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Engaging small-scale fishers in a circular bioeconomy: valorization of *Rhizostoma pulmo* (Macri, 1778) jellyfish bycatch for sustainable collagen production

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Jellyfish bycatch poses challenges for small-scale fisheries by increasing costs and generating underutilized biomass. Yet this same biomass could represent a valuable resource, as jellyfish are an emerging source of collagen with a wide range of biotechnological applications. Within the COLMED project, a collaboration between researchers and fishers was established to explore the sustainable valorization of jellyfish bycatch for collagen extraction as part of a circular bioeconomy strategy. The aims were to: (1) assess fishers' perceptions and willingness to engage in jellyfish valorization; (2) quantify bycatch occurrence and species composition; and (3) evaluate the structural and molecular integrity of collagen derived from bycatch specimens. Fishers' perspectives were gathered through semi-structured interviews across four small-scale fishing guilds in Catalonia and the Valencian Community, in the Spanish Mediterranean. Results revealed strong engagement and positive attitudes toward jellyfish valorization, although institutional, technical, and training support were key bottlenecks. Thirteen months of monitoring yielded the first quantitative baseline of jellyfish bycatch in the study area, with *Rhizostoma pulmo* and *Pelagia noctiluca* as the most abundant species. Collagen extracted from *R. pulmo*, whether hand-net collected or obtained as bycatch, retained molecular integrity, confirmed by SDS-PAGE, FTIR, and XRD analyses, demonstrating characteristic type I collagen bands, preserved amide groups, and native triple-helical patterns. These results show that incidental capture does not compromise collagen quality and support the use of *R. pulmo* bycatch as a sustainable marine collagen source. Overall, this study presents a novel interdisciplinary framework linking fisheries sustainability, ocean literacy, and the circular bioeconomy. It underscores the broader potential of jellyfish bycatch valorization to strengthen small-scale fisheries resilience and advance the development of high-value marine bioresources.

KEYWORDS
artisanal fisheries, blue biotechnology, Mediterranean, ocean literacy, Scyphozoa, zero-waste

1 Introduction

Jellyfish represent an important component of marine food webs and contribute to various ecosystem services (Graham et al., 2014), often reaching high densities in many coastal areas (Canepa et al., 2014; Marambio et al., 2021). Although they are a natural feature of healthy marine ecosystems, the increasing frequency and intensity of blooms have raised ecological and socio-economic concerns (Richardson et al., 2009). The fishing sector is among the industries most affected, particularly in the Mediterranean region, one of the areas most severely impacted (Bosch-Belmar et al., 2020). Accidental jellyfish capture (bycatch) causes net clogging, net breakage, and catch deterioration, and increases fishing time, fuel consumption, and the risk of stings to crew members (Palmieri et al., 2014; Bosch-Belmar et al., 2020; Mghili et al., 2022). Economic losses are difficult to quantify (Quiñones et al., 2013), yet data from the Northern Adriatic indicate that blooms can result in up to €8.2 million in annual losses, along with more than 460,000 € in fuel costs, and 89,000 hours of labor in net repairs (Palmieri et al., 2014). Several mitigation strategies have been proposed, ranging from the removal of medusae and the reorientation of fisheries toward targeted jellyfish exploitation, to the industrial processing of jellyfish obtained through directed harvesting and bycatch (D'Ambra and Merquiol, 2022; Pitt et al., 2025).

Directed jellyfish harvesting for human consumption has long been practiced in East and Southeast Asia, with China playing a central role in the development and dissemination of jellyfish processing and consumption practices to neighboring countries (Omori and Nakano, 2001). This long-standing tradition is largely attributed to their high collagen content, which can account for up to approximately half of the total protein content in edible jellyfish species and is associated with recognized nutritional and functional properties that support their use both as food and as a source of bioactive compounds (Khong et al., 2016; Leone et al., 2015; De Domenico et al., 2019). Beyond food applications, the structural and functional properties of jellyfish-derived collagen have attracted considerable interest in biomedical, cosmetic, and biotechnological fields (Chiarelli et al., 2023). As a biocompatible alternative to mammalian collagen (Song et al., 2006; Addad et al., 2011; Ahmed et al., 2021), jellyfish-derived collagen has demonstrated potential to promote cell proliferation (Rastian et al., 2018; Smith et al., 2023), and wound healing (Alkildani et al., 2021), with a reduced risk of allergic reactions and zoonotic disease transmission, making it a promising and sustainable option for biomedical applications (Addad et al., 2011; Chiarelli et al., 2023). In the Mediterranean Sea, the rhizostome jellyfish *Rhizostoma pulmo*, *Cotylorhiza tuberculata*, and *Rhopilema nomadica* have been identified as species of interest due to their nutraceutical properties and their potential for the development of collagen-based biomaterials (Ballesteros et al., 2025).

In this context, jellyfish biomass, particularly from fisheries bycatch, represents not only a management challenge but also as a potential resource. Circular bioeconomy strategies encourage converting underutilized biological materials into high-value products while reducing waste streams (Merli et al., 2018; Mozumder et al., 2022). Jellyfish bycatch is often discarded onshore after landing (Ballesteros et al., 2025) or returned to the sea during fishing operations (Bosch-Belmar et al., 2020), yet it remains an overlooked biomass with strong potential for valorization (D'Ambra and Merquiol, 2022).

Realizing this potential calls for close collaboration between scientists and fishers (D'Ambra and Merquiol, 2022; Ballesteros et al., 2025). Understanding fishers' perspectives and ensuring collagen integrity are both critical for successful implementation, as manual collection with hand nets reduces stress and physical damage compared to set nets or trawls (Edelist et al., 2021), which could otherwise compromise collagen quality. Integrating stakeholder perspectives aligns with global goals for sustainable ocean management and the UN Decade of Ocean Science for Sustainable Development (2021–2030). The Ocean Literacy (OL) movement promotes inclusive approaches linking scientific knowledge with local socio-economic perspectives (Ryabinin et al., 2019; Santoro, 2021; McKinley et al., 2023) and strengthens the connections between scientific evidence, ocean users, and coastal management (Ferreira et al., 2021; McKinley et al., 2023). Fishers' local ecological knowledge supports adaptive management and co-designed solutions for sustainable marine resource use.

The considerable knowledge gap regarding the management and valorization of jellyfish bycatch, as well as its incorporation into circular bioeconomy policies, underscores the importance of this issue. The COLMED project, *Jellyfish collagen, an innovative Mediterranean marine resource in blue biotechnology* (Programa Pleamar, n.d.), involving marine researchers and fishers, offers a unique opportunity to investigate these questions further. Accordingly, the present study aims to: (1) assess fishers' perceptions, knowledge, and willingness to engage in the valorization of jellyfish bycatch and its integration into the circular bioeconomy; (2) characterize the occurrence and patterns of jellyfish bycatch and identify the most abundant species incidentally captured by small-scale fisheries; and (3) validate the potential use of jellyfish bycatch as a source of collagen through assessment of electrophoretic profile and structural characteristics. By combining fishers' perceptions, field observations, and collagen characterization from jellyfish bycatch, this study presents an applied, real-world case that integrates socio-ecological perspectives and biochemical validation. It then offers novel insights into jellyfish bycatch management and its potential contribution to blue biotechnology and zero-waste initiatives while fostering Ocean Literacy through the co-production of knowledge between scientists and fishers.

2 Materials and methods

2.1 Study area and collaborative framework with small-scale fishing guilds

The study was conducted on Spain's western Mediterranean coast, in collaboration with four small-scale fishing guilds. Two of them, Port de la Selva and Roses, are situated in Catalonia, where fishing activities are primarily focused in Cap de Creus (42°19′12″ N, 03°19′34″E). The other two guilds, Jávea and Moraira, are located in the Valencian Community and operate along the northern coast of Alicante, between Cabo de San Antonio (38°48′ 10″N, 00°11′48″E) and Peñón de Ifach (38°37′58″N, 00°04′52″ E) (Figure 1).

The small-scale fishing fleet of the participating guilds consists primarily of small vessels, with an average length of 8 m, operating on weekdays in coastal bays and shallow waters, weather permitting. These vessels employ a variety of passive fishing gear, including pots, longlines, and nets such as gillnets and trammel nets, targeting a diverse assemblage of demersal species. Gillnets and trammel nets account for more than 50% of their fishing effort. Small-scale fisheries in these regions are characterized by physically demanding work and persistent exposure to environmental and economic uncertainty, coupled with a lack of generational renewal. Under the current EU framework, these vessels are classified as small-scale, as they are generally under 12 m in overall length and do not use towed fishing gear, consistent with the definition established in Regulation (EU) No. 2021/1139 of the European Parliament and of the Council (European Parliament & Council of the EU, 2021).

A participatory approach was adopted to improve understanding of jellyfish bycatch and promote sustainable resource use through scientist–fisher collaboration. This co-production of knowledge enhanced OL and supported the implementation of circular bioeconomy and zero-waste strategies by promoting the valorization of jellyfish as a source of collagen (Figure 2).

2.2 Fishers' perceptions on jellyfish bycatch valorization

Semi-structured interviews were conducted with small-scale fishers from the participating guilds between July and October 2025 (Figure 2A). Interviews were carried out at the guild facilities or in the harbor areas where fishers commonly gathered, to ensure a relaxed atmosphere that encouraged participation and open dialogue. A total of 16 fishers participated in the study, comprising all active small-scale fishers from the participating guilds and reflecting the limited number of active members. This sample size is consistent with previous qualitative research standards in fisheries and local ecological knowledge (LEK) studies, where in-depth semi-structured interviews involve between 7 and 20 participants (e.g (Trimble and Berkes, 2013; Fauconnet et al., 2019; Pita et al., 2020). In qualitative research, the emphasis is on depth of information rather than statistical representativeness. In relatively homogeneous samples, thematic saturation has been reported to occur within the first 12 interviews (Guest et al., 2006).

Prior to participation, all respondents were informed about the objectives of the study and signed an informed consent form in accordance with Spanish data protection regulations (Ley Orgánica 3/2018, 2018). The survey consisted of 28 questions organized into two main sections, combining closed-ended, multiple-choice, and open-ended items to capture both quantitative and qualitative insights.

The first section explored fishers' awareness, perceptions, and willingness to engage in jellyfish valorization, including their knowledge of potential commercial uses, interest in participating in pilot projects, and the types of support they would require to become involved. The second section focused on fishers' understanding and application of circular bioeconomy principles, examining their familiarity with the concept, current waste management practices, perceived barriers and opportunities for integrating jellyfish bycatch into circular bioeconomy models, and interest in receiving specific training. The final part of the questionnaire included Likert-scale items assessing knowledge, interest, and perceived feasibility of implementing jellyfish valorization initiatives at both local and national levels. Interviews were anonymized and coded for quantitative and qualitative analysis. The full version of the questionnaire is available in Supplementary Material (S1).

2.3 Jellyfish bycatch monitoring

To characterize jellyfish bycatch and identify abundant species, the research team and fishers implemented a monitoring scheme

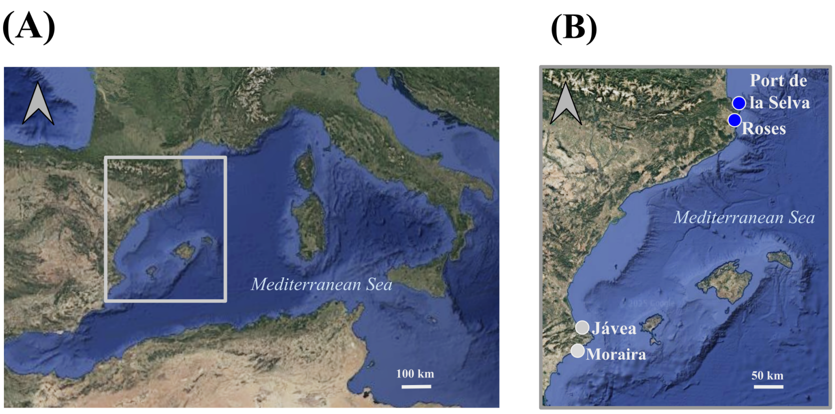

FIGURE 1
Study area. **(A)** Western Mediterranean coast of Spain. **(B)** Small-scale fishing guilds included in the study. Blue dots indicate guilds located in Catalonia (Port de la Selva and Roses), and grey dots indicate guilds located in the Valencian Community (Jávea and Moraira).

FIGURE 2
Co-production of knowledge supporting jellyfish valorization as a collagen source. **(A)** Knowledge-exchange meetings and interviews with fishers. **(B)** Training sessions in small-scale fishers' guilds to improve data collection and species identification of incidentally caught jellyfish. **(C)** On-board surveys conducted by the research team to support jellyfish bycatch identification and systematic recording. **(D)** *Rhizostoma pulmo* specimen incidentally captured. **(E)** Freeze-dried *R. pulmo* collagen. **(F)** Hands-on workshops showcasing the extracted collagen to fishers, fostering a tangible understanding of the valorization process.

combining training, systematic observation, and data validation. Data were collected from October 1, 2024, to October 31, 2025, during which time records were compiled by artisanal fishers participating and subsequently transcribed into the structured database by the research team (COLMED Project, 2025). From this initial database, additional information was incorporated, including fishing gear used, target fish species, and other contextual details to enable more comprehensive analyses. Training sessions were organized within the fishing guilds to enable the identification of jellyfish species caught as bycatch and to highlight those of greatest interest for collagen extraction (Figure 2B). The research team participated in the first six fishing trips to assist with species identification and with systematic recording (Figure 2C). All reports were verified by the researchers through photographic documentation.

Data visualization and mapping were carried out in R version 4.4.2 (R Core Team, 2022) using RStudio (Posit Team, 2023). Spatial data were processed with the "sf" package, and maps were generated using the "ggplot2" and "rnaturalearth" packages. Seasonal trends in jellyfish sightings were analyzed and visualized in R version 4.4.2 (R Core Team, 2022) using RStudio (Posit Team, 2023). Aggregated bar plots were produced with the "ggplot2" package to present the total number of sightings per species in each season (spring, summer, fall, and winter). Sightings from different abundance categories were pooled for each species and season to generate the figures.

2.4 Valorization of jellyfish bycatch: collagen extraction and comparative characterization

2.4.1 Sample collection

To validate the potential use of jellyfish bycatch as a source of collagen, *R. pulmo* specimens were obtained from two different sources: (i) bycatch and (ii) hand-net–collected specimens, which were collected to preserve their structural integrity. *R. pulmo* was selected because it is one of the Mediterranean jellyfish species with the highest reported collagen content (Addad et al., 2011).

Bycatch specimens were obtained from trammel net fisheries operating off the coast of Moraira (Alicante, Spain) in August 2024, during joint fishing trips with fishers from the Moraira guild (see Section 2.3) (Figure 2D). The target species of these fisheries was the red mullet (*Mullus surmuletus*). Trammel nets were deployed on rocky substrates at 20 m depth. They measured 1 meter in height and 1000 m in length and consisted of a 2.8-cm stretched-mesh inner panel between two 12-cm outer panels. At the port, jellyfish were removed from the nets and transferred to seawater containers. The total time elapsed between landing and processing in the laboratory was approximately 4 h. Upon arrival at the laboratory, bycatch specimens showed no bell pulsation, a loss of bell firmness, and excessive mucus production.

Hand-net–collected individuals were captured along the coast of Calpe (Alicante, Spain) in September 2024. Jellyfish were carefully transferred to seawater-filled containers on board the vessel. Regular water renewal and adequate spacing between specimens were maintained to avoid overcrowding, stress, and physical damage. Transportation to the laboratory did not exceed 1 h. Upon arrival, specimens exhibited bell pulsation, maintained normal bell firmness, and showed mucus production within typical levels.

In both cases, upon arrival at the laboratory, all specimens were thoroughly rinsed with filtered seawater to remove sediment and debris. The tissue was then dissected into 3-cm fragments, placed in airtight zip-lock bags, and stored at –20 °C. Finally, jellyfish were freeze-dried for later processing.

2.4.2 Collagen extraction

For each jellyfish group, collagen extraction was carried out in three independent batches, each consisting of 6 g of lyophilized whole jellyfish tissue. Extraction of acid-soluble collagen was performed according to Nagai et al. (2000) with slight modification. Lyophilized *R. pulmo* jellyfish powder was suspended in 0.1 M sodium hydroxide at a tissue-to-solution ratio of 1:50 (w/v) and incubated under continuous stirring for 24 h. To ensure the efficient removal of non-collagenous proteins, the alkaline medium was replaced with fresh 0.1 M NaOH after 12 h. Subsequently, the material was washed with distilled water until the pH reached neutrality. The treated tissues were resuspended in 0.5 M acetic acid at a 1:30 (w/v) ratio, and acid-soluble proteins were extracted for 72 h under continuous stirring. Insoluble particles were removed by centrifugation at 10,000 x g for 1 h. The supernatant was salted out by adding sodium chloride to a final concentration of 1 M, followed by gentle stirring until the salt fully dissolved. The mixtures were incubated overnight to promote precipitation of collagen, that was recovered by centrifugation at 5,000 x g for 1 h. The pellets were dissolved in 0.5 M acetic acid and sequentially dialyzed against 0.1 M, 0.05 M, and 0.025 M acetic acid using SnakeSkin™ dialysis tubing (MWCO 10,000; Thermo Fisher Scientific, United States) for 72 h, with three buffer changes per day. All extraction steps were carried out at 4 °C. The collagen solutions were stored at -20 °C until use. Protein concentrations of collagen solutions were determined using the Pierce™ Dilution-Free™ Rapid Gold BCA Protein Assay Kit (Thermo Fisher Scientific), according to the manufacturer's instructions.

2.4.3 Comparative structural characterization of collagen using SDS-PAGE, FTIR, and XRD

SDS-Polyacrylamide Gel Electrophoresis (SDS-PAGE). To assess the purity of the extracts and the molecular weight of the extracted collagen, it was analyzed by SDS-PAGE using a Bio-Rad Mini-PROTEAN® system (Bio-Rad, United States). Fifteen µl of collagen solutions containing 5–10 µg of protein were mixed at a 1:1 (v/v) ratio with Laemmli SDS sample buffer (Thermo Fisher Scientific) and heated for 10 minutes at 95 °C. Commercial rat tail collagen type I (CORNING®, Sigma-Aldrich, United States) was similarly prepared and used as a collagen standard. A 7.5% Mini-PROTEAN® TGX™ Precast Protein Gel (Bio-Rad, United States) was loaded with 30 µL of collagen samples and 10 µL of Spectra Multicolor Broad Range Protein Ladder (Thermo Fisher Scientific, United States). Electrophoresis was carried out at 100 V for 1 h using 1× TGS running buffer (Fisher Bioreagents, United States), and then the gel was stained with QC Colloidal Coomassie Stain (Bio-Rad, United States).

Fourier-transform infrared (FTIR) spectroscopy. Samples of extracted collagen were lyophilized prior to FTIR spectroscopy analysis. Spectra were acquired in attenuated total reflectance (ATR) mode using an Agilent Cary 630 FTIR spectrometer (Agilent Technologies, Australia), over the range 4,000–650 cm^{-1} at a resolution of 4 cm^{-1}, with 32 scans per sample. The recorded absorption bands were used to identify characteristic collagen functional groups, providing insight into the molecular structure. Graphical representations of the FTIR spectroscopy results were generated as scatter plots using SigmaPlot version 11.0 (Systat Software Inc., 2008).

X-ray diffraction analysis (XRD). Freeze-dried collagen samples were analyzed with a diffractometer (Bruker D8 Advance Twin–Twin, Bruker AXS GmbH, Bremen, Germany) equipped with Cu Kα radiation (λ = 1.5406 Å) and a linear SSD detector. Data were collected in Bragg–Brentano geometry with a divergence slit of 0.6 mm and 5 mm anti-scatter slit. The diffraction patterns were recorded in the 2θ range of 5–40°, with a step size of 0.02° and a counting time of 1 second per step. The interplanar spacing (d) values were calculated according to Bragg's equation, $d(A) = \frac{\lambda}{2\sin\theta}$, where λ is the X-ray wavelength and θ is the Bragg diffraction angle. Graphical representations of the XRD results were generated as scatter plots using SigmaPlot version 11.0 (Systat Software Inc., 2008).

3 Results

3.1 Fishers' perception assessment

Over half (56.3%) of the small-scale fishers who participated in the study reported being familiar with the concept of circular bioeconomy, 37.5% had heard of the term but were unsure of its meaning, and 6.3% were unfamiliar with the idea. Most participants (93.8%) associated the term with the reuse and recycling of materials, and 50% emphasized extending product lifespan.

When asked about circular bioeconomy practices, 62.5% reported that they had engaged in related activities, primarily focused on minimizing waste or reusing materials on board. Notably, 81.3% of respondents believed that accidental catches such as jellyfish could serve as a potential resource if properly valorized, and all respondents agreed that fishing residues could be transformed into useful products through adequate management.

A large majority (93.8%) expressed willingness to participate in pilot initiatives focused on jellyfish valorization, and all indicated they would be willing to dedicate part of their time or vessel to jellyfish collection if a stable market existed. Among perceived barriers, a lack of institutional incentives (75%) and an absence of market demand for jellyfish-derived products (68.8%) were the most frequently cited, followed by a lack of training or infrastructure (37.5%).

In terms of potential opportunities, 93.8% identified additional income sources as the main benefit, while 68.8% pointed to improved environmental awareness and sustainability of the sector. Although 31.3% had never previously considered jellyfish as a bioeconomic resource, 81.3% believed that their valorization could provide a real opportunity for diversification in small-scale fisheries. Economic and technical support were identified as key requirements for engagement in future initiatives (Figure 3).

3.2 Jellyfish bycatch analysis

A total of 70 cases of jellyfish bycatch were recorded in the study area, from three species: *R. pulmo*, *C. tuberculata*, and *Pelagia noctiluca* (Figures 4, 5). Most of the bycatch events (82.86%) occurred during trammel net operations, while 17.14% occurred during gillnet operations.

On the Catalan coast, based on data reported by the fishing guilds of Port de la Selva and Roses, 42 bycatch events were recorded. The most frequent species was *P. noctiluca* (57.89%, 2299 individuals), followed by *R. pulmo* (44.73%, 691 individuals), and *C. tuberculata* (7.89%, 7 individuals). In the Valencian Community, according to reports from the fishing guilds of Jávea and Moraira, 27 bycatch events were recorded. *R. pulmo* predominated (77.8%, 151 individuals), while *P. noctiluca* and *C. tuberculata* each represented 11.1% (9 and 16 individuals, respectively).

In terms of seasonality (Figure 5), *R. pulmo* was recorded throughout the year, with the highest number of events in fall (13) and summer (11). The number of individuals per event generally ranged between 2 and 10, with occasional occurrences of 51–100 individuals during spring. *P. noctiluca* was mainly reported in winter and spring, accounting for more than 20 events, with abundances exceeding 100 individuals in several cases. *C. tuberculata* appeared exclusively during summer, with 6 events and abundances ranging from 1 to 10 individuals. All collected data are provided in the Supplementary Material (S2).

3.3 Collagen extraction and characterization

Based on the estimation derived from the total protein content of the acid-soluble collagen extracts, collagen yield showed close values between hand-net–collected and bycatch specimens, at 0.75 ± 0.13 and 0.69 ± 0.21 mg g^{-1} dry weight, respectively.

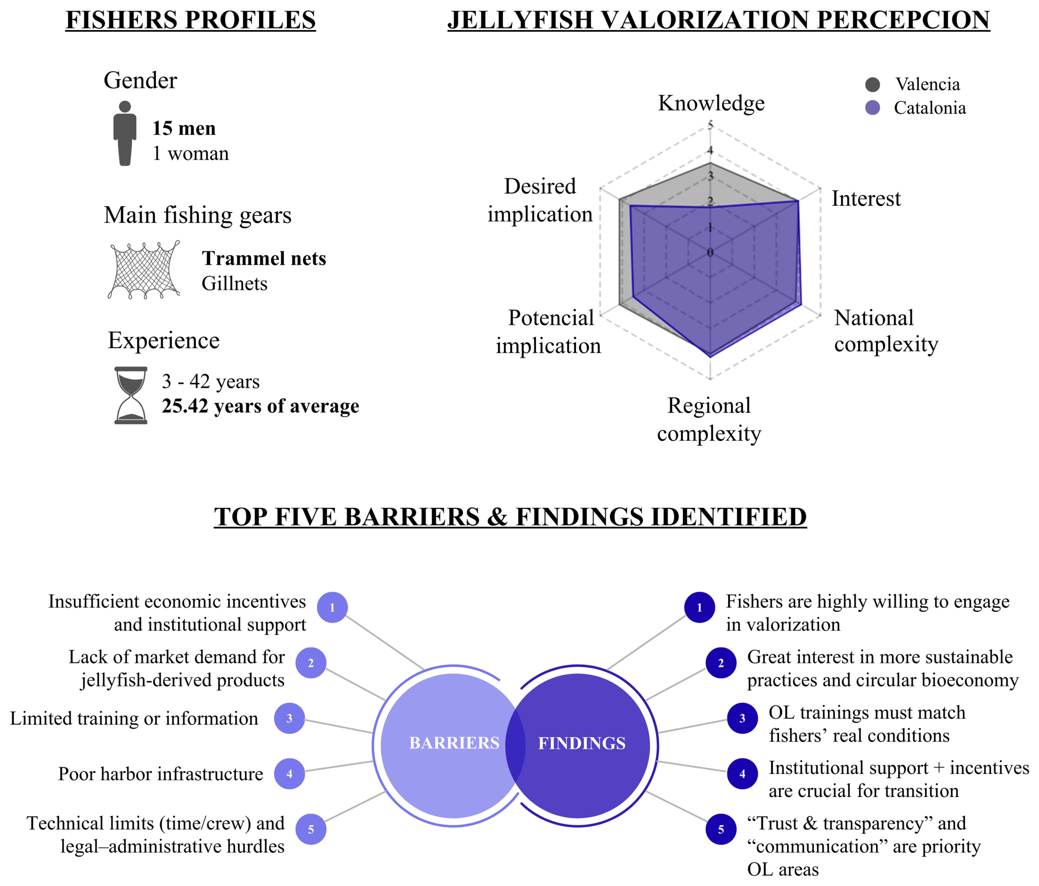

FIGURE 3
Fishers' perceptions regarding jellyfish valorization and the circular bioeconomy, including fishers profiles, key perceptions, barriers, and opportunities identified by the artisanal fishing guilds of Catalonia and the Valencian Community.

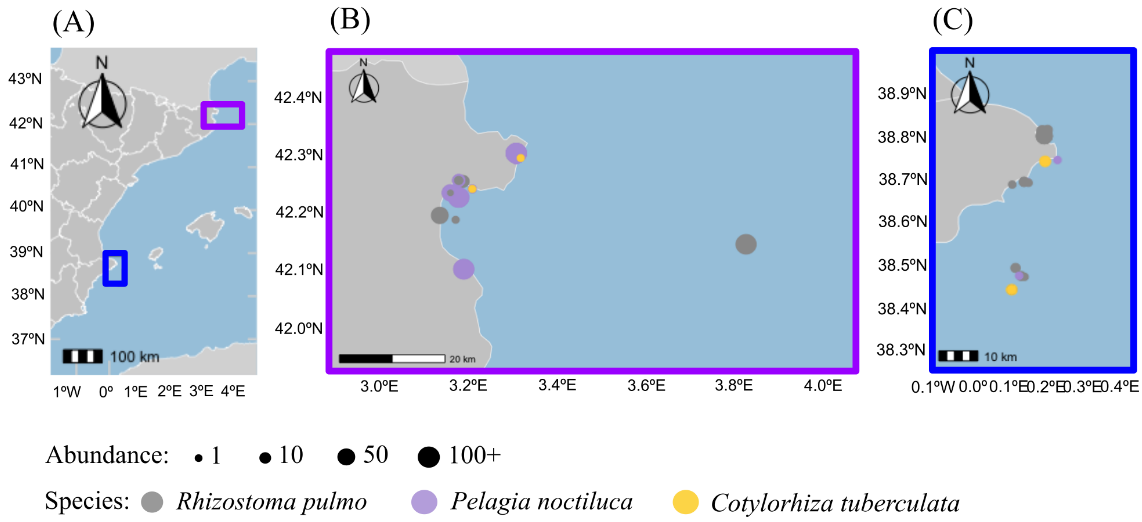

FIGURE 4
Spatial distribution and abundance ranges of jellyfish bycatch recorded between October 2024 and October 2025. **(A)** Study area. **(B)** Detailed views of Catalonia (violet inset) and **(C)** the Valencian Community (blue inset). Circle size represents the relative abundance of Rhizostoma pulmo (grey circles), Pelagia noctiluca (violet circles), and Cotylorhiza tuberculata (yellow circles).

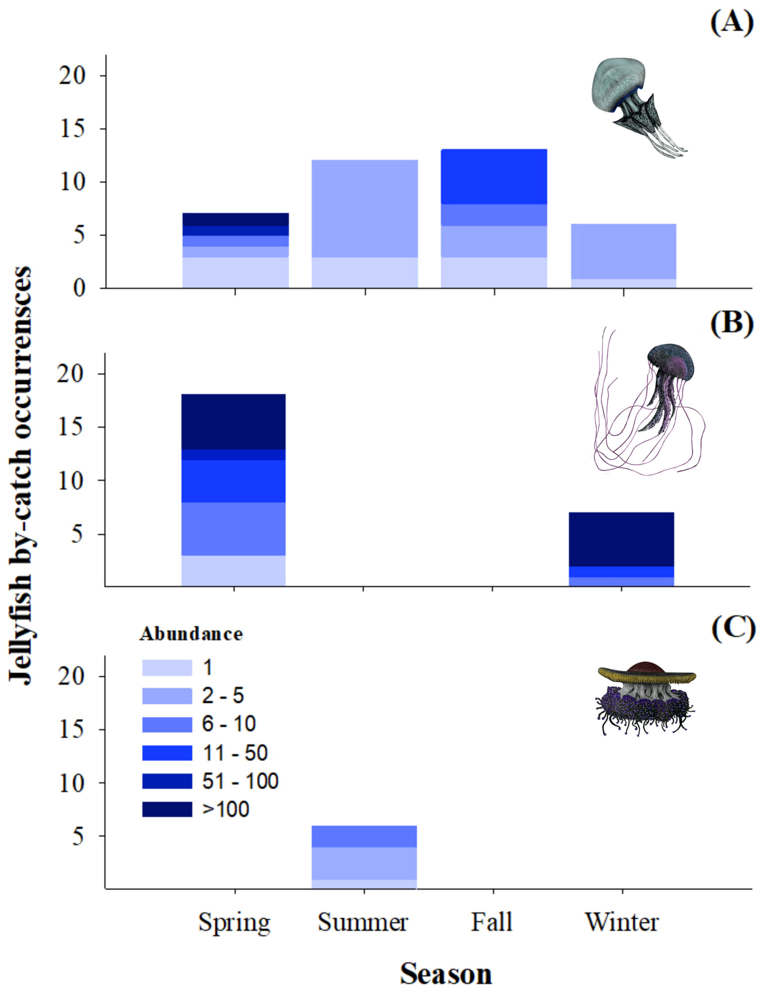

FIGURE 5
Jellyfish bycatch events and abundance ranges per species and season for **(A)** Rhizostoma pulmo, **(B)** Pelagia noctiluca, and **(C)** Cotylorhiza tuberculata. Color intensity indicates abundance ranges, with darker colors representing higher numbers of individuals per event.

SDS-PAGE analysis revealed identical banding patterns for collagen extracted from hand-net and bycatch-collected *R. pulmo* specimens, with α1 and α2 chains of approximately 150 and 160 kDa, respectively, and a β dimer chain of 260 kDa (Figure 6). In comparison, the rat type I collagen used as a control displayed the expected α1 and α2 bands of 129 and 139 kDa, respectively, and a 260 kDa β band. An extra band at approximately 100 kDa was observed in extracted jellyfish collagen, but not in rat collagen.

FTIR spectra of collagen extracted from specimens obtained through both hand-net–collected and bycatch methods revealed nearly identical profiles, displaying the characteristic absorption bands of protein functional groups (Figure 7A). Five main peaks corresponding to amide groups were detected in both samples: amide A (3,278 cm^{-1}), amide B (2,918 cm^{-1}), amide I (maximum at 1,644 cm^{-1} within the 1,600–1,700 cm^{-1} region), amide II (1,551 cm^{-1}), and amide III (1,234 cm^{-1}).

XRD analysis (Figure 7B) revealed no differences in diffraction patterns between the extracted collagens, with two main peaks located at approximately $2\theta = 8.6°$ and at $2\theta = 19.4°$, which are characteristic of fibrillar, undenatured collagen. Using Bragg's law, the corresponding interplanar spacings were calculated as $d = 10.27$ Å and d = 4.57 Å, respectively.

4 Discussion

Jellyfish bycatch is still a significant challenge for small-scale fisheries, as it is often discarded during or after fishing and generates large amounts of unutilized biomass (Ballesteros et al., 2025). Within a circular bioeconomy framework, this biomass represents a valuable resource that can be transformed into high-value products, such as collagen, with potential commercial applications in food-related products, cosmeceutical, nutraceuticals, and functional biomaterials (Chiarelli et al., 2023). However, collaboration with fishers is essential for integrating practical collection methods, sharing knowledge on jellyfish bycatch management, and gathering their perspectives on implementing valorization strategies within their professional activities.

The assessment of fishers' perspectives provided valuable insights into knowledge exchange, awareness, and attitudes toward jellyfish valorization within a circular bioeconomy framework in the western Mediterranean, highlighting key Ocean Literacy (OL) needs. All participants demonstrated strong commitment and contributed valuable local ecological knowledge. They also showed a high willingness to engage in circular bioeconomy initiatives, consistent with previous successful

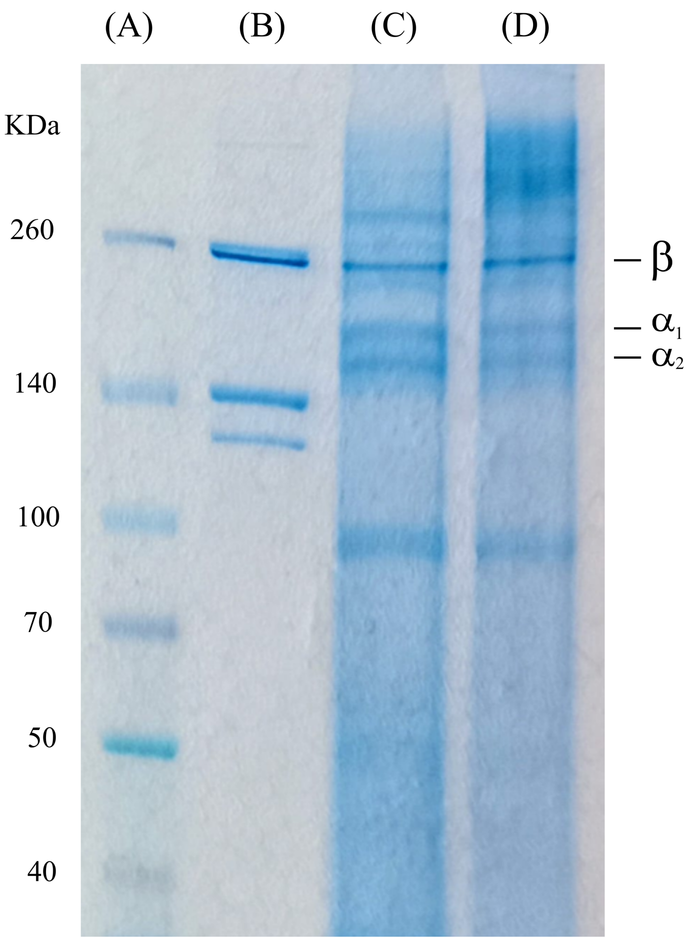

FIGURE 6
SDS–PAGE analysis of *Rhizostoma pulmo* collagen. **(A)** Molecular weight markers **(B)** Type I rat tail collagen **(C)** Hand-net-collected jellyfish **(D)** Bycatch jellyfish.

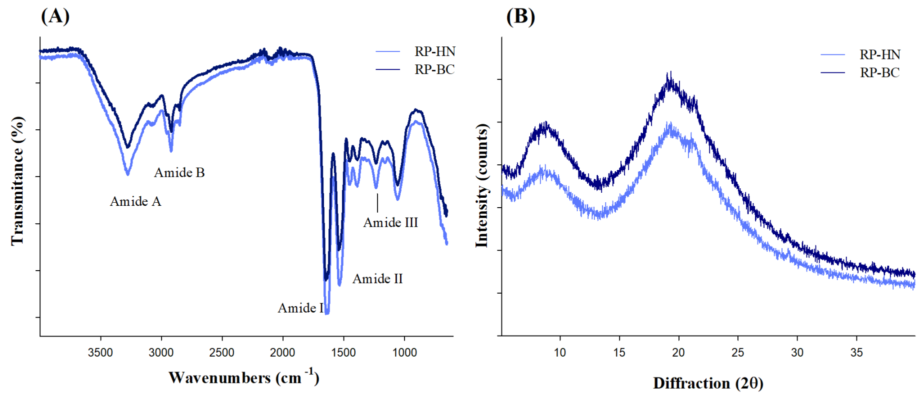

FIGURE 7
FTIR and XRD analysis of Rhizostoma pulmo collagen. **(A)** FTIR and **(B)** XRD. Bycatch jellyfish (dark blue) and hand-net-collected jellyfish (light blue).

collaborations between small-scale fishers and marine scientists in the same Catalan study area (e.g., Santín et al., 2022; Biel-Cabanelas et al., 2023). Notably, in the Valencian Community, this study represents the first systematic effort to explore jellyfish valorization, highlighting the novelty of this approach in the region.

Key needs for a sustainable blue circular bioeconomy strategy include stronger policymaker support, greater involvement in decision-making, and tailored OL training. These results align with previous studies on small-scale fishers' involvement in scientific initiatives, which revealed that OL training cannot be taken for granted and should be adapted to each audience (Salazar et al., 2024). Their demand for greater institutional support is also consistent with previous findings showing that fishers often feel excluded from decision-making processes that directly affect them, highlighting the need for further work in the OL dimensions of "trust and transparency" and "communication" among fishers, policymakers, and other stakeholders operating in coastal communities (Salazar et al., 2025). Transparency in the context of fisheries, policymakers, and civil society can be challenging and should be addressed appropriately, recognizing its difficulties. Nevertheless, it is crucial for sustainable management and fundamental for building trust-based relationships among stakeholders (Skerritt, 2024). These findings also align with the goals of the UN Ocean Decade of empowering ocean users with knowledge, skills, and values that foster responsible interaction with marine ecosystems (Santoro, 2021).

Jellyfish have a severe impact on fisheries (Palmieri et al., 2014) and are often perceived as hazardous species. However, emerging uses and narratives, such as those developed within the COLMED project (Programa Pleamar, n.d.), can reposition jellyfish as flagship species for OL, promoting sustainable behaviors and providing educational opportunities (Salazar et al., 2025). Considering the need to move from eco-anxiety to eco-hope in OL discourses and to focus on solutions (Betro', 2024), jellyfish as a collagen source, as described in this study, may also serve as a resource for OL educational purposes. Overall, our findings highlight the importance of participatory and tailored strategies for advancing blue technology and responsible ocean stewardship.

Monitoring seasonal changes in jellyfish occurrence remains a complex and costly undertaking using standard scientific methods (Edelist et al., 2025). Citizen science has greatly expanded data collection on jellyfish presence and absence, both at sea and from stranded individuals along Mediterranean coastlines (Marambio et al., 2021; Dobson et al., 2023; Edelist et al., 2025), and substantial efforts in Spain have further strengthened these initiatives (Gutiérrez-Estrada et al., 2021; Marambio et al., 2021; Dobson et al., 2023). In line with our observations, the most frequently sighted species, including *P. noctiluca*, *R. pulmo*, and *C. tuberculata*, were likewise the main jellyfish species recorded in bycatch. Since the aim of this study was to demonstrate tools for bycatch monitoring rather than to analyze long-term biogeographical or phenological patterns, which require multi-year time series (Marambio et al., 2021; Dobson et al., 2023), the species presence data collected will be integrated into the *Alerta Medusas* database of the citizen science platform *Observadores del Mar* (Observadores del Mar, n.d) as part of the COLMED project (Programa Pleamar, n.d.). The initiative of this study highlights the crucial role of fishers in expanding the spatial and temporal coverage of observations, improving data quality, and reinforcing collaboration between scientists and local stakeholders, fostering responsible ocean stewardship.

Across the Mediterranean, fishers reported jellyfish different species as interfering with fishing activities (Öztürk and İşinibilir, 2010; Palmieri et al., 2014; Mghili et al., 2022). In the western Mediterranean, Mghili et al. (2022) identified jellyfish species such as *P. noctiluca*, *R. pulmo*, and *Chrysaora hysoscella* in the bycatch of a mixed fleet, including small-scale artisanal fisheries, whereas Palmieri et al. (2014) reported bycatch of *R. pulmo* and *Aurelia aurita* in the Northern Adriatic. In the eastern Mediterranean, *R. nomadica* dominates the bycatch due to its high abundance (Öztürk and İşinibilir, 2010; Edelist et al., 2021). Complementing these regional reports, our study identified bycatch jellyfish species including *R. pulmo*, *P. noctiluca*, and *C. tuberculata*, with the first two being the most frequent and abundant. Here, jellyfish bycatch events occurred mainly in trammel nets, although interactions with other gear types such as trawls or purse-seine nets have been reported previously (Palmieri et al., 2014; Bosch-Belmar et al., 2020; Mghili et al., 2022). On the Catalan coast, *P. noctiluca* represents the most frequent species in the incidental catch (57.89%, 2,299 individuals); however, despite its high abundance and the presence of type I collagen, its low extractable yield (0.074 mg/g) limits its suitability for collagen valorization compared to rhizostome jellyfish such as *R. pulmo* (0.83–10.3 mg/g) and *C. tuberculata* (0.45–1.94 mg/g) (Addad et al., 2011).

Nevertheless, *P. noctiluca* represents an industrially relevant resource, as proteomic characterization has identified a range of bioactive proteins, including zinc metalloproteinases with ShK toxin domains, red fluorescent proteins with potential applications as molecular markers, and antioxidant enzymes such as peroxiredoxins with possible anti-UV and biomedical applications (Frazão et al., 2017). Furthermore, pharmacological evidence indicates that *P. noctiluca* venom exhibits analgesic and neuroactive properties without acute toxicity, reinforcing its potential for biomedical applications (Ayed et al., 2016). To date, the valorization of *P. noctiluca* bycatch remains largely unexplored, highlighting promising opportunities for future research in collaboration with fishers under a circular bioeconomy approach.

In contrast, *R. pulmo* was recorded in bycatch events throughout the year, peaking in summer and fall and with occasional high abundances in spring. Due to its frequent occurrence and suitability as a collagen source, *R. pulmo* was selected for collagen extraction as part of ongoing efforts to promote circular bioeconomy and zero-waste valorization. Although *R. pulmo* collagen has been widely investigated for biomedical applications (Ballesteros et al., 2025), studies based on bycatch individuals remain scarce, with only one study demonstrating its suitability for tissue engineering (Morelli et al., 2024).

Comparable amounts of acid-soluble collagen were extracted from both hand-net–collected and bycatch specimens (0.75 ± 0.13 and 0.69 ± 0.21 mg g^{-1} dry weight, respectively), indicating that incidental capture did not compromise collagen recovery under the conditions of this study. Direct comparisons are limited by the lack of previously reported acid-soluble collagen yields for this species; however, the values obtained here are lower than those reported for pepsin-solubilized collagen (0.83–10.3 mg g^{-1} wet tissue; Addad et al., 2011) or pepsin-assisted ultrasonication methods (up to 47% of lyophilized dry weight; James et al., 2023). These differences are mainly attributable to methodological factors, as pepsin-assisted extraction is known to enhance collagen solubility and recovery, especially when combined with ultrasonication (Khong et al., 2018). In this study, pepsin digestion was avoided, as the objective was not to maximize yield but to assess native collagen characteristics using a standardized acid extraction protocol that allowed direct comparison between bycatch and hand-net–collected specimens.

SDS-PAGE results indicated that collagen extracted from *R. pulmo* exhibited a protein profile consistent with fibrillar type I–like collagen, including α1, α2, and β chains of approximately 150, 160, and 260 kDa, respectively. This molecular weight profile was consistent with that reported *R. pulmo* collagen (Addad et al., 2011; Rigogliuso et al., 2023; Smith et al., 2023; Morelli et al., 2024) and aligns with type I-like collagen described in other jellyfish species, including *Rhopilema esculentum* (Cheng et al., 2017), *Catostylus mosaicus* (Rastian et al., 2018), and *A. aurita* (Balikci et al., 2024). Besides jellyfish, comparable type I protein profiles have been reported for collagen recovered from fish-processing by-products such as skin, scales, and bones (Blanco et al., 2019; Batista et al., 2022; Jaziri et al., 2022; Martins et al., 2022).

Rhizostoma pulmo collagen displayed electrophoretic banding patterns similar to those of commercial rat tail type I collagen, although the α chains showed slightly higher apparent molecular weights. This shift likely reflects the atypical SDS-PAGE migration behavior of triple-helical proteins, which is not strictly correlated with their molecular mass. It is well established that collagen α chains often migrate more slowly than predicted from their amino acid sequences, likely due to the rigidity conferred by their high proline and hydroxyproline content (Scheller et al., 2021). In jellyfish collagen, differences in amino acid composition, including lower levels of hydroxyproline, proline, glycine, and glutamic acid, may further influence electrophoretic mobility and contribute to the higher apparent molecular weights observed (Song et al., 2006; Addad et al., 2011; Barzideh et al., 2014; Paradiso et al., 2019). Despite their role in stabilizing quaternary structure, these differences do not appear to compromise overall collagen integrity (Sorushanova et al., 2019). Notably, β chains appeared more intense than α chains, which suggested a higher degree of intermolecular crosslinking. In line with this interpretation, Martins et al. (2022) similarly related a more intense β band in fish collagens (relative to bovine collagen) to intermolecular crosslinking. Whereas Cheng et al. (2017) associated reduced β/γ bands and dominant α bands to partial collagen degradation following pepsin treatment, the strong β chains observed here suggest that molecular interactions and overall collagen organization have been preserved during extraction.

A distinctive ~100 kDa band, absent in rat tail collagen, was observed in *R. pulmo* and has been previously reported (Rigogliuso et al., 2023; Smith et al., 2023; Morelli et al., 2024). This band has been tentatively attributed to a collagen or collagen-associated protein characteristic of marine invertebrates (Smith et al., 2023), although alternative interpretations have been proposed. Previous studies indicate that some jellyfish species contain three distinct α chains, including a possible α3 chain, depending on species-specific collagen composition (Nagai et al., 2000). In addition, Carvalho et al. (2022) reported that *R. pulmo* collagen exhibits electrophoretic features comparable to type II collagen, including β, α1, and α3 chains with molecular weights close to 260, 130, and 100 kDa, respectively. In this context, the ~100 kDa band observed here may correspond to an α3 chain, consistent with the atypical and evolutionarily ancient molecular organization of jellyfish collagens. However, as SDS-PAGE provides only a preliminary assessment of molecular composition, definitive classification would require proteomic analyses (Smith et al., 2023). Overall, although the electrophoretic profile is broadly consistent with type I jellyfish collagen, structural overlap with type II cannot be excluded, highlighting the limitations of applying vertebrate collagen nomenclature to marine invertebrates.

From an applicability perspective, the similarity of *R. pulmo* collagen to type I, together with its possible overlap with type II–like features, suggests a wider range of potential biomedical uses. Type I collagen is widely used for tissue-engineering scaffolds, tissue substitutes, and wound dressings, as well as for controlled delivery of drugs, growth factors, and cell carriers (Amirrah et al., 2022). In line with this, *R. pulmo* collagen has been successfully evaluated *in vivo* as implantable collagen scaffolds with good host tolerance and biocompatibility, alongside favorable tissue repair and resorption profiles (Widdowson et al., 2018; Flaig et al., 2020). Type II collagen is considered particularly suitable for cartilage tissue-engineering strategies (Wu et al., 2021). In this context, *R. pulmo* collagen supported chondroprogenitor cell proliferation within the scaffold and promoted chondrogenic differentiation, particularly in the presence of transforming growth factor beta 1 (TGFβ1) (Ahmed et al., 2021).

FTIR spectroscopy supported the collagenous nature of the extracted material, in agreement with the electrophoretic analysis. The main amide bands (A, B, I, II, and III), typically associated with collagen (Belbachir et al., 2009) were detected, indicating the secondary structure was preserved in both hand-net–collected and bycatch *R. pulmo*, and suggesting it was not affected by fishing conditions. The amide bands revealed hydrogen bonding (amide A), CH stretching vibrations from side chain groups (amide B), CO stretching vibrations of the peptide backbone (amide I), which confirm preservation of the helical conformation, NH bending (amide II), and Gly-X-Y tripeptide arrangement (amide III), confirming the typical triple-helix conformation (Riaz et al., 2018; Jafari et al., 2020). Moreover, the spectra were consistent with those reported for *R. pulmo* (Paradiso et al., 2019; Morelli et al., 2024), for other jellyfish species, such as *A. aurita* (Balikci et al., 2024), *R. esculentum* (Cheng et al., 2017), and *Cyanea nozakii kishinouye* (Zhang et al., 2014). Overall, they were also comparable to collagen from other marine sources such as fish (Kittiphattanabawon et al., 2010; Carvalho et al., 2018; Jaziri et al., 2022; Martins et al., 2022), starfish (Vate et al., 2022), or sea cucumber (Li et al., 2020), as well as mammalian sources (Belbachir et al., 2009; de Campos Vidal and Mello, 2011).

XRD analysis was used to assess the supramolecular organization of collagen fibrils. Both *R. pulmo* samples, from bycatch and hand-net collection, showed two diffraction peaks at 2θ angles of 8.6° and 19.4°. The first peak (d = 10.27 Å) represents the intermolecular spacing of the collagen triple helix, while the second (d = 4.57 Å) corresponds to the distance between helical backbones (Jaziri et al., 2022). These values are consistent with the structural dimensions of collagen comprising a triple helix and a left-handed helical chain (Jeong et al., 2013). The results further support that the native, undenatured conformation of *R. pulmo* collagen was preserved after extraction regardless of the jellyfish capture method. The diffraction patterns were consistent with those reported for other collagen sources, including lizardfish bone (*Saurida tumbil*) (Jaziri et al., 2022), codfish skin (*Gadus morhua*) (Bisht et al., 2021), ovine tendon (Fauzi et al., 2016), and *R. pulmo* collagen itself (Morelli et al., 2024).

The combined evidence from SDS-PAGE, FTIR, and XRD indicated that the extracted material corresponds to native, non-denatured collagen, with key structural features that were preserved regardless of specimen origin. No differences were detected between hand-net–collected and bycatch individuals, suggesting that incidental capture did not compromise collagen quality under the conditions tested. However, this characterization remains partial. Further analyses, including amino acid profiling, circular dichroism, and advanced molecular characterization, are necessary to more comprehensively assess extract purity, triple-helix integrity, and collagen classification.

From a processing perspective, yield optimization was beyond the scope of this comparison but represents an important next step. Collagen recovery could potentially be enhanced through pepsin-assisted and/or ultrasound-assisted extraction, which have been shown to improve solubilization and overall yield in marine collagens (Khong et al., 2018). Additionally, to better align collagen production with circular bioeconomy principles, greener extraction media such as Deep Eutectic Solvents (DES) could be explored, as they have improved yield and processing efficiency in other fishery bycatch-derived collagens (Batista et al., 2022), although they have not yet been evaluated for jellyfish collagen.

5 Conclusion

This study demonstrates that jellyfish bycatch from small-scale fisheries can be effectively valorized, providing a sustainable source of native collagen while advancing circular bioeconomy practices. *R. pulmo* was identified as the most abundant bycatch species and a viable source of high-quality collagen in the western Mediterranean. This collagen and its hydrolyzed products could be further explored for value-added applications in cosmetics, nutraceuticals, biomedicine, and other biotechnological sectors. Actively involving fishers in data collection, knowledge sharing, and decision-making within an Ocean Literacy framework is essential for the successful implementation of such bioeconomy strategies. Beyond their participatory role, the valorization of jellyfish bycatch could generate complementary income streams, reduce economic losses associated with unwanted catches, and contribute to the diversification and resilience of small-scale fisheries facing increasing environmental and market pressures. Together, these findings support the feasibility of integrating circular bioeconomy principles into small-scale fisheries management and highlight the need for further research on other recurrent jellyfish bycatch species such as *C. tuberculata*.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving humans were approved by Universidad Católica de Valencia San Vicente Mártir, 46001 Valencia, Spain. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Ethical approval was not required for the study involving animals in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

RT: Formal Analysis, Writing – original draft, Writing – review & editing, Data curation, Investigation, Methodology. JS: Formal Analysis, Data curation, Investigation, Methodology, Writing – review & editing, Writing – original draft. FR: Writing – review & editing, Methodology, Investigation. JT: Writing – review & editing, Funding acquisition. AB: Writing – review & editing, Methodology, Project administration, Supervision, Writing – original draft, Investigation, Conceptualization, Funding acquisition.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2026.1760045/full#supplementary-material.

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