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Research trends in stable isotope analysis: a revision on unconsolidated intertidal ecosystems

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ABSTRACT

This study investigates the role of stable isotope analysis in unconsolidated sediment coastal systems, focusing on scientific production and research trends over time. Existing literature was analyzed to identify knowledge gaps and highlight the importance of stable isotope techniques in understanding coastal ecosystems. A comprehensive bibliometric analysis was conducted using the Scopus database to collect and categorize relevant publications on stable isotope ecology. Key indicators—including publication trends, authorship patterns, and the geographic distribution of research—are shown. The temporal scope of studies was systematically assessed, with particular attention to methodological approaches employed. Co-authorships networks and co-occurring keywords were examined to explore the intellectual structure of the field and identify collaborative patterns among authors. Over 140 publications were identified, authored by over 400 researchers, with interest increasing significantly over time, particularly in trophic studies involving macrobenthos. Mudflats emerged as a focal point, receiving more attention than sandy beaches. The analysis indicates that seasonality is the predominant temporal scale, while mesoscale studies dominate spatial investigations. A plateau in publication growth appears to coincide with the emergence of alternative methodologies for trophic ecology studies. Major contributions come from France, the United States, and Australia. Co-authorship analysis revealed fragmented collaboration networks, with limited international engagement among developing nations. Overall, the importance of stable isotopes in understanding coastal ecosystems is underscored, while the need for methodological diversity and increased collaboration in future research is highlighted.

Keywords: Unconsolidated intertidal, Research output, Science maps, Stable isotopes, Geographic distribution

INTRODUCTION

Unconsolidated intertidal ecosystems are coastal areas regularly exposed and submerged by tides, characterized by loose sediments such as sand, mud, gravel, or combinations thereof, and lacking aquatic vegetation. These environments are exposed at low tide and submerged at high tide, encompassing both sandy and muddy sedimentary habitats. Historically, they have been less studied than other coastal ecosystems, such as rocky shores, as life in these habitats may be less evident (McLachlan and Defeo, 2018). However, in recent decades, research in these environments has grown uninterruptedly (Lercari, 2023). Sandy beaches have received particular attention due to their scenic and recreational value, as well as their high biodiversity. They serve as models for various

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processes and provide habitat for numerous species—from visible organisms such as clams, snails, insects, crabs, and worms to microscopic ones such as protozoans, bacteria, and algae (McLachlan and Defeo, 2018). Coastal flats have a more evident load of organic matter, making them more productive environments. All of these systems are open and highly interconnected, with their proximity facilitating flows of energy and organic matter that determine the structure of biological communities (Polis and Hurd, 1996; Polis et al., 1997; Schlacher and Connolly, 2009).

In ecology, stable isotopes are helpful tools for tracking nutrient cycling and clarifying the origin and destination of elements circulating in the biosphere, with particular focus on those representing an important fraction of the planet's organic matter, such as carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) (Fry, 2006). In trophic ecology, stable isotopes provide space- and time-integrated information on trophic relationships among organisms (Layman et al., 2011). Carbon isotopes are used to determine the source of organic matter consumed by organisms, based on the close relationship between the $\delta^{13}C$ of consumers and that of their food sources. Marked differences occur among primary producers depending on the type of photosynthesis, as well as origin and availability of CO_2 (De Niro & Epstein, 1978; Peterson and Fry, 1987). Nitrogen isotopes are used to estimate trophic position, since deamination and transamination processes enrich $\delta^{15}N$ in consumer tissues relative to their diet, with this enrichment being consistently maintained across trophic transfers (De Niro & Epstein, 1981; Peterson and Fry, 1987). Sulfur isotopes do not show such enrichment between consumers and their diet, and are used to differentiate sources of organic matter, being useful to identify anthropogenic influences on sulfur cycle and pollution (Peterson and Fry, 1987). Hydrogen and oxygen isotopes are highly used in hydrological studies due to their relationship with the water cycle and fractionation processes during evaporation and condensation, enabling the tracking of water movement in the biosphere (Fry, 2006; Penna et al., 2018). Additionally, atmospheric oxygen isotopes are useful for assessing respiration and photosynthesis processes (Fry, 2006).

In the face of multiple threats to coastal ecosystems—stemming from urbanization, industrialization, unsustainable resource use, and the effects of climate change (Defeo et al., 2021)—it is important to understand how the scientific community is addressing these issues with tools such as stable isotopes. Although research in these environments has grown with the development of new techniques, it remains limited to few regions of the world or within small research teams, highlighting a pressing need for greater interdisciplinarity (Nel et al., 2014). Thus, scientometric analysis emerges as a useful approach, since it quantitatively examines the scientific output of a research community. This method helps assess productivity within a specific field, highlight dominant research themes, reveal knowledge gaps, and identify leading research groups or countries with differing levels of scientific contribution (Bornmann and Mutz, 2015). Additionally, the creation of science networks or maps provides an accessible graphical representation of the data (van Eck and Waltman, 2010), enabling the visualization of the degree of connection between actors (e.g., co-authorship maps between authors or countries) or the identification of recurring research topics (e.g., via keyword co-occurrence maps). These approaches offer a systematic, transparent, and reproducible framework for reviewing the literature (Aria and Cuccurullo, 2017), supporting the identification of research trends and the development of future work strategies.

This study aims to quantitatively analyze global research on isotopic ecology in coastal ecosystems with unconsolidated sediments. Specifically, it seeks to; 1) provide a bibliometric description of scientific production over time (e.g., number of publications, relevant works, main countries researching in this field; 2) identify the main research topics in this field; and 3) analyze the collaboration dynamics among authors and countries involved.

METHODS

Publications analyzed were retrieved from the Scopus (Elsevier) database, a major repository of scientific literature. The study considers publications on a global scale, from the earliest work meeting the search criteria to 2024. A preliminary list was compiled based on two criteria: methodology (use of isotopes) and environment (sandy beaches, sandy coastal wetlands [sandflats], or muddy coastal wetlands [mudflats]). To this end, three searches were performed in Scopus, restricting results to works containing the following terms in their title, abstract, or keywords: 1) (isotope*) AND (mud AND flat*) OR (mudflat*); 2) (isotope*) AND (sand AND flat*) OR (sandflat*); and 3) (isotope*) AND (sandy beach*). The results from these three searches were consolidated into a single list. Subsequently, abstracts were screened to remove studies unrelated to ecology or not using stable isotopes. The steps to obtain the final list followed the PRISMA diagram guidelines (Page et al., 2021), showing the selection criteria and the number of articles selected or discarded at each stage. These details are provided as Supplementary Material (Supplementary Material 2, Figure S1).

Bibliometric description

For all articles in the final list, several bibliometric indicators were collected. First, general information about the dataset was gathered, including: the period covered, number of sources (such as journals, books, book chapters), number of documents, annual growth rate, and average citations per document. Author-related data were also included, such as the total number of authors, number of authors in single-and multi-authored work, co-authors per document, and percentage of international co-authorship. Document type was also considered, classifying works as articles, notes, or books.

To evaluate the evolution of scientific output over time, annual production, measured as the number of documents per year, was determined. To obtain an overview of the current landscape, the main publishing countries in this field were analyzed, and their dynamics over time were evaluated based on annual publication counts. Additionally, the most influential works were assessed considering total and annual citations, along with the countries of all authors. Bibliometric analysis was performed using the bibliometrix package in R (Aria and Cuccurullo, 2017).

Research topics

To identify the main research topics in the dataset, all works were reviewed and analyzed for the following characteristics: 1) main research focus, 2) secondary research focus, 3) number of taxa studied, 4) study group employed, 5) tissue sampled, 6) environment, 7) ocean, 8) oceanic region, 9) distance covered, 10) temporal scale, 11) spatial scale, and 12) isotopes used. Studies were categorized according to these attributes, and the frequency of occurrence for each was recorded. When insufficient information was available to assign a document to a given category, the label “no data” (ND) was applied. For categories in which multiple classifications were possible—namely, study group employed, tissue sampled, environment, and isotopes used—documents were included in all applicable categories.

To evaluate the focus of each study, two categories were created: “main focus,” defined as the primary topic the study aims to investigate, and “secondary focus,” referring to additional but less critical areas that complement or contextualize the main focus. For the number of taxa, studies were divided into six categories: 1, 2–10, 11–20, 21–100, 101–200, and ND. The “study group” category aimed to classify studies by type of taxa for living organisms or material for non-living components. Studies were also categorized by the type of tissue sampled, complementing this classification. The “environment” category identified field sites where the research was conducted (e.g., sandy beach, mudflat, sandflat). Since all studies were conducted in coastal systems, the ocean where each study took place was classified, along with the geographic region, defined by cardinal points (e.g., Northwestern Atlantic, Southwestern Pacific). Temporal scale was categorized based on the duration of the experiment or fieldwork into five groups: day-scale, month-scale, seasonal, annual, and multi-annual. The spatial scale classification was adapted from McLachlan and Defeo (2018) and organized into micro-scale (single sampling site), meso-scale (multiple sites within the same system, such as a beach or mudflat), macro-scale (different systems within the same geographic region), biogeographic (sites across different geographic regions), and experimental (studies using laboratory microcosms or mesocosms instead of field sites). The isotopes used for the analyses were also considered and categorized.

Additionally, a keyword co-occurrence network was created using VOSViewer software (van Eck and Waltman, 2010). Only keywords appearing in more than five documents were included, excluding terms implicit in the search that do not provide additional insight, such as “stable isotope” and its variants (isotope, isotopes, stable isotope, stable isotopes, stable isotope analysis, stable isotope ratio, isotopic analysis, isotopic ratio, isotopic composition).

Scientific collaboration

Two co-authorship networks were created using VOSviewer: one to assess collaborative dynamics among research groups at the author level, focusing on how teams interact and form clusters; and another to analyze international collaboration by mapping connections between the countries of corresponding authors.

In the authors’ network, a maximum of 25 authors per document was set, and only authors with at least two publications in the list were considered. For the countries’ network, a maximum of 25 countries per document was set, and all countries in the list were considered. Countries without connections were excluded from visualization.

RESULTS

Bibliometric description

The timespan between the first document matching the criteria (1985) and the most recent (2024) is 39 years. During this period, 135 works were published across 58 sources (Supplementary Material 1). The annual growth rate was 3.62%, with an average of 30.07 citations per document. A total of 457 authors contributed to the publications, averaging 4.53 authors per document, with only three single-authored works. International co-authorship accounted for 34.07% of publications. The dataset includes 132 articles, two conference papers, and one note (Table 1). Annual scientific production ranged from 0 to nine documents per year (Figure 1), with peaks of nine documents in 2008, 2011, and 2019. A nine-year gap with no publications meeting the criteria occurred between 1988 and 1995.

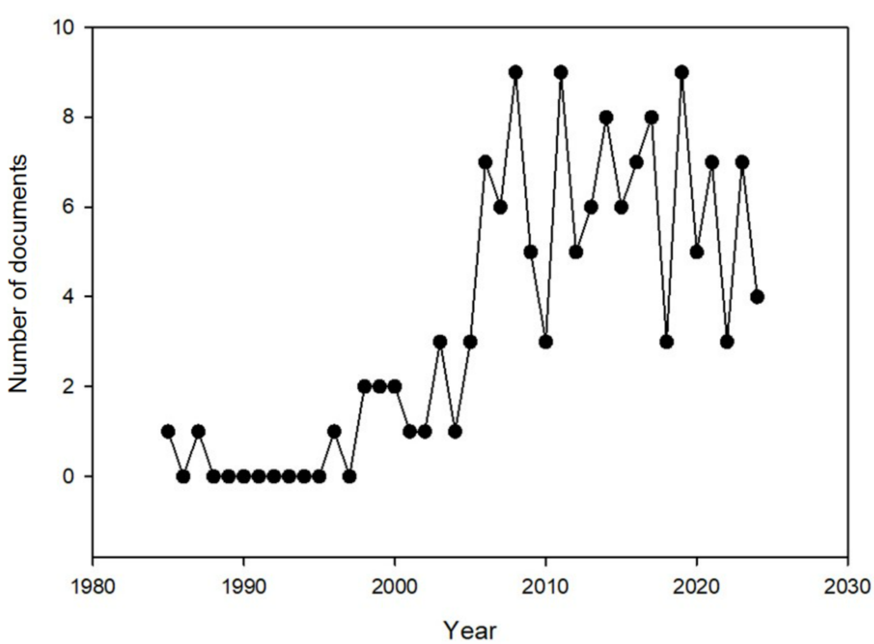

Figure 1. Annual scientific production regarding stable isotope analysis on unconsolidated sediment coastal systems from the Scopus database.

Table 1. Bibliometric information of the published documents regarding stable isotope methodology on unconsolidated sediment coastal systems in the Scopus database.

Description	Results
Main information	
Timespan	1985–2024
Sources	57
Documents	135
Annual Growth Rate %	3.62
Average citations per document	30.07
Authors	
Authors	457
Single-authored documents	3
Co-authors per document	4.53
International co-authorships %	34.07
Document type	
Article	132
Conference paper	2
Note	1

The top-cited studies (Table 2) primarily focus on using stable isotope analysis to identify key food sources and trophic relationships in coastal benthic ecosystems. These include spatial assessments of fish nutrition (Melville and Connolly, 2003; 166 citations), the role of marine macrophytes in supporting sandy beach fauna (Ince et al., 2007; 131 citations), feeding ecology of suspension-feeding bivalves in muddy sediments (Kang et al., 1999; 121 citations), ontogenetic diet shifts in deposit-feeding polychaetes (Hentschel, 1998; 121 citations), and food sources for intertidal nematodes (Riera et al., 1996; 110 citations). Collectively, these studies emphasize the importance of habitat-specific organic matter in structuring benthic food webs.

Regarding countries, France has the highest number of corresponding authors (21), followed by the United States (13), and then Australia and Japan (12 each). France also leads in scientific production with 100 published documents, followed by Japan (64) and the United States (51). The first article in the selection had a United States affiliation, and the country remained the top producer until 2007, when it was overtaken by France. Since then, France maintained the lead, followed by Japan and the United States (Figure 2).

Table 2. Most globally-cited articles regarding stable isotope ecology on unconsolidated sediment coastal systems from the Scopus database. TC = total citations; TCY = total citations per year.

Paper	Authors	Sources	TC	TCY
Spatial analysis of stable isotope data to determine primary sources of nutrition for fish	Melville and Connolly, 2003.	Oecologia	166	7,5
Marine macrophytes directly enhance abundances of sandy beach fauna through provision of food and habitat	Ince et al., 2007.	Estuarine Coastal and Shelf Science	131	7,3
Food sources of the infaunal suspension-feeding bivalve *Cerastoderma edule* in a muddy sandflat of Marennes-Oléron Bay, as determined by analyses of carbon and nitrogen stable isotopes	Kang et al., 1999.	Marine Ecology Progress Series	121	4,7
Intraspecific variations in δ_{13}C indicate ontogenetic diet changes in deposit-feeding polychaetes	Hentschel, 1998.	Ecology	121	4,5
Food source of intertidal nematodes in the Bay of Marennes-Oleron (France), as determined by dual stable isotope analysis	Riera et al., 1996.	Marine Ecology Progress Series	110	3,8
Parasites alter host phenotype and may create a new ecological niche for snail hosts	Miura et al., 2006.	Proceedings of the Royal Society B: Biological Sciences	103	5,4
The importance of mangroves, mud and sand flats, and seagrass beds as feeding areas for juvenile fishes in Chwaka Bay, Zanzibar: gut content and stable isotope analyses	Lugendo et al., 2006.	Journal of Fish Biology	101	5,3
Stable isotope addition reveals dietary importance of phytoplankton and microphytobenthos to saltmarsh infauna	Galván et al., 2006.	Marine Ecology Progress Series	93	5,5
Isotopic evidence for phytoplankton as a major food source for macrobenthos on an intertidal sandflat in Ariake Sound, Japan	Yokoyama et al., 2005.	Marine Ecology Progress Series	91	4,6
Preferential food source utilization among stranded macroalgae by *Talitrus saltator* (Amphipod, Talitridae): a stable isotopes study in the northern coast of Brittany (France)	Adin and Riera, 2006.	Estuarine Coastal and Shelf Science	90	4,1

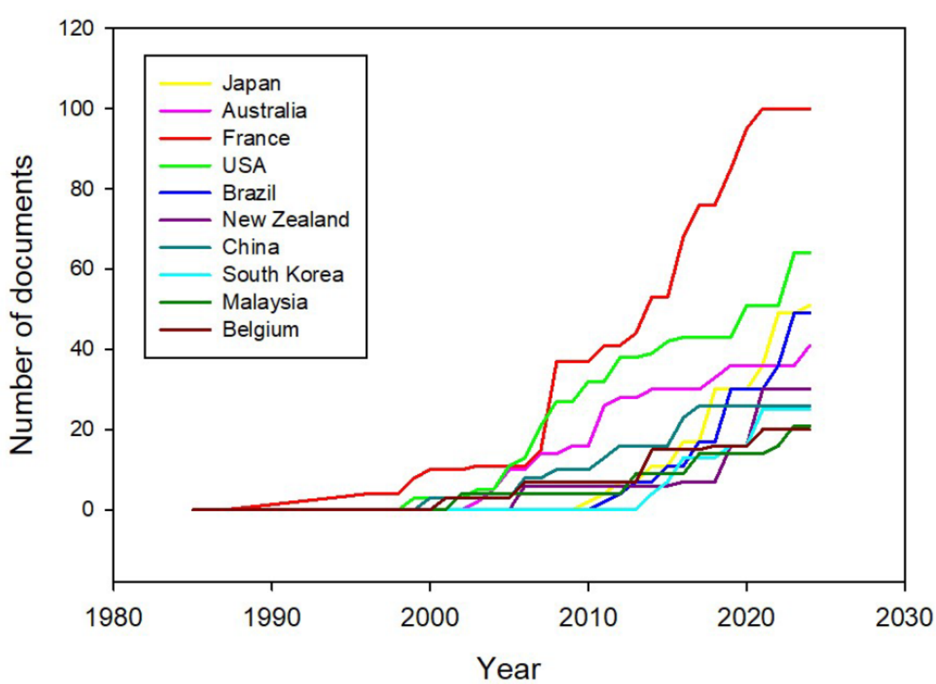

Figure 2. Research production over time by the ten most productive countries regarding stable isotope analysis on unconsolidated sediment coastal systems from the Scopus database.

Research topics

Most documents in the dataset (121) have trophic ecology as their main focus. Other primary topics include environmental nutrients (6), environment (5), spatial distribution (2), and intraspecific competition (1) (Figure 3a). As a secondary focus, the documents primarily address diet (40), community (38), and ecosystem (28). Nutrient cycling, behavior, eutrophication, and parasitology also appear as secondary topics (Figure 3b).

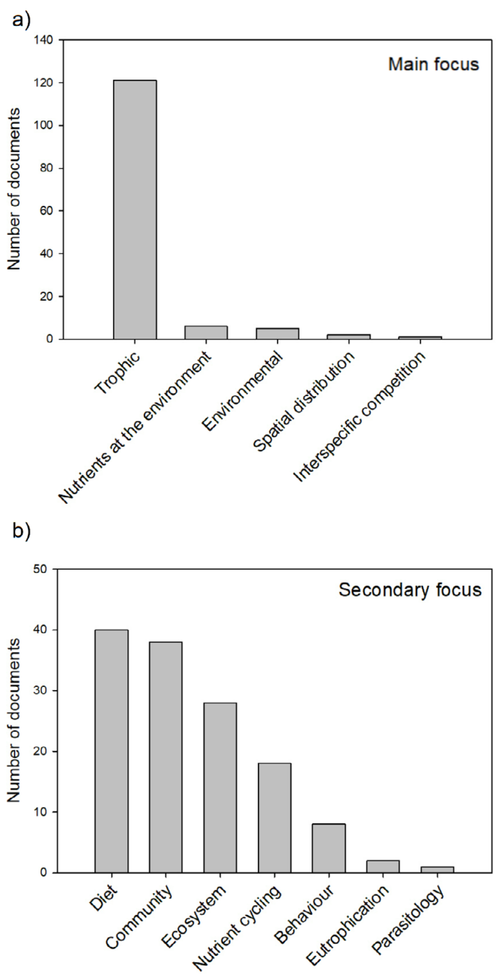

Figure 3. a) Main and b) secondary focus of the documents from the dataset regarding stable isotope analysis on unconsolidated sediment coastal systems from the Scopus database.

Of the documents reviewed, 42 focused on a single taxon, 71 employed a multispecies approach, and for 22, this information was not available (ND). Among the 71 multispecies studies, 53 included 2–10 taxa, seven included 11–20 taxa, 10 included 21–100 taxa, and one included 101–200 taxa (Supplementary Material 2, Figure S2). Most studies targeted macrobenthos (83 documents, Figure 4a). Regarding sampled tissue, most used whole-body samples (53 documents) or muscle tissue (52 documents) for stable isotope analysis (Figure 4b).

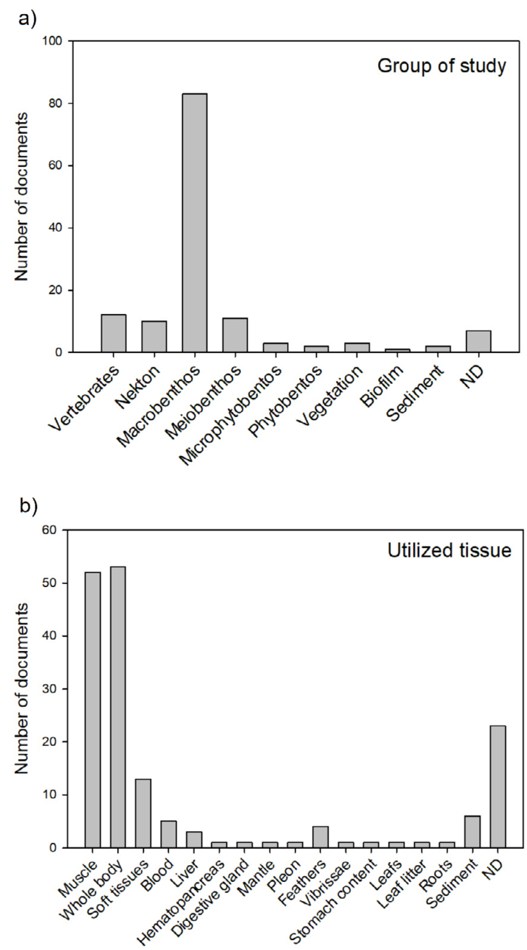

Figure 4. a) Study group employed and b) tissue used in documents from the dataset regarding stable isotope analysis on unconsolidated sediment coastal systems from the Scopus database. ND = no data.

Mudflats were the most studied environment, with 66 publications conducted in these systems. Sandy beaches were also commonly investigated (40 documents), while sandflats appeared in 14 studies. Artificial mudflats and sandflats, as well as a polychaete reef, were also reported. Some documents did not specify sediment type and were categorized as intertidal environments or tidal flats (Figure 5a). Regarding oceans, research was conducted along the Atlantic (65 documents), Pacific (45 documents), and Indian (23 documents) coasts, with one study covering multiple oceans (Figure 5b). The oceanic regions are detailed in Figure 5c, with the Northeastern Atlantic (39) and the Northwestern Pacific (24) being the most frequently studied areas.

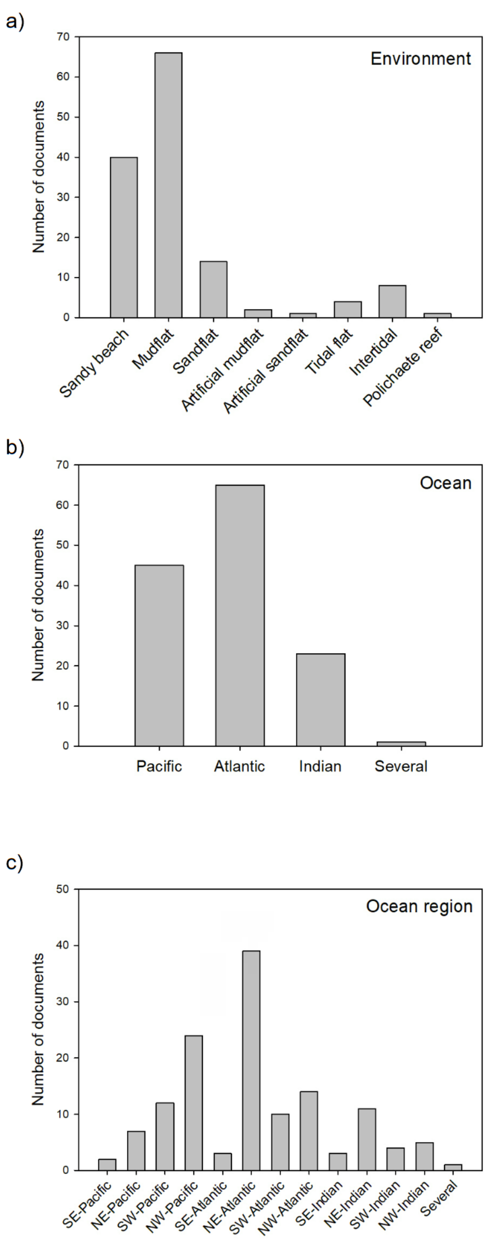

Figure 5. a) Environment, b) ocean, and c) region where the research was conducted, from documents of the dataset regarding stable isotope analysis on unconsolidated sediment coastal systems from the Scopus database.

Regarding temporal scale, most studies reporting this information were conducted on a seasonal basis (55 documents), with additional studies on a daily scale (43), monthly scale (7), annual scale (1), and multi-annual scale (17) (Figure 6a). For spatial scale, most of the fieldwork was conducted at the meso-scale level (61 documents) (Figure 6b). Sampling distance was reported in 103 documents. Of these, 20 covered less than 1 km, 36 ranged from 1–10 km, 26 ranged from 11–50 km, seven ranged from 51–100 km, nine ranged from 101–500 km, one ranged from 501–1,000 km, and four over 1,000 km (Supplementary Material 2, Figure S3).

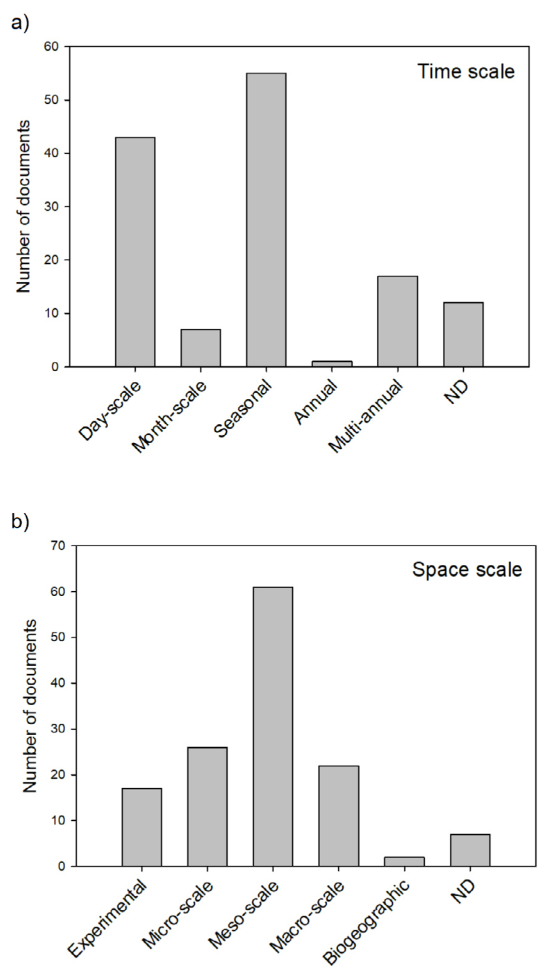

Figure 6. a) Time-scale, and b) space-scale in which the research was conducted, from the documents of the dataset regarding stable isotope analysis on unconsolidated sediment coastal systems from the Scopus database. ND = no data.

Regarding stable isotopes, the most frequently used was carbon ($\delta^{13}C$), appearing in 130 studies, followed by nitrogen ($\delta^{15}N$), used in 115 studies (Supplementary Material 2, Figure S4). These isotopes were often analyzed together, with 112 documents reporting combined carbon-nitrogen stable isotope analysis. Sulfur (δ34S) was used in four studies, and hydrogen ($\delta^{2}H$) in one study.

The keyword co-occurrence network was composed of 234 keywords, and three clusters were formed (Figure 7). Cluster 1 focuses on physical and biological components of ecosystems (e.g., mudflats, sediments, feeding patterns). Cluster 2 emphasizes biological interactions, particularly invertebrates and algae on sandy beaches, highlighting how trophic interactions and diet are central to understanding ecosystem dynamics. Cluster 3 underscores estuarine environments and their biotic components, such as fish and crustaceans, emphasizing food webs and habitat use. Each cluster represents a different facet of stable isotope ecology, with distinct emphasis on physical environments, trophic interactions, and community structure in coastal systems.

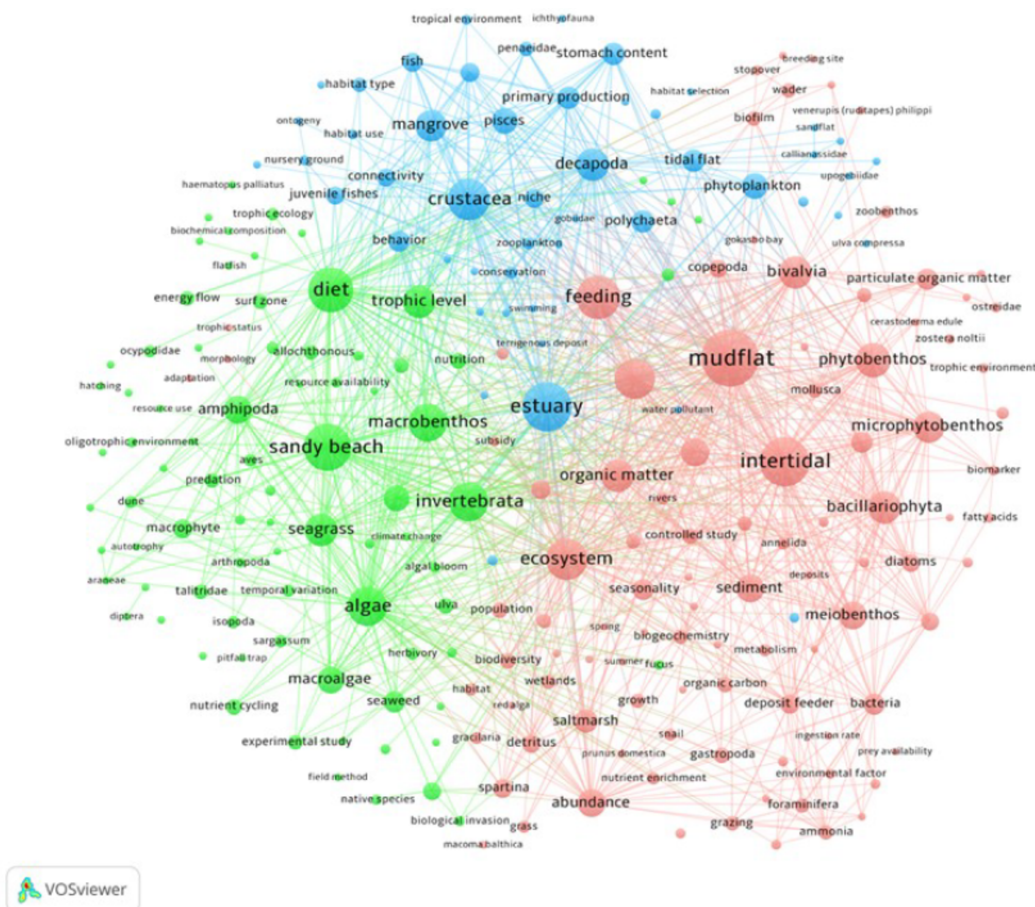

Figure 7. Network visualization of keywords on documents regarding stable isotope analysis on unconsolidated sediment coastal systems from the Scopus database.

Scientific collaboration

Of the 457 authors in the dataset, 99 appeared in multiple documents, thus becoming part of the authors' collaboration network (Figure 8a). Among these, 18 showed interconnections with authors from other groups. For example, certain clusters of authors (Niquil N, Richard P, and Pascal PY) are interconnected and represent researchers from France, reflecting the country's significant contribution to this field. Connolly RM is central to a cluster of Australian researchers, while de Torch M serves as the central author from Belgium.

Regarding countries, 40 of the 44 listed are interconnected; those without connections were excluded from the network visualization (Figure 8b). Country clusters in stable isotope ecology research reveal key geographical and linguistic patterns. Cluster 1 includes European and Southern Hemisphere countries such as Germany, Australia, and Spain, connected via global academic networks. Cluster 2 is dominated by France, with strong ties to French-speaking regions such as French Guiana and Uruguay. Cluster 3 features a mix of European countries, including Belgium, and global partners such as Brazil and India, reflecting diverse international collaborations. Cluster 4 is led by the United States and the Netherlands, with links extending to Africa and the Caribbean. Cluster 5 consists mostly of English-speaking countries, including Canada and the United Kingdom, while Cluster 6 centers on Asia, with Japan and Malaysia forming regional hubs and cross-continental links to Panama. These clusters illustrate how geography and language shape global research partnerships.

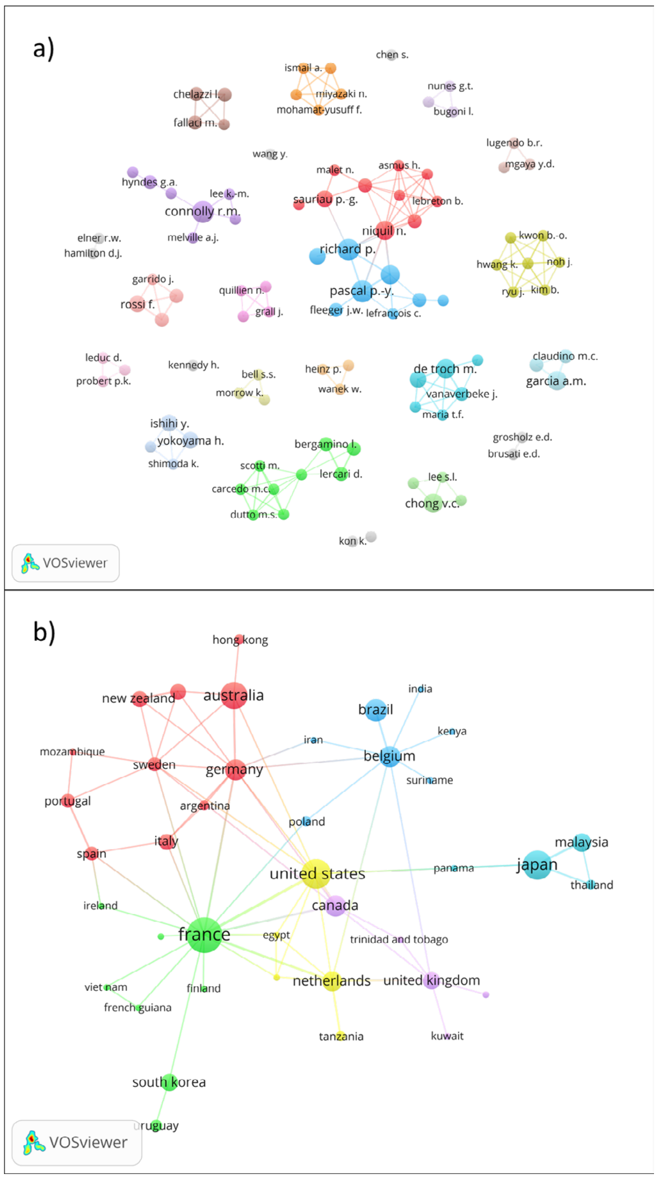

Figure 8. Co-authorship network among a) authors and b) countries producing studies related to stable isotope analysis on unconsolidated sediment coastal systems from the Scopus database.

DISCUSSION

Introduction to findings

Our science mapping analysis revealed over 140 documents and more than 400 authors, indicating a growing interest in stable isotope ecology within unconsolidated sediment coastal systems. Publication output has increased over time, eventually reaching a plateau with notable fluctuations. The main papers garnered over 100 citations each. France, the United States, and Australia emerged as the leading countries in this research area. Trophic studies, focusing on the diet of entire communities, were the primary research topic, with macrobenthos being the most studied community. Mudflats were investigated more frequently than sandy beaches, and seasonality was the most commonly analyzed temporal scale, while mesoscale studies (covering hundreds of kilometers) were the most typical spatial scale. Additionally, three conceptual clusters based on environments (beaches, estuaries, and mudflats) were found, along with several authors and country clusters showing significant disconnections.

Scientific production and temporal trends

publications on stable isotope ecology in unconsolidated intertidal environments have steadily increased over the years, recently reaching a plateau, with marked interannual fluctuations. Initial growth was gradual, but from the early 2000s onward, a noticeable acceleration occurred, largely driven by the expanded use of isotopic mixing models. These models, particularly Bayesian approaches, enabled more complex analyses by incorporating multiple sources and addressing uncertainties. Peaks in publication volume were observed in 2008, 2011, and 2019, likely reflecting technological advancements and an increased focus on diverse ecological applications of stable isotopes, particularly in coastal ecosystems. However, the recent growth stagnation may be attributed to the emergence of alternative trophic analysis methods, such as fatty acid profiling and environmental DNA (eDNA), which have gained traction in ecological research. These methods offer different insights into trophic interactions and biodiversity assessments, potentially shifting research priorities away from traditional stable isotope analysis. A similar growth pattern in stable isotope studies was observed in other regions, as shown by a systematic review of Baltic Sea food webs (Eglite et al., 2023), reflecting a broader global trend. Moreover, the rise in stable isotope research parallels advancements in megafauna studies, insect ecology, and climate change research (França et al., 2022; Liu et al., 2023; Quinby et al., 2020). This highlights both the versatility of stable isotope analysis and the influence of emerging techniques on the future of ecological research.

Geographical distribution of research

Our results generally align with global scientific production trends of leading countries, as reflected in the Nature Index. France has emerged as the leading country in this field, surpassing the United States, which had dominated until 2007. This shift mirrors broader research trends observed in other studies. For instance, Costa and Caldeira (2018) noted the United States' initial leadership in ocean literacy, later complemented by significant contributions from the United Kingdom and Canada. Similarly, Sun et al. (2012) highlighted the United States' long-standing dominance in estuary pollution research, with increasing contributions from China. The Nature Index also highlights France's growing influence and the United States' continued high output across various fields. Japan's consistent role as a top contributor in our study, as well as in other research, underscores its stable and significant position in marine and environmental sciences. These findings may also be influenced by the historical development of intertidal ecology in different countries and by geographical factors, such as the prevalence of mudflats and sandy beaches in major research regions. The dominance of specific countries in these environments likely reflects their historical focus and regional advantages in studying these ecosystems.

The analysis of country connections in stable isotope ecology research highlights significant disparities in global collaboration (Figure 9). While 40 out of 44 countries are interconnected, the central role of Belgium within predominantly European networks emphasizes a geographical concentration that marginalizes developing nations such as Brazil and India. Clusters dominated by French- and English-speaking countries illustrate linguistic barriers that hinder broader partnerships, particularly with regions facing ecological challenges in Africa and the Caribbean. This reflects trends in overall ecological research, where the Global North produces the majority of knowledge and citations, leaving the Global South underrepresented. Consequently, there is an urgent need for inclusive research frameworks that engage developing nations to enhance ecological understanding and inform global conservation efforts (Fisher and Christopher, 2007; Martin et al., 2012).

The co-authorship network analysis reveals a fragmented landscape of research collaboration. Of the 457 authors identified, only 99 contributed to multiple publications, forming a collaborative network. Within this network, interconnections among authors are sparse, indicating that while some clusters exist, many researchers operate in isolation or maintain minimal ties to other groups. Overall, the co-authorship landscape is characterized by disjointed groups conducting parallel studies with limited collaboration. This lack of interconnectivity highlights opportunities for enhanced collaboration and knowledge exchange, including the integration of molecular data in stable isotope ecology research (Glibert et al., 2018). Strengthening these connections could foster more integrated research efforts, expanding the understanding of ecological dynamics in coastal systems and facilitating innovative approaches to shared challenges. Such collaboration may be instrumental in advancing the scientific community's collective knowledge of stable isotope methodologies and their applications across different geographic regions and ecological contexts.

Research topics and methodological approaches

Consistent with our results, stable isotopes are valuable tools in trophic ecology and dietary studies, especially for ecologists working with species difficult to observe in their natural environments (Boecklen et al., 2011). This is based on the application of trophic discrimination factors to consumers' isotopic values, which can be directly compared and associated to their diet, and may vary according to dietary composition, physiology, and behavior (Fry, 2006). Stable isotope analysis offers methods that increase resolution in food web studies across various temporal and spatial scales (Boecklen et al., 2011).

Our findings reveal a predominant focus on studies conducted at a seasonal time scale, reported in 55 studies, followed by daily, monthly, annual, and multi-annual scales. This pattern reflects a strong interest in capturing temporal variability over relatively short periods, likely due to the dynamic nature of coastal ecosystems and logistical constraints in fieldwork. Spatially, most studies were conducted at the meso-scale level, as seen in 61 works. This preference aligns with observations of Wiens (1989) and Levin (1992), who emphasize the importance of intermediate scales in understanding ecological processes. Data on sampling distances further supports this pattern, with most studies covering areas between 1 and 50 km, reinforcing the trend toward meso-scale investigations. Only a minority of studies extended beyond 100 km, highlighting the challenges of conducting large-scale ecological research, which may be constrained by logistical, financial, or temporal limitations (Heffernan et al., 2014). Thus, our analysis underscores the continued relevance of meso-scale research while pointing to opportunities for broader studies across larger spatial and temporal scales, particularly in the context of global change and biogeographic patterns (Wiens and Bachelet, 2010). For future studies in unconsolidated intertidals, it should be noted that isotopic trophic metrics are strongly influenced by the spatial extent of sampling, which controls the environmental heterogeneity experienced by individual consumers; greater sub-habitat heterogeneity leads to greater variation in resource use (Reddin et al., 2017). This reinforces the need for isotopic studies to consider temporal variation in baseline food webs, for example due to seasonal variation in allochthonous inputs, making the determination of baselines across study periods and geographic ranges imperative (Reddin et al., 2017).

The keyword network visualization from documents on stable isotope ecology in unconsolidated sediment coastal systems reveals a well-defined structure with multiple thematic clusters (Figure 8). These clusters represent different aspects of coastal systems, including physical environments, biological interactions, and community structure. For instance, one cluster focuses on mudflats, emphasizing the role of primary producers such as phytobenthos and phytoplankton, while another highlights trophic dynamics on sandy beaches, particularly interactions between invertebrates and stranded algae. Estuarine environments, which combine elements of both sandy beaches and mudflats, form a separate cluster, with attention to food webs and habitat use among fish and crustaceans. Overall, the relatively strong integration of these clusters suggests that stable isotope methodology serves as a unifying scientific tool across various intertidal environments. Despite the diversity of ecosystems studied, stable isotope analysis consistently links studies on biogeochemical cycling, trophic interaction, paleoenvironments, and baseline tracking, demonstrating its versatility and broad applicability in ecological research (Glibert et al., 2018). This cohesive framework enables scientists to bridge gaps between different coastal systems, enhancing understanding of ecological processes and interactions across these dynamic landscapes.

Environmental and oceanographic focus

in line with Lercari (2021), who extensively analyzed research on sandy beaches, our findings reveal a greater emphasis on mudflats in stable isotope studies. This preference likely stems from the more complex biogeochemical processes in mudflats, where nutrient cycling and sediment dynamics are more intricate compared to the relatively simpler sandy beach systems. Furthermore, consistent with Gattuso et al. (2005), we observed a significant concentration of studies in the Atlantic Ocean, particularly the Northeastern Atlantic. This geographic focus may result not only from the high density of researchers based in the United States and Europe but also from the uneven global distribution of mudflats and sandy beaches. Notably, the Atlantic and Pacific Oceans, which account for the largest shares of tidal flats (Murray et al., 2019), host vast macrotidal mudflats along coasts such as Northern Europe, Southeast Asia, and Australia. The historical development of marine science in European institutions, especially along the North Sea tidal flats, likely reinforces this trend. These observations align with Potter and Pearson (2023), who highlight significant regional disparities in research output and stress the importance of international collaboration. The concentration of research in the Atlantic and Pacific Oceans underscores the need for more balanced global studies, as these basins currently dominate scientific discourse on coastal ecosystems.

Most studies in stable isotope ecology primarily utilize carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), with 112 studies focusing on these isotopes. This dominance reflects their efficacy in tracing organic matter sources and trophic relationships. However, sulfur ($\delta^{34}S$) and hydrogen isotopes are rarely used, although their potential in coastal ecology is increasingly recognized. For instance, sulfur isotopes, when used alongside carbon and nitrogen, can help differentiate benthic and pelagic organic matter sources, especially in coastal environments with complex salinity gradients (Davis et al., 2024; Raoult et al., 2024). Sulfur isotopes offer unique insights into sediment processes and may complement carbon isotopes in identifying primary producer sources with similar $\delta^{13}C$ values (Holmer and Hasler-Sheetal, 2014; Peterson and Howarth, 1987). The potential of $\delta^{34}S$ is becoming more evident in studies aimed at distinguishing carbon pathways, suggesting promising applications in coastal systems. Moreover, nitrogen isotopes are crucial in ecotoxicology, helping to quantify contaminant biomagnification, such as mercury and PCBs, via food webs (Cabana and Rasmussen, 1996; Hobson, 2023). Furthermore, ammonium inputs on coastal systems from treated effluent discharge are enriched in ^{15}N compared to nitrate (Savage, 2005). Despite the growing application of isotopes in various contexts, their use in intertidal ecosystems remains limited, presenting new challenges and opportunities for future research. Stable isotopes can improve understanding of how populations and communities respond to habitat stressors, including urbanization, as suggested in studies on ecological and physiological impacts of urban development on freshwater fishes (Burbank et al., 2022). It should be noted that individual physiological status also influences $\delta^{13}C$ and $\delta^{15}N$ values, and consequently trophic metrics, via metabolic fractionations, making this interpretation complex and requiring careful consideration (Gorokhova, 2017; Karlson et al., 2018). Thus, integrating stable isotopes with other biochemical tracers, such as fatty acids, enhances the ability to trace carbon sources and assess the nutritional quality of organic matter in aquatic food webs (Bergamino and Richoux, 2015; Twining et al., 2020). This multi-isotope and multi-tracer approach improves understanding of complex food web dynamics and ecological processes in coastal environments. Experimental studies may further enhance the interpretation of stable isotope data. For example, manipulating the presence or absence of an invasive species may provide insights into trophic shifts of native species in response to invasions. Since stable isotopes only reveal energy flow and offer limited information regarding functional relationships, such as predator abundance controls, experimental manipulations may provide complementary data (Layman et al., 2011).

Citation and influence of key studies

Stable isotope ratios offer a valuable tool for tracing protein pathways and understanding trophic relationships, with studies varying widely in focus and methodology. For example, Kang et al. (1999) examined nutrient dynamics in muddy sandflats by identifying food sources for suspension-feeding bivalves, while Ince et al. (2007) highlighted the role of marine macrophytes in enhancing sandy beach fauna by providing both food and habitat. Miura et al. (2006) combined stable isotope analysis with parasitological approaches to investigate ecological niche differentiation, providing insights into host-parasite interactions. Foundational studies, such as Melville and Connolly (2003), applied spatial isotope analysis to elucidate primary nutritional sources for fish, and Hentschel (1998) revealed ontogenetic diet shifts in deposit-feeding polychaetes via intraspecific $\delta^{13}C$ variations. These studies have established key ecological frameworks and methodologies that have informed and expanded subsequent research in coastal benthic food webs.

A significant proportion of these studies focus on defining food sources across a variety of species, including filter feeders, nematodes, amphipods, and fish, advancing knowledge on trophic structures in unconsolidated intertidal food webs. Typically, the isotopic composition of terrestrial organic matter (OM) differs from that of marine OM (Lamb et al., 2006). Studies on sandy beaches confirm that these environments receive diverse food sources, including terrestrial inputs, freshwater discharges, macro- and microalgal production, and coastal phytoplankton. Most research targets macrobenthic species, although meiobenthic fauna has also been studied. For example, Riera et al. (1996) and Couch (1989) examined meiobenthos, with Riera highlighting the importance of microphytobenthos as a primary carbon source for tidal flat nematodes. Seasonal variability in isotopic composition was another focus; Kang et al. (1999) found that seasonal shifts in primary producer availability significantly affected suspension-feeding bivalves. However, studies on higher trophic levels, including nekton and vertebrates, remain limited. Melville and Connolly (2003) made significant contributions by identifying key food sources—such as microphytobenthos, seagrass epiphytes, and detritus—across multiple locations, demonstrating spatial variation in food sources for fish consumers. These foundational analyses promote the understanding of fundamental ecological mechanisms in unconsolidated intertidal ecosystems, advancing research in this domain.

Limitations of the study

Our study, based solely on Scopus, has limitations related to data omissions, including important research not indexed in Scopus, studies published in non-English journals, and non-peer-reviewed works such as theses and technical reports. This may lead to underrepresentation of certain regions or emerging fields. Additionally, biases toward certain taxa and ecosystems are possible, with sandy beaches and mudflats receiving more attention than other unconsolidated intertidal habitats. Ambiguities in defining environments, such as mangroves associated with mudflats, further complicates the inclusion of relevant studies and may exclude research within the scope of our analysis. These factors suggest a need for future research to address underrepresented taxa and environments and to expand beyond a single database.

CONCLUSION

The increasing number of publications and authors in stable isotope ecology indicate a growing interest in understanding coastal ecosystems, particularly unconsolidated sediment environments such as sandy beaches and mudflats. Established methodologies, including isotopic mixing models, have driven the field toward greater specialization. Looking forward, combining stable isotope analysis with other techniques like eDNA and fatty acid profiling could open new research avenues, offering more comprehensive insights into ecosystem processes and their response to environmental changes.

The predominance of studies focusing on seasonal dynamics and meso-scale spatial resolutions reflects the naturally dynamic behavior of coastal ecosystems. However, there is a clear gap in long-term interannual studies and large-scale spatial replication, which limits our understanding of ecosystem stability and change. Future research should prioritize long-term monitoring programs that capture seasonal and interannual variability, providing a clearer picture of ecosystem responses to climatic and anthropogenic pressures, as well as a broader spatial representation across multiple sites and regions.

Stable isotope records offer valuable insights into shifts in ecological interactions under climate change, particularly regarding species' dietary adaptations and nutrient sources. However, few studies fully exploited the potential of isotopic analysis for long-term monitoring, limiting our ability to track these changes over extended periods. Expanding the use of long-term stable isotope records could greatly improve our understanding and prediction of ecosystem responses to climate change, facilitating improved management strategies for ecosystems affected by environmental stressors such as rising temperatures, ocean acidification, and habitat loss.

The geographic distribution of stable isotope research remains uneven, with most studies originating from countries like France, United States, and Australia, while other regions, particularly developing countries, are underrepresented. This disparity is further exacerbated by fragmented collaboration networks, often hindered by linguistic and institutional barriers. Future efforts should focus on fostering more inclusive and equitable international collaboration, especially involving regions facing pressing ecological challenges, to promote a more balanced distribution of scientific knowledge and resources.

Carbon and nitrogen isotopes remain the primary tools in stable isotope ecology due to their essential role in tracing nutrient flows and unraveling food web interactions in coastal environments. However, other isotopes, such as sulfur and hydrogen, remain underutilized despite their potential to provide complementary ecological insights. Future research should encourage a broader application of these lesser-used isotopes to enhance the depth of ecological understanding. Moreover, integrating stable isotope data with trophic models like Ecopath could improve food web representation and ecosystem management, especially in coastal regions where anthropogenic impacts are significant.

Mudflats have received more attention than sandy beaches in stable isotope studies, likely due to their more complex biogeochemical processes. Research is also concentrated in the Atlantic Ocean, particularly the Northeastern Atlantic, reflecting the historical development of marine science in this region. This geographic imbalance highlights the need for more research in underrepresented ecosystems and ocean basins, such as the Pacific and Indian Oceans. Broadening the geographical scope of stable isotope studies could provide a more comprehensive understanding of coastal ecosystems globally, addressing regional differences in biogeochemical processes and ecosystem services.

Stable isotope analysis, traditionally used to study nutrient cycling and food web dynamics, is increasingly recognized for its potential in emerging ecological contexts, including climate change resilience. Integrating stable isotopes with methods such as eDNA and fatty acid profiling can provide more nuanced insights into ecological responses to environmental stressors. Future research should explore these approaches, offering new perspectives on ecosystem functioning and adaptability under changing environmental conditions and anthropogenic pressures.

Collaboration is essential for advancing stable isotope ecology, particularly by integrating isotopic data with other ecological models and frameworks. International and multidisciplinary collaborations can better address global ecological challenges and advance ecosystem science. Future studies should emphasize multi-scalar and experimental research designs, combining stable isotope analysis with trophic modeling and ecosystem monitoring to enhance the understanding, management, and conservation of coastal ecosystems.

AI use disclosure

Artificial intelligence (ChatGPT, OpenAI) was used exclusively to refine the English language of this manuscript. The content was carefully reviewed by the authors to ensure consistency and correctness, and the authors are fully responsible for the final version of the manuscript.

Data availability statement

Whole dataset of documents is available as supplementary material at Zenodo.

Supplementary material

Supplementary material is available at Zenodo.

Supplementary Material 1, including the whole dataset of documents, and Supplementary Material 2, including additional figures: https://doi.org/10.5281/zenodo.13920415

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Author contributions

N.S.: Conceptualization; Investigation; Formal Analysis; Writing – original draft; Writing – review & editing.

L.B.: Investigation; Writing – original draft; Writing – review & editing.

D.L.: Conceptualization; Investigation; Writing – original draft; Writing – review & editing; Supervision.

Conflict of interest

The authors declare no competing interests.

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