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Geochemical Controls and Long-Term Spatiotemporal Forecasting of Persistent Organic Pollutants in Indian Environmental Systems

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Persistent organic pollutants (POPs), particularly organochlorine pesticides (OCPs) such as hexachlorocyclohexane (HCH), dichlorodiphenyltrichloroethane (DDT), and endosulfan, continue to present long-term environmental and public health challenges across India despite regulatory bans on their manufacture and use. Their sustained occurrence reflects legacy contamination combined with strong molecular stability and geochemical processes governing environmental persistence, partitioning, and intermedia transport. This contribution synthesizes current geochemical understanding of POP behavior across interconnected atmospheric, aquatic, and terrestrial compartments, emphasizing the roles of mineral–organic matter interactions, sediment sorption capacity, redox gradients, salinity, and microbial mediation in controlling contaminant mobility and bioavailability. Hydrophobic POPs preferentially associate with fine-grained sediments and soil organic carbon, forming long-term geochemical reservoirs in riverine, estuarine, and coastal environments. However, environmental perturbations such as pH shifts, organic matter mineralization, flooding events, and redox fluctuations can promote remobilization, transforming sedimentary sinks into secondary contamination sources. To address spatial heterogeneity and monitoring gaps, geospatial predictive frameworks integrating geochemical parameters (organic carbon content, clay mineralogy, and sorption behavior) with land-use patterns and anthropogenic input proxies are applied to generate contamination risk maps across decadal to multi-decadal timescales. Projections extending to 2075 suggest expansion of high-risk zones in intensively cultivated regions, urban–industrial corridors, and vulnerable groundwater systems, driven by climate-modulated transport processes and slow degradation kinetics. Intermedia transfer through atmospheric volatilization–deposition cycles, surface runoff, and sediment resuspension contributes to the redistribution of legacy pollutants, consistent with the “grasshopper effect” in tropical environments. These coupled geochemical pathways enhance long-range mobility while sustaining localized exposure hotspots. Key future challenges include limited nationwide monitoring coverage, insufficient chemical speciation data, inadequate characterization of atmospheric transport, and poor understanding of combined organic pollutant–metal interactions influencing toxicity. Strengthening mechanistic geochemical frameworks through isotope tracing, molecular-scale characterization, and reactive transport modeling will be essential for improving long-term risk assessment, remediation planning, and evidence-based policy development. By linking geochemical dynamics with spatiotemporal forecasting, this work provides a predictive foundation for managing POP legacies and mitigating future health risks in rapidly evolving environmental systems.