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FORAMINIFERAL RESEARCH IN THE BRAZILIAN COASTAL ZONE: A REVIEW OF ITS SCIENTIFIC TRAJECTORY SUPPORTED BY BIBLIOMETRIC ANALYSIS (2000–2025)

PESQUISA SOBRE FORAMINÍFEROS NA ZONA COSTEIRA BRASILEIRA: REVISÃO DA SUA TRAJETÓRIA CIENTÍFICA APOIADA EM ANÁLISE BIBLIOMÉTRICA (2000–2025)

INVESTIGACIÓN SOBRE FORAMINÍFEROS EN LA ZONA COSTERA BRASILEÑA: REVISIÓN DE SU TRAYECTORIA CIENTÍFICA APOYADA EN ANÁLISIS BIBLIOMÉTRICO (2000–2025)

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ABSTRACT

Benthic foraminifera are widely used as bioindicators in Brazilian coastal ecosystems, but the trajectory of this research field had not been assessed specifically for the coastal zone after 2019. This review examined the trajectory of scientific production on foraminifera in the Brazilian coastal zone between 2000 and 2025, combining full-text reading with bibliometric tools (Bibliometrix/Biblioshiny and VOSviewer) to characterize the temporal, thematic, institutional, and collaborative evolution of the studies. A Scopus search of titles, abstracts and keywords ("Foraminifera" AND "Brazil"), carried out in January–February 2026, retrieved 418 records; after screening by period, document type, language and theme, 83 records remained, and 52 articles (2001–2024) formed the final corpus. Output was low and irregular in the first decade (14 articles in 2001–2010) and increased to 23 articles in 2011–2020 and 15 in 2021–2025, with 25 articles (48%) published between 2018 and 2024. Environmental characterization predominated in 2001–2010 (42.9%), whereas environmental quality (40.0%) and bioindication (26.7%) predominated in 2021–2025; interdisciplinary studies rose from 7.1% to 20.0%. Keyword co-occurrence revealed a stable core (foraminifera, Brazil, coastal zone) and recent terms linked to environmental monitoring, ecological quality status and geochemistry. Institutional occurrences were concentrated in southeastern universities (UERJ, UNIRIO, USP, UFRJ and UFF), with UFBA as the main northeastern hub, and collaboration with the University of Urbino intensified from the mid-2010s. The field has expanded without abandoning its descriptive base, incorporating biotic indices and multiproxy approaches. Because the analysis relies on a single database, two languages and a small corpus, the trends should be read as indicative; broader database coverage and regional calibration of foraminiferal indices are priorities.

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Keywords: Benthic Foraminifera. Estuarine Ecosystems. Bioindication. Collaboration Networks. Bibliometric Analysis.

RESUMO
Os foraminíferos bentônicos são amplamente empregados como bioindicadores em ecossistemas costeiros brasileiros, mas a trajetória desse campo de pesquisa ainda não havia sido avaliada especificamente para a zona costeira após 2019. Esta revisão examinou a produção científica sobre foraminíferos na zona costeira brasileira entre 2000 e 2025, combinando leitura integral dos artigos com ferramentas bibliométricas (Bibliometrix/Biblioshiny e VOSviewer) para caracterizar a evolução temporal, temática, institucional e colaborativa dos estudos. A busca na base Scopus, realizada em janeiro–fevereiro de 2026 nos campos de título, resumo e palavras-chave ("Foraminifera" AND "Brazil"), recuperou 418 registros; após a triagem por período, tipo de documento, idioma e tema, restaram 83 registros, e 52 artigos (2001–2024) compuseram o corpus final. A produção foi baixa e irregular na primeira década (14 artigos em 2001–2010) e aumentou para 23 artigos em 2011–2020 e 15 em 2021–2025, com 25 artigos (48%) publicados entre 2018 e 2024. A caracterização ambiental predominou em 2001–2010 (42,9%), ao passo que a qualidade ambiental (40,0%) e a bioindicação (26,7%) predominaram em 2021–2025; os estudos interdisciplinares passaram de 7,1% para 20,0%. A coocorrência de palavras-chave revelou um núcleo estável (foraminíferos, Brasil, zona costeira) e termos recentes ligados a monitoramento ambiental, status de qualidade ecológica e geoquímica. As ocorrências institucionais concentraram-se em universidades do Sudeste (UERJ, UNIRIO, USP, UFRJ e UFF), com a UFBA como principal polo do Nordeste, e a colaboração com a Universidade de Urbino intensificou-se a partir de meados da década de 2010. O campo expandiu-se, sem abandonar sua base descritiva, ao incorporar índices bióticos e abordagens multiproxy. Como a análise se apoia em uma única base, dois idiomas e um corpus pequeno, as tendências devem ser lidas como indicativas; a ampliação das bases consultadas e a calibração regional dos índices de foraminíferos são prioridades.

Palavras-chave: Foraminíferos Bentônicos. Ecossistemas Estuarinos. Bioindicação. Redes de Colaboração. Análise Bibliométrica.

RESUMEN
Los foraminíferos bentónicos se utilizan ampliamente como bioindicadores en los ecosistemas costeros brasileños, pero la trayectoria de este campo de investigación aún no se había evaluado específicamente para la zona costera después de 2019. Esta revisión examinó la producción científica sobre foraminíferos en la zona costera brasileña entre 2000 y 2025, combinando la lectura completa de los artículos con herramientas bibliométricas (Bibliometrix/Biblioshiny y VOSviewer) para caracterizar la evolución temporal, temática, institucional y colaborativa de los estudios. La búsqueda en Scopus, realizada en enero–febrero de 2026 en los campos de título, resumen y palabras clave ("Foraminifera" AND "Brazil"), recuperó 418 registros; tras el cribado por período, tipo de documento, idioma y tema, quedaron 83 registros, y 52 artículos (2001–2024) conformaron el corpus final. La producción fue baja e irregular en la primera década (14 artículos en 2001–2010) y aumentó a 23 artículos en 2011–2020 y 15 en 2021–2025, con 25 artículos (48%) publicados entre 2018 y 2024. La caracterización ambiental predominó en 2001–2010 (42,9%), mientras que la calidad ambiental (40,0%) y la bioindicación (26,7%) predominaron en 2021–2025; los estudios interdisciplinarios pasaron del 7,1% al 20,0%. La coocurrencia de palabras clave reveló un núcleo estable (foraminíferos, Brasil, zona costera) y términos recientes vinculados

al monitoreo ambiental, al estado de calidad ecológica y a la geoquímica. Las ocurrencias institucionales se concentraron en universidades del Sudeste (UERJ, UNIRIO, USP, UFRJ y UFF), con la UFBA como principal polo del Nordeste, y la colaboración con la Universidad de Urbino se intensificó a partir de mediados de la década de 2010. El campo se amplió sin abandonar su base descriptiva, incorporando índices bióticos y enfoques multiproxy. Como el análisis se basa en una sola base de datos, dos idiomas y un corpus pequeño, las tendencias deben interpretarse como indicativas; la ampliación de las bases consultadas y la calibración regional de los índices de foraminíferos son prioridades.

Palabras clave: Foraminíferos Bentónicos. Ecosistemas Estuarinos. Bioindicación. Redes de Colaboración. Análisis Bibliométrico.

1 INTRODUCTION

Benthic foraminifera have been widely used in studies of environmental characterization, bioindication, and environmental quality assessment across different Brazilian coastal ecosystems (Eichler et al., 2001; Duleba; Debenay, 2003; Vilela et al., 2004; Burone; Pires-Vanin, 2006; Batista; Vilela; Koutsoukos, 2007; Semensatto Junior et al., 2009; Teodoro; Duleba; Gubitoso, 2011; Machado; Araújo, 2014; Alves Martins et al., 2020; Oliveira et al., 2022; Nunes et al., 2023).

This widespread use is related to several characteristics of these organisms, including rapid reproduction rates, high abundance in samples, a high degree of ecological specialization, and strong responsiveness to different sources and types of pollution. They also exhibit clear assemblage succession along environmental stress gradients (Dimiza et al., 2016; Alves; Petsch; Barros, 2020; Parent et al., 2021), thereby contributing to the description and characterization of environmental conditions and, in some cases, enabling the prediction of environmental scenarios in which they occur.

Considering the scientific literature on foraminiferal research in the Brazilian coastal zone, it is essential to characterize this body of research by identifying researcher networks and their collaborations, changes in scientific and social research patterns, and the spatial distribution of studies and their approaches across the country (Mathankar, 2018). At the global scale, recent bibliometric assessments have shown that foraminiferal research has grown steadily over two centuries and that environmental biomonitoring has become one of its main domains, with benthic foraminifera increasingly used as bioindicators of marine pollution (Abd Malek; Frontalini, 2024; Amao; Kaminski; Frontalini, 2025). How this international movement has been incorporated into the study of the Brazilian coast, however, has not been examined in detail.

A previous scientometric analysis of foraminiferal research in Brazil (Lima Vieira et al., 2021) identified a strong concentration of scientific output in the Southeast region and highlighted research gaps along the northern and northeastern margins of the country. However, that study included publications only through 2019 and addressed Brazilian foraminiferal research broadly, without restricting the analysis to coastal ecosystems and environmental applications. In this context, the present study extends the temporal scope through 2025 and focuses specifically on scientific research related to Brazilian coastal environments, seeking to understand the evolution of research approaches, collaboration networks, and the incorporation of applications related to environmental monitoring,

ecological quality assessment, and interdisciplinary approaches.

The general objective of this study is to analyze the trajectory of foraminiferal research focused on the Brazilian coastal zone between 2000 and 2025, combining a literature review based on full-text reading with complementary bibliometric techniques. Specifically, the study sought to:

1.1 SPECIFIC OBJECTIVES

a) quantify and characterize the temporal distribution of the scientific output during the study period;

b) classify the studies into thematic categories and identify how these categories changed across three periods (2000–2010, 2011–2020 and 2021–2025);

c) describe the conceptual structure of the field and its temporal evolution through author-keyword co-occurrence;

d) identify the most productive researchers and their coauthorship networks;

e) identify the national and international institutions where this research is conducted and contextualize them with the research groups registered in Brazil.

2 THEORETICAL BACKGROUND

2.1 BENTHIC FORAMINIFERA AS INDICATORS OF COASTAL ENVIRONMENTAL QUALITY

The use of benthic foraminifera to diagnose coastal environmental conditions rests on a well-established body of evidence. Early syntheses showed that estuarine assemblages respond to organic enrichment, trace metals and hydrocarbons through changes in density, diversity, dominance of opportunistic taxa and frequency of test abnormalities (Alve, 1995; Frontalini; Coccioni, 2011). In Brazil, comparable responses were documented early on, including a higher frequency of test abnormalities in polluted than in non-polluted environments (Geslin et al., 2002). Because their tests are preserved in the sediment, foraminiferal assemblages can be used both to assess present conditions and to reconstruct reference states prior to anthropogenic impact, an advantage over most macrofaunal indicators (Alve, 1995; Bouchet et al., 2012).

Over the last fifteen years, this descriptive knowledge has been converted into standardized assessment tools. The FOBIMO initiative proposed a common protocol for soft-bottom monitoring studies (Schönfeld et al., 2012), and biotic indices based on diversity,

sensitivity or stress-tolerant taxa — such as exp(H'bc), Foram-AMBI, the Foram Stress Index and the FoRAM Index for reef systems — were developed and tested mainly in European and Mediterranean transitional waters (Hallock et al., 2003; Bouchet et al., 2012; Alve et al., 2016; Dimiza et al., 2016; Bouchet; Goberville; Frontalini, 2018; Jorissen et al., 2018). These indices depend on assigning species to ecological groups of sensitivity to organic enrichment, an assignment that is region-specific and still incomplete for tropical and subtropical faunas (Bouchet et al., 2021; O'Brien; Polovodova Asteman; Bouchet, 2021). Comparative applications have shown that different indices may yield divergent classifications and that their performance depends on local calibration (El Kateb et al., 2020; Parent et al., 2021). More recently, environmental DNA metabarcoding has been combined with morphological analysis, offering faster and taxonomically broader assessments (Pawlowski et al., 2014; Frontalini et al., 2020). These developments provide the conceptual framework against which the trajectory of Brazilian coastal research is interpreted in this review.

2.2 BIBLIOMETRIC ANALYSIS AS A COMPLEMENT TO LITERATURE REVIEWS

As a means of characterizing research, literature reviews are crucial for synthesizing findings from previous studies, enabling the effective use of existing knowledge, the advancement of research lines, and the generation of evidence-based insights that support professional judgment and expertise. Within this context, bibliometric techniques can be employed as complementary tools to quantify and visualize temporal, institutional, collaborative, and thematic patterns in the selected literature (Aria; Cuccurullo, 2017; Moraes; Kafure, 2020).

Science-mapping techniques — performance analysis, coauthorship networks and co-word analysis — allow the intellectual and social structure of a field to be described from bibliographic metadata, but their interpretation requires a defined research question, transparent data cleaning and awareness of the coverage of the databases used (Zupic; Čater, 2015; Donthu et al., 2021). Software such as VOSviewer and Bibliometrix/Biblioshiny has made these analyses accessible and has been applied to coauthorship networks and Scopus-based literature maps in different fields (Van Eck; Waltman, 2010; Lima, 2011; Aria; Cuccurullo, 2017; Oliveira et al., 2023; Campina López; Lorca Marin; De Las Heras Pérez, 2024). In thematic reviews with relatively small corpora, as in the present study, bibliometric indicators are most informative when combined with qualitative reading of the articles, because counts alone do not capture the objectives and approaches of each study.

3 MATERIALS AND METHODS

3.1 SEARCH STRATEGY AND DATABASE

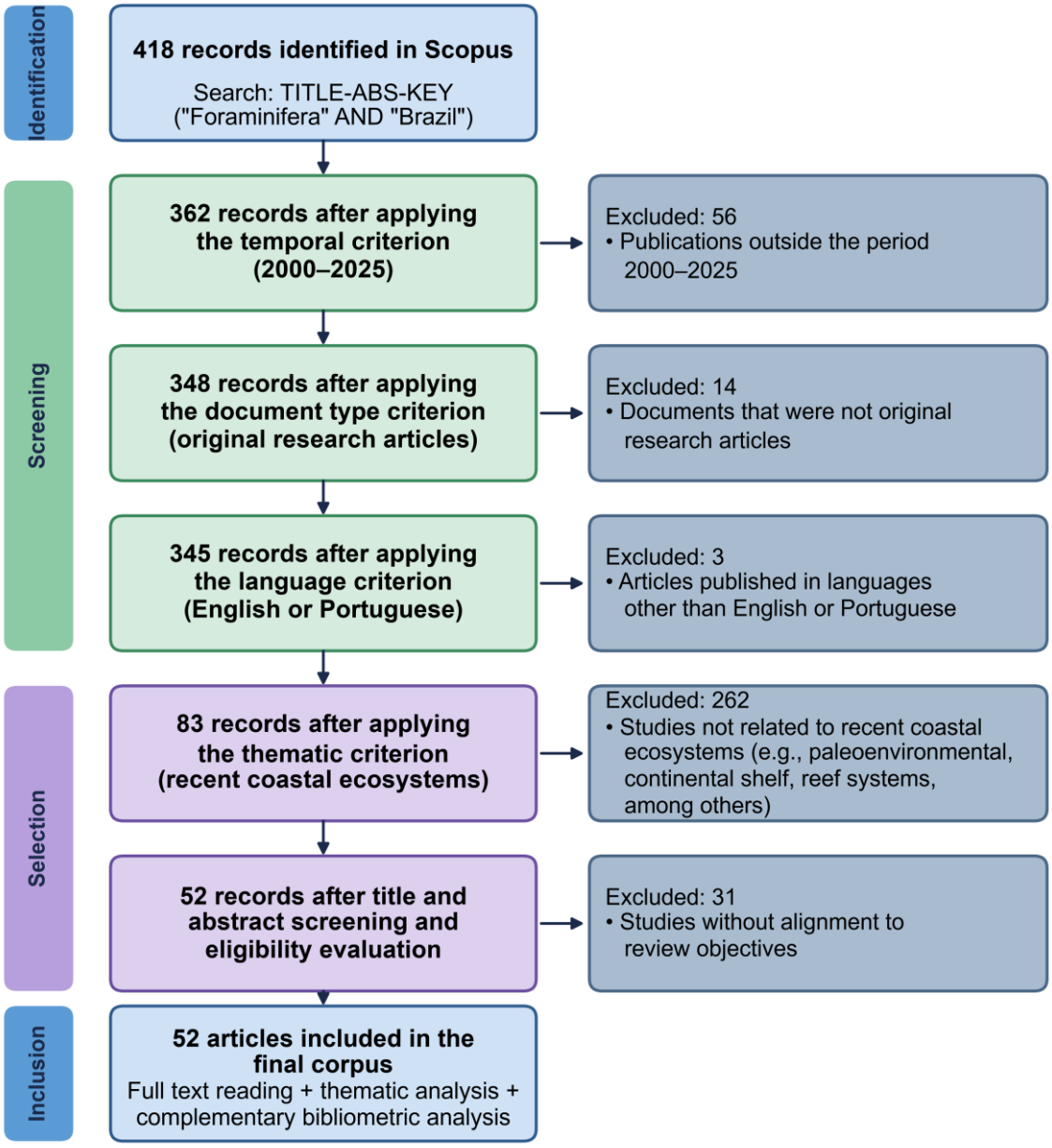
This study is a literature review that uses bibliometric analysis as a complementary tool. The bibliographic search, illustrated in Figure 1, was conducted in the Scopus database using the *TITLE-ABS-KEY* field, with the complete search string "Foraminifera" AND "Brazil". Data collection was conducted between January and February 2026, and the metadata were exported in CSV (comma-separated values) format. The search initially retrieved 418 documents, with no duplicate records identified throughout the entire export process. Scopus was the only database consulted; Web of Science, SciELO and other regional sources were not searched, and the exact date of the final export was not reported. The implications of these choices are discussed in Section 4.6.

3.2 SELECTION AND ELIGIBILITY CRITERIA

A total of 418 records were identified and successively screened according to temporal (2000–2025), document type (original research articles), language (English or Portuguese), and thematic (recent coastal ecosystems) criteria, resulting in 83 studies. Figure 1 shows that 56 records were excluded for falling outside the 2000–2025 period, 14 because they were not original research articles, three because they were published in languages other than English or Portuguese, and 262 because they did not address recent coastal ecosystems (e.g., paleoenvironmental, continental shelf or reef-system studies). Following title and abstract screening and eligibility assessment, 31 further records were excluded for lack of alignment with the review objectives, and 52 articles were selected to constitute the final corpus. Full-text availability was not used as an eligibility criterion. The included studies were subjected to full-text reading and thematic classification, while bibliometric analysis was employed as a complementary tool to characterize temporal, institutional, collaborative, and term co-occurrence patterns. The flowchart follows the identification–screening–inclusion logic of the PRISMA 2020 statement (Page et al., 2021); the number of reviewers involved in the screening and the procedure for resolving disagreements were not reported.

Figure 1

Flowchart of the identification, screening, selection and inclusion stages of the studies included in the review of scientific research on foraminifera in the Brazilian coastal zone; search in Scopus covering 2000–2025 and final corpus of 52 articles.



Source: Authors' elaboration.

3.3 THEMATIC CLASSIFICATION

For the temporal analysis, the study period was divided into three intervals: 2000–2010, 2011–2020, and 2021–2025. For each period, the authors classified the articles into five thematic categories based on full-text reading. Classification was based on the central research question or the most relevant stated objective of each study. Each article was

therefore assigned to a single category, and no measure of agreement between classifiers was reported. The categories and their respective operational definitions are presented below:

Species inventory: studies primarily focused on documenting taxonomic composition and distribution.

Environmental characterization: studies relating foraminiferal assemblages to physicochemical, sedimentological, or hydrodynamic variables without an explicit biomonitoring framework.

Bioindication: explicit use of foraminiferal assemblages or species as indicators of a specific environmental stressor.

Environmental quality: application of an explicit ecological quality assessment, index, or framework.

Interdisciplinary approaches: studies integrating foraminifera with two or more analytical domains or independent sources of evidence, such as sedimentological, geochemical, microbiological, molecular, or hydrodynamic data.

3.4 COMPLEMENTARY BIBLIOMETRIC ANALYSIS

Bibliometric analysis was employed as a complementary procedure to the literature review and was not intended to replace the qualitative analysis of the selected studies. Whereas the review enabled characterization of the objectives and research approaches of the studies through full-text reading, bibliometric tools were used to identify temporal, institutional, collaboration, and term co-occurrence patterns. For this purpose, VOSviewer (version 1.6.19) and Bibliometrix/Biblioshiny were used based on metadata exported from Scopus in CSV format, including the following fields: titles, authors, publication year, keywords, affiliations, and abstracts (Van Eck; Waltman, 2010; Aria; Cuccurullo, 2017).

The analytical procedures comprised five stages: (i) Temporal production, involving the construction of an annual time series (2000–2025) to identify publication trends; (ii) Author analysis, involving the identification of the most productive researchers; (iii) Institutional analysis, involving the mapping of institutions with the highest publication output and the geographic distribution of scientific production; (iv) Coauthorship networks, involving the construction of author collaboration networks from the same metadata; and (v) Thematic content analysis, based on the co-occurrence of *author keywords*, using a minimum threshold of five occurrences after data cleaning, removal of generic terms, synonymization, and

application of a customized thesaurus. The original description of the methods assigns the coauthorship network to VOSviewer, whereas the network figure presented in Section 4.4 was exported from Biblioshiny; the counting method, the clustering algorithm, the minimum number of documents per author and the thesaurus file were not reported. Institutional occurrences correspond to the number of author–affiliation records per institution, not to the number of distinct articles.

In addition, research groups registered in the Directory of Research Groups in Brazil of the National Council for Scientific and Technological Development (DGP/CNPq) whose activities relate to foraminifera were surveyed for institutional contextualization only; this survey was not part of the bibliographic corpus, and its search terms and consultation date were not reported.

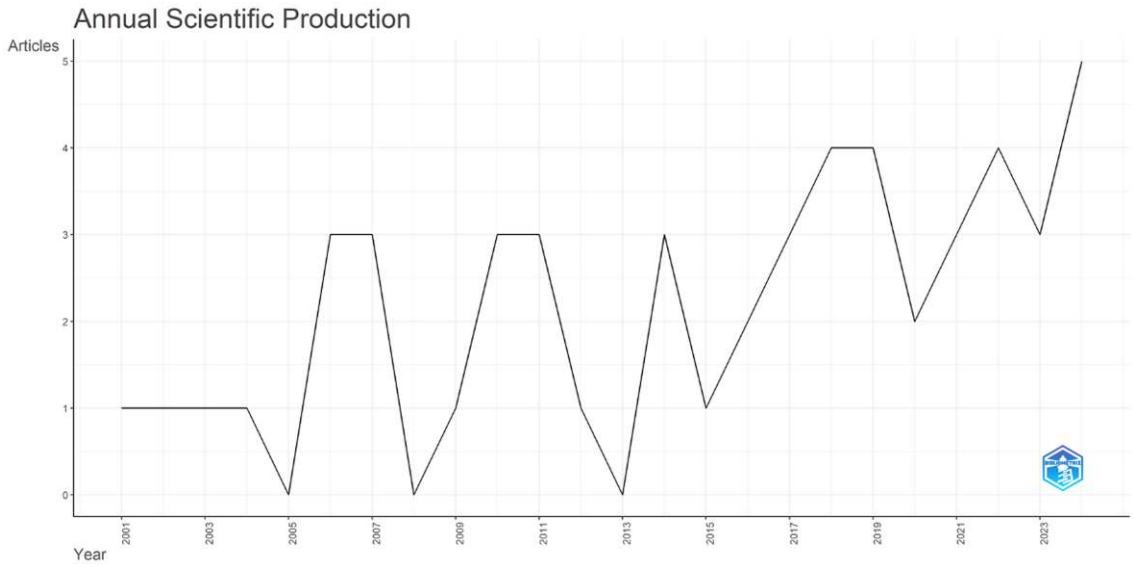
4 RESULTS AND DISCUSSION

4.1 TEMPORAL DISTRIBUTION OF SCIENTIFIC PRODUCTION

The annual distribution of scientific research on foraminifera in the Brazilian coastal zone between 2000 and 2025 is presented in Figure 2. No eligible publications were identified for 2000, 2005, 2008, 2013, or 2025. Application of the eligibility criteria resulted in a final corpus of 52 articles published between 2001 and 2024. The selected studies were individually systematized according to year, title, authors, ecosystem, study location, state/region, objective, thematic category, main institutions/affiliations, keywords, and document type.

Figure 2

Annual number of articles on foraminifera in the Brazilian coastal zone included in the final corpus (n = 52), 2001–2024; no eligible article was retrieved for 2000 or 2025.



Source: Authors' elaboration with Biblioshiny, based on Scopus data.

The series in Figure 2 shows annual outputs between zero and five articles. Between 2001 and 2004 one article per year was recorded, followed by alternating peaks of three articles (2006–2007, 2010–2011 and 2014) and years without eligible publications (2005, 2008 and 2013). From 2017 onward the series no longer returns to zero, and the seven years from 2018 to 2024 concentrate 25 of the 52 articles (48.1%), with the maximum of five articles in 2024. In terms of mean annual output, the corpus grew from 1.4 articles per year in 2000–2010 to 2.3 in 2011–2020 and 3.0 in 2021–2025 (3.75 if only the four years with eligible articles, 2021–2024, are considered).

This increase is consistent with the global growth of foraminiferal studies applied to environmental biomonitoring (Abd Malek; Frontalini, 2024; Amao; Kaminski; Frontalini, 2025), but the absolute numbers remain small: a difference of one or two articles changes the annual pattern considerably, so the series is better interpreted as a shift in level than as a continuous trend. The absence of eligible articles in 2025 should also be read with caution, because the data were collected in January–February 2026 and recent publications may not yet have been fully indexed.

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4.2 THEMATIC CATEGORIES ACROSS PERIODS

The distribution of the five thematic categories by period is summarized in Table 1, and their relative proportions are illustrated in Figure 3.

Table 1

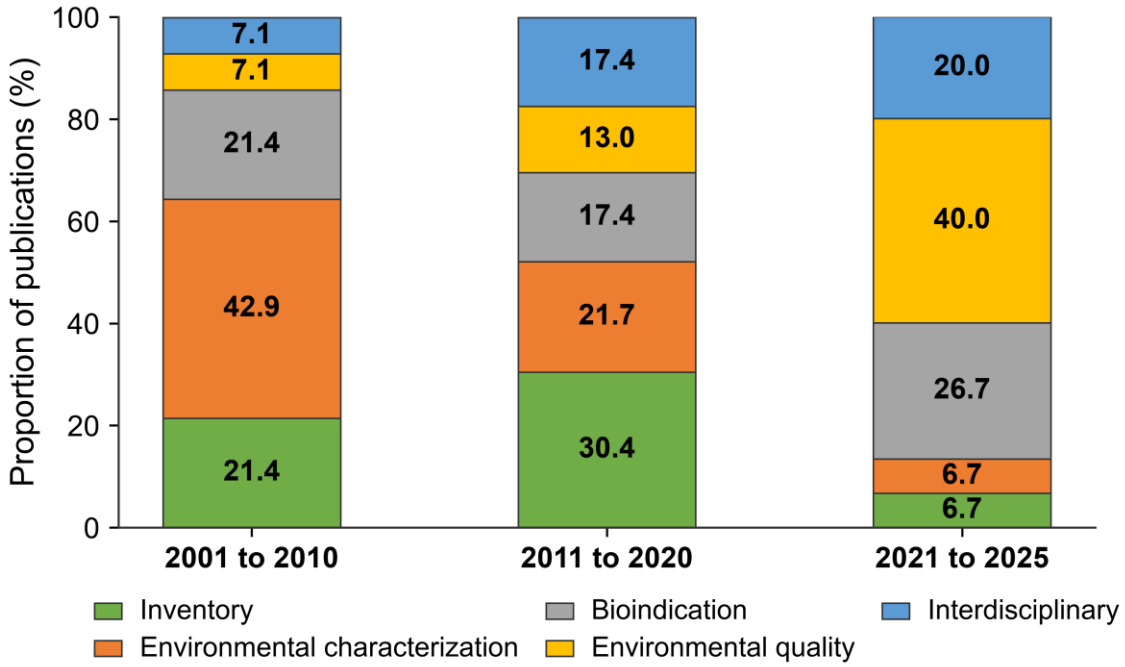
Distribution of the 52 articles of the corpus among the five thematic categories, by period, in absolute (n) and percentage (%) values.

Period	Inventory		Environmental characterization		Bioindication		Environmental quality		Interdisciplinary		Total
	n	%	n	%	n	%	n	%	n	%	
2000–2010	3	21.4	6	42.9	3	21.4	1	7.1	1	7.1	**14**
2011–2020	7	30.4	5	21.7	4	17.4	3	13.0	4	17.4	**23**
2021–2025	1	6.7	1	6.7	4	26.7	6	40.0	3	20.0	**15**
Total	**11**	21.2	**12**	23.1	**11**	21.2	**10**	19.2	**8**	15.4	**52**

Source: Authors' elaboration based on full-text reading of the corpus. Percentages refer to the total of each period; in the Total row they refer to the 52 articles (calculated in this revision). As no eligible article was published in 2000 or 2025, the first and last periods effectively correspond to 2001–2010 and 2021–2024.

Figure 3

Percentage of each thematic category (inventory, environmental characterization, bioindication, environmental quality and interdisciplinary) by period. The label "2001 to 2010" corresponds to the 2000–2010 period of Table 1, since no eligible article was published in 2000.



Source: Authors' elaboration.

Between 2001 and 2010, 14 articles were identified, with a predominance of environmental characterization studies, which accounted for 42.9% of the publications during this period. These studies primarily addressed the distribution of foraminiferal assemblages and their relationships with environmental, sedimentological, and hydrodynamic variables (Duleba; Debenay, 2003; Burone; Pires-Vanin, 2006; Batista; Vilela; Koutsoukos, 2007; Burone et al., 2007; Santos et al., 2007; Laut et al., 2010). Taxonomic inventories and bioindication studies accounted for 21.4% of the studies each, whereas environmental quality and interdisciplinary approaches each represented 7.1% (Eichler et al., 2001; Geslin et al., 2002; Vilela et al., 2004; Eichler et al., 2006; Zerfass et al., 2006; Semensatto Junior et al., 2009; Bomfim; Vilela; Guedes, 2010; Souza et al., 2010). Collectively, these studies contributed to documenting the diversity, distribution, and variability of foraminiferal assemblages across different coastal environments, establishing a foundation for subsequent environmental interpretations.

Between 2011 and 2020, 23 articles were recorded, revealing a more balanced distribution among the thematic categories. Taxonomic inventories remained the most frequent category, accounting for 30.4% of the studies, followed by environmental characterization (21.7%), bioindication (17.4%), interdisciplinary approaches (17.4%), and environmental quality (13.0%). Studies during this period expanded the integration of assemblage composition with different environmental variables, incorporating sedimentological, geochemical, and biological information more frequently (Laut et al., 2011; Teodoro; Duleba; Gubitoso, 2011; Donnici et al., 2012; Clemente et al., 2015; Laut et al., 2016; Vilela; Macedo; Baptista Neto, 2017; Belart et al., 2018; Duleba et al., 2018; Alves Martins et al., 2020). Thus, alongside the continued development of taxonomic inventories and environmental characterization studies, there was a growing emphasis on bioindication and the assessment of environmental changes.

From 2021 to 2025, 15 articles were identified, with environmental quality emerging as the predominant category, accounting for 40.0% of the studies, followed by bioindication (26.7%) and interdisciplinary approaches (20.0%). Taxonomic inventories and environmental characterization each represented 6.7% of the studies during this period. Recent studies include applications of ecological quality indices, assessments of the effects of anthropogenic interventions, and integration of multiple sources of environmental information (Eichler; Barker; Miranda, 2021; Laut et al., 2021; Oliveira et al., 2022; Raposo et al., 2022; Filippos et al., 2023; Nunes et al., 2023; Sousa et al., 2023; Alves Martins et al., 2024; Damasceno et

al., 2024; Fontana et al., 2024; Laut et al., 2024).

Considering the three periods together, the results indicate an expansion of the thematic scope rather than a linear replacement of previous approaches. Taxonomic inventories and environmental characterization studies remain important for establishing patterns of assemblage composition, distribution, and relationships with environmental gradients. However, their relative contribution decreases in the most recent period, while contributions related to bioindication, environmental quality assessment, and the integration of different sources of evidence increase. Although the interdisciplinary category accounts for 8 of the 52 articles in the corpus, it also shows a proportional increase across the periods, rising from 7.1% to 17.4% and 20.0%, respectively. Overall, these results indicate a diversification of research questions and greater integration between assemblage analysis and the assessment of environmental conditions, while maintaining faunal characterization as a fundamental component of coastal research in Brazil.

The rise of the environmental quality category after 2020 reflects the arrival in Brazil of the index-based framework developed internationally. Studies in Guanabara Bay, Sepetiba Bay and the Cigarras beach applied living benthic foraminiferal indices to classify ecological quality status (Alves Martins et al., 2020; Filippos et al., 2023; Nunes et al., 2023; Alves Martins et al., 2024), and Damasceno et al. (2024) combined metabarcoding with morphology in Sepetiba Bay, following an approach previously tested in Europe (Pawlowski et al., 2014; Frontalini et al., 2020). Because the sensitivity assignments underlying Foram-AMBI and related indices were calibrated mainly with European and Mediterranean faunas (Alve et al., 2016; Jorissen et al., 2018; Bouchet et al., 2021), their transfer to tropical and subtropical Brazilian estuaries requires regional calibration, a need also identified in other non-European settings (El Kateb et al., 2020; O'Brien; Polovodova Asteman; Bouchet, 2021). In this sense, the inventories and environmental characterization studies of the first two periods are not merely precursors: they provide the species–environment information from which regional ecological groups can be derived. It should be noted that the proportions in Table 1 are based on 14 to 23 articles per period, so that a single article changes a category share by about 4 to 7 percentage points.

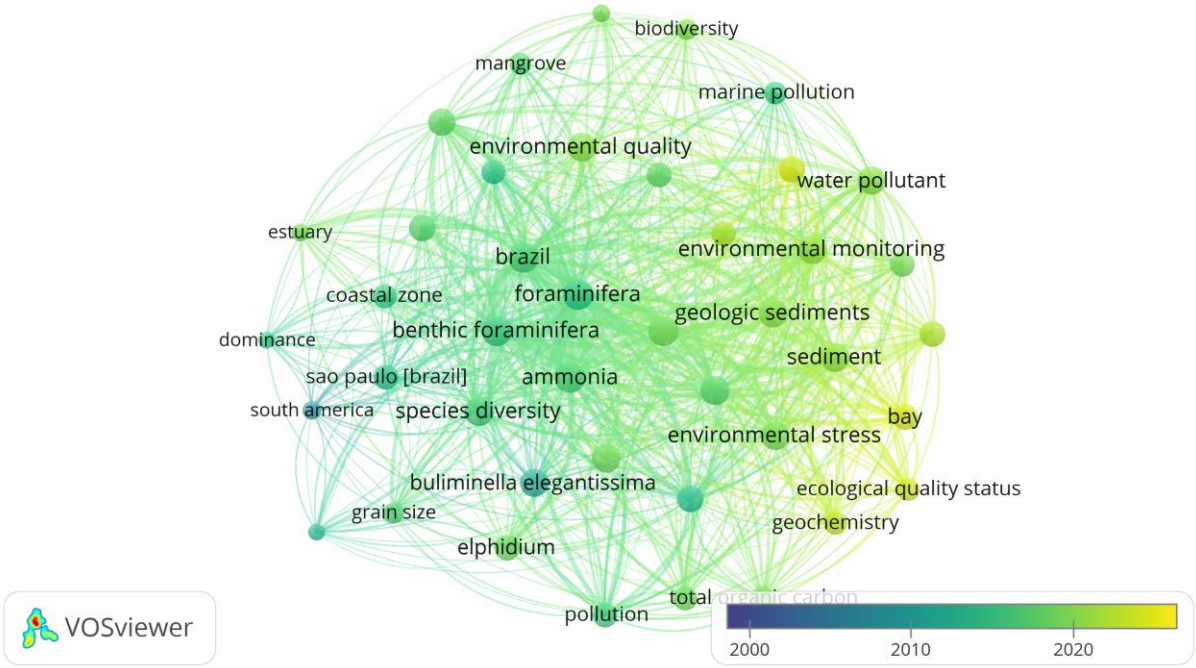
4.3 KEYWORD CO-OCCURRENCE NETWORK AND THEMATIC TRAJECTORY

The keyword co-occurrence network (Figure 4), combined with the thematic classification of the studies, provides a complementary perspective on the trajectory of

foraminiferal research in the Brazilian coastal zone. While the thematic classification highlights the distribution of research approaches across the periods analyzed, the co-occurrence network identifies the main concepts associated with the corpus and the relationships among them.

Figure 4

Temporal overlay of the keyword co-occurrence network (minimum of five occurrences) showing the conceptual structure and temporal evolution of Brazilian coastal foraminiferal research, 2001–2024. Node size reflects the number of occurrences, links represent co-occurrence, and the color scale indicates the average publication year of the documents in which each term appears.



Source: Authors' elaboration with VOSviewer, based on Scopus data.

The structure of the network presents a core centered on *foraminifera*, *benthic foraminifera*, *Brazil*, and *coastal zone*, connected to terms related to biodiversity, coastal environments, sediments, pollution, environmental stress, and ecological quality assessment (Burone; Pires-Vanin, 2006; Zerfass et al., 2006; Donnici et al., 2012; Raposo et al., 2022; Alves Martins et al., 2024).

The temporal dimension incorporated into the map adds a dynamic perspective to this structure. Terms associated with earlier publications are primarily related to species diversity,

distribution, and environmental characterization, reflecting the predominantly taxonomic and ecological nature of a substantial proportion of the initial studies (Duleba; Debenay, 2003; Burone; Pires-Vanin, 2006; Zerfass et al., 2006; Semensatto Junior et al., 2009). Terms associated with more recent periods include *environmental quality*, *environmental monitoring*, *water pollutant*, *ecological quality status*, and *geochemistry* (Alves Martins et al., 2020; Raposo et al., 2022; Nunes et al., 2023; Alves Martins et al., 2024; Damasceno et al., 2024). Thus, the network makes it possible to observe the reconfiguration of the conceptual relationships that have structured the scientific field over time.

Two features of the map require caution. First, several labels — such as *geologic sediments*, *water pollutant*, *species diversity* and *sao paulo [brazil]* — correspond to controlled-vocabulary terms typical of the index keywords assigned by Scopus, which suggests that the map may combine author and index keywords; this should be confirmed against the exported data. Second, the label *ammonia* may refer either to the foraminiferal genus *Ammonia* or to the chemical compound, since the indexing vocabulary does not distinguish them; together with *Elphidium* and *Buliminella elegantissima*, it indicates that genus and species names also structure part of the network.

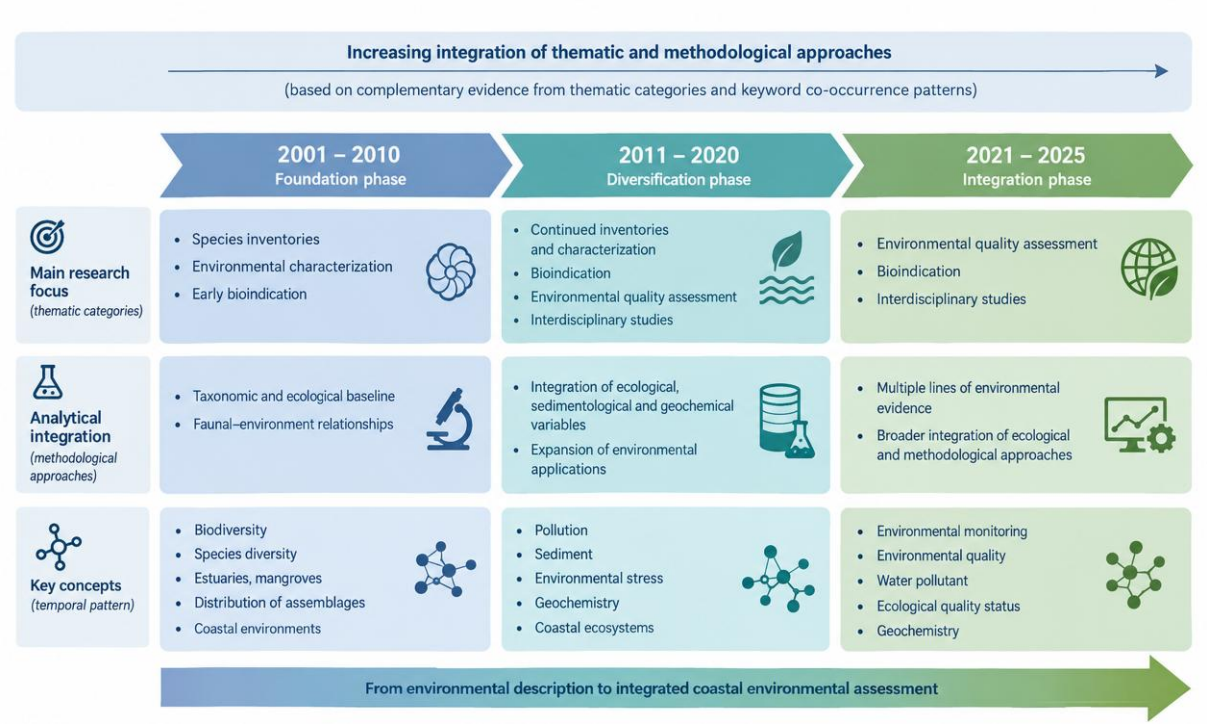
Accordingly, the evidence points to a process of expansion of the field in which taxonomy and ecology remain foundational elements, while concepts associated with environmental monitoring, environmental quality, and geochemistry have assumed increasingly prominent positions in the thematic organization of recent research (Teodoro; Duleba; Gubitoso, 2011; Duleba et al., 2018; Azevedo et al., 2022; Damasceno et al., 2024).

The shift observed in the literature does not simply represent the replacement of one topic by another, but rather the progressive incorporation of new concepts and connections into an established knowledge base, in which ecological and faunal approaches continue to be employed in recent environmental assessment studies (Eichler; Barker; Miranda, 2021; Laut et al., 2021).

Figure 5 synthesizes this trajectory, demonstrating that it does not represent a linear evolution of research, but rather the progressive expansion and integration of the approaches employed to investigate foraminifera in Brazilian coastal environments. The synthesis organizes the three periods as foundation (2001–2010), diversification (2011–2020) and integration (2021–2025) phases, crossing the dominant thematic categories with the analytical approaches and the key concepts identified in the co-occurrence network.

Figure 5

Conceptual synthesis of the main thematic and methodological transitions identified in Brazilian coastal foraminiferal research between 2001 and 2025, based on the temporal distribution of thematic categories and keyword co-occurrence patterns.



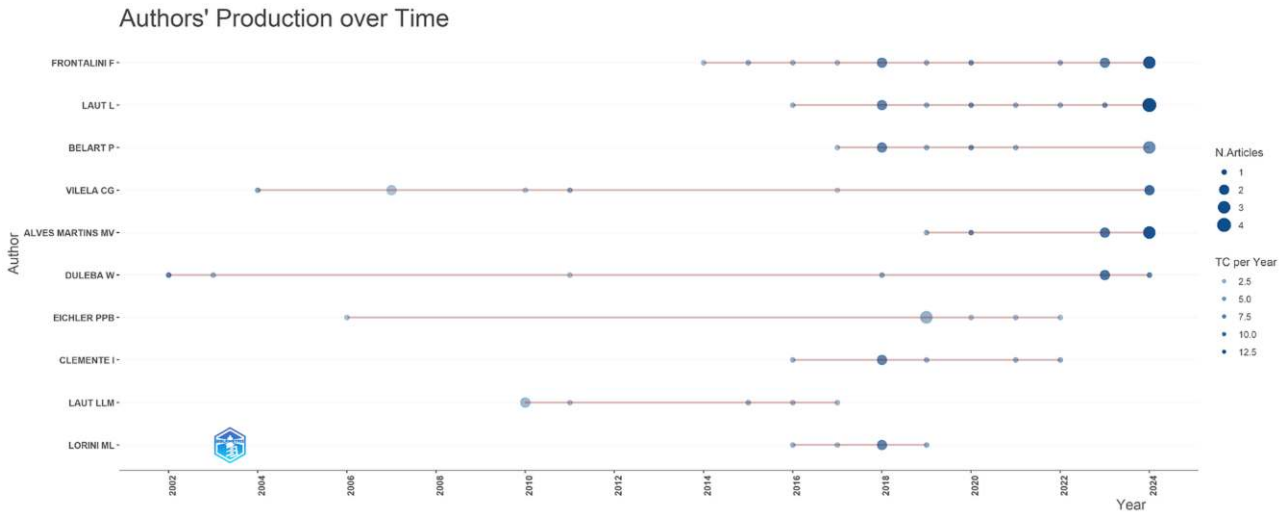
Source: Authors' elaboration.

4.4 KEY RESEARCHERS AND COLLABORATION NETWORKS

Figure 6 presents the temporal distribution of the scientific output of the main authors involved in foraminiferal research in the Brazilian coastal zone during the study period. The visualization reveals distinct patterns of productivity over the period analyzed.

Figure 6

Temporal distribution of the scientific output of the ten most productive authors in the corpus on foraminifera in the Brazilian coastal zone, 2001–2024. Circle size indicates the number of articles per year and color intensity the total citations per year (TC per year).



Source: Authors' elaboration with Biblioshiny, based on Scopus data.

The earliest publications, concentrated between 2002 and 2010, are associated with researchers such as Eichler, Vilela, and Duleba, who are among the prominent researchers in this field in Brazil, with contributions that were sporadic but consistent throughout the first decade of the 21st century. During this period, their research primarily addressed assemblage characterization, foraminiferal distribution, and relationships between faunal associations and environmental conditions, including studies of hydrodynamic circulation and assemblage preservation (Duleba; Debenay, 2003; Vilela et al., 2004; Eichler et al., 2006, 2008).

From the mid-2010s onward — Frontalini from 2014, Laut from 2016 and Belart from 2017, according to Figure 6 — greater participation by these researchers can be observed, with a higher concentration of publications between 2018 and 2024. These researchers account for a substantial proportion of the publications during this period, reflecting the intensification of research activities and the consolidation of national and international collaborative networks, particularly Italian–Brazilian collaborations. This body of research includes studies focused on environmental characterization, bioindication, ecological quality assessment, and the investigation of environmental changes in coastal systems (Clemente et al., 2015; Belart et al., 2017, 2018, 2019; Alves Martins et al., 2020; Raposo et al., 2022; Damasceno et al., 2024).

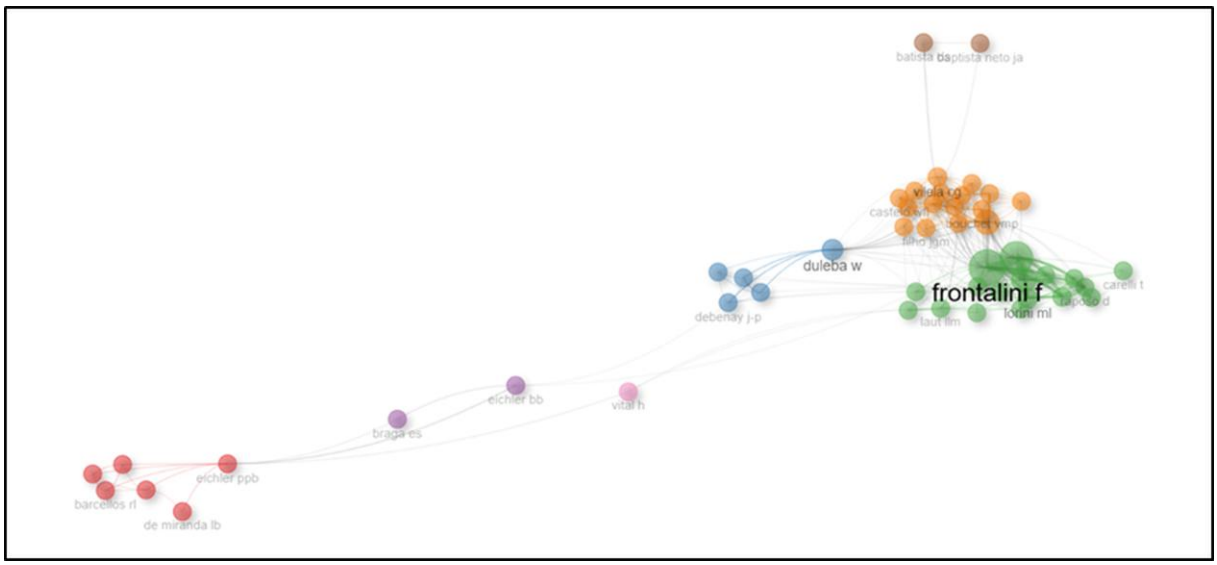
The contributions of researchers such as Alves Martins, Clemente, and Lorini are also

noteworthy, although their publication output is less concentrated than that of the three aforementioned researchers. Their research has predominantly been published since 2016, aligning with the broader growth of the field and incorporating studies related to environmental quality assessment, bioindication, and the integration of different approaches to the analysis of coastal environments (Clemente et al., 2015; Alves Martins et al., 2020; Damasceno et al., 2024). Figure 6 also reveals a limitation of author-level indicators: the same researcher appears under two name variants (*Laut L* and *Laut LLM*), and earlier articles by Alves Martins were indexed under *Martins* (e.g., Martins et al., 2016), so individual outputs are fragmented and probably underestimated. Errors of this kind in database author identifiers are well documented (Kawashima; Tomizawa, 2015).

Researcher collaboration networks (Figure 7) represent coauthorship relationships established among the authors in the corpus, allowing the structure and connectivity of scientific collaborations during the study period to be visualized (Aria; Cuccurullo, 2017). The network analysis identified five clusters, and their interpretation considered the main author associations and, as a complementary approach, the predominant themes addressed in their publications.

Figure 7

Coauthorship network among researchers on foraminifera in the Brazilian coastal zone (2001–2024). Node colors indicate clusters: green (international collaboration core), orange (Brazilian collaboration core), blue (environmental and geochemical studies), purple (regional core) and red (regional or independent core); a two-author group (brown) and an isolated node (pink) are also shown.



Source: Authors' elaboration with Biblioshiny, based on Scopus data.

Green cluster – international collaboration core: This cluster primarily comprises Brazilian and international researchers connected to Frontalini, with contributions to studies on benthic bioindication, environmental quality, ecology, and foraminiferal taphonomy. The configuration of this cluster highlights the presence of an Italian–Brazilian collaboration network and its connections with different researchers within the corpus. The participation of researchers affiliated with the *Università degli Studi di Urbino Carlo Bo* is particularly evident in publications produced from the second half of the 2010s onward (Clemente et al., 2015; Raposo et al., 2016, 2018, 2022; Belart et al., 2017, 2018, 2019; Alves Martins et al., 2020; Damasceno et al., 2024).

Orange cluster – Brazilian collaboration core: This cluster is characterized by multiple connections among researchers who have been consistently involved in studies of coastal foraminifera in Brazil. Prominent authors include Vilela, Eichler, Laut, and Belart. Connections between this cluster and the green cluster highlight the integration of researchers associated with national and international networks in studies addressing environmental characterization, bioindication, and impact assessment in coastal environments (Vilela et al., 2004; Eichler et al., 2006; Souza et al., 2010; Belart et al., 2017).

Blue cluster – collaboration core with participation in environmental and geochemical studies: This cluster comprises researchers whose publications employ different approaches to investigating environmental conditions in coastal systems. Duleba and Debenay are particularly prominent, with contributions related to the ecology, morphology, preservation, and environmental applications of foraminifera. Connections between this cluster and the other groups indicate its integration into different coauthorship networks and its participation in studies relating foraminiferal assemblages to the environmental characteristics of coastal systems.

Purple cluster – regional collaboration core: This cluster comprises researchers primarily associated with studies conducted in different Brazilian coastal environments. Its lower density of connections with the more central clusters in the network indicates a more localized collaboration structure. This finding demonstrates the coexistence of regional networks alongside the national and international collaboration cores identified in the analysis.

Red cluster – regional or independent core: This cluster comprises a group with a lower frequency of coauthorship relationships with the more densely connected cores of the network. Its more peripheral position should not be interpreted as indicating lower scientific relevance, but rather as a characteristic of the collaboration structure established within the corpus. The presence of this cluster highlights the diversity of researchers and institutional contexts involved in scientific research on foraminifera along the Brazilian coast.

Besides these five clusters, Figure 7 shows a two-author group and an isolated node that were not interpreted, and the dense overlap of nodes in the green and orange clusters prevents most author names from being read. The overall structure — two dense, interconnected cores linked to peripheral regional groups by few bridging authors — is typical of fields in which a small number of research groups concentrate equipment, students and international partnerships, and it implies that the continuity of research lines depends on a limited number of senior researchers.

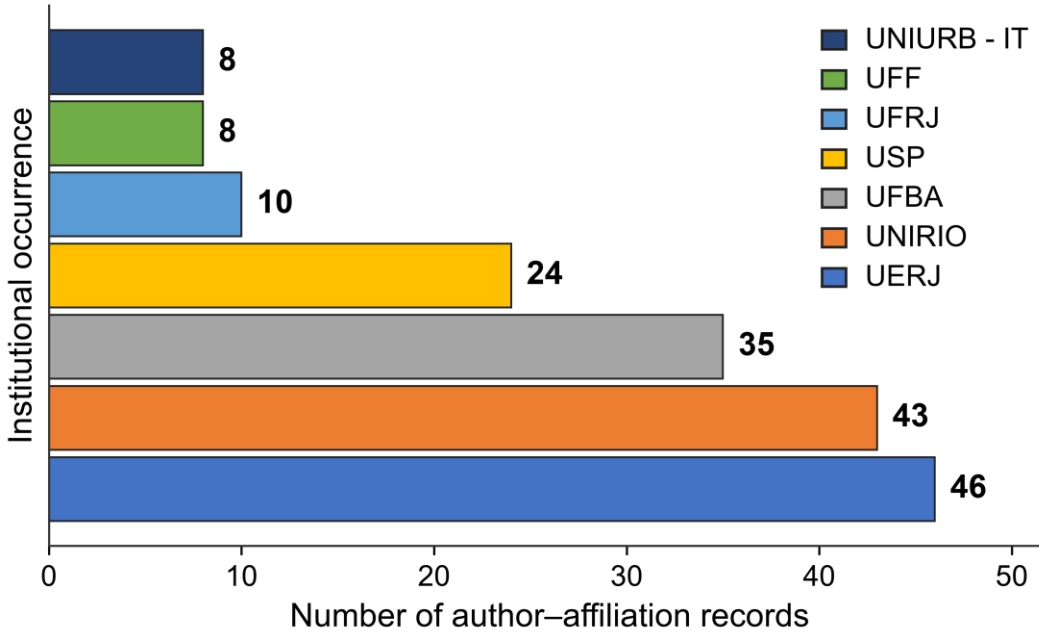
4.5 MAJOR INSTITUTIONS AND RESEARCH GROUPS

The analysis of institutional participation (Figure 8) reveals that public universities in southeastern Brazil account for the largest share of institutional occurrences in studies of foraminifera in the coastal zone. In Rio de Janeiro, these include UERJ (46), UNIRIO (43), UFRJ (10), and UFF (8), while USP (24) represents the main institution in São Paulo. This

pattern reflects the historical concentration of research groups in the region, consistent with the regional asymmetry previously reported for Brazilian foraminiferal research (Lima Vieira et al., 2021). The sum of institutional occurrences exceeds the 52 articles in the corpus because some studies include multiple institutional affiliations. Together, the five southeastern institutions account for 131 of the 174 occurrences (75.3%) of the seven institutions shown in Figure 8.

Figure 8

Institutional occurrences (author–affiliation records) of the seven most frequent institutions among the 52 articles included in the review of scientific research on foraminifera in the Brazilian coastal zone, 2001–2024. UERJ = Rio de Janeiro State University; UNIRIO = Federal University of the State of Rio de Janeiro; UFBA = Federal University of Bahia; USP = University of São Paulo; UFRJ = Federal University of Rio de Janeiro; UFF = Fluminense Federal University; UNIURB-IT = University of Urbino Carlo Bo, Italy.



Source: Authors' elaboration based on Scopus data.

However, the substantial participation of UFBA (35) is noteworthy, positioning Bahia as an important regional research hub identified in the corpus. These findings indicate that, although the Southeast maintains the highest institutional concentration, Bahia represents a significant regional center of scientific production within the corpus. The presence of the *Università degli Studi di Urbino Carlo Bo*, with eight institutional occurrences, highlights its participation in the international collaboration networks associated with the corpus,

particularly in studies conducted in collaboration with Brazilian researchers (Leipnitz et al., 2014; Martins et al., 2016; Raposo et al., 2016, 2018; Nunes et al., 2023).

The geographic pattern of institutions is mirrored by the distribution of study areas. Coastal systems of Rio de Janeiro, especially Guanabara Bay, and of São Paulo and the southern states have been studied repeatedly (Bonetti; Eichler; Debenay, 2001; Figueira; Vilela; Baptista Neto, 2007; Vilela et al., 2011; Eichler et al., 2012; Díaz; Rodrigues; Eichler, 2014; Leipnitz et al., 2014; Passos; Kukimodo; Semensatto, 2017; Eichler et al., 2020), whereas studies in the North and Northeast are fewer and more dispersed, although they cover estuaries, deltas, mangroves and beachrocks with distinctive faunas (Laut et al., 2010; Souza et al., 2010; Machado; Araújo, 2014; Araújo et al., 2018; Farias et al., 2019; Oliveira et al., 2019; Laut et al., 2021; Sariaslan; Langer, 2021; Azevedo et al., 2022; Bérgamo; Oliveira; Rosa Filho, 2022; Oliveira et al., 2022). This asymmetry is not exclusive to foraminifera: knowledge of marine and coastal biodiversity and of estuarine benthic communities in Brazil is also unevenly distributed along the coast, and the macrotidal, river-dominated estuaries of the North and Northeast differ markedly from the microtidal systems of the Southeast and South (Amaral; Jablonski, 2005; Bernardino et al., 2015, 2016). Because estuarine benthic assemblages respond differently to climate and environmental drivers across Brazilian marine ecoregions (Bernardino et al., 2015), indices calibrated in southeastern bays cannot be assumed to be valid along the entire coast.

A complementary survey was conducted of research groups registered in the DGP/CNPq database whose research activities are related to foraminifera, including recent and/or paleoenvironmental studies (Table 2). However, this survey was not part of the bibliographic corpus analyzed and was used exclusively for institutional contextualization. The first groups, established between 2002 and 2003 (UnB and UFRGS), focused on microfossil taxonomy and stratigraphic and paleoceanographic applications. Between 2006 and 2009, research groups were established in Pará, Bahia, and Sergipe, incorporating environmental and paleoecological approaches. From 2011 onward, new groups (UNIRIO, UFPE, UFSC, and UERJ) introduced integrative research lines combining micropaleontology with geochemistry, sedimentology, and multiple environmental indicators.

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Table 2

Main research groups and lines of research on foraminifera registered in the Directory of Research Groups in Brazil (DGP/CNPq), in chronological order of establishment.

Research group	Year of establishment	Institution	Research lines
Micropaleontology and Paleoenvironment	2002	UnB – University of Brasília	Microfossil taxonomy
Micropaleontology	2003	UFRGS – Federal University of Rio Grande do Sul	Micropaleontological analysis applied to the stratigraphy and paleoceanography of southern Brazil
Paleontology and Paleobiology of Paleoinvertebrates and Phanerozoic Microfossils of Brazil	2006	UFPA – Federal University of Pará	Study of Tertiary fossil foraminifera, focusing on biostratigraphy and paleoenvironmental evolution
Foraminifera Study Group (GEF)	2007	UFBA – Federal University of Bahia	Focus on biostratigraphy and coastal paleoenvironments; taxonomic and environmental studies using foraminifera and ostracods. Research on bioindicators and biogenic composition of surface and estuarine sediments. Relationship between foraminiferal distribution and environmental parameters; paleoecological reconstruction. Investigation of taphonomic processes and microfossil preservation in coastal and estuarine environments.
Paleontology and Biostratigraphy of the Marine Cretaceous	2009	UFS – Federal University of Sergipe	Biostratigraphic study of Cretaceous marine fossils; includes correlations with foraminifera in coastal sedimentary contexts. Emphasis on marine paleontology and paleoecological reconstruction using fossil foraminifera.
Integrated Studies in Geosciences	2011	UNIRIO – Federal University of the State of Rio de Janeiro	Applied micropaleontology, coastal sedimentation, and marine bioindicators.
Marine Sedimentology and Geochemistry Study Group (GSGMar)	2014	UFPE – Federal University of Pernambuco	Integrates micropaleontology, geochemistry, and sedimentology; use of foraminifera in paleoenvironmental reconstructions.
Geological Oceanography Group (GOG)	2017	UFSC – Federal University of Santa Catarina	Study of paleoceanographic and climatic changes based

Research group	Year of establishment	Institution	Research lines
			on microfossils, including foraminifera.
MIAP Research Group – Multiple Environmental and Paleoenvironmental Indicators	2019	UERJ – Rio de Janeiro State University	Interdisciplinary approach integrating foraminifera, ostracods, and other environmental and paleoenvironmental indicators.

Source: Authors' survey of the DGP/CNPq database (consultation date not reported).

The chronology in Table 2 helps to explain the temporal and institutional patterns of the corpus: the groups established at UNIRIO in 2011 and at UERJ in 2019, which combine micropaleontology with bioindication and multiple environmental indicators, coincide with the institutions that lead the occurrences in Figure 8 and with the growth of environmental quality and interdisciplinary studies after 2011, while the UFBA group, established in 2007, underpins the regional hub identified in Bahia. Conversely, USP, UFRJ and UFF, which appear in Figure 8, are not represented in Table 2, possibly because their registered groups do not mention foraminifera in their names or research lines; this indicates that the survey is illustrative rather than exhaustive.

4.6 LIMITATIONS AND IMPLICATIONS

The results should be interpreted in light of several limitations. First, database coverage: the corpus was retrieved from Scopus only, and the coverage of this database is uneven across disciplines, countries and journals (Mongeon; Paul-Hus, 2016). Brazilian geoscience journals in which a substantial part of the regional foraminiferal literature is published may be indexed only partially or only from certain years, so early and regional output — particularly from the North and Northeast — is probably underestimated; searches in Web of Science, SciELO and national repositories would be needed to confirm the patterns. Second, language: only articles in English or Portuguese were included, and both major databases are biased towards English-language publications (Vera-Baceta; Thelwall; Kousha, 2019); three articles in other languages were excluded, and Portuguese-language articles in non-indexed journals were not captured at all. Third, the temporal window: the absence of eligible articles in 2000 and 2025 means that the corpus effectively covers 2001–2024, and the most recent year is affected by indexing delays.

Fourth, the search string ("Foraminifera" AND "Brazil" in titles, abstracts and keywords) may have missed studies that refer only to the state, bay or estuary studied, or that use

derived terms such as *foraminiferal*; the thematic criterion, in turn, excluded reef systems and the continental shelf, although a few studies cited as part of the coastal literature address a reef environment or shelf water masses (Batista; Vilela; Koutsoukos, 2007; Eichler et al., 2008), which indicates that the boundary between categories required judgment. Fifth, author and institution indicators are sensitive to name variants and affiliation formats (Kawashima; Tomizawa, 2015), and the thematic classification assigned each article to a single category without a reported agreement test. Finally, the small size of the corpus (52 articles) limits the statistical robustness of temporal comparisons.

Despite these limitations, the review provides an updated and coastal-focused synthesis that complements the national scientometric survey of foraminiferal research in Brazil (Lima Vieira et al., 2021) and the global bibliometric assessments of foraminiferal research (Abd Malek; Frontalini, 2024; Amao; Kaminski; Frontalini, 2025). Its main contributions are: (i) empirical, by documenting the transition from descriptive studies to index-based environmental quality assessment in Brazilian coastal systems; (ii) territorial, by quantifying the institutional concentration in the Southeast and identifying Bahia as a regional hub; and (iii) for management and monitoring, by indicating that the operational use of foraminifera in Brazilian coastal monitoring programs depends on regional calibration of ecological groups, adoption of standardized sampling protocols (Schönfeld et al., 2012) and expansion of research effort in the North and Northeast.

5 CONCLUSION

The literature review, supported by bibliometric tools, enabled the characterization of the trajectory of foraminiferal research in the Brazilian coastal zone between 2000 and 2025 across temporal, thematic, institutional, and collaborative dimensions. The final corpus comprised 52 articles, whose temporal distribution indicates an increase in scientific output over the study period, particularly in the most recent years.

The thematic classification revealed changes in the relative composition of research. Between 2001 and 2010, environmental characterization studies predominated, followed by taxonomic inventories and bioindication, whereas the 2011–2020 period showed greater diversification among inventory, environmental characterization, bioindication, environmental quality, and interdisciplinary approaches. Between 2021 and 2025, studies addressing environmental quality, bioindication, and interdisciplinary integration accounted for a larger proportion of the corpus. These findings indicate not a linear replacement of previous

approaches, but rather an expansion of the scope of foraminiferal applications in the investigation of coastal environments.

The keyword co-occurrence analysis reinforced this interpretation by demonstrating the persistence of concepts associated with taxonomy, diversity, and ecology, alongside the increasing presence of terms related to environmental monitoring, environmental quality, pollution, and geochemistry. The coauthorship network, in turn, revealed the coexistence of national research cores and international connections, with particular emphasis on the participation of institutions from southeastern Brazil and collaborations involving the *Università degli Studi di Urbino Carlo Bo*.

Overall, the results indicate that Brazilian research on coastal foraminifera has undergone a process of thematic, methodological, and collaborative diversification, while maintaining faunal characterization as a fundamental basis and expanding its applications in bioindication and environmental assessment. Regional asymmetries nevertheless persist, highlighting the need to expand research coverage across different sectors of the Brazilian coast and strengthen national collaboration networks.

These conclusions are restricted to the articles indexed in Scopus, published in English or Portuguese and retrieved by the search string adopted, and should be considered indicative given the size of the corpus. Future reviews should combine multiple databases, include regional journals and repositories, and assess how biotic indices and molecular tools are being calibrated for Brazilian coastal faunas, which is the condition for foraminifera to become routine instruments in the monitoring and management of the Brazilian coastal zone.

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