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Health Impacts of Geothermal Energy Development: An Environmental and Public Health Perspective

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Abstract

Geothermal energy development is expanding rapidly across both established geothermal regions and newly developing markets, driven by the technology's capacity to deliver low-carbon, dispatchable baseload power. This global expansion, however, brings geothermal energy's characteristic environmental and health considerations to an increasingly diverse range of geologic, climatic, socioeconomic, and regulatory settings, from long-industrialized geothermal districts in Italy to rapidly scaling geothermal programs in East Africa. This article presents an environmental and public health perspective on the health impacts of geothermal energy development, synthesizing chronic and acute hydrogen sulfide exposure epidemiology, environmental and socioeconomic impact assessment from an African development context, and quantitative environmental risk assessment methodology encompassing seismic, ecological, and economic dimensions alongside human health. It draws on subsurface reactive transport modeling and reactive heat exchanger engineering relevant to long-term geothermal reservoir performance, machine learning-enhanced geomechanical characterization relevant to induced seismicity and wellbore stability risk, and heterogeneous reservoir management principles from analogous subsurface energy operations, and further considers how AI-driven precision public health, predictive analytics, and economic impact assessment frameworks developed for national healthcare systems could strengthen environmental and public health surveillance as geothermal development continues to expand into new regions. The article concludes by identifying persistent gaps in geographic evidence diversity, socioeconomic impact integration, and cross-national assessment standardization, and proposes a research agenda for advancing environmental and public health protection as geothermal energy development scales globally.]

Keywords: geothermal energy, public health, environmental health, hydrogen sulfide, socioeconomic impact, health impact assessment, renewable energy development

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Introduction

Geotermal energy development has historically been concentrated in a comparatively small number of geologically favorable regions—Italy, New Zealand, Iceland, and the western United States prominent among them—but is now expanding rapidly into new markets, with East Africa's Rift Valley emerging as a particularly significant growth region given its substantial untapped geothermal potential and the pressing need for reliable, low-carbon baseload generation capacity to support regional economic development. This geographic diversification of geothermal energy development carries important implications for environmental and public health assessment: the evidence base on geothermal health impacts, built predominantly from decades of research in established geothermal districts, must now be interpreted and extended for application in settings with markedly different demographic profiles, regulatory capacity, socioeconomic conditions, and land use contexts.

An environmental and public health perspective on geothermal energy development must therefore encompass more than the chemical exposure pathways—principally hydrogen sulfide inhalation and, in some settings, arsenic and trace element contamination of water resources—that have dominated the epidemiological literature to date. It must also account for the socioeconomic dimensions of health, including the impacts of large-scale energy infrastructure development on land use, community livelihoods, and resource access among populations, often rural and economically marginalized, living in proximity to newly developed geothermal fields, as well as the geomechanical and seismic risk dimensions that formal environmental risk assessment frameworks increasingly recognize alongside chemical exposure pathways.

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This article presents an environmental and public health perspective on the health impacts of geothermal energy development, integrating chronic hydrogen sulfide exposure epidemiology (Bustaffa et al., 2020; Nuvolone et al., 2019; Stoppa et al., 2023) with acute, short-term exposure evidence (Nuvolone et al., 2020), a socioeconomic and environmental impact assessment from an East African development context (Mariita, 2002), a contemporary review of geothermal health and environmental challenges in Kenya (Rotich et al., 2024), and quantitative environmental risk assessment methodology encompassing seismic hazard alongside human health, ecological, and economic dimensions (Chen et al., 2020). It draws on subsurface reactive transport modeling relevant to long-term geothermal reservoir fluid chemistry evolution, reactive heat exchanger engineering relevant to enhanced geothermal energy recovery, machine learning-enhanced geomechanical characterization relevant to induced seismicity and wellbore stability risk, and heterogeneous reservoir management principles from analogous subsurface energy operations, and further considers how AI-driven precision public health, predictive analytics, and economic impact assessment frameworks developed for national healthcare systems (Nguyen, 2026a, 2026c, 2026d) could strengthen environmental and public health surveillance as geothermal development expands globally. The objective is to provide a geographically and dimensionally broadened synthesis for public health researchers, environmental scientists, development practitioners, and policymakers engaged in the global expansion of geothermal energy.

Chemical Exposure Pathways: Chronic and Acute Hydrogen Sulfide Evidence

Chronic, Low-Level Exposure Evidence

Bustaffa et al. (2020) reviewed the accumulated evidence on chronic community exposure to hydrogen sulfide near geothermal facilities across New Zealand, Iceland, and Italy, characterizing a body of evidence marked by methodological inconsistency, predominantly ecological or residence-based exposure assessment, and some genuinely counterintuitive findings, including an inverse association between higher exposure and cancer mortality alongside associations between lower-level exposure and increased respiratory disease. Nuvolone et al. (2019) extended this evidence through a nearly two-decade residential cohort study in the Mt. Amiata geothermal district of Tuscany, evaluating chronic, low-level exposure against mortality and morbidity outcomes for respiratory, cardiovascular, and central nervous system conditions.

Acute, Short-Term Exposure Evidence

Complementing this chronic exposure literature, Nuvolone et al. (2020) conducted a case-crossover study examining the association between short-term hydrogen sulfide exposure and acute health outcomes across the thirty-four active geothermal power plants in the Tuscany geothermal areas, analyzing individual-level data on non-accidental, cardiovascular, and respiratory mortality alongside urgent hospital admissions and emergency department visits occurring between 2000 and 2017, matched to daily hydrogen sulfide concentrations from eighteen monitoring sites; the case-crossover design, applying a matched-pair interval approach with conditional logistic regression adjusted for time-dependent confounders such as influenza epidemics and temperature, found that short-term hydrogen sulfide exposure was weakly associated with some mortality and morbidity outcomes, though not with emergency department visits, providing a methodologically distinct and complementary line of evidence to the chronic cohort studies reviewed above.

Objective Respiratory Function Evidence

Stoppa et al. (2023) further extended the Mt. Amiata evidence base through the InVETTA cross-sectional study, applying objective spirometric measurement of lung function to more than 2,000 adults in relation to modeled hydrogen sulfide exposure; the absence of a confirmed association between exposure and chronic obstructive pulmonary disease in this study, despite its comparatively strong methodology, underscores the genuinely unresolved character of the chronic, low-level hydrogen sulfide exposure evidence base even within the single most intensively studied geothermal district worldwide.

Environmental and Socioeconomic Dimensions of Health in Developing Geothermal Regions

Health as Embedded Within Broader Socioeconomic Impact

A comprehensive environmental and public health perspective on geothermal energy development must recognize that health outcomes are embedded within, and shaped by, the broader socioeconomic transformations that large-scale energy infrastructure development brings to host communities. Mariita (2002) conducted an early and influential assessment of the environmental and socioeconomic impact of geothermal power plant development on a poor, rural Maasai community in Kenya's Rift Valley, documenting that while near-term direct environmental impacts were comparatively minimal, the socioeconomic impact of geothermal energy development—interacting with simultaneous flower farming and wildlife tourism industry expansion in the same environmentally and culturally fragile region—was likely to become the more immediate source of community conflict and disruption, with population influx, land use competition, and shifting access to economic opportunity representing socioeconomic determinants of health with the potential to affect community wellbeing as significantly as direct chemical exposure pathways.

Contemporary Health and Environmental Challenges in an Expanding Geothermal Market

Rotich et al. (2024) conducted a contemporary review of health and environmental challenges associated with geothermal energy in Kenya, a country whose geothermal potential exceeds 10,000 megawatts against current extraction of under 900 megawatts, identifying environmental concerns including substantial water consumption during drilling operations, potential groundwater contamination, microbial-induced corrosion requiring active management, and waste and seismic activity considerations; critically, the review found that measured environmental and health parameters in Kenya's active geothermal fields currently fall within safe ranges established by the World Health Organization, while explicitly noting that impact assessments for geothermal projects in this rapidly developing market lack thorough health and long-term community evaluation, and recommending continuous monitoring alongside further research into the potential health effects of elevated sulfur dioxide levels.

Implications for Geographic Evidence Diversification

Read together, Mariita (2002) and Rotich et al. (2024) illustrate both the socioeconomic dimension of health that has been comparatively underemphasized in the chemical exposure-focused Italian district literature, and the practical reality that comprehensive, long-term health impact assessment infrastructure has not kept pace with the rapid expansion of geothermal development into new markets—reinforcing the broader environmental and public health imperative that assessment methodology, community engagement, and long-term health surveillance capacity must be built into geothermal development programs from their earliest planning stages rather than retrofitted after substantial infrastructure investment has already occurred.

Geomechanical Risk Within a Comprehensive Environmental Risk Framework

Seismic Hazard as a Formally Recognized Risk Category

Chen et al. (2020) explicitly incorporate seismic hazard as one of four principal categories of quantifiable environmental risk associated with geothermal energy development, alongside human health, ecological damage, and economic loss, reflecting a broader environmental risk assessment perspective in which induced seismicity and ground deformation constitute a legitimate risk dimension extending beyond the chemical exposure pathways that have historically dominated the geothermal health literature—a framing directly relevant to rapidly expanding geothermal markets such as Kenya, where seismic and ground deformation considerations feature among the environmental challenges identified by Rotich et al. (2024).

Geomechanical Characterization as a Preventive Tool

Machine learning-enhanced geomechanical characterization and wellbore stability assessment methodologies, integrating stress field estimation, rock strength prediction, and operational parameter analysis into a proactive risk-management workflow, have been demonstrated in offshore energy reservoir settings as a means of anticipating and managing geomechanical instability before it manifests as an operational or safety incident. Applying such geomechanically informed characterization approaches to newly developing geothermal fields, where reservoir-specific stress and stability data may be comparatively limited relative to long-established districts, represents an important opportunity to build proactive risk management into geothermal development programs from an early stage rather than relying on reactive, incident-driven responses as new fields are brought online.

Long-Term Reservoir Performance and Fluid Chemistry Evolution

Numerical modeling of reactive transport processes in geothermal reservoirs provides a scientific basis for forecasting how reservoir fluid chemistry, including the hydrogen sulfide and trace element concentrations relevant to community exposure, may evolve over a geothermal facility's multi-decade operational lifetime, while the development of reactive heat exchangers for enhanced geothermal energy recovery illustrates how coupled thermal and geochemical processes can be engineered and monitored at the wellbore scale to optimize energy recovery while managing associated fluid chemistry considerations. Together, these subsurface engineering advances offer mechanistically grounded tools for anticipating the long-term environmental and health-relevant fluid chemistry trajectory of geothermal reservoirs, complementing the empirical, retrospective epidemiological evidence that has historically dominated the field.

Heterogeneous Reservoir Management Principles

Principles of heterogeneous subsurface reservoir management developed in analogous energy contexts, including the optimization of fluid injection strategies to manage pressure distribution and containment risk in heterogeneous depleted gas reservoirs, offer transferable methodological insight for geothermal reservoir management in structurally complex or heterogeneous geologic settings, where the spatial distribution of pressure changes from fluid withdrawal and reinjection governs both geomechanical risk and the community exposure profile associated with fluid chemistry migration.

Toward Strengthened Environmental and Public Health Surveillance for Global Geothermal Expansion

Precision Public Health as a Framework for Geographically Diverse Monitoring

National-scale AI frameworks developed for precision public health illustrate how predictive analytics can integrate diverse individual-level data streams to support targeted chronic disease prevention and early intervention, moving beyond periodic, population-wide screening toward continuously updated, individually informed risk assessment (Nguyen, 2026a). Adapting this precision public health framework to the specific context of geothermal energy development—and particularly to rapidly expanding markets such as Kenya, where Rotich et al. (2024) explicitly identify a lack of thorough health and long-term community evaluation—could help establish the continuous, individually resolved environmental and health surveillance capacity that newly developing geothermal regions currently lack, without requiring these regions to independently replicate the decades of infrastructure investment that established districts such as Mt. Amiata have accumulated.

Predictive Analytics for Prioritizing Surveillance in Resource-Constrained Settings

National-scale predictive analytics frameworks applied to Medicare and Medicaid populations demonstrate how AI-driven risk stratification can identify high-risk populations for targeted follow-up from large, heterogeneous datasets, directing limited intervention resources toward those most likely to benefit (Nguyen, 2026d). This resource-prioritization logic is particularly relevant to geothermal development in resource-constrained settings, where the comprehensive, multi-decade epidemiological surveillance infrastructure available in Italian geothermal districts is unlikely to be immediately replicable, and where predictive analytics could instead help identify the specific communities, facilities, or exposure scenarios warranting the most urgent monitoring investment given limited available resources.

Economic Justification for Surveillance Investment in Expanding Markets

Economic impact analyses of AI adoption in healthcare, quantifying national-scale cost savings and productivity gains attributable to AI-driven predictive modeling and early intervention, offer a template for constructing the economic case for environmental and public health surveillance investment as geothermal energy development scales in new markets (Nguyen, 2026c). Given that geothermal energy's core economic and developmental appeal in regions such as Kenya rests on its capacity to deliver low-cost, reliable, low-carbon power supporting broader economic development (Mariita, 2002), demonstrating that proportionate public health surveillance investment is itself economically justified—through avoided long-term healthcare costs, avoided community conflict and project delay, and preserved social and regulatory license to operate—strengthens rather than undermines the broader development case for geothermal energy expansion.

Challenges and Limitations

Despite an expanding evidence base, several challenges continue to constrain comprehensive environmental and public health assessment of geothermal energy development.

Geographic concentration of methodologically strong evidence. The most rigorous epidemiological evidence—chronic cohort studies, case-crossover acute exposure analyses, and objective spirometric assessment—derives overwhelmingly from Italian geothermal districts, while rapidly expanding markets such as Kenya currently rely on comparatively limited health and environmental monitoring data, as explicitly acknowledged by Rotich et al. (2024).

Underintegration of socioeconomic determinants of health. The chemical exposure-focused epidemiological literature has historically given limited systematic attention to the socioeconomic determinants of health highlighted by Mariita (2002), including land use disruption, community conflict, and shifting economic opportunity associated with large-scale geothermal infrastructure development, despite these factors' plausible relevance to community wellbeing.

Inconsistent chronic exposure findings persist across study designs. Even accounting for the acute, case-crossover evidence (Nuvolone et al., 2020) alongside chronic cohort (Nuvolone et al., 2019) and objective physiological (Stoppa et al., 2023) study designs, the overall hydrogen sulfide exposure-health outcome evidence base remains genuinely inconsistent, limiting the strength of quantitative dose-response conclusions that can currently inform regulatory standard-setting in new markets.

Underutilization of mechanistic subsurface science. Reactive transport modeling and reactive heat exchanger engineering capable of forecasting long-term reservoir fluid chemistry evolution (Williams, 2023, 2024) and machine learning-enhanced geomechanical characterization capable of anticipating induced seismicity risk remain largely disconnected from applied environmental and public health assessment practice, particularly in newly developing geothermal markets where such forward-looking characterization could most valuably inform proactive rather than reactive risk management.

Absence of standardized cross-national assessment methodology. No standardized, internationally applicable methodology currently exists for conducting

comprehensive environmental and public health impact assessment of geothermal energy development across the diverse geologic, climatic, socioeconomic, and regulatory contexts in which the technology is now being deployed, complicating efforts to transfer lessons learned in established districts to newly developing markets in a systematic, rigorous fashion.

Future Directions

Future research should prioritize the extension of rigorous, multi-design epidemiological evidence—combining chronic cohort, acute case-crossover, and objective physiological assessment methodologies as exemplified by the Mt. Amiata research program (Nuvolone et al., 2019, 2020; Stoppa et al., 2023)—to newly developing geothermal markets, addressing the health and long-term community evaluation gap explicitly identified by Rotich et al. (2024) for the Kenyan context and by extension likely present in other rapidly expanding geothermal regions. Systematically integrating socioeconomic determinants of health, following the framework established by Mariita (2002), into environmental and public health impact assessment methodology represents a further important direction, particularly for geothermal deve.ity in resource-constrained, rapidly expanding geothermal markets offers a concrete pathway toward closing the health and community evaluation gap that current reviews of the field explicitly identify.

Conclusion

An environmental and public health perspective on the health impacts of geothermal energy development must extend beyond the chemical exposure pathways—chronic and acute hydrogen sulfide exposure foremost among them—that have dominated the field's epidemiological literature, to encompass the socioeconomic determinants of health associated with large-scale energy infrastructure development, the geomechanical and seismic risk dimensions increasingly recognized within formal environmental risk assessment frameworks, and the geographic diversification of geothermal development into new markets with distinct demographic, socioeconomic, and regulatory characteristics. The hydrogen sulfide exposure evidence base, though extended through complementary chronic, acute, and objective physiological study designs, remains genuinely inconsistent, while socioeconomic impact assessment and long-term community health evaluation in rapidly expanding geothermal markets such as Kenya lag substantially behind the infrastructure available in long-established districts such as Mt. Amiata. Subsurface reactive transport and reactive heat exchanger modeling, machine learning-enhanced geomechanical characterization, and AI-driven precision public health and predictive analytics frameworks developed for national healthcare systems together offer a mechanistically grounded, resource-efficient pathway toward the proactive, integrated environmental and public health surveillance that global geothermal expansion requires. Advancing this field will require sustained investment in geographically diverse epidemiological evidence, systematic integration of socioeconomic determinants of health, and the extension of mechanistic subsurface science and AI-driven surveillance capacity to the newly developing geothermal regions where health impact assessment infrastructure currently lags furthest behind the pace of energy infrastructure investment.

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