Tracing the Footprints of Contaminants In Water through Stable Isotope Techniques

Isotope Technology for Societal Benefits

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The contamination of freshwater resources is a significant challenge in achieving the Sustainable Development Goals (SDGs) proposed for the future well being of the world. The current state of water health worldwide is concerning. According to the World Health Organization (WHO), over 2 billion people reside in water-stressed countries, and nearly 1.7 billion people consume contaminated water. Climate change and anthropogenic factors have severely impacted both the quantity and quality of accessible water resources. To unravel the primary causes of pollution and find effective remediation techniques, a thorough and in-depth study is imperative. Among number of available techniques, Isotope techniques offer a significant advantage in identifying pollution origins, clarifying breakdown pathways, and evaluating the dynamics of both widespread and emerging pollutants such as microplastics, pesticides, fugitive gases, greenhouse emissions, and persistent organic compounds.

Environmental isotopes have been used as potential tools in geochemical & hydrogeological investigations, land-biosphere-atmosphere interfaces, nutrient cycling, degradation behavior of contaminants and identification of origin of contaminants. Environmental radioisotopes, on the other hand, provide a measure of groundwater residence time and its renewability. A bibliographic analysis of SCOPUS data from 2012 to 2018 indicates the potential of isotope applications in biodegradation, water treatment, water pollution, water quality and monitoring etc (Fig.1).

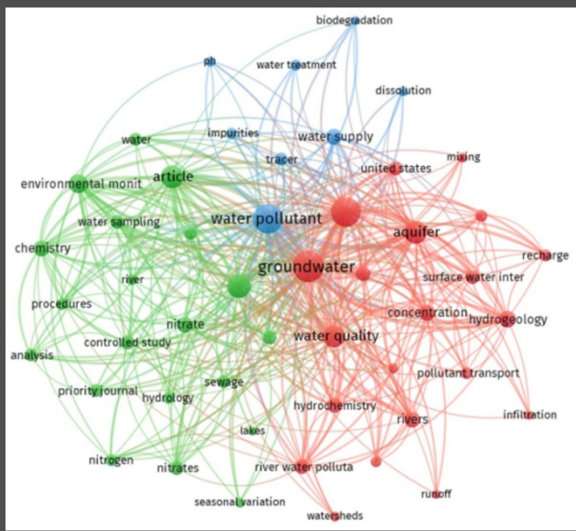

Fig.1: Network visualization of water contamination studies and their temporal association.

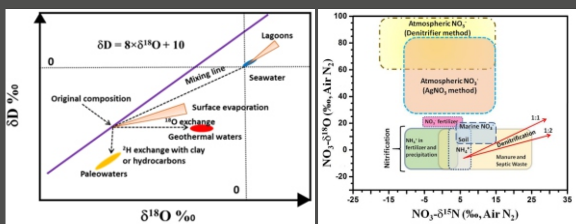

Fig.2: Isotope systematics of water isotopes indicating various end-members (left), Dual isotope plot of ^{15}N and ^{18}O isotopes demonstration various sources and processes (right).

The isotope studies in the early stages were mainly concentrated on the water isotopes, i.e., stable water isotopes (^{2}H and ^{18}O). The outcome from these studies were helpful in examining the processes occurring at rock-water interface, recharge and transport mechanism, geochemical evolution and interconnection among water sources (Fig.2(left)). In later stages, ^{13}C became an isotope of interest, especially for distinguishing natural and anthropogenic sources in various groundwater systems. This differentiation is based on the distinct isotopic signatures between biogenic (derived from living organisms) and thermogenic (from ancient, buried organic matter) hydrocarbon. It was subsequently realized that dual isotopic signatures provide better demarcation among contaminant sources with similar nature. Dual isotope systematic of NO^-(^{15}NNO and ^{18}ONO) can be used to identify the nitrogen source and understand the transformation process in surface and groundwater systems (Fig.2(right)). The δ^{34}S signature was also used to identify the climate-driven redox change. It can also provide information on shift in bottom-water and/or sediment oxygenation from glacial oxic to interglacial anoxic/euxinic conditions that are primarily driven by climate-induced changes in biogenic productivity. Metal isotopes are also very helpful in representing different sources and processes in water systems. Noble gas isotopes serve as valuable tracers, revealing Earth's environmental history and providing insights into hydrological processes and climate changes. Aspects like groundwater migration, age dating, palaeoclimate assessment through measurement of the recharge temperatures, geochemical processes in the shallow waters can be studied using noble gases and their isotopic ratios.

As contamination of water varies between regions, tailored approaches become necessary for remediation, which must account for the diverse climate, geology, hydrogeology, geomorphology, and other factors. Creating big database of isotopes and integrating it with advanced techniques (geo-statistical, geo-informatics, remote sensing); and modeling tools (including machine learning) can lead to solving problems on a regional scale with predictive modeling capabilities. Finally, efforts should be made towards interdisciplinary collaborations looping in water authorities, public health units, pollution control and sanitation departments for safeguarding the water resources against contamination threats, and pave the path for achieving the SDGs. The complete article can be found at Current Opinion in Environmental Science & Health, 2024, 40:100559.

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