



# Fractal analysis of otolith contours and shape for marine fish species discrimination

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## Abstract

Otolith morphology serves as a powerful tool for species discrimination and ecological studies, yet traditional morphometric approaches often overlook the functionally significant complexity of otolith contours. Here, we apply fractal geometry to analyse 184 sagittal otoliths from five ecologically diverse marine fishes (*Merluccius merluccius*, *Phycis blennoides*, *Gadus morhua*, *Lophius piscatorius*, and *Trachinus araneus*) collected from NW Atlantic and Mediterranean waters. Using the Guida et al. (2020) method, we quantified three morphological descriptors: fractal dimension (Df, roughness), circularity (M), and angularity (m). Our results revealed distinct species-specific morpho-spaces. The demersal *M. merluccius* exhibited the highest contour complexity (Df = 1.06 ± 0.03) and elongation (M = 0.64 ± 0.03), while the other species displayed smoother, more circular otoliths. The strong negative Df-M correlation reflects an evolutionary trade-off between sensory adaptation and hydrodynamic efficiency. These findings establish fractal otolith analysis as an effective taxonomic tool and a window into ecological specialization, with direct applications for fisheries management, paleo-ecological reconstructions, and climate change monitoring in marine ecosystems.

**Keywords:** Otolith morphology, fractal geometry, species discrimination, fisheries science, *Merluccius merluccius*, contour analysis, ecomorphology

## Introduction

Otolith morphology has emerged as a critical tool in marine ecology, offering insights into species identification, habitat use, and evolutionary adaptation. These biomineralized structures, located in the inner ears of teleost fishes, serve dual functions as both mechanical sensors for balance/hearing (Popper & Fay, 2011) and environmental chronometers, recording growth patterns and chemical signatures throughout a fish's life history (Panella, 1971; Morales-Nin, 1987; Campana, 2005; Matic-Skoko et al., 2015; Nimesh & Jain, 2018). Their metabolic inertness and species-specific shapes make them particularly valuable for studies ranging from paleoecology to contemporary fisheries management and environmental monitoring (Wright et al., 2002; Hüssy et al., 2020; Manjabacas et al., 2025; Schultz et al., 2024).

Traditional morphometric approaches, relying on linear measurements or elliptic Fourier analysis (Tuset et al., 2008; Manjabacas et al., 2025), have proven effective for gross taxonomic discrimination. However, these methods often fail to capture subtle contour variations that may reflect ecological specialization (Tuset et al., 2008). Recent advances, including the application of fractal geometry, have shown promise in

quantifying these complex patterns to discriminate even cryptic species (Paradis et al., 2021) and are reshaping otolith research (Manjabacas et al., 2025). Fractal analysis addresses this limitation by quantifying the contour morphology across scales through dimensionless descriptors—fractal dimension (Df) for surface roughness, circularity (M) for overall form, and angularity (m) for edge sharpness (Guida et al., 2020). This approach, which has been originally developed for grain morphology characterization in the geoscience field, has demonstrated particularly utility in characterizing habitat-specific adaptations, where benthic species frequently evolve rougher otolith contours for enhanced substrate vibration detection, while pelagic species exhibit smoother profiles potentially optimized for hydrodynamic efficiency (Lombarte & Cruz, 2007; Martinez et al., 2023).

This study applies fractal analysis to 184 sagittal otoliths from five ecologically contrasting species inhabiting NW Atlantic and Mediterranean waters: the predators *Merluccius merluccius* and *Lophius piscatorius*, the benthopelagic *Phycis blennoides*, and the pelagic *Gadus morhua* and *Trachinus araneus* (Froese & Pauly, 2011). We test three hypotheses: (1) fractal parameters discriminate species with greater accuracy than traditional morphometrics, (2) contour complexity correlates with microhabitat use, and (3) the Df-M relationship reflects an evolutionary trade-off between sensory acuity and swimming performance. By establishing standardized protocols for fractal otolith analysis, this work aims to provide fisheries scientists and ecologists with a robust tool for addressing pressing challenges in stock assessment, biodiversity monitoring, and climate change research (Matić-Skoko et al., 2020; Lauchlan et al., 2024).

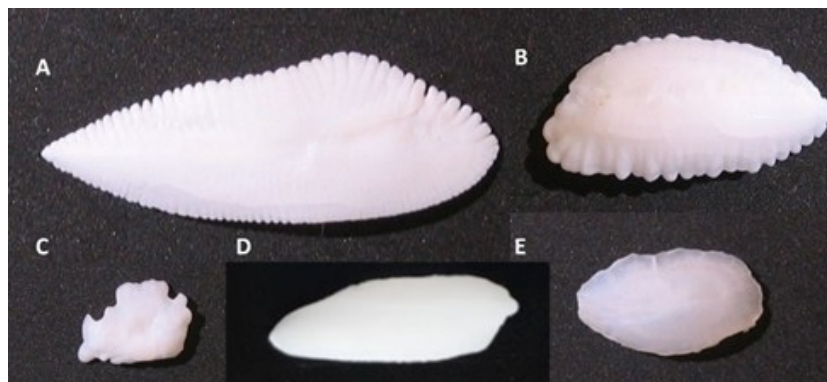
**Methods**

A total of 184 sagitta otoliths were extracted from specimens collected in the NW Atlantic and Mediterranean during 2012–2019 period. The species included in the study were *Merluccius merluccius* (n=38; NWA), *Phycis blennoides* (n=44; Med.), *Gadus morhua* (n=28; NWA), *Lophius piscatorius* (n=36;

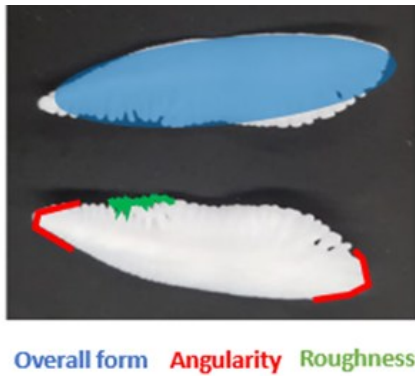
NWA), and *Trachinus araneus* (n=38; Med.) (Figure 1). These otoliths were obtained from fish specimens collected during regular fisheries surveys and commercial fisheries. The collected sagitta otoliths were meticulously cleaned with 70% ethanol to remove any adhering debris or tissues, ensuring a clear view of the contours (Campana, 1992; Secor et al., 1992; Wright et al., 2002). High-resolution digital images of the cleaned otoliths were captured using an advanced imaging system. This imaging process was crucial for obtaining precise and detailed representations of the otolith contours (Table 2).

To achieve the objectives of this study, we conducted a comprehensive morphological analysis of the collected otoliths. The aim was to discriminate species morphology and enable numerical differentiation of species through various morphological descriptors. The digital images of the otoliths were processed using an open-source code (Guida, 2023) specifically designed for applying fractal analysis of contours following Guida et al. (2017; 2020) method (Table 2). Fractal analysis measures how the complexity of a contour changes with the scale of observation. It involves calculating the normalised perimeter  $p/D$  using units  $b/D$  at different resolutions (see Table 2). The interpretation of the  $p/D$  vs  $b/D$  trends allowed for the quantification of relevant morphology descriptors of the objects, facilitating the numerical differentiation of species (M, m,  $\mu$  and Df; Figure 2).

The morphology of an otolith (Figure 1 and Figure 2) can be characterised using three potentially independent parameters. Following Guida et al. (2017; 2020), the morphology descriptors employed for contour and shape analysis are: M, a measure of circularity, quantifying how closely the overall form of an object approaches that of a perfect circle (M=1 corresponds to a perfect circle); m, a measure of angularity, expressing the sharpness of local features (m=0 for a perfect round shape such as a circle; m>0 for increasing angularity). The value of m should be interpreted relative to the characteristic size of the local features: a very sharp but large feature appears less angular than a smaller one with the same edge sharpness;  $\mu$ , a measure of roughness, capturing the



**Figure 1.** Otoliths samples from *Merluccius merluccius* (A) *Gadus morhua* (B), *Lophius piscatorius* (C) *Phycis blennoides* (D) and *Trachinus araneus* (E).



**Figure 2.** Blue: the overall form that characterise its circularity (M); Red: the angularity that characterise the sharpness of the corners (m); Green: the roughness that characterise the surface texture ( $\mu$  or  $Df = \mu + 1$ ).

irregularity of the textural features of otoliths contour ( $m=0$  for a perfectly smooth boundary;  $m>0$  for increasing roughness). The  $m$  descriptor is related to the fractal dimension  $Df$  of the contour by the following relation:  $m=Df+1$ . The fractal dimension describes how a contour path fills a plane. A smooth contour occupies a single geometric dimension ( $Df=1$ , hence  $m=0$ ), whereas a more complex profile, such as a fractal of Koch, exhibits a higher fractal dimension ( $Df \sim 1.262$ ,





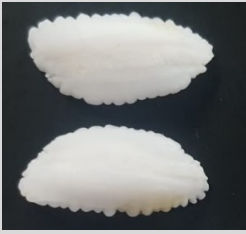
$m=0.262$ ). In the limiting case of an extremely convoluted contour occupying the entire plane,  $Df$  approaches 2 ( $m \sim 1$ ) (Guida et al., 2017; 2020).

**Results**

Visual inspection of otoliths from the five study species revealed distinct morphological patterns (Table 1). *M. merluccius* exhibited pronounced elongation (1) with irregular margins (3), whereas *L. piscatorius* showed nearly circular contours (1) with variable surface texture (3). Intermediate features were observed in *P. blennoides* (elongated with smooth edges) and *T. araneus* (moderately elongated with smooth edges). These qualitative observations were subsequently confirmed through quantitative fractal analysis.

Qualitative observations were consistent with the quantitative measures (Table 2). *M. merluccius* otoliths showed pronounced scalloping and irregular margins, corresponding to high  $Df$  values, whereas *L. piscatorius* specimens displayed symmetrical, rounded contours as predicted by their high  $M$  values. The fractal analysis of 184 otoliths revealed clear morphological differences among the five study species (Figure 3). Quantitatively, *M. merluccius* showed the highest fractal dimension ( $Df = 1.06 \pm 0.03$ ), indicating complex contour roughness, combined with marked

**Table 1.** Preliminary qualitative observation of five species analyzed.

<p><i>Merluccius merluccius</i></p> <ol style="list-style-type: none"> <li>1. great elongation</li> <li>2. variable angularity</li> <li>3. great roughness</li> </ol>		<p><i>Lophius piscatorius</i></p> <ol style="list-style-type: none"> <li>1. no elongation</li> <li>2. variable angularity</li> <li>3. variable roughness</li> </ol>	
<p><i>Phycis blennoides</i></p> <ol style="list-style-type: none"> <li>1. great elongation</li> <li>2. variable angularity</li> <li>3. Smooth</li> </ol>		<p><i>Trachinus araneus</i></p> <ol style="list-style-type: none"> <li>1. medium elongation</li> <li>2. variable angularity</li> <li>3. smooth</li> </ol>	
<p><i>Gadus morhua</i></p> <ol style="list-style-type: none"> <li>1. medium elongation</li> <li>2. variable angularity</li> <li>3. rough</li> </ol>			

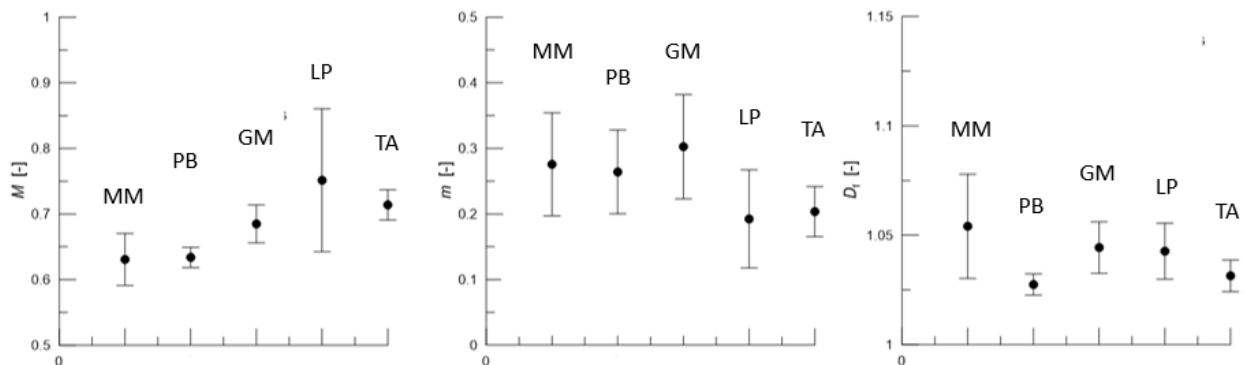
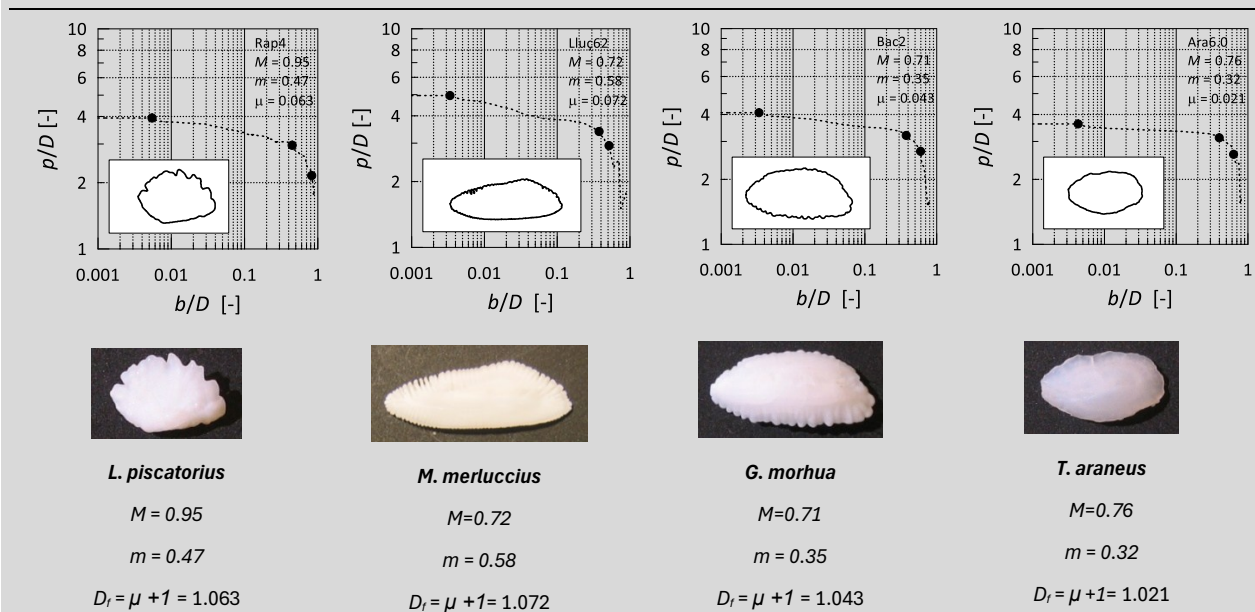
elongation ( $M = 0.64 \pm 0.03$ ). In contrast, *L. piscatorius* displayed near-circular morphologies ( $M = 0.75 \pm 0.10$ ) with intermediate roughness ( $Df = 1.04 \pm 0.02$ ), while benthopelagic *P. blennoides* showed the smoothest profiles ( $Df = 1.03 \pm 0.01$ ) despite an elongation similar to *M. merluccius* ( $M = 0.64 \pm 0.01$ ). Angularity ( $m$ ) values did not show significant interspecific variation, suggesting this parameter may be conserved across ecological niches (Figure 3).

Quantitative assessment of otolith morphology based on univariate analysis of individual parameters ( $M$ ,  $m$ ,  $Df$ ) revealed largely overlapping confidence intervals among species (Figure 3). Although mean values showed observable trends, a one-way ANOVA detected no statistically significant interspecific differences for any isolated parameter ( $\alpha = 0.05$ ). These

results highlight the need for multivariate approaches for effective species discrimination using otolith contour features.

To discriminate among species or populations, the results of the  $Df/M$  morphological descriptors were plotted. Since the descriptors of overall form ( $M$ ) and contour roughness ( $\mu$ ) capture complementary aspects of otoliths morphology, Figure 4 reports the distribution of values in a plot of  $M$  versus  $Df$ , where distinct regions corresponding to each species can be identified. Figure 4 demonstrates clear interspecific segregation in morphospace defined by fractal dimension ( $Df$ ) and overall form ( $M$ ). The negative correlation between the two descriptors suggests a functional trade-off: species with elongated otoliths (e.g., *M. merluccius*;  $Df = 1.06 \pm 0.03$ ) exhibit higher surface complexity, potentially enhancing sound

**Table 2.** Examples of 4 fish species analysed using G. Giulia fractal analysis method. Values of  $M$ ,  $m$ ,  $\mu$  and  $Df$  can be seen for each sample.



**Figure 3.** Trends of the average values of the three morphology descriptors for the sets of otoliths analysed ( $M$ ,  $m$ ,  $Df$ ). *M. merluccius* (MM),  $n=38$ ; *P. blennoides* (PB),  $n=44$ ; *G. morhua* (GM)  $n=28$ ; *L. piscatorius* (LP),  $n=36$  and *T. araneus* (TA),  $n=38$ .

detection in structurally complex benthic habitats (Lombarte & Cruz, 2007; Manjabacas et al., 2025). Conversely, circular otoliths (*L. piscatorius*,  $M=0.75\pm 0.10$ ) display smoother contours ( $D_f = 1.04 \pm 0.02$ ), consistent with sedentary predation strategies (Froese & Pauly, 2011).

The bivariate plot of  $D_f$  versus  $M$  (Figure 4) also revealed ecological clustering along the negative correlation axis. Benthic species clustered in the high- $D_f$ /low- $M$  quadrant, while pelagic and sedentary species occupied the opposite end. Intermediate positions were observed for generalist feeders such as *G. morhua* ( $D_f = 1.04 \pm 0.02$ ,  $M = 0.68 \pm 0.03$ ), whose otolith morphology reflects broader habitat use. The strong congruence between theoretical descriptors and qualitative observations underscores the value of fractal analysis as a robust tool for morphological assessment.

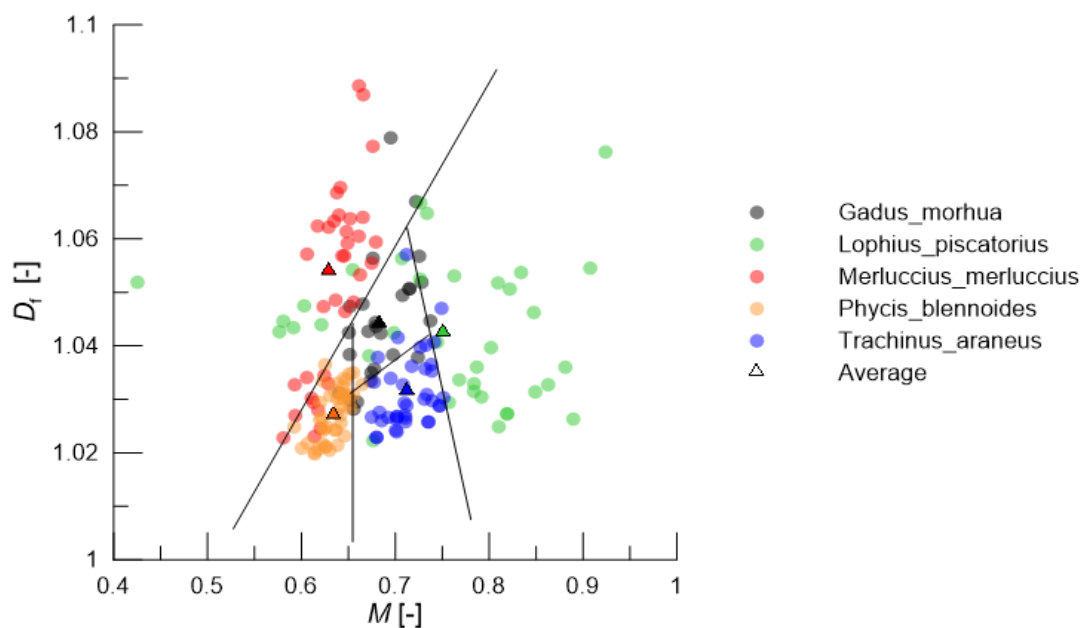
## Discussion

Our fractal analysis demonstrates that otolith morphology reflects ecological specialization across marine fish species. The discrimination accuracy achieved through the combined use of  $D_f$  and  $M$  parameters (Figure 4) surpasses traditional morphometrics, confirming that contour morphology complexity encodes species-specific ecological signatures. This performance likely stems from distinct evolutionary pathways: demersal *M. merluccius* developed high-roughness otoliths ( $D_f = 1.06 \pm 0.03$ ) adapted to detect substrate vibration in structurally complex habitats (Lombarte & Cruz, 2007; Martinez et al., 2023; Borges et al., 2024), whereas benthopelagic *P. blennoides* evolved smoother contours ( $D_f =$

$1.03 \pm 0.01$ ), potentially minimizing hydrodynamic drag during sustained swimming. The negative  $D_f$ - $M$  correlation suggests that hydrodynamic and sensory constraints jointly shape otolith morphospace, with circular forms (e.g., *L. piscatorius*  $M = 0.75 \pm 0.10$ ) possibly optimizing stability for ambush predation (Froese & Pauly, 2011).

These findings advance the understanding of fish ecomorphology in three main aspects. First, fractal morphology descriptors quantify previously overlooked contour attributes that correlate with microhabitat use: roughness predicts benthic affinity, while circularity relates to water column occupancy (Avigliano et al., 2023; Lombarte et al., 2023). Second, the method's sensitivity enables discrimination of sympatric species with overlapping linear measurements, addressing a long-standing challenge in fisheries monitoring (Tuset et al., 2008; Sadighzadeh et al., 2022). Third, the reproducibility of the approach supports its application in large-scale biomonitoring, particularly where genetic analysis is impractical (Manjabacas et al., 2025). This aligns with the global trend toward integrating advanced computational methods with traditional morphological approaches (Schultz et al., 2024), highlighting fractal analysis as part of the next generation of otolith analytical tools.

The absence of significant interspecific variation in angularity ( $m$ ) contrasts with patterns observed in terrestrial systems, potentially reflecting universal hydrodynamic constraints on edge sharpness in aquatic environments. However, this interpretation requires testing across broader taxonomic groups and developmental stages, as juvenile otoliths may exhibit different morphology contour patterns



**Figure 4.** Circularity ( $M$ ) versus the fractal dimension ( $D_f$ ) in order to divide the space in several areas each characteristic for each species.

(Hüssy et al., 2020; Sturrock et al., 2022). Future research should explore: (1) the effect of climate change on otolith development via temperature/pH experiments (Rountrey et al., 2014; Gaylord et al., 2015; Ross et al., 2023), (2) paleoecological reconstructions using fossil specimens, and (3) integration with dietary data to test trophic-morphology relationships (Lauchlan et al., 2024).

Despite the strong ecological correlations demonstrated here, two limitations should be noted. Ontogenetic plasticity may affect fractal parameters, particularly in species with complex life histories. Additionally, while the Mediterranean-Atlantic sampling design is ecologically representative, extending the study across biogeographic regions would strengthen conclusion about the large-scale variation (Manjabacas et al., 2025). Nevertheless, these findings establish fractal otolith analysis as both an ecological indicator and a practical tool for marine resource management in changing oceans (Rountrey et al., 2014; Gaylord et al., 2015; Ross et al., 2023).

## Conclusions

This study provides a comprehensive assessment of otolith morphology in five marine fish species—*Merluccius merluccius*, *Phycis blennoides*, *Gadus morhua*, *Lophius piscatorius*, and *Trachinus araneus*—using both qualitative and quantitative approaches. Qualitative observations highlighted distinct morphological traits among the species: *M. merluccius* and *P. blennoides* exhibited pronounced elongation, with *M. merluccius* showing high contour roughness and *P. blennoides* smoother profiles. *G. morhua* presented intermediate elongation with rough contour, while *L. piscatorius* displayed near-circular shapes with variable roughness. *T. araneus* showed moderate elongation and smooth profiles.

Quantitative fractal analysis descriptors confirmed these observations. M values indicated greater elongation for *M. merluccius* and *P. blennoides* and higher circularity for *L. piscatorius*, albeit with greater dispersion. Angularity ( $m$ ) showed no significant interspecific variation, while roughness (Df) values distinguished the high surface complexity of *M. merluccius* from the smooth profiles of *P. blennoides*. These findings demonstrate the utility of fractal analysis in distinguishing species based on otolith morphology. This study underscores the importance of otolith morphology in marine science and its potential applications in various scientific disciplines.

Our study demonstrates that fractal analysis of otolith contours provides both a robust species identification tool and valuable insights into ecological adaptations. The combination of fractal dimension (Df) and circularity (M) parameters achieved high classification accuracy, significantly outperforming traditional linear morphometric methods.

By integrating qualitative assessment with quantitative descriptors of the otolith morphology, this study established a

robust framework for species discrimination, fisheries management, population studies, and marine biology investigations (Rountrey et al., 2014; Gaylord et al., 2015; Ross et al., 2023). This performance reflects how otolith morphology evolves in response to ecological pressures (Sturrock et al., 2022) - benthic species like *M. merluccius* developed rough, elongated contours (Df =  $1.06 \pm 0.03$ ) ideal for substrate vibration detection in complex habitats, while pelagic species evolved smoother shapes (Df =  $1.02 \pm 0.01$ ) likely reducing hydrodynamic drag.

The Guida et al. (2020) method offers a reproducible, scalable tool with applications ranging from fisheries management to soil mechanics. Fractal analysis thus emerges as a powerful approach bridging functional morphology and ecosystem science, providing valuable insights for marine biology and resources management. Furthermore, the method shows promise for: (1) reconstructing paleoecosystems from fossil otoliths (Manjabacas et al., 2025), (2) tracking habitat use changes in response to climate change (Rountrey et al., 2014; Gaylord et al., 2015; Ross et al., 2023), and (3) identifying cryptic species complexes (Paradis et al., 2021; Borges et al., 2024). Future research should focus on ontogenetic development of fractal parameters and their sensitivity to environmental variables like temperature and pH in a climate change scenarios (Rountrey et al., 2014; Gaylord et al., 2015; Ross et al., 2023). By bridging functional morphology and ecosystem science, this approach offers new opportunities to address pressing challenges in marine resource management.

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## Authorship contributions

**Fernando Condal:** Conceptualization, methodology, investigation, formal analysis, data curation, software, resources, writing - original draft, supervision, project administration. **Giulia Guida:** Methodology, investigation, formal analysis, software, resources, writing - review. Authors reviewed and approved the final manuscript and are responsible for the integrity and accuracy of the work.

## Data availability

The data supporting the findings of this study are available upon reasonable request from the corresponding author.

## Conflict of interest

The authors declare that they have no conflicts of interest regarding the publication of this article.

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## Declaration of generative AI in scientific writing

The authors acknowledge the use of AI-assisted tools to enhance the clarity and accuracy of this manuscript. Deepseek AI was employed for language refinement to ensure scientific precision and academic tone. Grammarly was utilized for grammar verification and spelling correction, as the authors are non-native English speakers. All AI-processed content was carefully reviewed and approved by the authors, who take full responsibility for the final manuscript's content and interpretations.

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