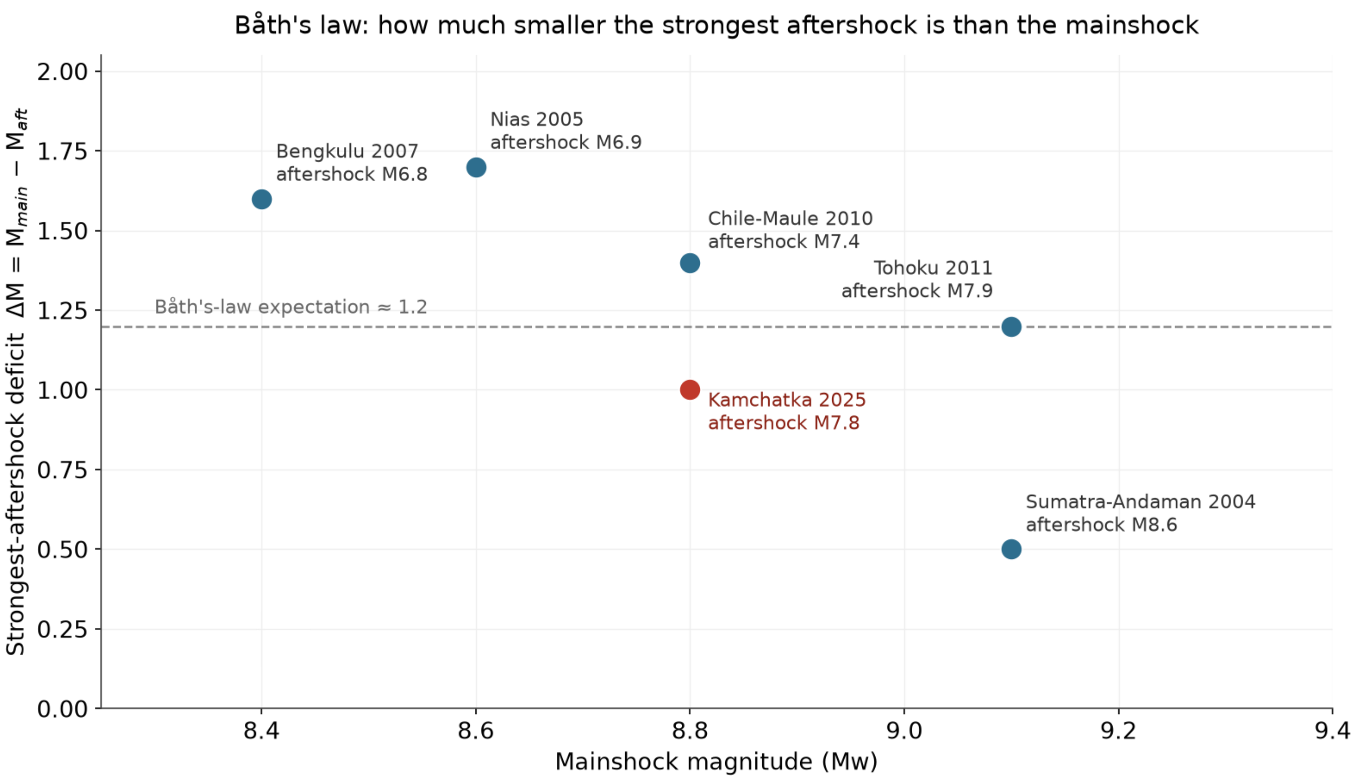

Figure 6.

Båth's law: the difference in magnitude between the mainshock and the largest aftershock in a dataset of great megathrust earthquakes. For Kamchatka, the difference is 1.0, based on the magnitude 7.8 aftershock. This is smaller than the average expected difference of approximately 1.2, but the Sumatra–Nias pair is even more extreme, at approximately 0.5. Data: USGS catalog.

Taken together, the comparison based on the two empirical laws yields a fairly clear picture. According to Båth's law, that is, in terms of the relative magnitude of the strongest aftershock, Kamchatka 2025 and other events in the Kuril–Kamchatka region generally do not differ from the global dataset. A different picture emerges when Omori's law, which describes the temporal evolution of aftershock activity, is considered. In the modern era, the strongest aftershock in this region has tended to occur later, from several weeks to several months after the mainshock.

This conclusion resonates with another puzzle surrounding the event. The short interval of only seventy-three years between two mega-earthquake-class ruptures on the same segment is difficult to reconcile with the classical concept of the seismic cycle, according to which such enormous earthquakes release accumulated strain and recur only after centuries. Moreover, according to current models, the 2025 rupture displaced the fault by more than nine meters, with estimates ranging from eight to fourteen meters, whereas slow plate motion since 1952 could have restored only about six meters of elastic strain [3, 23]. The earthquake appears to have released more strain than had accumulated in the intervening period, a phenomenon known as “overshoot” [24]. Overshoot is also indicated by the nature of the aftershocks within the area of maximum slip. Normal-faulting earthquakes were recorded there, whereas thrust-faulting events would be expected under the prevailing compressional regime. This local reversal in the sign of shear stress indicates that the dynamic impulse of the rupture released the accumulated stress in excess [24].

One interpretation is that the 1952 earthquake was seismically “inefficient” and left a substantial portion of the stress unreleased. Another is that stress was redistributed from adjacent segments of the plate boundary. A third explanation allows for the possibility that the 1952 and 2025 earthquakes released strain in different depth ranges within the same megathrust segment. According to one reconstruction, the main slip in 1952 occurred at greater depths, approximately 30–60 kilometers, whereas in 2025 it was concentrated primarily at depths of about 15–30 kilometers. However, the rupture depth of the 1952 earthquake remains uncertain. Alternative models indicate substantial shallow slip and considerable overlap between the areas of large displacement in the two events (see references in [7]). Under the former interpretation, the 2025 event was not a repeat rupture of the same fault patch.

A fourth hypothesis concerns deeper processes, such as the influence of plume-like mantle structures on the Okhotsk Sea block. This should be regarded as a line of inquiry requiring separate investigation. It is supported by seismic tomography data showing extensive low-velocity mantle anomalies beneath Kamchatka and at its junction with the Aleutian Arc, as well as a tear in the Pacific Plate through which heated material rises toward the base of the mantle wedge [25, 26]. These thermal heterogeneities produce a patchwork distribution of locked areas along the plate boundary, and the boundaries of the largest ruptures often coincide with the edges of these areas.

Any of these possibilities introduces uncertainty into the simple linear models often used to estimate where and when great earthquakes recur, and none can be resolved through aftershock counts alone. However, the counts themselves provide a sufficiently robust observation on which to base further research. Using the same catalog, magnitude threshold, and mainshock-aligned time windows, the 2025 Kamchatka earthquake produced one of the most prolific aftershock sequences of the modern era, second only to Tohoku 2011, while also featuring an unusually strong foreshock and aftershock. This is a robust quantitative signal: one of the planet’s most hazardous fault systems is exhibiting behavior that can be described only partially by established benchmark cases. Further research should therefore focus on targeted modeling, new field and geodetic observations, and continued monitoring of coastlines where great earthquakes remain a recurring feature of tectonic reality.

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Why Do Plastics Easily Acquire Electrostatic Charge and Wood Does Not?

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Jan Kára is an IT specialist. He holds a Master's degree in Computer Science (Charles University, Prague, 2003) and a Ph.D. in Discrete Models and Algorithms (Charles University, Prague, 2007). In his computer science research he worked mostly on graph algorithms and constraint satisfaction problems; his most cited paper, "The complexity of temporal constraint satisfaction problems," currently has over two hundred citations.

Today he works on the development of the Linux Kernel — the core of the Linux operating system — as a maintainer of several subsystems, and he specializes in measuring and analyzing the performance of the kernel and of applications running on Linux.

In his free time he follows current research in physics, astronomy, and climate science. He works on the analysis of several publicly available seismic databases and has developed a methodology and programs for correlating and merging data from them.

Few physical phenomena are as familiar—and as poorly understood by most people—as static electricity. Almost everyone has experienced a small electric shock after walking across a carpet, watched a balloon cling to a wall after being rubbed on clothing, or noticed how plastic wrap stubbornly sticks to surfaces. Plastic combs attract hair, synthetic fabrics crackle when separated, and plastic containers seem unusually effective at collecting dust. These everyday observations all arise from the accumulation of electrostatic charge on material surfaces.

The phenomenon has been known for thousands of years. Ancient Greek observers noted that amber, when rubbed with fur, could attract lightweight objects such as feathers and bits of straw. In fact, the modern word "electricity" ultimately derives from the Greek word elektron, meaning amber. During the sixteenth century, the English natural philosopher William Gilbert systematically studied these effects and distinguished them from magnetism, laying the foundations for the scientific study of electrical phenomena.

Despite this long history, scientists still do not fully understand the microscopic processes responsible for static charge generation. The phenomenon, known as **contact electrification** or **triboelectric charging, occurs whenever two materials touch** and subsequently separate. For centuries, researchers assumed that contact electrification was a relatively straightforward transfer of electrical charge from one material to another. Yet many experimental observations resisted simple explanation. Why do some materials charge strongly while others hardly charge at all? Why can identical materials become oppositely charged after contact? And why do electrically insulating materials such as plastics retain charge for remarkably long periods?

During the past two decades, advances in measurement techniques have revealed that contact electrification is considerably more complex than previously believed. Rather than simply transferring a small amount of charge from one object to another, contact and separation can generate intricate patterns of positive and negative charge across surfaces, accompanied by chemical changes at the molecular level. These discoveries have transformed static electricity from a seemingly solved problem into an active area of research at the intersection of physics, chemistry, materials science, and engineering.

What actually happens when two surfaces touch?

At first glance, contact electrification appears simple. When two materials touch, atoms and molecules at their surfaces come into close proximity. Upon separation, some electrical charge remains on each surface, leaving one object with a net positive charge and the other with an equal negative charge. The resulting electric field can attract nearby objects or produce a visible spark when the charge is discharged.

For many years, researchers sought to explain this process using the transfer of electrons between materials. The idea was inspired by the behavior of metals, where electrons can move relatively freely. If electrons preferentially move from one material to another during contact, the two surfaces would naturally become oppositely charged after separation.

While this picture works reasonably well for some conductive materials, it encounters difficulties when applied to insulating materials such as polymers. Plastics are among the strongest triboelectric materials known, yet their electrons are not free to move through the material as they do in metals. Furthermore, experiments have shown that even two pieces of the same material can sometimes become oppositely charged after contact, a result that is difficult to reconcile with simple electron-transfer models.

A major breakthrough came when researchers began examining charged polymer surfaces with much higher spatial resolution than had previously been possible. Conventional measurements typically determine only the overall charge on an object.

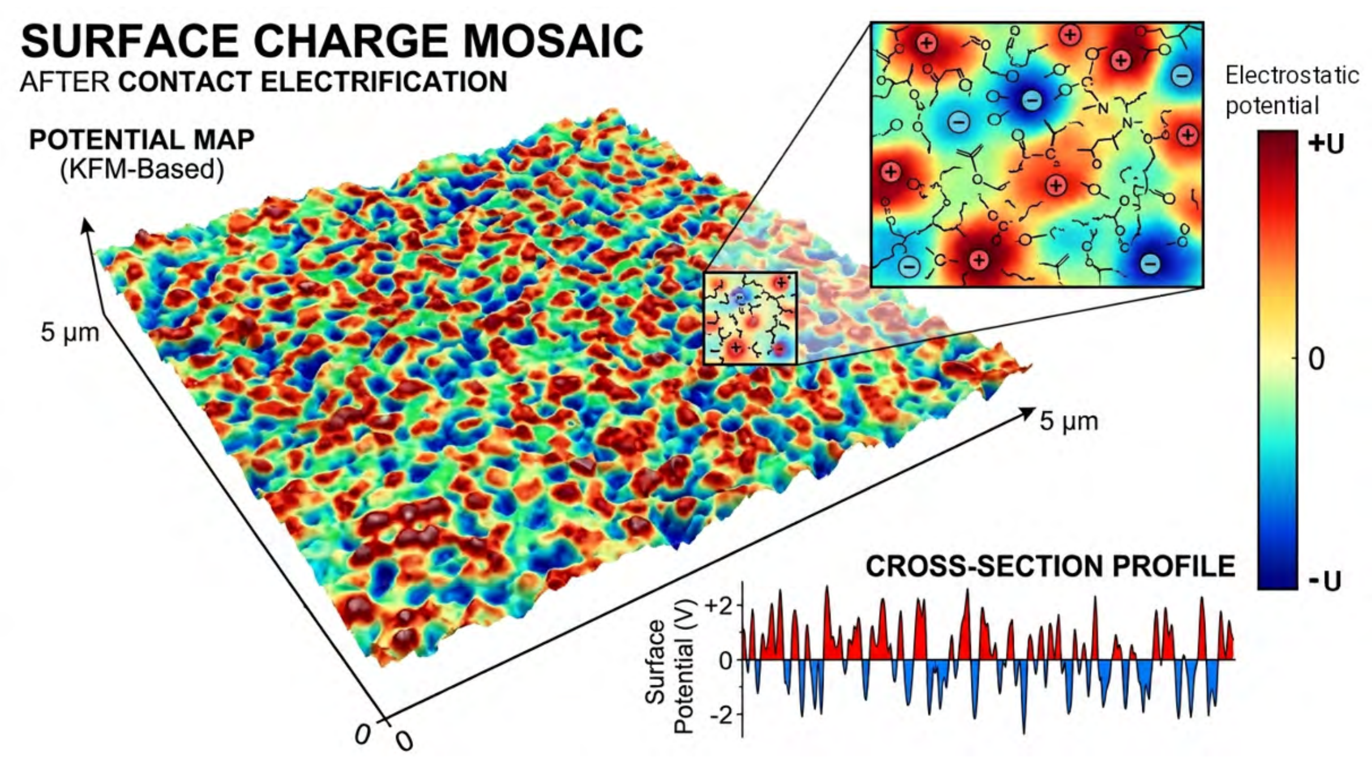
Such measurements reveal whether an object is net positive or net negative, but they provide little information about how charge is distributed across the surface. New imaging techniques made it possible to map charge distributions directly, revealing a picture far more complicated than anyone had anticipated.

The hidden landscape of charge

Using techniques such as Kelvin probe force microscopy and electrostatic force microscopy, researchers have visualized the distribution of charge on surfaces following contact electrification. Rather than observing uniformly charged surfaces, they found complex mosaics of microscopic charge domains. Regions carrying positive charge coexist alongside regions carrying negative charge, often separated by distances of only a few hundred nanometers. In some cases, neighboring domains possess surface charge densities that differ by orders of magnitude.

One of the most influential studies was conducted by Baytekin and colleagues in 2011 [1]. By examining polymer surfaces after contact and separation, the researchers showed that contact electrification generates a patchwork of oppositely charged regions rather than a simple uniform charge distribution. The net charge measured on the entire object represents only the small imbalance between much larger quantities of positive and negative charge distributed across the surface. In other words, most of the charge generated during contact electrification remains hidden from conventional measurements because positive and negative regions partially cancel one another when averaged over large areas. In fact, the study of Baytekin has shown that the actual amount of charge separated during contact can be three orders of magnitude greater than the net charge inferred from macroscopic measurements. This discovery significantly altered researchers' understanding of contact electrification.

The existence of these charged domains also provides clues about the underlying mechanism.



If charge transfer occurred uniformly across an interface, one might expect relatively smooth charge distributions. Instead, the observed patchwork suggests that contact electrification is governed by highly localized events occurring at microscopic points of contact. Each contact region may undergo its own charge-generation process, producing positive and negative domains that become trapped on the surface after separation.

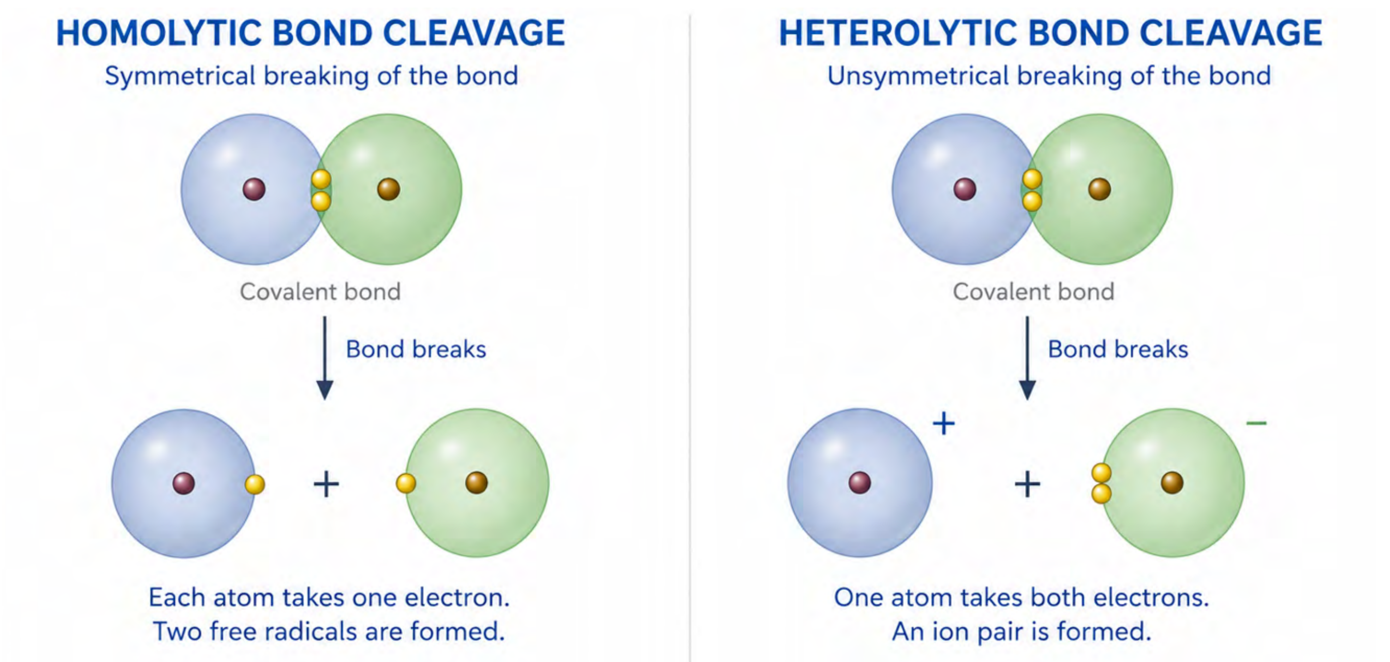
The discovery of hidden charge landscapes raised an important question: what microscopic process creates and stabilizes these domains, particularly in polymers that can retain charge for long periods? Answering that question led researchers beyond classical electrostatics and into the realm of **mechanochemistry**, where mechanical forces can directly alter chemical bonds.

When mechanical force breaks chemical bonds

Mechanochemistry may seem unfamiliar, but its effects are encountered in everyday life. Materials subjected to stretching, grinding, friction, or fracture can undergo chemical transformations that would not occur under ordinary conditions. When a material is stressed sufficiently, some chemical bonds experience forces large enough to cause them to break. The process is particularly important in polymers, whose long molecular chains can transmit mechanical stresses over considerable distances.

At first sight, the forces involved in routine contact and separation of surfaces might appear far too small to break covalent bonds. However, real surfaces are rough on microscopic and nanoscopic scales. When two materials touch, contact occurs only at a limited number of asperities—tiny protrusions where the local pressure can become extremely high. During separation, molecular chains may be stretched, pulled, and detached from one another. Under these conditions, a small fraction of bonds can indeed undergo mechanical scission.

When a covalent bond breaks, the result depends on how the bonding electrons are distributed between the two fragments. In a process known as **homolytic bond cleavage**, each fragment retains one electron, producing two highly reactive species called **free radicals**. In contrast, **heterolytic bond cleavage** leaves both bonding electrons on one fragment, producing a positively charged ion and a negatively charged ion. Mechanical stress can induce both types of processes, generating mixtures of radicals and ionic species at the interface between separating materials.



Experiments performed by Baytekin and coworkers [2, 3] have shown that the mosaic of charge is generated by a combination of transfer of material between two touching surfaces and creation of ions due to bond cleavage, and it is also accompanied by the creation of radicals. This insight helps explain several long-standing puzzles. First, it accounts for the highly localized nature of charge generation. Bond-breaking events occur only at specific microscopic contact points, naturally producing the patchwork of charged domains observed by high-resolution imaging. Second, it explains why identical materials can sometimes become oppositely charged. Small variations in surface structure, local stresses, and bond-breaking pathways can lead to different distributions of ions and radicals, even when the two surfaces are chemically similar.

Perhaps most importantly, the mechanochemical model offers an explanation for the remarkable persistence of electrostatic charge in polymers. Once generated, radicals and ions are often trapped within a rigid insulating matrix. Unlike charges in metals, which can move freely and rapidly recombine, charges in polymers may remain confined to specific molecular environments. In fact, the research has revealed an intriguing relationship between radicals and electrostatic charge. Apparently, valence electrons of radicals interact with electron shells of ions, leading to charge stabilization at the polymer surface [4].

Evidence for this connection comes from experiments in which radical-scavenging additives were incorporated into polymers. When substances known to neutralize radicals have been added to plastics, even at a low concentration of 0.1%, the accumulated charge after contact electrification reduced to about 25% and dissipated within minutes, whereas the non-doped material stayed significantly charged even after 24 hours [2]. Such observations suggest that radicals are not merely incidental by-products of bond breaking but active participants in the processes that stabilize separated charge. These findings provide a direct bridge between electrostatics and polymer chemistry and help explain why different materials exhibit dramatically different charging behavior. They also open a completely new avenue for the design of antistatic materials which so far relied on various additives improving the electrical conductivity of a material.

Finally, researchers have also shown that the created charge patterns in their experiment are very similar in standard and water-free atmospheres [2, 5]. This ruled out a significant influence of the redistribution of aquatic ions (H^+, OH^-) adsorbed to the surface on contact electrification in this experiment, which is one of the polymer contact electrification mechanisms proposed by Whitesides et al. [6].

The emerging picture is therefore far richer than the traditional textbook description of static electricity. Contact electrification is not simply a transfer of electrons or aquatic ions between surfaces. At least in many insulating materials, it involves microscopic mechanical damage, the breaking of chemical bonds, the formation of radicals and ions, and the subsequent trapping and stabilization of these species within the material. Static electricity, long regarded as a purely physical phenomenon, turns out to have a substantial chemical component.

Why does wood behave differently?

At first glance, wood and plastic appear to have much in common from an electrical and chemical perspective. Both are generally classified as electrical insulators and both contain long chains of polymers. Yet anyone who has handled everyday objects is familiar with an important difference: plastic readily accumulates static charge and often retains it for long periods, while wood rarely exhibits comparable electrostatic behavior. Why is this the case?

Traditionally, the weak electrostatic charging of wood has largely been attributed to its moisture content. When water is present, it facilitates the movement of ions and thus the dissipation of electrostatic charge. However, experiments published in [7] show water is not the only contributor to the antistatic properties of wood.

Wood is a composite of three main components - cellulose (30-50%), hemicellulose (20-35%), and lignin (15-40%). Cellulose is a natural polymer that is known to easily acquire an electrostatic charge similar to plastic polymers [8].

Hemicellulose has the same chemistry and thus similar charging behavior as cellulose is expected. Indeed, the experiments described in [7] showed that chemically removing lignin from wood caused it to behave much more like common plastics: after contact, lignin-free wood accumulated large electrostatic charges and retained them for extended periods. When lignin was added back, even a concentration of about 5% was sufficient to restore the antistatic behavior.

To confirm that lignin itself was responsible for the effect, the researchers performed the opposite experiment. They incorporated lignin into the plastic polymer polydimethylsiloxane (PDMS). Adding only 1% lignin noticeably reduced electrostatic charging, while 5% rendered the polymer effectively antistatic.

The authors proposed that lignin acts this way because of its well-known radical-scavenging properties. Lignin contains numerous phenolic groups that readily donate hydrogen atoms to neutralize free radicals generated during mechanochemical bond breaking. According to the radical-stabilization model discussed in the previous section, removing these radicals destabilizes nearby trapped charges, allowing them to recombine more readily and causing the electrostatic charge to dissipate much faster.

The experiments with lignin reveal that wood is not antistatic simply because it is an electrical insulator containing moisture. Rather, its chemical composition actively suppresses long-lived electrostatic charge. Plastics are composed largely of chemically inert polymers that can preserve radicals and trapped charges for long periods. Wood, in contrast, naturally contains lignin—a polymer rich in antioxidant phenolic groups—that continuously scavenges radicals and promotes charge dissipation. From this perspective, wood can be viewed as a naturally occurring antistatic composite, whereas most commodity plastics lack this built-in protection.

These discoveries not only explain familiar everyday observations but also suggest new strategies for designing antistatic materials, from safer plastics for industry to possible approaches to neutralizing the surface charge of nanoplastic particles already circulating in our environment.

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THE IMMUNE SYSTEM'S FIRST TEACHER: How the Thymus Shapes Health Throughout Life

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Rinat Akhmetzakirov is a radiologist of the highest qualification category, specializing in X-ray, CT, MRI, ultrasound, and nuclear medicine diagnostics. He graduated from Semipalatinsk State Medical Academy (Kazakhstan) in 2004 with a degree in General Medicine and completed a surgical internship in 2004–2005, qualifying as a surgeon. In 2012 he completed professional retraining at the Almaty State Institute for Advanced Medical Training and obtained his qualification in radiology (diagnostic imaging).

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Alongside his clinical practice, he trains young specialists and serves as a mentor to residents in radiology, with experience in scientific and educational work. He also takes part in projects studying the influence of environmental and climatic factors on population health.

Before the immune system can protect the body, it must first be taught how.

Most people never think about the thymus. Hidden behind the breastbone, this small organ remained one of the great mysteries of the human body for centuries. Its function was unknown, and it was often regarded as an insignificant anatomical structure [1–3].

Scientific discoveries during the second half of the twentieth century completely transformed that understanding. Today, the thymus is recognized as one of the central organs of the immune system, responsible for the development of T lymphocytes and the establishment of immunological tolerance [1–3].

Yet the significance of the thymus may extend well beyond immunology. Its story offers a new perspective on human development, the importance of early childhood, the processes of aging and regeneration, and the complex relationship between the human body and its environment.

Before the immune system can protect the body, it must first undergo training. One of its earliest and most important teachers is a small organ that most people never think about: the thymus.

Where the Immune System Learns

For much of the twentieth century, the immune system was viewed primarily as a defense mechanism, a biological army designed to recognize and eliminate threats. Modern immunology, however, has revealed a far more complex picture. Before the immune system can protect the body, it must first undergo a remarkable process of training [1–3].

At the center of this process is the thymus. Hidden behind the breastbone and little known outside the medical community, this small organ serves as one of the immune system's first and most important "schools." It is here that T lymphocytes mature and are trained, preparing them to protect the body throughout life [4, 5].

The story of this education begins even before birth. During the earliest stages of embryonic development, precursor cells destined to become T lymphocytes arise sequentially in several hematopoietic tissues, first in the yolk sac, then in the fetal liver, and later in the bone marrow. From these sites, they migrate to the thymus, where they undergo a complex process of maturation and selection [4, 6].

Not every cell successfully completes this journey. Within the thymus, developing T lymphocytes undergo multiple rounds of rigorous testing. Some cells are eliminated because they cannot recognize the molecular signals required for immune surveillance. Others are removed because they react too strongly to the body's own tissues. Only a small fraction successfully pass every stage of selection and are permitted to leave the thymus and enter the bloodstream [4, 5].

This process establishes the delicate balance that underlies the normal function of the immune system. It must be strong enough to recognize and eliminate infectious agents, yet at the same time sufficiently discerning to avoid attacking the body's own tissues. In this sense, the thymus is far more than a factory for producing immune cells. It is a school where the immune system learns to distinguish self from non-self [7–9].

Our understanding of the processes that take place within the thymus has fundamentally reshaped the concept of immunity. Today, an increasing number of researchers view the immune system not merely as a defense mechanism, but as a dynamic system built on education, adaptation, and the maintenance of immunological tolerance [6–10].

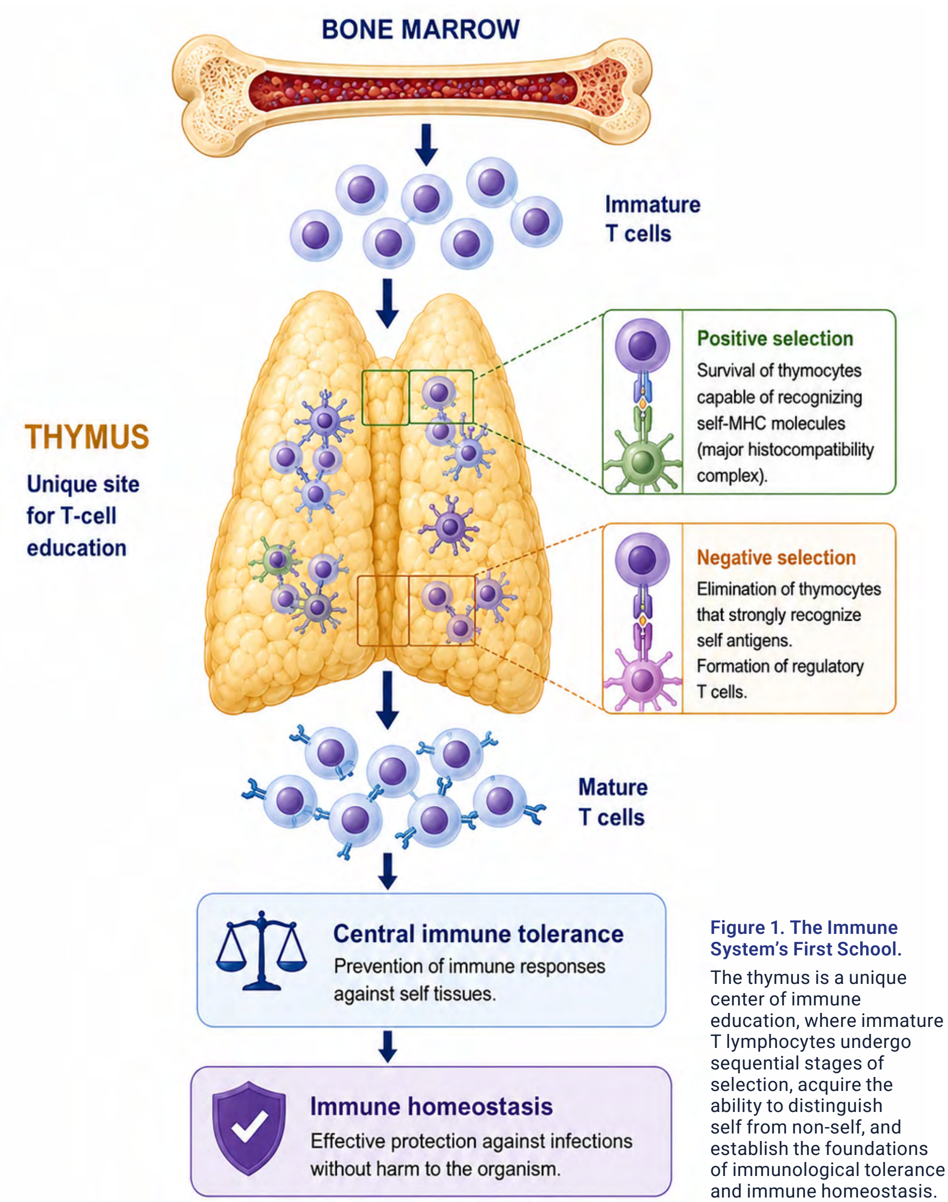

Figure 1. The Immune System's First School.
The thymus is a unique center of immune education, where immature T lymphocytes undergo sequential stages of selection, acquire the ability to distinguish self from non-self, and establish the foundations of immunological tolerance and immune homeostasis.

How the Immune System Learns to Tell Friends from Foes

Building an effective defense system requires more than the ability to recognize and eliminate potential threats. It must also prevent attacks against the body's own tissues. In fact, one of the immune system's greatest achievements is not its ability to wage war, but its ability to maintain peace [5, 7].

This is precisely the role of the thymus. As T lymphocytes mature, the thymus serves as a kind of examiner, guiding developing immune cells through successive stages of evaluation known as positive and negative selection [4, 5].

During positive selection, only cells capable of recognizing major histocompatibility complex (MHC) molecules, which are essential for immune surveillance, are allowed to survive. Cells that lack this ability fail to receive the signals necessary for survival and are eliminated [4, 5].

An even more critical stage, however, is negative selection. During this process, T lymphocytes that react too strongly to the body's own tissues are removed, greatly reducing the risk of autoimmune disease [5, 7].

For many years, scientists believed that a protein called **AIRE** played the central role in this process. AIRE drives the expression of a wide variety of tissue-specific antigens, allowing developing T lymphocytes to become familiar with molecules normally found in different organs and tissues throughout the body [8]. More recent research, however, has shown that this system is far more sophisticated. Scientists have identified another key regulator, the protein **FEZF2**, which independently controls the expression of a distinct set of self-antigens. Today, it is believed that the combined actions of AIRE and FEZF2 provide developing T cells with a more comprehensive "introduction" to the body's own tissues, significantly improving the establishment of immunological tolerance [11, 12].

In a sense, the thymus introduces future immune cells to a "map" of the body, teaching them to distinguish self from non-self.

Not all potentially dangerous cells are eliminated, however. Some instead develop into **regulatory T cells (Tregs)**, a specialized population responsible for maintaining immunological tolerance and preventing excessive immune responses [9]. These cells play an essential role in preserving the delicate balance between effective immune defense and self-inflicted damage.

The immune system, therefore, is much more than a mechanism for fighting infections. Its proper function depends on its ability to maintain a delicate balance between action and restraint [7–10, 12]. Perhaps one of the immune system's greatest achievements is not its ability to attack, but its ability to know when not to.

Why Childhood Matters

The immune system is not fully formed at birth. Like many other systems in the body, it develops gradually, progressing through a series of complex stages of maturation and adaptation. An increasing body of research shows that many aspects of adult health are shaped by events that occur long before the first symptoms of disease appear, and even long before adulthood itself [6, 13, 14].

This concept is reflected in the **Developmental Origins of Health and Disease (DOHaD)** framework, which views early life as a critical window during which the body's long-term biological functions are established [13-15]. According to this model, conditions during fetal development, nutrition, environmental exposures, and many other factors can influence health in ways that may not become apparent until decades later.

Particular importance is now placed on the **first 1,000 days of life**, the period from conception through the second birthday. During this time, the body's organs and physiological systems undergo rapid development, including the immune system. It is also during this period that the mechanisms enabling the body to adapt to its environment and maintain internal balance are established [13-15].

One of the most active organs during this critical window is the thymus. Even in the earliest stages of development, it begins shaping the T-cell immune system. Throughout childhood, the thymus reaches its peak functional activity, supplying the body with a diverse repertoire of T lymphocytes while establishing the mechanisms that underlie immunological tolerance [6, 10].

For this reason, adult health cannot be understood solely as the result of lifestyle choices or events that occur later in life. Growing evidence suggests that many aspects of health have much deeper origins. Long before a child ever walks through the doors of a school, the body has already passed through some of its most critical developmental stages, laying the foundation for health throughout life [13-15].

The First 1,000 Days of Life

Over the past several decades, the period from conception through the second birthday, known as the **first 1,000 days of life**, has become a major focus of scientific research. Today, it is recognized as one of the most important **windows of opportunity** in human development, profoundly influencing health across the decades that follow [13-15].

During this period, the body exhibits remarkable plasticity, allowing it to adapt to its environment. At the same time, this heightened adaptability also makes developing organs and physiological systems particularly sensitive to external influences.

The immune system is among the systems most profoundly shaped during this time. The first years of life are marked by the rapid establishment of the T-cell repertoire, the development of immunological tolerance, and the formation of the intricate interactions between the immune system and other physiological systems [6, 10].

Throughout this critical window, the thymus reaches its peak functional activity, guiding the maturation and education of the cells that will help maintain immune homeostasis throughout life [6, 10]. In other words, some of the most important lessons that shape lifelong health are learned long before a child speaks their first words or takes their first steps.

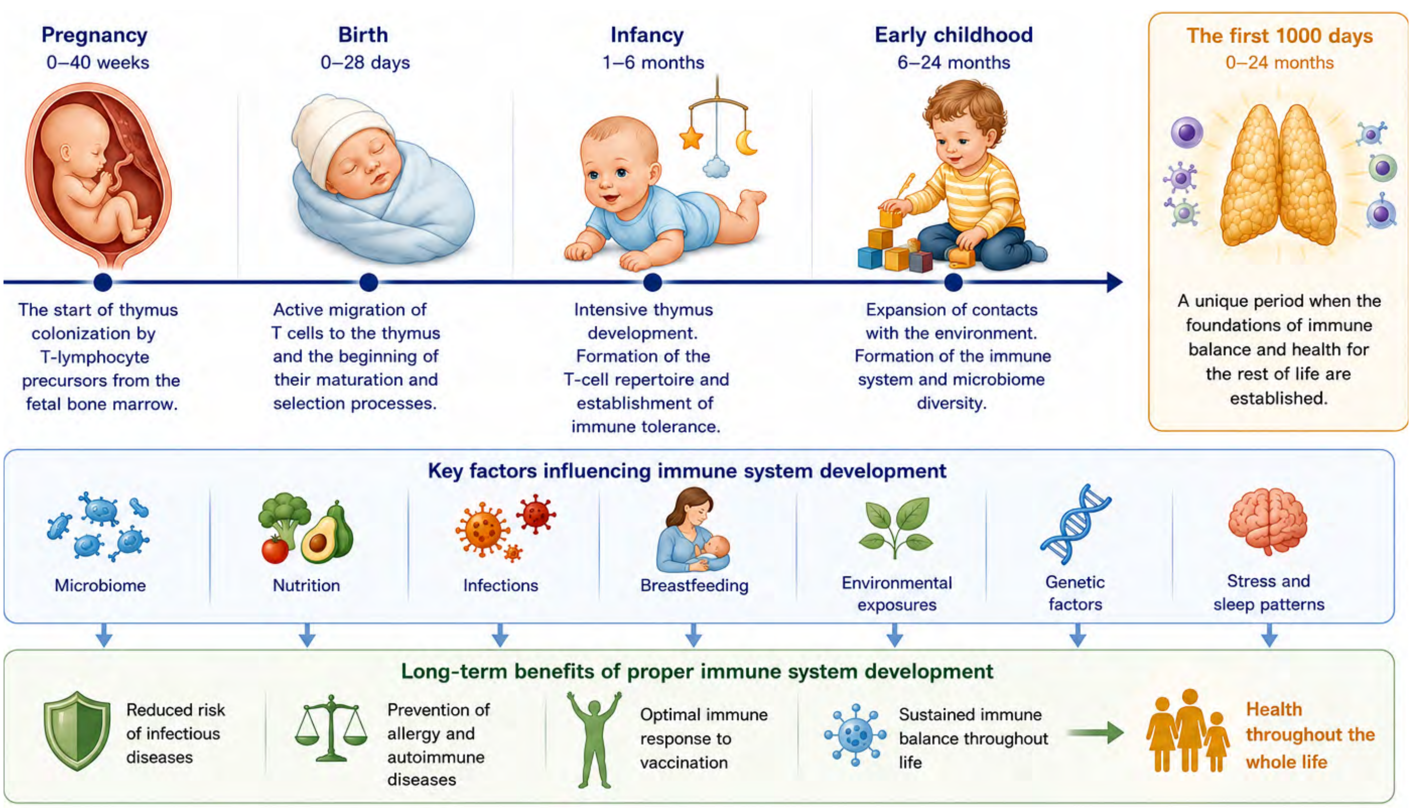

Figure 2. The First 1,000 Days of Life.

The period from conception through the second birthday is a critical stage in the development of the immune system. During this time, the thymus plays a central role in the education of T lymphocytes and the establishment of immunological tolerance, processes that can influence health throughout life.

When the First Teacher Grows Old

Throughout childhood, the thymus is one of the most active organs of the immune system. Yet soon after puberty, it begins to undergo gradual changes known as **thymic involution**. Over time, the organ's functional tissue progressively shrinks and is increasingly replaced by adipose (fat) tissue [16].

At first glance, this may seem paradoxical. Why would an organ so essential to the development of the immune system begin to decline so early in life? Despite decades of research, there is still no definitive answer. Current hypotheses suggest that thymic involution may be part of an evolutionarily conserved strategy for reallocating the body's resources once the active formation of the T-cell repertoire is largely complete. However, these ideas remain the subject of ongoing investigation [16, 17].

The changes that occur in the thymus are part of a broader process known as **immunosenescence**, or immune aging. As we grow older, the production of new T lymphocytes declines, the composition of the immune system shifts, and the diversity of the T-cell repertoire gradually decreases. Together, these changes can influence the body's ability to respond to infections, reduce the effectiveness of vaccination, and impair the maintenance of immune homeostasis [16, 17].

Even so, thymic aging does not mean that the organ loses its importance. The thymus continues to contribute to immune function throughout adulthood, and its influence extends across the lifespan. Although the generation of new T lymphocytes gradually declines, the thymus continues to support their renewal and helps preserve the immune diversity required for effective immune responses [6, 10, 16].

Today, age-related thymic involution is regarded as one of the most intriguing and still unresolved questions in immunology. A deeper understanding of the mechanisms underlying this process could have important implications for the biology of aging, transplantation medicine, oncology, and many other fields.

Can the First Teacher Recover?

For many years, age-related thymic involution was considered an essentially irreversible process. The gradual loss of the organ's functional tissue was viewed as an inevitable consequence of aging, with little potential for recovery [16].

More recent research, however, has revealed that the thymus possesses far greater plasticity than previously believed. Even after significant injury, the organ can activate biological mechanisms that promote the partial restoration of its structure and function [18].

Particularly compelling are studies of thymic regeneration following infections, chemotherapy, radiation therapy, and bone marrow transplantation. In response to these challenges, the body can activate a complex network of signaling molecules and growth factors that help rebuild the thymic microenvironment and restore the production of new T lymphocytes [18, 19].

Over the past several years, researchers have identified several key molecular pathways involved in thymic regeneration. Among the most important are signaling pathways associated with **bone morphogenetic protein 4 (BMP4), interleukin-22 (IL-22)**, and **keratinocyte growth factor (KGF)**, along with other molecules that support the repair of thymic epithelial cells and the restoration of the organ's specialized microenvironment [18-20]. These discoveries have significantly expanded our understanding of the thymus's regenerative capacity and opened new avenues of research in immunology and regenerative medicine.

Today, growing attention is focused on whether thymic function can be preserved or restored in older adults. Although clinical applications remain under active investigation, findings from experimental studies suggest that the thymus should be viewed not only as an organ affected by aging, but also as a promising target for future immune-based therapies [18, 20].

Current evidence indicates that age-related thymic involution is not an entirely irreversible process. The capacity for partial regeneration may, in fact, be one of the most remarkable characteristics of living systems.

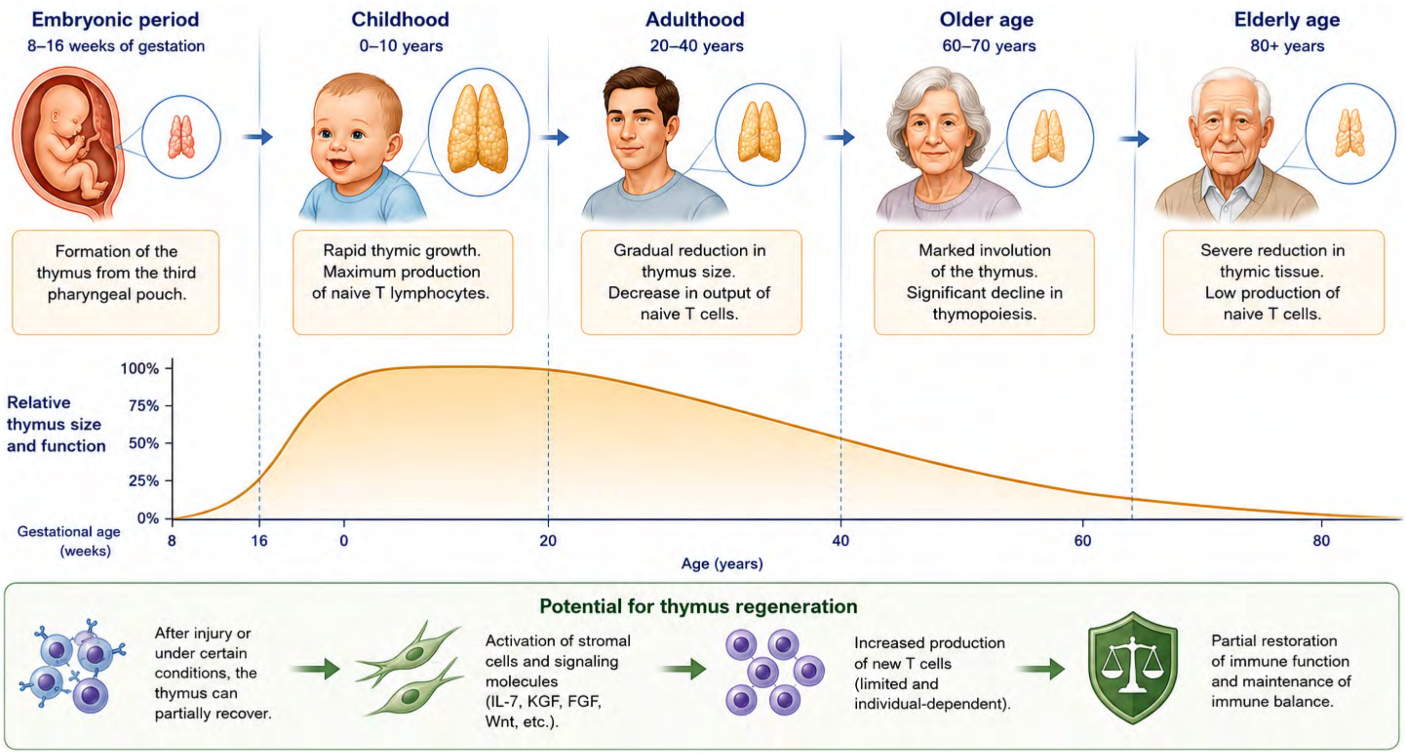

Figure 3. The Thymus Throughout Life.

The thymus reaches its peak functional activity during childhood and then gradually undergoes age-related involution. However, modern research indicates that even in adulthood and old age, the organ retains a measurable capacity for partial regeneration.

Environmental Challenges

The immune system does not develop or function in isolation. Throughout life, it remains in constant interaction with the environment, responding to a wide range of internal and external influences. Some of these are a natural part of human life, while others have emerged relatively recently and have become the focus of intensive scientific investigation.

Among the best-studied factors affecting the thymus are infectious diseases. Many viral, bacterial, and parasitic infections can cause temporary changes in the organ's structure and function. In most cases, once the infection has been cleared, regenerative mechanisms are activated, allowing the thymus to partially or even fully restore its normal function [18, 21].

Stress is another important influence. The immune, nervous, and endocrine systems are tightly interconnected, forming a complex regulatory network. Chronic stress can alter hormone levels, which in turn affect the biological processes taking place within the thymus [22].

Nutrition also plays a critical role in the development of the immune system. Its importance is particularly evident early in life, when the body's organs and physiological systems are developing rapidly. Deficiencies in protein, vitamins, or essential micronutrients can alter thymus structure and disrupt the maturation of immune cells.

As industrialization has advanced, researchers have increasingly focused on other environmental factors. Air pollution, endocrine-disrupting chemicals, and **per- and** polyfluoroalkyl substances (PFAS) have become the subject of extensive research over the past several decades. Growing evidence suggests that some of these exposures can affect multiple components of the immune system, particularly during critical periods of immune development [23, 24].

These findings have gradually broadened the traditional view of immunology. It is becoming increasingly clear that immune health is shaped by a complex interplay of interconnected biological and environmental processes. As a result, modern science faces new questions that require integrating knowledge from immunology, toxicology, developmental biology, and environmental health sciences.

A New Question for Environmental Science

Over the past several decades, advances in immunology and toxicology have greatly expanded our understanding of the factors that influence the development and function of the immune system. Infections, nutrition, chronic stress, and a wide range of chemical exposures have long been recognized as key components of the complex interactions between the body and its environment.

In recent years, researchers have turned their attention to another class of environmental factors: **microplastics and nanoplastics**. As scientific evidence has accumulated, it has become clear that plastic released into the environment can gradually fragment into particles small enough to approach the size of cells and even subcellular structures. This realization has raised important new questions about how such particles may interact with living systems [25, 26].

Experimental studies indicate that microplastics and nanoplastics can interact with immune cells, enter certain cell types, and trigger a range of biological responses. Across various experimental models, researchers have observed increased oxidative stress, activation of inflammatory signaling pathways, including **NF-κB**, disruption of cellular metabolism, and alterations in the mechanisms of programmed cell death. These processes are considered among the possible pathways through which microplastics and nanoplastics may influence immune function [25, 26].

Animal studies have also reported changes in lymphoid organs, including the spleen and thymus, as well as alterations in immune cell populations, cytokine production, and immune responses. At the same time, findings from experimental models cannot be directly extrapolated to humans and require further confirmation through clinical research [25, 26].

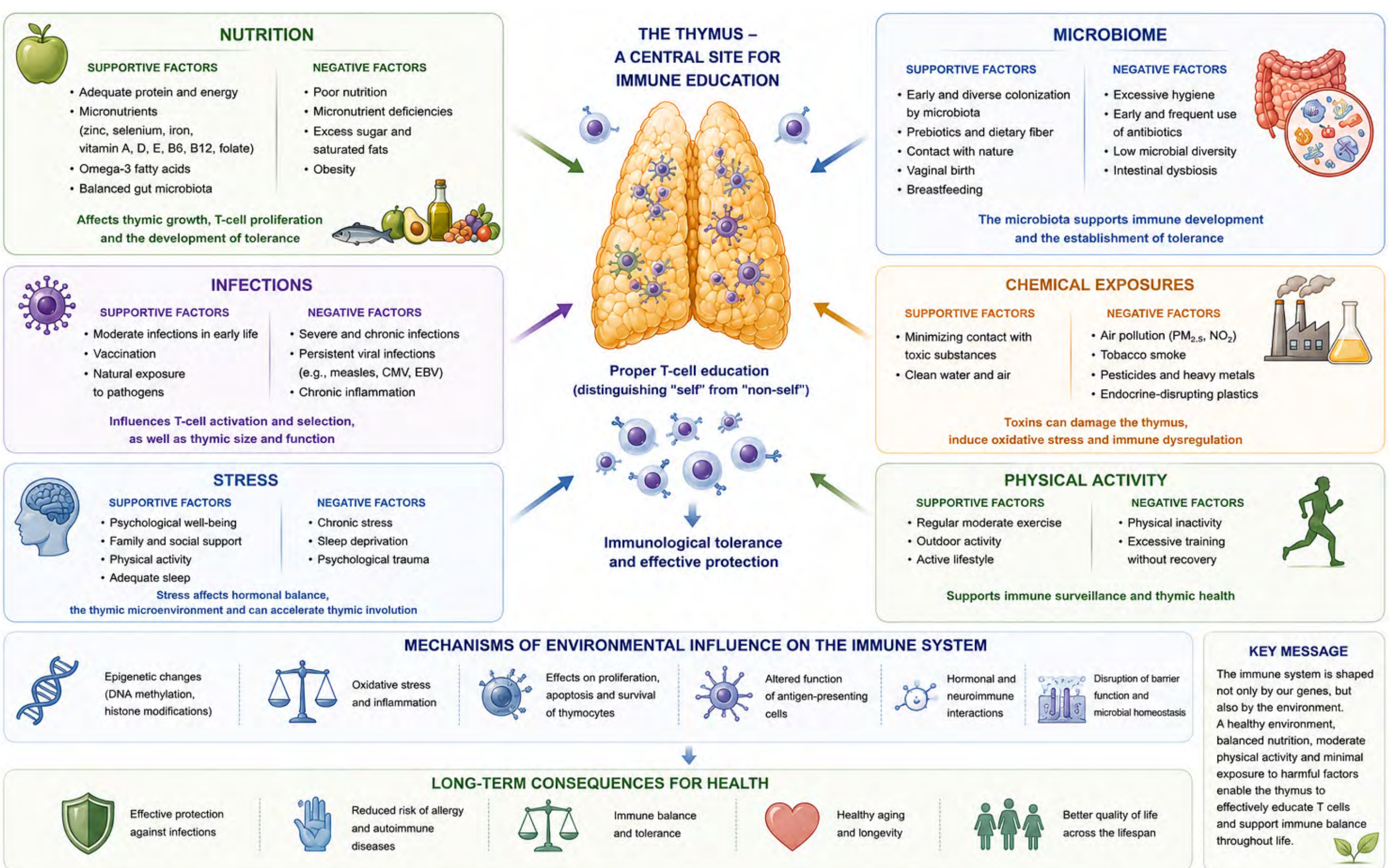

Figure 4. Environmental Factors and Immune System Development.

The immune system develops and functions under the influence of numerous interconnected environmental factors. Nutrition, infections, the microbiome, stress, chemical exposures, and lifestyle can all shape the processes through which the immune system is trained, immunological tolerance is established, and immune homeostasis is maintained.

Interest in this field has grown further following the first reports of microplastic and nanoplastic particles detected in human tissues and biological fluids, including the placenta and blood [27, 28]. These findings, by themselves, do not demonstrate that such particles cause disease. However, they underscore the need for a deeper understanding of the potential biological effects of long-term exposure.

For this reason, the effects of microplastics and nanoplastics on the human immune system remain an active area of scientific investigation. Although research in this field is advancing rapidly, many questions remain unanswered. Further studies are needed to standardize research methods, establish realistic levels of human exposure, and conduct long-term investigations that can better clarify the potential implications of these particles for human health [25, 26].

Perhaps one of the most important challenges facing modern science is understanding how emerging environmental factors interact with the biological processes that shape the immune system. In this context, the earliest stages of immune development deserve particular attention, as this is the period during which immunological tolerance is established, and the immune system receives its earliest and most fundamental training.

What We Still Don't Know

The history of science shows that progress is driven not only by the answers we discover but also by our willingness to ask new questions. Many of the greatest breakthroughs have been made because researchers were prepared to acknowledge that there were still fundamental aspects of nature waiting to be understood.

Despite remarkable advances in immunology, the thymus continues to hold many mysteries. One of the most enduring questions is why this organ undergoes age-related involution. Why does an organ that plays such a central role in establishing immunity begin to decline soon after puberty? Despite decades of investigation, there is still no definitive answer [16, 17].

Another important question concerns the limits of the thymus's regenerative capacity. Although modern research has demonstrated that the organ is capable of partial regeneration, the biological mechanisms underlying these processes remain an active area of investigation [18-20].

Many unanswered questions also relate to the earliest stages of life. Growing evidence suggests that fetal development and the first years after birth play a critical role in shaping the immune system. Yet the full extent and long-term consequences of these early developmental processes have yet to be fully understood [13-15].

The same is true for newly recognized environmental factors that have only recently become the focus of intensive scientific research. Although evidence regarding microplastics and nanoplastics is accumulating rapidly, many aspects of how these particles interact with living systems remain poorly understood, and their long-term implications for human health require investigation [25-28].

Uncertainty is not a sign of weakness in science. On the contrary, the willingness to recognize unanswered questions lies at the heart of scientific progress. As new discoveries continue to emerge, our understanding of the immune system will continue to evolve, opening new frontiers for research.

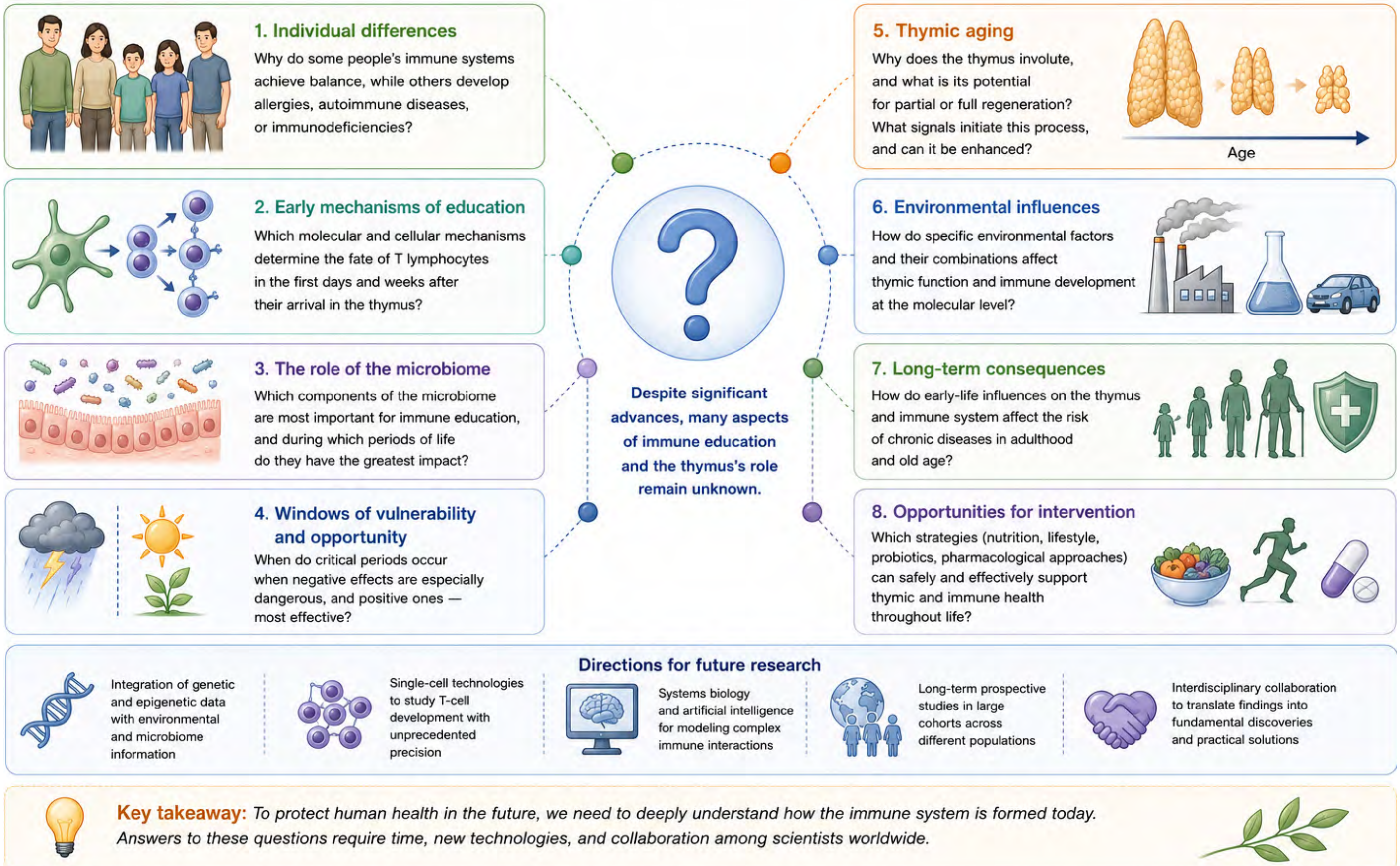

Figure 5. Questions That Remain.
Despite significant progress in understanding the thymus and the immune system, many aspects of their development, aging, regeneration, and interactions with the environment remain under active investigation. Advances in technology and interdisciplinary research are creating new opportunities to answer these fundamental questions.

The Immune System's First Teacher

For centuries, the thymus remained one of the most mysterious organs in the human body. Its function was unknown, and it was often regarded as little more than an anatomical curiosity. Scientific discoveries during the second half of the twentieth century, however, completely transformed that view [1–3].

Today, the thymus is recognized as one of the central organs responsible for shaping the immune system. It is here that T lymphocytes undergo the complex process of education that enables them not only to recognize potential threats, but also to maintain the delicate balance between immune defense and immunological tolerance [4, 5, 7–9, 12]. In this sense, the thymus is far more than a site where immune cells mature. It is a school where the immune system receives its first, and perhaps its most important, lessons.

Modern research has shown that the thymus's influence extends far beyond childhood. Despite the changes it undergoes with age, the organ remains an important part of the complex network that supports immune health throughout life [6, 10, 16–20]. At the same time, new discoveries continue to deepen our understanding of development, aging, and the body's interactions with the environment.

The story of the thymus is also a story of how science advances. What was once considered a minor and insignificant structure is now recognized as one of the most important components of the system that safeguards human health.

Perhaps the immune system's greatest achievement is not its ability to wage war, but its ability to maintain balance. And it is the thymus that helps lay the foundation for this remarkable capacity.

The story of the thymus reminds us that the most important processes in the body are not always the most visible. Sometimes, the smallest and least conspicuous structures exert an influence that lasts a lifetime.

Before the immune system can protect the body, it must first undergo training.

And one of its first, and most important, teachers remains a small organ hidden behind the breastbone, one that most people never think about: the thymus.

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The Integration of Neural Networks as Tools in Scientific Research

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Scientific instruments have consistently expanded the frontiers of what is observable. The telescope enabled the observation of distant objects, while the microscope revealed microscopic structures. Currently, machine learning is facilitating the discovery of patterns concealed within complex datasets. Its significance for science extends beyond accelerating calculations. In certain research contexts, algorithms assist in recognizing relevant variables, prioritizing hypotheses for testing, and determining appropriate descriptions of the phenomena under investigation.

When Data Outpaced Understanding

The history of science is frequently characterized as a succession of significant ideas. Equally important, however, is the history of scientific instruments.

The telescope made Jupiter's moons observable. The microscope revealed cells and microorganisms. X-ray diffraction enabled the investigation of the internal structure of crystals. For centuries, scientific progress depended on expanding the scales accessible to observation. New instruments revealed phenomena concealed by distance, size, or the limitations of the human senses.

In the twenty-first century, science has encountered a new limitation. Modern instruments and computational models generate extensive data on molecular motion, cellular activity, genome sequences, atmospheric conditions, and material properties. Acquiring information is now often less challenging than discerning which aspects of the data are most significant.

This problem is particularly apparent in the study of complex systems. A molecular simulation may contain the coordinates, velocities, and energies of an enormous number of particles. A climate model describes numerous interconnected processes in the atmosphere, the ocean, and on Earth's surface. Biological databases integrate the sequences, structures, and functions of millions of molecules.

In each instance, the data are already available. However, scientific explanations do not arise solely from the volume of data collected. Researchers must identify variables that render a system's behavior comprehensible. Appropriately selected variables can reveal consistent relationships, whereas poorly chosen variables may obscure them, even within precise datasets. Consequently, scientific discovery often begins not with new measurements, but with creative approaches to describing phenomena.

Thermodynamics became possible when researchers learned to relate macroscopic quantities, such as temperature, pressure, and volume, to the state of matter. Molecular biology was transformed when heredity could be described in terms of the structure and sequence of DNA.

Within high-dimensional systems, the relevant variables are frequently unknown a priori. Researchers must identify them among thousands or even millions of potential features. In this context, machine learning assumes a novel and critical role.

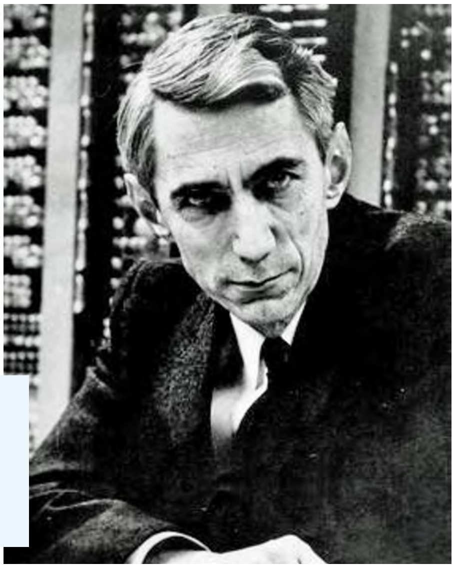
For decades, computers primarily accelerated calculations that had already been formulated by humans. Researchers defined the model, the equations, and the quantities to be determined. The machine performed the calculations.

Contemporary algorithms can contribute at earlier stages of research. They can identify structure in data, reduce dimensionality by selecting essential variables, and isolate feature combinations that are challenging to detect through manual analysis.

Understanding how computational systems acquired this role requires consideration of two foundational concepts that predate modern neural networks: predictions can be formulated probabilistically, and rules can be both programmed and learned from experience.

From Rules to Learning

In one experiment, participants were presented with a segment of text and asked to predict the subsequent letter. As the amount of contextual information increased, their predictions became more accurate. The preceding characters constrained the range of likely continuations. Thus, language can be conceptualized as a probabilistic system. Context reduces uncertainty, and knowledge of the prior text enables the estimation of the probabilities of subsequent elements.



Claude Shannon. In 1951, he demonstrated that predicting how a text will continue could be described mathematically.

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Shannon's research addressed information, redundancy, and uncertainty, and demonstrated that predicting continuations can be formulated mathematically [1]. This principle was incorporated into everyday technology prior to the emergence of artificial intelligence. For example, in the 1990s, Tegic Communications developed T9 (Text on 9 Keys), which expedited text entry on mobile phones. Rather than pressing a key multiple times, users pressed each number once per letter, and the software matched the sequence to an electronic dictionary, ranking words by frequency of use. Although T9 did not interpret messages or construct language representations comparable to modern models, it exemplified the use of context and statistical methods to select probable continuations [2].

T9 did not constitute artificial intelligence in the contemporary sense, nor was it a direct precursor to large language models. However, both systems share a conceptual similarity: they evaluate possible continuations based on the provided context. For T9, the objective was to select a word corresponding to the entered numeric sequence. In contrast, modern language models estimate the probabilities of the next token, which may be a word, a word fragment, punctuation, or another textual element.

The difference in scale is enormous. T9 operated with a compact dictionary and relatively simple statistical rules. A modern AI model is trained on vast amounts of text and uses billions of parameters to account for complex relationships among words, concepts, and contexts.

Yet the underlying question still derives from Shannon's information theory: What is most likely to come next?

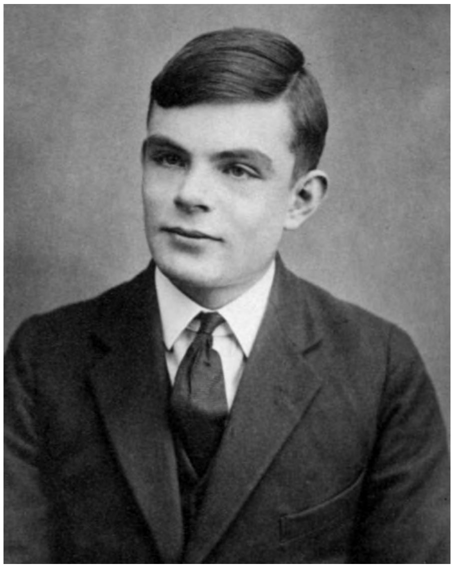
Prediction represented only one aspect of the challenge. T9 also exemplifies the limitations inherent in systems that operate solely according to parameters predefined by developers. Estimating the probability of a word required a human-constructed dictionary and statistical data, with all significant relationships specified in advance. This raises a critical question: how can systems address problems where the underlying rules or features cannot be fully articulated beforehand?

In conventional programming, a developer analyzes a problem, formulates a procedure, and translates it into code. The computer executes the instructions. This approach is effective when the rules are known. Accounting systems, engineering calculations, navigation software, and spacecraft software were all created in this way. But many problems are difficult to describe exhaustively.

For example, a child rapidly learns to distinguish cats from dogs without memorizing formal descriptions of every breed. Through exposure to examples, making mistakes, and adjusting their understanding, children are able to recognize animals they have not previously encountered.

Efforts to replicate this ability in conventional programs encounter major challenges. For instance, while dogs are often assumed to have longer snouts and cats more rounded faces, exceptions such as pugs complicate this distinction. Ear shape, fur length, paw size, tail shape, and body proportions introduce additional variability, leading to numerous exceptions. As additional rules are introduced, the list of exceptions can outpace the rules themselves. The core issue is not simply computational power; much of the knowledge humans apply confidently is difficult to formalize as a finite set of instructions.

As early as 1950, Alan Turing proposed a different approach. Instead of attempting to program the behavior of an adult mind from the outset, he considered the possibility of creating a "child machine" whose abilities would develop through learning [3].



Alan Turing. In 1950, he proposed creating not a fully formed intelligence, but a system that learns from experience.

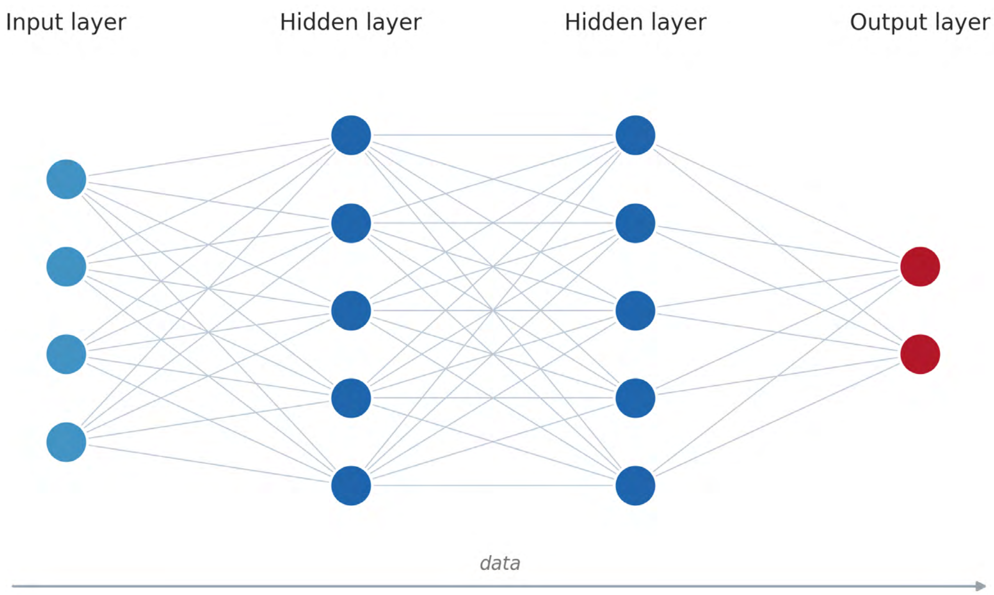
Source: Wikimedia Commons.
License: Public domain.

This development marked a significant shift in the formulation of the problem. Rather than focusing on which rules should be explicitly programmed, researchers began to consider how experience could be structured to enable a system to derive rules autonomously.

One of the first practical answers was Arthur Samuel's checkers program. It used game results and generalization procedures to improve its evaluation of game positions. In his 1959 paper, "Some Studies in Machine Learning Using the Game of Checkers," Samuel described two machine-learning procedures and demonstrated that a program could improve its play through experience [4].

The role of the developer evolved rather than disappeared. Researchers continue to select the data, model architecture, objective function, and evaluation criteria. However, the specific relationships between inputs and outputs no longer need to be explicitly programmed; instead, they are encoded in the model's parameters during training.

A neural network begins training with parameters that do not yet reflect the structure of the problem. It receives an example, makes a prediction, compares it with the known result, and calculates the magnitude of the error. The parameters are then adjusted slightly to reduce the likelihood of a similar error in the future. This process is repeated many times, sometimes millions or billions of times. After numerous iterations, the model develops internal representations that are useful for solving the problem.



Neural network architecture. The connections between input and output are not specified manually but are adjusted during training.

These internal representations are not equivalent to human concepts. A model does not possess an understanding of a cat, a word, or a protein analogous to human cognition. Instead, it encodes statistical relationships that facilitate distinction, prediction, or data generation.

For a long time, the capabilities of this approach were limited by small datasets, insufficient computing power, and the difficulty of training deep networks. By the beginning of the twenty-first century, these limitations had begun to diminish.

A landmark event was the 2012 ImageNet competition. Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton introduced a deep convolutional neural network that later became known as AlexNet [5]. It was trained on more than 1 million labeled images and tasked with distinguishing among 1,000 object categories.

At the time, many of the best computer vision systems relied on features designed in advance by researchers. Specialists determined which edges, textures, and geometric characteristics should be extracted from an image and then passed them to a classifier.

AlexNet simultaneously learned to identify relevant features and perform the primary classification task, substantially outperforming previous object classification systems. Its performance advantage was significant enough to alter the trajectory of the entire field. Notably, the network's method of organizing internal image processing was particularly influential.

The first layers responded to relatively simple elements, such as edges, line orientations, and color contrasts [5]. Deeper layers combined them into textures, object parts, and complex configurations. This produced a hierarchy of representations, progressing from local visual features to categories of entire objects [6].

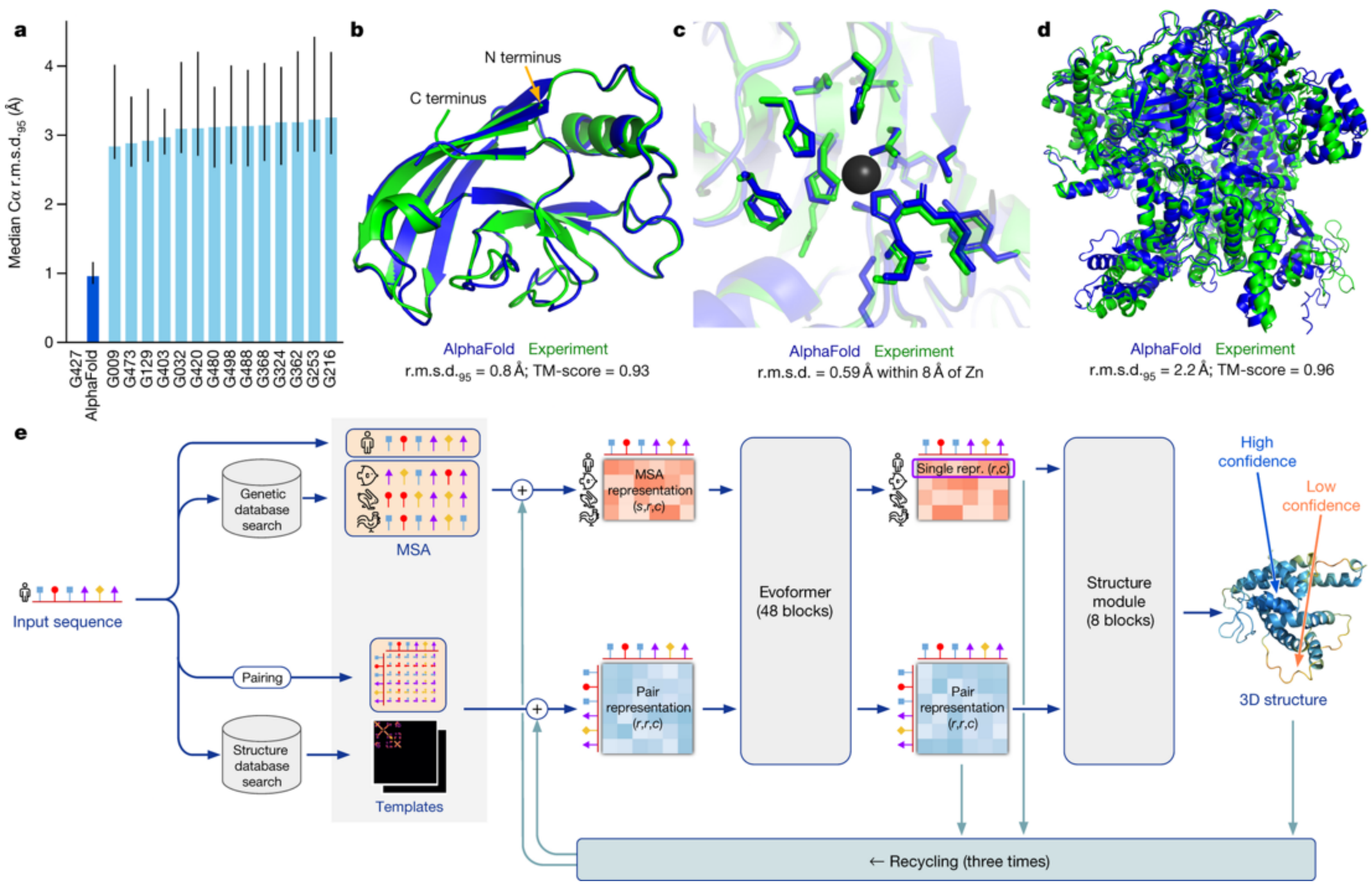
This hierarchical structure was not manually defined by researchers; rather, it emerged during the training process. This outcome demonstrated that a neural network could autonomously discover effective representations of complex data for specific tasks. The success of this approach with images prompted further inquiry into its applicability to other types of information, leading to the expansion of scientific applications for machine learning.

From Prediction to Scientific Representation

In numerous scientific disciplines, researchers address highly complex systems. However, complexity does not equate to randomness. Experimental data and numerical modeling frequently reveal consistent patterns. With sufficient observations, algorithms can learn to recognize intricate relationships between input data and outcomes of interest. Many contemporary scientific machine-learning systems are founded on this principle.

One of the best-known examples is AlphaFold2.

A protein begins as a linear chain of amino acids, but its biological function is largely determined by the three-dimensional structure that the chain assumes after folding. Experimentally determining this structure often requires considerable time and resources. AlphaFold2 used amino acid sequences, evolutionary information about related proteins, and patterns extracted from known protein structures to predict the most probable three-dimensional structure of a protein. In 2021, its developers reported a dramatic improvement in the accuracy of computational protein structure prediction. In many cases, the results approached the level of accuracy required for practical structural analysis [7].



AlphaFold2: Comparison of predicted and experimentally determined protein structures and an overview of the model architecture.
Source: Jumper et al., Nature 596 (2021), CC BY 4.0.

The model did not eliminate the need for experimental validation or resolve all challenges in structural biology. However, it substantially altered the initial conditions for research. In many instances, scientists gained access to computational models sufficiently accurate to support further analysis.

The same general principle also proved effective in meteorology. GraphCast was trained on global reanalysis data, reconstructions of atmospheric conditions that combine real-world observations with the results of physical models. Given two consecutive snapshots of the atmosphere, the model forecasts the atmosphere's subsequent evolution for up to 10 days. In a 2023 study, GraphCast outperformed the operational deterministic system of the European Centre for Medium-Range Weather Forecasts on most of the selected evaluation metrics [8].

This development does not imply that the neural network supplanted physical models of the atmosphere. Its training data were derived from decades of observations and outputs from physical models. GraphCast instead demonstrated that the behavior of complex dynamic systems can be effectively modeled by leveraging patterns present in extensive datasets.

A similar approach was implemented in materials science. GNoME used graph neural networks to evaluate the stability of the proposed crystal structures. As a result, researchers obtained approximately 381,000 new structures computationally predicted to be stable. This does not mean that every one of these materials can be synthesized or that all of them will prove useful in practice. However, the system drastically reduced the number of candidates that must be tested using more expensive methods, significantly accelerating the search for new materials. The model enables ranking candidates and directing resources toward those with a higher probability of producing a significant result [9].

Although AlphaFold2, GraphCast, and GNoME appear to address distinct scientific challenges, they are unified by a common computational principle. In each case, the task is predefined: researchers specify the input data and the desired type of model output. But there is another class of scientific problems. Sometimes, not only is the answer unknown, but it is also unclear which variables should be used to describe the phenomenon. This type of problem is illustrated by a study of liquid water published in Nature Physics on June 4, 2026 [10].

> ***“Water appears to be one of the simplest substances: each molecule consists of two hydrogen atoms and one oxygen atom. Yet the collective behavior of vast numbers of these molecules is exceptionally complex.”***
>
> *— Taliy Shkurupiy*

Unlike most liquids, water at atmospheric pressure reaches its maximum density at approximately 4 °C and begins to expand as it cools further. Its heat capacity, compressibility, and other properties also exhibit unusual behavior, particularly in the supercooled state.

One hypothesis links this behavior to two types of local molecular organization. In one, denser structure, the molecules are packed more closely together. In the other, they form a more open, nearly tetrahedral arrangement. These are statistically distinguishable local structures. The main difficulty lies in detecting them. A molecular dynamics simulation generates trajectories for vast numbers of molecules. Each configuration is described by coordinates, distances, angles, and hydrogen-bond characteristics. But this dataset does not indicate which combinations of parameters best distinguish the system’s states. Researchers typically select an order parameter in advance. This may be density, the number of neighboring molecules, or a measure of tetrahedrality. Such a choice already incorporates an assumption about the nature of the process.

In a 2026 study published in Nature Physics, researchers applied unsupervised learning methods to trajectories from molecular dynamics simulations of water. Within the resulting representation, they identified two families of local structures and different pathways of transition between them. Far from the transition region between the high- and low-density states, a relatively simple pathway was observed. Near this region, the transition structure became more complex. The authors interpreted this result as evidence supporting a two-state description of deeply supercooled water [10].

This conclusion warrants careful interpretation. The algorithm analyzed data from molecular dynamics simulations based on a specific water model, and the results alone do not establish that ordinary water comprises two coexisting macroscopic liquid phases. Comparison with alternative models and experimental data is necessary. Nonetheless, the methodological significance of this study extends beyond water physics. In this context, the algorithm facilitated the construction of a data representation in which local structures and their transition pathways could be distinguished. Thus, when the appropriate descriptive variables are not known a priori, machine-learning methods can assist in constructing representations that reveal previously hidden patterns.

Whereas early generations of scientific machine learning primarily accelerated the retrieval of known answers, the subsequent stage may prove substantially more consequential. Algorithms are now beginning to assist not only with calculations but also with identifying research questions. As a result, artificial intelligence is gradually becoming an integral component of the scientific method.

It is likely that the current period represents only the initial phase of machine learning's adoption in scientific research. The first telescopes did not immediately revolutionize astronomy, nor did the earliest microscopes promptly lead to cell theory. Historically, it has taken decades for scientists to differentiate genuine structures from instrument-induced artifacts and to translate new observations into established knowledge.

Machine learning is likely at a comparable developmental stage. Currently, it enables researchers to navigate data spaces that are inaccessible to direct analysis. In the future, it may become as integral to the scientific method as the microscope, spectroscopy, or computer modeling.

If this transition occurs, the principal contribution of machine learning will not be its capacity to answer questions on behalf of humans, but rather its ability to render observable patterns that previously remained concealed within complex datasets.

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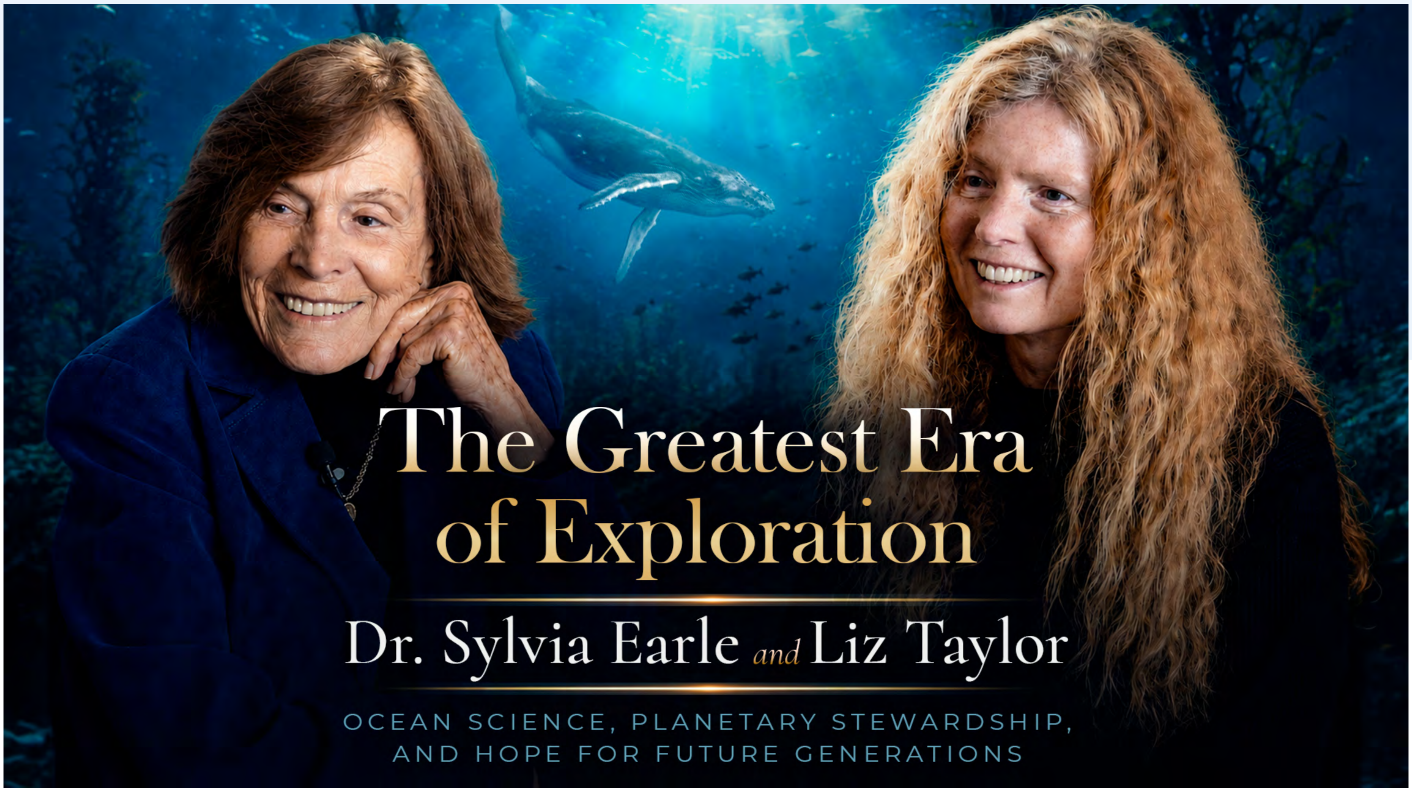
No Blue, No Green

Oceanographer Sylvia Earle and marine engineer Liz Taylor on the sea as humanity's life-support system — and the narrow window we have left to protect it.



Sylvia Earle is one of the most influential figures in the history of ocean science: a pioneering oceanographer, National Geographic explorer-in-residence, and founder of Mission Blue. Beside her is her daughter, Liz Taylor, president of DOER Marine, the company that builds the submersibles and robotic vehicles that carry science into the deep.

During the visit of Olga Schmidt, representing the ALLATRA research center, an exclusive interview — "The Greatest Era of Ocean Discovery" — was recorded with Dr. Earle and her daughter, Liz Taylor. The conversation ranged across industrial fishing, plastic and microplastic pollution, deep-sea mining, ocean acidification, and the loss of biodiversity. What follows is the edited, condensed version of that interview.

Imagine Earth without the ocean

Sylvia: One way to make people see that the ocean matters to everyone, everywhere, all the time is simple. Imagine Earth without the ocean. What have you got? A planet a lot like Mars. Ninety-seven percent of Earth's water is ocean. No ocean, no life. I sometimes say: no blue, no green. It's the life-support system — 97% of the biosphere. Astronauts are smart enough not to mess with their life-support system. Underwater, I learned the same thing fast: you take care of it, or it stops taking care of you.

> *"No blue, no green."*
>
> *— Sylvia Earle*

Liz: And since the industrial age we've done the opposite — treated the sea as the place to convey our waste, on the theory that the solution to pollution is dilution. It's not. It comes back to us as microplastics, heavy metals, toxins that bioaccumulate in the fish and shellfish people eat. When I was a kid, if you cut your hand they told you to go to the ocean to heal. Now an open wound near the water can mean flesh-eating bacteria.

Olga: So we disturbed a cycle the planet ran well without our help.

Liz: Exactly. The planet did the filtration for millennia. Our job now is to let it — protect the marshlands, the coasts, the open space that keep the water clean.

The magnitude of what we don't know

Olga: NOAA says only about 27% of the seafloor has been mapped in modern detail, and a tiny fraction has ever been seen by human eyes. You often say the ocean floor is less explored than the surface of Mars.

Sylvia: The most important thing we've learned about the ocean is the magnitude of what we don't know. On my watch we found not just new species — new families, new kingdoms of life. And we've explored only a tiny fraction of it. We make laws based on what we know, but we should leave room for what we're still learning. We've calculated how many tuna, swordfish, lobsters we think we can take "safely" — an artificial peace of mind, because we don't actually know how many there were, or are. If you understand that, you become far less greedy. We've already taken about half the life that was in the ocean.

De-wilding the ocean

Sylvia: Drag a net across the seafloor and you keep only a fraction of what you catch; the rest goes back overboard, dead. It's like dragging a net through a forest because you want the songbirds — you destroy the forest, and you only get the songbirds. We'd never do that on land, because we'd see it. People would be outraged.

Liz: Engineering pushed hard to help us take more. Containerization, refrigeration, freezing at sea — suddenly you can catch krill in Antarctica and ship it tens of thousands of miles. That industrialization created a deeply unfair approach to removal.

Srikanth Mannepuri / Ocean Image Bank

Sylvia: And a disconnect. Almost everything we take from the sea is a carnivore, and old. We eat lamb, not old sheep; we eat chickens within their first year. But we eat ten-year-old tuna, hundred-year-old orange roughy — and not long ago, turtles that live a century. We only stopped commercial whaling globally in 1986, and some whales live 200 years. Wouldn't we like to know their secrets?

Liz: The problem is the idea that wildlife is free for the taking.

Sylvia: One of the stupidest things we grow is salmon — a carnivore. We catch wild fish to feed it. Nobody could find salmon in markets in the 1950s; now it's everywhere, even farmed in South Florida. Liz, you mentioned rewilding the land. We are de-wilding the ocean — taking wildlife on a mega scale and disrupting the systems that make oxygen and hold this diversity together.

> *"We are de-wilding the ocean."*
>
> *— Sylvia Earle*

Liz: Most alarming is the push into the mesopelagic — the twilight zone. Those animals rise toward the surface every night in the biggest migration on the planet, and in doing so they help pump carbon into the deep. Now fleets trawl hundreds of meters down and crush them into fishmeal for salmon, or into fish-oil capsules we don't really need. The squid fleets are visible from space, lights blazing, jigging squid out of the ocean by the metric ton — legal and illegal.

Sylvia: You see cans of tuna on a shelf and assume someone decided it's fine, or it wouldn't be there. That's the power of marketing. We delude ourselves — and then it's gone. It's not gone yet.

Ghost nets and the plastic you can't see

Sylvia: When I was a child, plastic did not exist. Now it has reached every child on Earth — through the air, the water, the food. More than half the plastic in the ocean is discarded nets and lines. Once, a fishing net was handwoven, a big deal, like the quilts my mother made; if it was lost, you did everything to recover it. Now synthetics are cheap enough to lose.

Liz: And they're incredibly persistent — hundreds of years. They become ghost nets: they keep catching fish, entangle a whale, sink, decompose just enough to float up, and start killing again. Or they saw through a coral reef, or through a whale's tail.

Olga: Scientists were amazed to find micro- and nanoplastics down in the Mariana Trench and on top of Mount Everest. It has even turned up in the human placenta, and a 2025 study estimated 27 million tonnes of nanoplastics in the North Atlantic alone.

Umeed Mistry / Ocean Image Bank

Sylvia: And in the Antarctic — fa from where you'd think. How serious is it? We don't know. It's all new, and it takes time to see cause and effect reliably. But if plastic were essential to living systems, it would already be part of them; it can't just be there without an impact.

Liz: We've watched corals starve — they feel full of plastic and stop feeding. Albatross parents feed floating plastic to their chicks, and you find the bodies with a crop full of it. The nano stuff clogs the filter feeders — the oysters, mussels, clams people like to eat — and it bioaccumulates. So we're eating a dose of microplastic.

Sylvia: And not knowing it.

> *"We're eating a dose of microplastic. And not knowing it."*
>
> *— Liz Taylor and Sylvia Earle*

Liang Fu / Ocean Image Bank

The outlaw ocean, and the case for ecocide

Olga: You've supported recognizing ecocide as an international crime. Where does damage stop being a mistake and become a crime against life?

Sylvia: We face challenges of our own making. Whales didn't cause them; we did. It starts with knowing you have a problem.

Liz: Illegal fishing is wildlife trafficking — and it's tied to arms, drugs, and human trafficking. We've worked with Ian Urbina on his Outlaw Ocean Project.

The Outlaw Ocean Project is Ian Urbina's long-running journalistic investigation into crime, forced labor, and lawlessness on the high seas. — Ed.

Liz: People are lured from small villages with the promise of a job as a nanny or a gardener, and end up on a fishing vessel for years. If they stop working, they're thrown overboard — there's footage of people shot at sea. And it comes back to your table as catch of the day.

Sylvia: Legal, illegal, unreported, unregulated — and subsidized. Billions go to those who capture and market ocean wildlife. That's part of the problem, and part of the solution: bring those billions back and give the industry a soft landing. It's the same question we ask of oil and gas — can we convert these companies to positive impact rather than destroy them?

Liz: We've seen it work. In Isla Mujeres, Mexico, a hotel owner watched his diving tourism drop as the sharks disappeared. So he paid the shark fishermen the same money not to fish, hired their families in tourism, and had them turn in their hooks. They came home at reasonable hours, the families were happier, and tourism dollars went way up. Now people pay to watch a giant bull shark come in.

Sylvia: Instead of killing them. Nature positive.

Liz: And there's the new BBNJ treaty, to help protect the high seas. Now the question is how to enforce it.

BBNJ — the Agreement on Marine Biodiversity of Areas Beyond National Jurisdiction, known as the High Seas Treaty. — Ed.

Sylvia: It came into force just last year. But first we have to agree to protect at least 30% of the high seas from extractive industries: right now it's a tiny fraction of 1%.

Tools of hope

Sylvia: Mission Blue was never meant to be another bureaucracy — just a way to make people understand the danger. Now we have people in 116 countries, catalysts identifying places they love and pushing them toward protection. Every place matters; no part of the planet is superfluous. With Esri's GIS StoryMaps we've mapped each Hope Spot as a field station gathering shareable data. And with DOER's submersibles we can finally go beyond the first 100 meters, where most information stops.

Liz: French Polynesia — the Tetiaroa Society and the Tetiaroa Hope Spot — is our template: bring submersibles, training, jobs, and load all the GIS data into one platform with Tanzle so we can see big trends. What are the turtles doing in Tetiaroa versus the Gulf? Stop siloing the information. Submersibles are the most impactful technology we have. Sylvia took Ecuador's environment minister down; he was apprehensive, then a Mola mola swam up and gave him the side-eye, and he lit up like a child.

> *"With knowing comes caring."*
>
> *— Sylvia Earle*

Sylvia: I'd like to see this seriously scaled up — the people on the ground given the resources to explore, gather knowledge, and share it. If we want to speed it up, the next five years are the speed we need. Nature has a zero accounting base; a live whale, a thousand-year-old tree has to be worth more than a dead one.

Olga: How does science truly reach society and become action?

Sylvia: Scientists used to feel they'd pay a price for stepping out of their lane. That's shifting. Communicate with people in a language they understand — without compromising the truth.

Liz: As you said in your original TED talk, you use everything at your disposal — books, films, music, any kind of media, whatever you're good at.

Sylvia: Be the voice. Set a trend.

Olga: We're all drops in the ocean.

Liz: But together we make the whole ocean.

The Honor of Humanity Medal

Olga: Doctor Earle, on behalf of ALLATRA and our international community of people from many nations, it is my profound honor to present you with the Honor of Humanity Medal — in recognition of your historic contribution to ocean exploration, marine science, and the protection of Earth's living seas.

Sylvia: Thank you for this beautiful recognition — I'm not sure I deserve it. I'll keep trying. There's so much to do. We're right on the edge of the greatest era of exploration. And taking care of this little blue place that sits right in the center.

> *"Protect nature, especially the ocean, as if your life depends on it. Because it does."*
>
> *— Sylvia Earle*

Olga Schmidt (ALLATRA research center) and Dr. Sylvia Earle after the presentation of the Honor of Humanity Medal.

Watch the full interview, "The Greatest Era of Ocean Discovery," on YouTube: https://youtu.be/-Jg9C3AUTsM

A chronicle of scientific work: April–June 2026

The ALLATRA Global Research Center (GRC), a U.S.-based research organization, conducts interdisciplinary analysis of climate, geodynamic and environmental processes. This section gathers the achievements of the Center and its experts over recent months: scientific reports, expert talks and the development of international cooperation.

Nanoplastics conference at the European Parliament

Brussels, 24 February 2026

The expert conference **"NANOPLASTICS: HIDDEN CONNECTIONS AND EMERGING RISKS"** was held at the European Parliament under the auspices of MEP Ondřej Knotek in cooperation with ALLATRA GRC. Scientists from the United States, Israel, Germany and the Czech Republic presented their findings across four expert panels devoted to invisible micro- and nanoplastic pollution and its impact on human health, the environment and global natural processes.

Professor Antonio Ragusa, the first scientist to identify microplastics in the human placenta, presented his data; Alexander Masny spoke on how charged particles affect cellular mitochondria, and Jan Kára presented a hypothesis on the influence of micro- and nanoplastics on the water cycle and hail formation. The panels' shared conclusion: unified European standards are needed for measuring particles smaller than 10 microns, along with interdisciplinary cooperation between medicine, environmental science and the geosciences.

The "NANOPLASTICS: HIDDEN CONNECTIONS AND EMERGING RISKS" conference at the European Parliament, 24 February 2026

Strategic cooperation with Bolivia on climate security

La Paz, Bolivia, 25 February 2026

The Vice Ministry of Civil Defense of Bolivia and ALLATRA GRC launched a joint cooperation program aimed at improving the quality of public decision-making and building an integrated risk management system amid climate and geodynamic challenges. Bolivia faces growing vulnerability to floods, droughts, wildfires, landslides and seismic activity, so the emphasis is on scientific and analytical support, verified data and interdisciplinary assessments.

The parties noted Bolivia's interest in joining the "Sendai Dialogue Platform," launched by ALLATRA in 2025 in line with the UN Sendai Framework for Disaster Risk Reduction 2015–2030.

Working meeting between ALLATRA and the Vice Ministry of Civil Defense of Bolivia, La Paz

Expert workshop at the ChangeNOW 2026 summit in Paris

Paris, Grand Palais, 30 March – 1 April 2026

At one of the world's largest sustainability summits, ALLATRA GRC experts and movement participants held a workshop on 1 April, "Nanoplastics: The Invisible Threat and Global Risk: What Can We Do?"

Speakers Gabriela Szalayova and Alexander Masny presented data on the spread of particles in air, water, soils and food chains, and discussed the concept of "strategic electrostatic neutralization" as a direction for further research. About 80 people took part in the discussion.


The workshop "Nanoplastics: The Invisible Threat and Global Risk" at the Grand Palais, ChangeNOW 2026

Science outreach event in Milan

Milan, Civic Aquarium, 15 April 2026

The Civic Aquarium of Milan hosted the conference “Micro- and Nanoplastics: The State of Research and Innovative Perspectives,” organized by Milan's Microplastics Committee (Comitato Microplastiche). Researchers from the universities of Milan and Padua presented data on the penetration of particles into the human body and on the link between water quality and public health. Journalists from ALLATRA TV Italy conducted a series of interviews with experts and presented the Center's analytical material on the impact of micro- and nanoplastics on the biosphere.

The conference “Micro- and Nanoplastics: The State of Research and Innovative Perspectives,” Milan

A systematic report on the risks of nanoplastics to health and ecosystems

Washington, D.C., 23 April 2026

ALLATRA GRC released the scientific and analytical report “Nanoplastics. A Systematic Risk Analysis for Human Health, Ecosystems, and the Environment.” Drawing on 592 sources, it is among the most comprehensive open syntheses on the topic; the work is published under a CC BY 4.0 license and assigned a DOI, making it available to the scientific community, regulators and the general public.

The report's central point is that the problem is not only the volume of plastic: as it breaks down to micro- and nanoscale sizes, the particles fundamentally change their properties. Their specific surface area rises sharply (a fragment about 1 mm across corresponds by mass to roughly a trillion particles around 100 nm in size), their reactivity increases, and plastic begins to behave as a new class of anthropogenic particles that interact with proteins, cell membranes and the body's protective barriers: the intestinal, blood-brain and placental barriers. A dedicated section explores the hypothesis of an internal “charge architecture” of nanoparticles as a promising direction for future research.

“The goal of this report is to establish a more precise scientific framework and to consolidate fragmented data into a unified map of risks and research priorities.”

— Dr. John Ahn, lead author of the report, member of the ALLATRA GRC Scientific Advisory & Research Council

Cover of the ALLATRA GRC report “Nanoplastics. A Systematic Risk Analysis for Human Health, Ecosystems, and the Environment”

ALLATRA GRC at the scientific conference “Water in Bolivia”

Santa Cruz, Bolivia, 4–7 May 2026

The Center took part as one of the key partners of the scientific and academic event “Water in Bolivia: Science, Innovation and Alliances for Sustainable Futures,” marking the 60th anniversary of the Bolivian Catholic University “San Pablo.” The conference brought together researchers, universities, government institutions and local communities to discuss the water and environmental challenges of the 21st century, from integrated water resource management to the One Health approach. A central moment was the plenary presentation by John Ahn, “Water Under an Invisible Threat: Nanoplastics and the Need for Global Scientific Research,” in which he linked the risks of nanoplastics for water resources and ecosystems to the problem of anomalous ocean heat accumulation and the need to account for additional factors affecting the ocean's thermal state.

John Ahn during his plenary presentation at the “Water in Bolivia” conference, Santa Cruz

Dr. John Ahn on the micro- and nanoplastics crisis on the TEDx stage

St. Louis, USA, 30 May 2026

Dr. John Ahn, Chief Scientist and Chair of ALLATRA GRC, spoke at TEDxStLouis at the Missouri History Museum with the talk “Too Small to See, Too Dangerous to Ignore: Micro- and Nanoplastics.” He described micro- and nanoplastics as “invisible pollution” that does not disappear but accumulates in ecosystems and organisms, and highlighted the role of electrostatic charge as a possible key to understanding particle behavior.

He also noted the growing institutional attention to the topic: in April 2026 the U.S. Department of Health and Human Services and the Environmental Protection Agency formally recognized micro- and nanoplastics as a public health concern, launching STOMP, a five-year, $144 million program.

> ***“Maybe we are asking the wrong question. It's not about how to remove these tiny plastics, but how to make them less harmful.”***
>
> *— Dr. John Ahn*

Dr. John Ahn on the TEDxStLouis stage, Missouri History Museum

CALL FOR CONTRIBUTIONS

ALLATRA Natural Science Review is published quarterly by the ALLATRA Global Research Center. We invite scientists, researchers, environmental experts, engineers, data analysts, educators, healthcare professionals, and policy-oriented practitioners to contribute to forthcoming issues.

The Review works in four thematic areas.

- Planetary Systems covers climate systems, geodynamic processes, natural hazards, ocean–atmosphere interactions, and long-term environmental change.
- Micro- and Nanoplastics covers environmental pathways, human exposure, ecosystem effects, toxicology, and public health implications.
- Ecological Resilience covers biodiversity, soil and water systems, food systems, landscape ecology, adaptation, and preparedness.
- Emerging Science and Society covers data science and AI in research, biosecurity and biotechnology, science communication and public understanding, and the relationship between science, institutions, and strategic decision-making.

Formats and length

Format	Words	Characters with spaces
Feature article	1,200–1,800	approx. 8,000–12,000
Short analysis, field note	600–1,000	approx. 4,000–6,500
Interview or conversation	900–1,500	approx. 6,000–10,000
Author profile	up to 250	approx. 1,700

The word count does not include the title, the standfirst, the reference list, figure captions, or the author profile. Materials longer than 2,000 words are considered only by a separate decision of the editorial team.

Each submission should be accompanied by a standfirst of 30 to 50 words; two to five visuals (images, charts, diagrams, maps, or photographs) with clear captions, image credits, and confirmation of usage rights; a high-resolution photograph of the author; an author profile stating title, affiliation, expertise, and relevant links; and disclosure of any relevant conflicts of interest.

References

References follow the ALLATRA Natural Science Review house style, which applies the bibliography-entry form of The Chicago Manual of Style, eighteenth edition, to a numbered reference list. Sources are cited in the text by numeral in square brackets and are numbered in the order of their first appearance. Each article carries its own reference list, printed at the end of the article in numerical order. Footnotes and endnotes are not used.

The house style departs from the Chicago Manual in six declared points. All author names are inverted, with the surname preceding the initials and no comma between them. Given names are presented as initials. Up to three authors are listed in full; where a work has four or more authors, the first three are given, followed by et al. Issue numbers of journals are not given. An entry ending with a DOI or a URL carries no final full stop. Page ranges are given in full.

Authors are asked to provide a DOI for each source for which one exists and, for material published online, the date of publication; a date of access should be given only where the page carries no date of publication, and a reference to an archived copy is welcome where a page is subject to change or withdrawal. Where formatting conflicts arise, editorial formatting takes precedence.

Examples

- Andrady A. L. "Microplastics in the Marine Environment." Marine Pollution Bulletin 62 (2011): 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030
- Bergmann M., Mützel S., Primpke S., et al. "White and Wonderful? Microplastics Prevail in Snow from the Alps to the Arctic." Science Advances 5 (2019): eaax1157. https://doi.org/10.1126/sciadv.aax1157
- Barker D. J. P. Mothers, Babies and Health in Later Life. 2nd ed. Churchill Livingstone, 1998.
- United Nations Environment Programme. Turning Off the Tap: How the World Can End Plastic Pollution and Create a Circular Economy. UNEP, 2023.
- Quigley M. "Was Venezuela Struck by an Earthquake 'Doublet'? Here's What We Know So Far." The Conversation, June 25, 2026. https://theconversation.com/was-venezuela-struck-by-an-earthquake-doublet-heres-what-we-know-so-far-286136
- NOAA Climate Prediction Center. Oceanic Niño Index (ONI). Accessed July 2, 2026. https://www.cpc.ncep.noaa.gov/data/indices/oni.ascii.txt

Language and style

Articles should be written in formal, clear English that remains accessible to readers who are not specialists in the field. Authors are asked to state clearly what remains uncertain, the main reasons for that uncertainty (e.g., limited data, measurement limits, confounders, or model assumptions), and how it affects the strength of the claim.

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