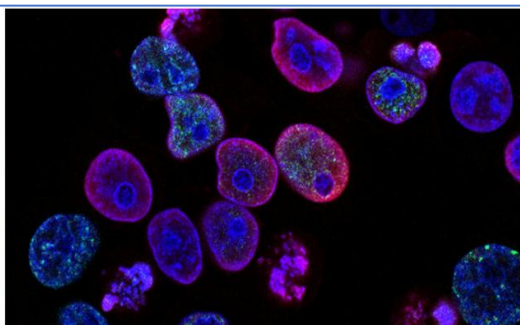




VANTAGE POINT

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Brain-Eating Amoeba and India's Biosecurity Preparedness: A Call for Action

Sanjana V

Primary Amoebic Meningoencephalitis (PAM), also called the brain-eating amoeba, is a rare but almost always fatal brain infection caused by the free-living amoeba *Naegleria fowleri*, which thrives in warm, stagnant freshwater environments such as lakes, ponds, and poorly maintained pools. The amoeba enters the human body through the nasal passage during activities such as swimming or bathing, and then rapidly migrates to the brain, leading to destruction of brain tissue. While reported cases have historically been sporadic, India and, particularly, the states of Kerala and Maharashtra have recently witnessed a drastic increase in cases of PAM across diverse age groups, with the mortality rate remaining alarmingly high despite advances in treatment and diagnosis. The disease's swift onset, challenging diagnosis, and extremely high fatality rate highlight its significance as both a public health and biosecurity concern.

India's first documented PAM case occurred in 1971. Kerala began reporting cases only in 2016, but has witnessed a dramatic increase since 2023, with over 70 cases and 19 deaths in 2025 alone. The age range affected is striking- the victims vary from infants to the elderly. Kerala's improved survival rate is attributed to early detection and rapid, targeted treatment protocols. The epidemiology of PAM in India reflects the recent surge in reported cases, not only in Kerala but also in Maharashtra. Maharashtra has reported multiple incidences of PAM over the past few years, often linked to environmental exposure in warm freshwater bodies. These cases are parallel to Kerala's outbreaks, contributing to the growing national concern over outbreaks in diverse geographic regions

with similar climate and water and sanitation vulnerabilities. While earlier clusters were predominantly associated with contaminated water sources, the recent occurrence of sporadic cases suggests widespread environmental contamination has complicated epidemiological investigations.

The global fatality rates stand at 97-98 per cent, which stresses the lethality of the pathogen and clinical challenges. Survival critically depends on early diagnosis and therapeutic intervention, yet even with improved protocols, medical professionals struggle with limited treatment options and poor outcomes.

Several environmental and social factors fuel the increase of PAM in India. Primarily, increasing temperatures and unpredictable rainfall due to climate change create more favourable conditions for amoebas' proliferation. Furthermore, poor sanitation and untreated communal freshwater sources increase the risk of exposure. Many communities remain unaware of PAM risks despite media coverage, which limits effective behavioural interventions. This, coupled with sporadic water testing and delayed diagnosis, leads to late-stage detection.

Biosecurity Challenges and National Response

Such outbreaks have underscored the need to strengthen our national surveillance mechanisms and inter-agency coordination. Hospitals and the National Centre for Disease Control (NCDC) have started to investigate every case of meningoencephalitis for amoebic infection. Further, environmental Sampling, water source testing, and immediate treatment initiation are

also undertaken at the state-level a shift towards a more resilient public health system.

Kerala's development of specialised PAM treatment and standard operating procedures (SOPs) shows an emergent best practice model. These SOPs have contributed to reduced fatality rates compared to the near lethality observed globally. Public health teams and community drives in the state have been advocating for the chlorination of pools, the regular testing of wells, and the overall education of citizens on safe water practices. Kerala's targeted awareness initiatives aim to foster behavioural change, such as avoiding untreated freshwater swimming and promoting boiling or chlorination of water.

However, these measures face several challenges related to infrastructure and sociocultural factors. India's fragmented water management and sanitation infrastructure creates persistent vulnerabilities. Major outbreaks linked to communal bathing or religious festivals could strain the emergency response system and risk wider public panic. Behavioural practices, including religious and recreational communal water use, require nuanced risk messaging that respects local traditions.

Threat Scenarios

1. Waterborne Outbreaks

A mass outbreak in a densely populated Indian city, following exposure at a public reservoir or religious event, could overwhelm local health infrastructure. A legacy vulnerability in water testing and treatment compounds this risk, with insufficient stockpiles of medical countermeasures, which is a concern raised by both national and international biosecurity assessments.

2. Laboratory and Research Security

With India's rapidly expanding network of pathogen research facilities, the absence of comprehensive biosafety auditing and dual-use research oversight presents significant risk. A laboratory incident involving the accidental release or deliberate misuse of a *Naegleria fowleri* strain could escalate into a public health emergency, independent of naturally occurring outbreaks.

3. Interface with Global Epidemic Preparedness

As a G20 member and a regional leader in One Health initiatives, India's interoperability within global biosecurity systems is central to regional stability. However, fragmented data integration between human, environmental, and waterborne disease monitoring systems could create intelligence gaps in early detection. Such fragmentation may delay coordinated response efforts and allow emerging pathogens to cross borders unchecked, amplifying regional and transnational biosecurity risks.

One Health Approach

Sustainable public health requires investment in water infrastructure, laboratory capabilities for rapid testing, and patient care facilities. The integration of animal health surveillance with environmental and human disease monitoring is advocated for India, although PAM is non-zoonotic, which requires specialised adaptation of these frameworks.

India's [One Health policies](#) aim to integrate efforts across the human, animal, and environmental health sectors, mainly to combat zoonotic diseases. This cross-sectoral approach brings together various agencies and funds projects focused on pandemic preparedness, particularly for threats such as bird flu and rabies. However, in the case of PAM, which spreads through contaminated water rather than

through animals, these existing strategies are insufficient. Accordingly, India's biosecurity and preparedness must expand focus from just animal disease surveillance to also include strong water quality management, improved sanitation, and better public education.

Recommendations for Strengthening Biosecurity

In light of the outlined scenarios, certain measures are essential to strengthen India's biosecurity architecture. Firstly, environmental monitoring must be expanded to incorporate targeted water quality surveillance, particularly in high-risk regions, to enable early detection of potential pathogenic contamination. Simultaneously, we should accelerate the development and deployment of rapid molecular diagnostic capacities across district and rural hospitals.

Enhanced laboratory readiness would significantly improve clinical response times and facilitate the timely containment of outbreaks. Research advancements in therapeutics and diagnostics must be encouraged within a framework of responsible innovation, ensuring stringent oversight on dual-use research risks and adherence to robust biosafety protocols.

Strengthening water infrastructure remains a crucial component of biosecurity preparedness.

Upgrading sanitation and chlorination systems, particularly for communal water sources in both rural and urban settings, is critical to reducing exposure risks. Public education on water safety should be prioritised through sustained community engagement initiatives led by local health workers, stressing the importance of safe bathing, swimming, and water consumption practices.

Operationalising the One Health framework to encompass environmental pathogens beyond its conventional zoonotic focus can provide a holistic mechanism for addressing threats such as PAM. Integrating veterinary, environmental, and public health expertise under this model will foster coordinated surveillance and response mechanisms.

As we have seen, PAM represents a distinctive biosecurity challenge for India. Although national and state-level preparedness has improved, sustained evolution is required to strengthen environmental surveillance, rapid diagnostic capabilities, and resilient water management systems. This outbreak should be viewed not only as a biosecurity warning but as a catalyst for constructing a resilient and adaptive biosecurity infrastructure in an era increasingly defined by climate-induced infectious disease risks.

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Globalisation and Invasive Species as a Security Challenge

Kashvi A

[Emerald ash border](#), a tiny, iridescent beetle that hitchhiked thousands of miles from Asia inside untreated wooden shipping crates. In just over two decades, it has decimated tens of millions of ash trees, causing billions of dollars in economic damage and fundamentally altering entire ecosystems. The story of this unassuming beetle is a reminder that in our interdependent world, a seemingly minor ecological problem can quickly escalate into a full-blown national security issue.

While globalisation is celebrated for its economic benefits, its [unchecked vectors in trade and transport](#) have facilitated the global spread of invasive species, which now constitute a significant and overlooked biosecurity threat to economies, public health, critical infrastructure, and food security. Globalization has created a vast and interconnected network of trade and transport, evading natural geographical barriers that once prevented species from migrating.

The movement of people and goods across borders constitutes the primary driver of these biological invasions. Every ship, cargo plane, and tourist serves, often unintentionally, as a potential vector for the translocation of species across ecological boundaries. Among these pathways, maritime transport through ballast water exchange remains the most significant vector for marine and aquatic invasions. Large commercial vessels take in millions of gallons of water at one port to maintain balance and subsequently discharge it at another, inadvertently releasing a complex mixture of microorganisms, algae, plankton, and larval organisms into new ecosystems. This mechanism was responsible for the [introduction of the Zebra Mussel \(*Dreissena polymorpha*\)](#) from its native Eurasian waters to the North American Great Lakes, where it has caused extensive ecological disruption

and billions of dollars in infrastructure damage by obstructing pipelines and water intake systems.

Terrestrial invasions are similarly facilitated by global freight movement, as cargo and packaging materials act as vehicles for pests and pathogens. Pests and pathogens can hitch a ride in wooden crates, pallets, and shipping containers. A prominent example is the [Asian Long-Horned Beetle \(*Anoplophora glabripennis*\)](#), which was transported to North America and Europe through untreated wooden packaging from China. Its introduction resulted in the destruction of hundreds of thousands of hardwood trees, leading to significant ecological and economic losses. Similarly, invasive fire ant species have successfully colonised ports around the world by stowing away in shipping cargo, demonstrating how interconnected supply chains can serve as conduits for biological invasions.

Beyond accidental introductions, deliberate but often irresponsible human actions have exacerbated the problem through the ornamental plant and pet trades. The movement of species for horticultural or exotic pet purposes frequently leads to their release into non-native environments where they become ecologically dominant. The [Burmese Python \(*Python bivittatus*\)](#), for instance, was introduced into the Florida Everglades after people released them into the wild, where they have since become a top predator, decimating native wildlife populations.

While globalisation provides the pathway, climate change often provides the opportunity for an invasive species to thrive. A warming planet enables these biological invaders to establish and spread in new regions where they previously could not survive.

As global temperatures rise, species can expand their habitats into higher latitudes and altitudes that were once too cold for them. The [Mountain Pine Beetle](#) (*Dendroctonus ponderosae*) native to western North America has been able to spread into previously unaffected forests in Canada due to shorter, milder winters that no longer kill off large portions of its population.

Climate induced events like droughts, wildfires and floods weaken the native ecosystem making them more susceptible to invasion. Disturbed lands offer a competitive advantage to invasive species, which are often generalists that can quickly colonise and dominate a new, stressed environment. This creates a dangerous feedback loop, where invasive species further degrade ecosystem resilience, making them even more vulnerable to climate impacts. While many see invasive species as solely an environmental issue, their impacts extend far into national and global security. By disrupting critical systems, these biological threats can cause widespread economic instability and social unrest.

Invasive pests and pathogen and pathogens pose a direct threat to global food security by devastating staple crops. [The Fall Armyworm](#) (*Spodoptera frugiperda*), native to America, has rapidly spread across Africa and Asia. It prefers to feed on crops like maize, rice, and sugarcane, which are crucial for the diets and economies of many countries. In Africa, the pest has caused an estimated maize yield reduction of 8 to 16 million tons per year, resulting in an economic loss of \$2.4 to \$4.8 billion annually.

Similarly, the Cassava Mosaic Disease (CMD) a viral infection spread primarily by whiteflies, can cause yield losses ranging from 20 per cent to as high as 95 per cent in heavily infected fields. This has devastating consequences for communities in Africa and Asia that rely on cassava as a primary food source and cash crop, threatening rural livelihoods and national economies.

Invasive species can directly compromise essential infrastructure, leading to massive economic costs

and disruptions to vital services. [The Zebra Mussel and Quagga Mussel](#) both native to the Caspian Sea region were introduced to the North American Great Lakes via the ballast water of cargo ships in the late 1980s. These mussels attach to and colonise hard surfaces in large clumps, including inside water intake pipes, dams, and power plant cooling systems. Their presence can clog and damage critical infrastructure, leading to service interruptions and a need for expensive, ongoing maintenance. It is estimated that the economic impact of these mussels in the United States and Canada reaches around \$140 million per year in damage and control costs.

The spread of invasive species can introduce new vectors for diseases posing a direct threat to public health. The [Asian Tiger Mosquito](#) (*Aedes albopictus*) is considered one of the most invasive mosquito species worldwide. It is a competent vector for numerous viruses, including those causing dengue, Zika and Chikungunya. The eggs of this mosquito are highly resistant to drought, which allows them to be easily transported in things like used tires and other goods, facilitating their global spread. The presence of the Asian Tiger Mosquito has been linked to the first localized transmissions of dengue and Chikungunya in regions where these diseases were not previously a concern, such as in parts of France and Italy.

Combating this threat of invasive species requires a comprehensive and coordinated biosecurity strategy that goes beyond simple border checks. It must integrate advanced science, international policy, and public education. The most effective way to mitigate a biological invasion is to stop it before it can take hold. This relies on robust early detection and rapid response systems. Sophisticated monitoring systems at high risk entry points, such as ports, airports, and border crossings, are crucial.

Modern technologies are revolutionising this field. For instance, eDNA (environmental DNA) analysis allows scientists to detect the presence of a species

by analysing trace amounts of its genetic material in water or soil samples. This non-invasive and highly sensitive method can provide an early warning of an invasive species' arrival, enabling a quick and targeted response. Moreover, sentinel surveillance, in which strategically placed plants, animals, or traps are monitored for the first signs of a new pest, is vital for on-the-ground surveillance.

Since invasive species do not recognise national borders, a fragmented, country-by-country approach is insufficient. Effective biosecurity necessitates international cooperation, with the sharing of data and the adoption of harmonized policies. Organisations like the International Plant Protection Convention (IPPC) play a crucial role in setting global standards for plant health and providing a framework for governments to regulate the spread of plant pests. The [IPPC's phytosanitary guidelines](#), for example, recommend treatments for wooden packaging to prevent the spread of forest pests. International agreements are crucial for coordinating efforts, sharing scientific research, and establishing protocols for addressing cross-border threats.

Individual actions can significantly impact the spread of invasive species, making public education a vital component of any biosecurity strategy. Campaigns should focus on informing travelers and the public about simple preventative measures. This includes educating travelers on the risks of transporting plants, animals, or agricultural products across borders, and highlighting the importance of cleaning hiking and fishing gear to avoid the unintentional transfer of seeds or aquatic organisms.

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By fostering a sense of shared responsibility, public awareness initiatives can turn every citizen into a front-line defender against biological invasions. The threat of invasive species is not just limited to biology or environmental science. As globalisation makes the world smaller, it allows these silent invaders to spread more easily. This has turned them into a major biosecurity concern with wide-ranging effects.

The impact of invasive species extends well beyond ecological damage. They can cripple national food security, disrupt critical infrastructure, and introduce new disease vectors that threaten public health. The Fall Armyworm's devastation of maize crops, the Zebra Mussel's clogging of power plants, and the Asian Tiger Mosquito's spread of dengue are not isolated incidents; they are symptoms of a systemic vulnerability in our interconnected world.

A reactive approach attempting to manage invasions after they have already occurred is a costly and often losing battle. The only viable solution is a proactive and interdisciplinary approach. This strategy must effortlessly integrate biological sciences which identify and track these threats with trade policy which regulates their movement and national security, which recognizes their profound risk. By prioritising early detection through advanced technologies like eDNA analysis and fostering international cooperation through organizations like the IPPC we can build a more resilient global biosecurity framework. Ultimately, mitigating this growing threat requires a collective will to act, acknowledging that the security of our economies, health, and ecosystems is intricately linked to the biosecurity of our planet.

Genetic Diseases and National Security: The Unseen Link

Krithika V

When we think of national security, the mind turns to soldiers, borders, and weaponry. Yet some of the gravest threats to a nation's strength lie not on the battlefield but in the genetic code of its people. Genetic disorders, as initially cataloged by [Victor A. McKusick \(1966\)](#), are conditions caused by abnormalities in an individual's DNA, which may be inherited or occur spontaneously, affecting one or more genes or chromosomes. These are often treated as a narrow healthcare concern, quietly shape economic stability, military readiness, social cohesion, and even biosecurity. For India, with its vast and young population, this link deserves urgent attention.

Globally, more than 300 million people live with rare diseases, about 80 per cent of which have a genetic origin. In India, estimates suggest nearly [70 million individuals](#) are affected by rare genetic conditions. Each year, around 470,000 newborns are estimated to have congenital anomalies, many of which are genetic in origin. Conditions such as thalassemia, sickle cell anemia, Duchenne muscular dystrophy, and spinal muscular atrophy impose lifelong challenges. These are not only personal tragedies but also structural vulnerabilities for the nation.

Unlike infectious diseases, genetic conditions rarely have quick cures. They require specialised diagnostics, long-term treatment, and consistent medical follow-up. In India, awareness is limited and stigma widespread, leading to delayed diagnoses. Families may spend anywhere from tens of thousands to several lakhs annually on care. For instance, [lifelong thalassemia management](#) requires regular transfusions and chelation therapy, which can cost households substantial sums. Many families fall into debt or withdraw from the workforce to provide care. At a macro level, untreated or poorly managed

genetic disorders translate into reduced productivity, rising healthcare costs, and weakened resilience during crises. From households to the nation, the cost of genetic disease is an economic story.

A nation's resilience depends on its economic vitality. Genetic diseases undermine this by reducing workforce participation and increasing household poverty. As healthcare costs mount, government spending shifts toward chronic care, leaving fewer resources for defence, infrastructure, and development. This "silent diversion" weakens economic security. A population drained by long-term genetic conditions is less able to contribute productively, creating vulnerabilities that adversaries or crises can exploit.

However, the impact extends beyond financial considerations, reaching the heart of military readiness. The armed forces draw strength from the health of their recruits. Chronic genetic conditions reduce the number of medically eligible young people, narrowing the pipeline of soldiers and officers. Beyond the military, a society with a significant burden of chronic disorders has fewer able-bodied citizens available for civil defence, emergency relief, and disaster management. In a country that must prepare for both external threats and natural disasters, such hidden health burdens can undermine readiness.

A practical example is India's tribal communities in central states, where [sickle cell anemia prevalence is high](#). This condition not only affects daily life but also restricts the pool of fit recruits in these regions. Ignoring such realities risks underestimating how genetics shapes defense preparedness.

At the same time, genetic health quietly shapes our resilience to future health threats. The COVID-19 pandemic highlighted how pre-existing conditions worsen outcomes and overload health systems. Populations with untreated genetic vulnerabilities such as immune deficiencies or metabolic disorders face similar risks during future pandemics or bioterrorism events.

Equally critical is genomic data security. India is building large genetic databases to advance research and precision medicine. But genetic information, if compromised, could be misused for discrimination or even the development of population-specific bioweapons. Protecting genomic data must therefore be treated as seriously as guarding borders or cyber networks.

Behind these statistics lie real families, carrying the weight of social and emotional strain. Security is not only external but also internal. Families affected by genetic diseases often experience psychological stress, stigma, and loss of income. In rural or marginalized areas, this can deepen inequalities, fuel frustration, and strain social cohesion. When large numbers of families face such hidden burdens, the cumulative effect weakens national unity.

If resilience is the essence of national security, then genetic counseling becomes an invisible line of defence. Therefore, strengthening genetic health requires not just technology but guidance. Genetic counselors bridge science and society by helping families understand diagnoses, explore treatment, and make informed decisions. [Research shows that counseling reduces diagnostic delays](#), avoids unnecessary interventions, and supports family planning.

Their impact extends to security. By lowering misinformation and unnecessary costs, counselors bolster economic stability. By guiding early interventions, they strengthen the pool of healthy citizens for defense and civil service. As ethical

interpreters of biotechnology, they also ensure public trust in emerging tools such as gene editing. In this sense, while soldiers guard borders, genetic counselors quietly guard the nation's biological resilience. Yet in an era of powerful biotechnology, even our genetic data demands protection.

What India Must Do

Recognising genetic health as an integral pillar of national security necessitates a series of coordinated, actionable steps. The expansion of newborn screening programs is essential to ensure the early identification and treatment of preventable or manageable genetic conditions. Early intervention not only improves individual health outcomes but also contributes to the long-term reduction of healthcare burdens on the state.

Equally important is the urgent need to scale up the training and deployment of genetic counselors across the country. India currently faces a significant shortfall in this specialised workforce, which limits the capacity of healthcare institutions to provide accurate diagnosis, risk assessment, and informed counseling to families affected by genetic disorders. Addressing this gap requires targeted investments in higher education, professional certification, and institutional integration of genetic counseling services within public hospitals and community health systems.

To facilitate data-driven policy and clinical decision-making, national registries such as the Indian Council of Medical Research (ICMR) Rare Disease Registry must be strengthened and expanded. Standardised registries will enable more precise epidemiological mapping and support translational research into region-specific genetic disorders. Complementing this effort, community-level screening programs should be introduced in areas with a high prevalence of inherited diseases, such as sickle cell anemia in tribal regions. Such localised interventions, when embedded within broader public health initiatives,

can substantially enhance early detection and equitable access to care.

Finally, as India's genomic research ecosystem continues to advance, the enactment of stringent genomic data protection legislation is essential. Legal safeguards must be established to prevent the misuse of sensitive genetic information, while still enabling responsible data sharing for scientific and clinical research. Balancing innovation with ethical integrity will be crucial in ensuring that genetic health contributes meaningfully to both individual well-being and national resilience.

These are not health-sector luxuries. They are strategic investments in India's resilience. India's future strength will be measured not only by its military arsenal or GDP but by the genetic health of its people. A country where millions face untreated genetic diseases risks economic fragility, reduced defense readiness, and weakened social cohesion. By investing in screening, counseling, registries, and genomic security, India can secure not just its borders but also the resilience of its citizens. Strong borders mean little without strong genes. Genetic health, in this sense, is national security.

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Tepid Waters, Lethal Risks: Climate Change and the Upsurge of Brain Devouring Amoeba

Manisha S

With the rise in population every year, the need for basic necessities also increases, which in turn disturbs the environment as a whole. As a result, the concentration of greenhouse gases in the atmosphere surges, causing the capture of more heat than the Earth naturally releases into space, leading to an increase in global temperature. As global temperatures rise, lakes, rivers, and even treated water systems are becoming warmer for longer periods. This warming is not solely an environmental anomaly, it is rather a biological spark. This biological spark can also create a surface for microscopic predators to thrive in.

On a hot summer day, a swim in the pool feels so refreshing and cool. However, below the glistening surface, a microscopic predator sneaks. As the global temperatures rises, the line between a refreshing dip under the pool and the chances of a chillingly dead encounter becomes thinner, raising public health and biosecurity concerns. One such recent example is the case of “brain-eating amoeba” or *Naegleria fowleri*. The amoeba is an environmental microbe responsible for causing a fatal brain infection called primary amoebic meningoencephalitis (PAM). Despite the chances of infections remain rare, climate change is tilting the odds in this amoeba’s favour, creating warmer and more stable aquatic environments where it can thrive.

Climate change has emerged as a critical factor in the proliferation and geographic expansion of many pathogens. *Naegleria fowleri* thrives in temperatures ranging from 25°C to 46°C, and climate-induced heatwaves, along with extended warm seasons, prolong the period

during which lakes and rivers remain within this optimal range. [Data from the U.S. Centers for Disease Control and Prevention \(CDC\)](#) indicate that since 2010, cases of PAM have been reported in northern states such as Minnesota, Kansas, and Maryland. These regions were previously too cold to support the amoeba’s lifecycle.

A recent analysis published on *PreventionWeb* reported a [notable increase in rare disease outbreaks in 2023](#), including *Naegleria fowleri* infections in the United States. Researchers have linked this trend to anomalously warm waters and extreme weather events, both of which are intensifying due to climate change. While not every case can be directly attributed to climate variation, the pattern of expansion and seasonal persistence is unmistakable. These findings underscore the urgency of shifting from reactive crisis management to proactive, climate-informed biosecurity planning

Drought and water stagnation further compound the risk of infection. Prolonged dry spells shrink water bodies, concentrating organic material and elevating temperatures, while stagnant pools provide ideal environments for heat-loving microorganisms. On the other hand, heavy rainfall and flooding can redistribute *Naegleria fowleri* to new aquatic environments, including municipal water systems, if treatment and chlorination infrastructure are compromised. Such hydrological volatility shows us how climate extremes can simultaneously create and expand the ecological niches in which the pathogen thrives.

Rising temperatures can promote amoebic colonisation of municipal water systems, particularly in regions with aging pipelines or suboptimal chlorination. Accidental contamination could disrupt urban centers, necessitating widespread boil-water advisories and imposing significant economic costs.

Shifting recreational behaviours also play a role in exposure risk. Warmer summers and extended recreational seasons encourage greater human interaction with freshwater bodies, increasing the likelihood of infection. The combination of environmental change and altered social behaviour, therefore, creates multiple points of vulnerability within public health systems.

Biosecurity Risks beyond Public Health

The implications of *Naegleria fowleri* extend beyond individual health to encompass wider biosecurity concerns. As the pathogen's ecological footprint grows, surveillance gaps become increasingly apparent. Health authorities often rely on historical data to allocate resources, and regions newly affected by the pathogen may lack the monitoring infrastructure necessary to detect its presence in recreational waters, thereby delaying response efforts.

Diagnostic limitations further exacerbate the problem. Many clinical laboratories are [ill-equipped or unfamiliar with testing procedures](#) for *Naegleria fowleri*, and diagnostic errors can lead to misclassification of infections as “mysterious outbreaks,” potentially triggering public anxiety and straining emergency services.

Additionally, the study of *Naegleria fowleri* itself entails dual-use concerns. Research involving culturing the amoeba or developing countermeasures must adhere to strict biosafety standards to prevent accidental release or

potential misuse. The balance between advancing scientific understanding and maintaining biosecurity oversight is therefore essential within a comprehensive risk management framework.

Socio-Economic Dimensions

The threats posed by *Naegleria fowleri* are amplified by social and economic inequalities. Communities with limited access to healthcare services face delayed diagnosis and poorer clinical outcomes. Economically, regions dependent on tourism and freshwater recreation may experience substantial losses following even a single reported case, as public fear deters visitors and undermines local economies. Moreover, sensational media coverage of “brain-eating amoebae” can erode public trust in local authorities and water management institutions. The psychological and economic ripple effects of such outbreaks highlight how a microscopic organism, empowered by climate change, can have far-reaching societal consequences.

Mitigation and Preparedness

Mitigating the risks associated with *Naegleria fowleri* requires an integrated approach that combines public education, technological innovation, and international cooperation. Public awareness campaigns emphasising simple behavioural precautions such as avoiding swimming in warm freshwater during heatwaves, using nose clips, and refraining from submerging the head in untreated water can significantly reduce exposure. Enhanced surveillance systems integrating climate modeling, real-time water temperature monitoring, and genomic testing are essential for early detection and prevention.

Upgrading water infrastructure to ensure proper chlorination and regular maintenance of recreational facilities is equally critical to

minimising the pathogen's spread. Concurrently, investment in rapid diagnostic tools and the development of effective medical countermeasures should be prioritised to improve clinical outcomes.

Finally, as climate change transcends national borders, regional and international cooperation is vital. Data sharing, early warning networks, and coordinated response frameworks can

prevent localised incidents from escalating into transnational public health emergencies.

Effective mitigation and preparedness strategies must explicitly account for the accelerating impacts of climate change. Therefore, integrating climate adaptation into public health planning is therefore essential to ensure that prevention, surveillance, and response systems remain robust in an era of increasing environmental instability.

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