

Tracing Lives Through Atoms: The Role of Stable Isotope Analysis in Forensic Anthropology

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OPEN ACCESS

Keywords

Stable Isotopes, Forensic Anthropology, Human Identification, Isotope Analysis, Chemical Signature

How to cite this article:

Pandey, A. K. and Tiwari, A. K. 2025. Tracing Lives Through Atoms: The Role of Stable Isotope Analysis in Forensic Anthropology. *Vigyan Varta* 6 (10): 187-192.

ABSTRACT

Stable isotope analysis has emerged as a transformative approach in forensic anthropology, offering a chemical window into human identity, movement, and life history. By examining the natural variations of isotopes such as carbon, nitrogen, oxygen, hydrogen, sulphur, and strontium within human tissues, scientists can reconstruct dietary patterns, geographic origins, and migration pathways that traditional methods often overlook. Bones, teeth, hair, and nails act as chronological recorders—each preserving isotopic information from different periods of an individual's life. These biological archives have been instrumental in identifying unknown remains, resolving humanitarian cases, and providing crucial leads in criminal and disaster investigations. Despite challenges such as incomplete isotopic reference maps and post-burial alterations, advancements in analytical precision, micro-sampling, and isoscape modelling continue to expand its forensic potential. Ultimately, stable isotope analysis bridges chemistry and humanity, transforming atoms into evidence and revealing how every person carries within them a unique chemical signature of their life's journey.

INTRODUCTION - Every atom tells a story

Have you ever wondered how forensic scientists can determine an individual's place of origin, or

reconstruct aspects of their diet, simply from bones or teeth? How is it even possible to deduce whether someone spent their early

years in a coastal environment, an inland region, or even migrated across countries—without the aid of personal records or DNA databases? The answer lies in a powerful analytical approach known as **stable isotope analysis**.

Stable isotopes are non-radioactive forms of elements such as carbon(C), nitrogen(N), oxygen(O), hydrogen(H), strontium (Sr), and sulphur(S). These isotopes occur naturally in the environment and enter the human body primarily through food and water intake. Because isotope ratios vary according to geography, climate, and local ecosystems, they leave measurable chemical “signatures” within biological tissues. Unlike radioactive isotopes, which decay over time, stable isotopes remain preserved, providing a long-lasting record of dietary intake and residential history.

In forensic anthropology, isotope ratio analysis has become a powerful tool for reconstructing life histories and identifying unknown individuals. Teeth capture childhood isotopic values that reveal early geographic origins, while bone collagen reflects diet over the past decade. Hair and nails, meanwhile, record the most recent weeks or months. Together, these tissues create a multi-layered biogeochemical profile that enriches traditional identification methods.

The Science Behind Stable Isotopes

Whenever we think of anyone’s identity, we often imagine their name, face, or personal documents. But on a chemical level, our bodies carry their own records, those subtle isotopic signatures that quietly reflect what we eat, drink, and where we live. Each element tells a different part of the story, almost like chapters in a book.

Carbon($\delta^{13}\text{C}$)

Imagine comparing two dinner plates: one filled with rice and vegetables, the other with

maize tortillas or sugarcane products. The carbon isotopes in our bones and teeth can actually tell the difference. They separate diets based on C3 plants (like wheat and rice) from those based on C4 plants (like maize and millet). They even reveal whether someone relied more on land-based foods or fish from the sea(Wang *et al.*, 2022).

Nitrogen($\delta^{15}\text{N}$):

Nitrogen isotopes act like markers of protein. The higher the $\delta^{15}\text{N}$ value, the more animal or marine protein someone consumed. In infants, this signal is so sensitive that scientists can see the elevated nitrogen levels from breastfeeding which offers a rare glimpse into early childhood that no document could preserve(Hu *et al.*, 2022).

Oxygen($\delta^{18}\text{O}$) and Hydrogen($\delta^2\text{H}$):

These isotopes are linked to the water we drink. Because rainfall and groundwater vary with climate, altitude, and latitude, the isotopes lock in information about geography. A tooth formed in childhood might reflect to one region, while bone formed in adulthood might to another, the evidence of migration engraved into the body itself(Chesson & Berg, 2022).

Strontium($^{87}\text{Sr}/^{86}\text{Sr}$):

Strontium reflects the very ground beneath our feet. Different rock formations leave distinct strontium “fingerprints” in local soils, plants, and water. When people consume food and water from those places, their bodies carry that geological stamp, making strontium one of the most powerful tools for locating geographic origins.

Sulphur($\delta^{34}\text{S}$):

Sulphur tells us about coastlines. Marine environments are enriched in $\delta^{34}\text{S}$, so individuals who lived near the sea or ate lots of fish, often carry higher values than those from inland areas. It’s almost as if the ocean itself leaves a trace inside their bones.

Individually, each isotope offers a clue. While together, they weave a far richer narrative: diet, movement, and environment combined into a chemical biography (Chesson & Berg, 2022).

Human Tissues as Time Capsules

Our bodies are not only living systems but also biological archives. Each tissue type preserves chemical information for different periods of life, almost like pages of a diary written in isotopes. Bone collagen functions as a long-term record. Because bone is constantly remodelled, its isotopic composition reflects dietary and environmental inputs averaged over many years. Adult bone collagen can capture a decade or more of dietary history, providing insights into long-term habits and shifts. Tooth enamel and dentine preserve childhood experiences. Enamel, once formed, does not remodel, which means it permanently locks in the isotopic signals of early diet and drinking water. This allows investigators to determine childhood residence even decades later. Dentine can also provide incremental records of early development, revealing finer details of growth and diet. Hair and nails serve as short-term indicators. Because these tissues grow continuously, they capture isotopic signals from the final weeks or months of life. Patterns along a strand of hair, for example, can reveal seasonal dietary changes or recent travel between regions with different water sources. When these tissues are studied together, they create a layered timeline of life history. This multi-scale perspective transforms human remains into time capsules, allowing forensic scientists to reconstruct both the stability and change in a person's life (Alt *et al.*, 2022).

Principles of Stable Isotope Analysis

At its core, stable isotope analysis relies on the fact that not all atoms of an element are identical. While C, N, O, H, and Sr are the

same elements we encounter in daily life, they exist in nature as isotopes- atoms with the same number of protons but slightly different numbers of neutrons. This subtle difference in mass gives them unique chemical fingerprints that scientists can detect and measure.

The power of isotope analysis in forensic anthropology lies in how living organisms naturally incorporate isotopes from their surroundings. Every meal, sip of water, and breath leaves behind subtle isotopic “signatures” in our tissues. Carbon isotope ratios can distinguish diets based on wheat and rice (C-3 plants) from those rich in corn or millet (C-4 plants), while nitrogen isotopes reflect the level of animal or marine protein consumed. Oxygen and hydrogen isotopes mirror local rainfall and water sources, turning bones and teeth into natural GPS markers. Strontium, derived from the underlying geology and transferred through soil, plants, and water, adds another layer of geographic insight (Wang *et al.*, 2022).

These isotopic fingerprints are analyzed with extraordinary precision using **mass spectrometry (MS)**, where minute samples of bone, tooth, or hair are transformed into gas or plasma. The instrument separates and measures isotopes by mass, reporting them as delta (δ) values i.e. tiny numerical differences that, when interpreted, reveal profound stories about where a person lived, what they ate, and how their environment shaped their life.

What makes this method especially valuable in forensic anthropology is its permanence. Unlike soft tissues, which degrade quickly, hard tissues such as tooth enamel and cortical bone can preserve isotopic information for centuries. Teeth, for instance, lock in childhood dietary and geographic signatures that remain unchanged through adulthood, while bones continuously remodel and reflect the last decade or so of an individual's life.

Together, they create a timeline of movement, diet, and environment that can guide investigators in reconstructing a life history(Filer, 2025).

Applications in Forensic Anthropology

Stable isotope analysis is not just a theory but it has been actively used in forensic casework to illuminate identity, origin, and movement in ways that often would be impossible with other methods alone. Researchers and practitioners around the world have applied these techniques in diverse contexts, from unidentified remains in remote areas to mass disasters and border crossings.

One powerful application is **provenance unidentified corpses**. In Germany between 2010 and 2012, scientists analysed isotopic ratios (H, C, N, S) in bone collagen and hair of two adults and a newborn whose identities were unknown. Results were compared with reference collections of hair and bone samples from various geographic regions. The isotopic signatures allowed investigators to constrain where the individuals likely spent most of their life, offering new levers for identification(Lehn *et al.*, 2015).

Stable isotope techniques also play a pivotal role in **disaster victim identification (DVI)**. Remains in disasters are often fragmented, mixed, or degraded. By sampling tooth enamel, bone collagen, hair, and other tissues, isotopic data helps prioritize identification efforts i.e. narrowing down the potential regions of origin, linking body parts to individual persons, or excluding possible identities. This reduces time wasted on unsuitable DNA analyses or fruitless searches(Chesson *et al.*, 2024). There is also a strong humanitarian and border-security dimension. In the United States, “undocumented border crosser” (UBC) cases have applied stable isotopes to estimate childhood origin, long-term residence, and

recent travel history. These analyses guide repatriation efforts and help law enforcement to better serve both public safety and human rights(Ammmer *et al.*, 2024). Finally, isotopes have been used in criminal investigations showing identity of severely mutilated or deteriorated victims. In Ireland, isotope data has helped triangulate dietary and water signatures which corroborated DNA evidence, assisting in solving the case(Meier-Augenstein & Fraser, 2008).

Strengths and Challenges

Stable isotope analysis has earned its place in forensic anthropology because it bridges the gap between biology and geography in ways few other methods can. Its greatest strength lies in the durability of isotopic signatures. Unlike DNA, which can degrade under harsh environmental conditions, isotopic signals in bone, teeth, and hair often persist for decades or even centuries. This makes it invaluable for examining both modern forensic cases and historical remains. Moreover, it is a non-destructive and complementary tool which offers geographic and dietary insights that DNA, fingerprints, or morphology alone cannot provide. When used together, isotopes and genetic data form a far more holistic portrait of an individual’s life story. However, the method is not without its limitations. The accuracy of interpretation relies heavily on baseline reference maps, known as isoscapes, which show how isotope values vary across different regions. Unfortunately, these maps are still incomplete in many parts of the world, introducing uncertainty. Overlapping isotope values between geographically close regions can also blur distinctions, making precise origin assignment challenging. Additionally, diagenesis, or post-burial chemical alteration of tissues, can distort the original isotopic signals if samples are not carefully preserved or analyzed(Spies *et al.*, 2025).

Despite these hurdles, combining isotope data with genetic, archaeological, and anthropological evidence provides a balanced and reliable reconstruction of human identity and movement. The future of forensic anthropology lies not in replacing traditional tools, but in integrating them, each adding its own layer of truth to the human story.

Future Directions and Conclusion- Reading Humanity in Chemistry

Stable isotope analysis has transformed from a geochemical curiosity into one of the most powerful investigative tools in forensic anthropology. As analytical precision improves and global isotopic databases expand, its potential to reconstruct human lives will only deepen. Emerging techniques such as multi-isotope fingerprinting combines carbon, nitrogen, oxygen, hydrogen, sulfur, and strontium signatures that are enabling scientists to pinpoint origins with unprecedented accuracy. Advances in micro-sampling are also allowing isotopic analysis of minute tissue fragments, making it possible to work with highly degraded remains that once yielded little information.

The next frontier lies in isoscape refinement and data integration. Collaborative projects across continents are building high-resolution maps of isotopic variation in food, water, and human tissues. When coupled with machine learning and DNA databases, these efforts promise a future where the identity of unknown individuals can be determined faster, more ethically, and with global precision. But beyond technology, stable isotope analysis is a reminder of something profoundly human. Every molecule of oxygen we breathe, every drop of water we drink, and every grain of food we consume leaves a chemical signature within us, there is a silent witness to where we have lived and who we have been. In this way, our tissues are not just biological matter; they

are stories written in atoms, waiting to be read. As forensic anthropology continues to evolve, stable isotopes will remain one of its most poetic and scientifically grounded tools acting as a bridge between chemistry and identity, helping us piece together the narratives of lives that time had nearly erased.

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