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Growing together: Early-career perspectives on the current state and future of macrophyte research

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ABSTRACT

Early-career researchers (ECRs) play a vital role in advancing macrophyte research, bringing fresh perspectives, collaborative skills, and innovative methods to the field. Across marine and freshwater realms, macrophytes function as ecosystem engineers and key indicators of ecosystem health, yet they are declining due to a plethora of threats. As those who will shape the future of the field, ECRs are well-positioned to identify existing knowledge gaps and future priorities for the field in macrophyte research in a creative, integrative, and sustainable manner (both for the ecosystems and the ECRs themselves). Here, we present a unified perspective informed by the

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Science priorities
Survey

results of an international survey of 147 ECRs, capturing how ECRs see the field of macrophyte research at present and envision its future, including priorities for the field and how to overcome systemic barriers that ECRs face. Across realms and regions, ECRs currently use classical methods (e.g., field work, statistics) to study a wide range of topics including biodiversity, biotic interactions, and anthropogenic impacts. Regardless of research topic, ECRs are aware that technological advances are reshaping how research is conducted but acknowledge that they are not a silver bullet. Such advances should be harnessed to complement classical approaches, particularly taxonomy and field work. However, ECRs face structural barriers, including job insecurity and funding constraints, that disproportionately impact researchers in resource-limited regions within an already underrepresented field. Addressing these barriers and strengthening science-society connections is essential for the field's future, and requires collaborative, interdisciplinary, and innovative research grounded in a strong ecological foundation.

1. Introduction

Early-career researchers (ECRs), defined here as individuals at the early stages of their research careers, are recognised as the driving force behind the advancement of scientific research (Laudel and Gläser, 2008). Along with new ideas and perspectives, ECRs bring enthusiasm, creativity, and energy to research that provides the momentum necessary for labour intensive and long-term projects led by established researchers (Baer et al., 2023; Deng et al., 2022; Wu et al., 2019). They also play a substantial role in data collection and methodological innovation, especially in terms of the development and application of new techniques (Wiley and Kerby, 2018; Xu et al., 2022). Moreover, ECRs understand the need and the benefits of working collaboratively and across disciplines (Haider et al., 2018; Lerback et al., 2020; Millar, 2013; Naik et al., 2023; Pannell et al., 2019). Because ECRs are so deeply immersed in the current literature and emerging technologies, they are uniquely positioned to identify the current state of the field and promising directions for future research. Given this, understanding how ECRs perceive the current state and the evolution of their research field is critical, especially because today's ECRs are tomorrow's research leaders (Bankston et al., 2020).

Although ECRs are gaining recognition as key actors in scientific research, their perspectives remain underrepresented in research agendas, despite their research priorities likely becoming the central themes of future research. Typically, horizon scans and perspective pieces are written by the established leaders in the field or grounded in senior scholars' retrospective insights, reflecting the depth of experience and insight that accumulated expertise affords (Alahuhta et al., 2021; Bolpagni et al., 2024; Herbert-Read et al., 2022). While fields adjacent to macrophyte research have begun to incorporate ECR perspectives on the development and future of their fields (Graham et al., 2023; Yannelli et al., 2022), a data-driven synthesis of ECR perspectives in macrophyte research has not yet been documented.

Despite ECR perspectives being underrepresented, ECR-led research makes substantial contributions to the field. For example, recent research by ECRs has demonstrated novel pathways of carbon storage and methane flux (Cabrera-Lamanna et al., 2026; Chen et al., 2025), the importance of macrophyte life forms on ecosystem structure and functioning (Bomfim et al., 2025; Wang et al., 2025), and key differences between closely-related taxa with important implications for macrophyte conservation and management (Corbin and Oxenford, 2023; Petronilho and Castro, 2026). Furthermore, ECRs have begun harnessing the potential of enhanced computational power and tools, such as machine learning, to compile large datasets and answer persistent ecological questions using modern meta-analytical and synthetic frameworks (Foster et al., 2025; Mahdjoub et al., 2026; Trottier et al., 2026). This demonstrates that ECRs are already steering the field of macrophyte research in novel directions that refine existing theory, modernise our approaches, and improve our understanding of aquatic systems.

Central to this study are macrophytes, which are broadly defined as aquatic photosynthetic organisms large enough to be visible to the naked eye that grow permanently or periodically in fresh, brackish, or saline water and require waterlogged conditions to complete their life cycle (Chambers and Maberly, 2024; Hilt et al., 2022; Hopkinson et al., 2019). Macrophytes act as ecosystem engineers that create, maintain, or modify their physical and chemical environment, and they underpin the delivery of ecosystem functions and services that are essential for ecological integrity and human existence (Bennett et al., 2015; Polvi and Sarneel, 2018; Thomaz, 2023). Despite their ecological importance, society often perceives macrophytes as a nuisance that should be removed (Schneider et al., 2024; Thiemer et al., 2023), rather than a benefit to aquatic ecosystems (Thomaz, 2023; Yu et al., 2025). Together with numerous climatic changes and anthropogenic stressors (for examples see Davis et al., 2022; Duarte et al., 2018; Luo et al., 2025; Moreira et al., 2023; Stockbridge et al., 2020; Tasker et al., 2022), macrophytes are facing widespread declines (Botrel and Maranger, 2023; Dunic et al., 2021; Phillips et al., 2016). In the face of accelerating global change, identifying the precise impacts of such stressors and strategies to mitigate them is an urgent research priority, and ECRs are uniquely positioned to address this priority in a dynamic, interdisciplinary, and innovative manner.

Beyond identifying research priorities, the ability of ECRs to conduct research in the future relies on the mentorship they receive and their ability to overcome previously documented professional challenges (see Van Der Weijden and Teelken, 2023; Woolston, 2019). Securing a permanent research position and gaining recognition in the field is not merely a function of merit but is closely tied to the quality of mentorship received, particularly when mentors actively involve mentees in their collaborations and networks (Liénard et al., 2018). As such, it is also important to identify the barriers that ECRs face and how they can be overcome to ensure that future macrophyte research can progress efficiently.

In this study, we present a data-driven synthesis of ECR perspectives on the current state of macrophyte research and the future development of the field. Specifically, we aim to (1) characterise the current research foci and methods used by ECRs; (2) identify the knowledge gaps posing the greatest constraints on advances in the field; (3) determine the specific research foci ECRs anticipate will be important in the future and how ECRs envision the future of the field more generally; and, (4) highlight the key challenges ECR face and specific actions that can be taken to address them to support the future of the field. To do this, we conducted an anonymous, international online survey of ECRs who research macrophytes to quantify the demography and current research areas of the ECR community and compile their perspectives. When relevant, we considered factors such as gender, geographic distribution, career stage, and realm of study (freshwater, coastal, marine) in our synthesis, as they may influence ECR perspectives. We analysed the survey results quantitatively and qualitatively, highlighting points of agreement and expanding upon them by drawing on our individual areas of research expertise and our personal experiences as ECRs.

2. Methods

2.1. Definition of "Early-Career Researcher"

The term "Early-Career Researcher" (ECR) lacks a universally accepted definition. International funding bodies and policy frameworks use widely varying definitions, as shown in Table S1 (Supplementary Material 1). Across these definitions, ECRs are consistently defined as researchers in a transitional career phase, typically with limited independence, temporary employment conditions, and ongoing development of their research leadership skills and professional networks. In this study, we define ECRs using both time- and role- based criteria, that encompasses multiple career stages, including master's students, doctoral students and candidates, and postdoctoral and other researchers within eight years of their highest degree. It is important to note that the various career stages that exist within the broader definition of ECR do not represent a linear career trajectory (i.e., master's students do not necessarily become doctoral candidates, post-doctoral researchers do not necessarily become professors, etc.).

2.2. Survey design and dissemination

The survey was developed to characterise the ECR community in macrophyte research and to capture their current research areas and perspectives on the future of the field. It was conducted using Microsoft Forms between 4 June and 22 July 2025. Participation was voluntary and open to all ECRs per our definition (see Section 2.1) whose research involved aquatic macrophytes across freshwater, coastal, and/or marine systems, regardless of geographic location, institutional affiliation, research focus, career stage, or gender. This inclusive approach aimed to capture diverse perspectives across the global ECR macrophyte research community. The survey was conducted in accordance with the ethical guidelines of the Poznań University of Life Sciences (Resolution No. 17/2025). Respondents were informed about the study purpose and data use, responses were collected anonymously, and no identifiable personal data were retained.

The survey included 48 questions written in English (Supplementary Material 2). Of the 48 questions, 45 were closed-ended, with multiple-choice, ranking, Likert-scale, or categorical response options. The questions were organised into five thematic sections:

(1) Respondents' background (career stage, years post-PhD, age, gender identity, and geographic origin and current location);
(2) Research profile (e.g., study systems, taxa, methods, and spatial scale);
(3) Funding situation and career development (e.g., employment status, funding sources, grant experience, perceived barriers);
(4) Development of macrophyte research (e.g., knowledge gaps, priorities, and future directions); and,
(5) Final reflections (e.g., innovation, collaboration, and community gaps).

The remaining three open-ended questions addressed: (i) current knowledge gaps in macrophyte research, (ii) future development of the field over the next 15 years, and (iii) general comments. The survey was distributed by authors MB, AL, AP, and LLT via professional networks, mailing lists, and social media platforms (e.g., LinkedIn, BlueSky, X) to maximise international reach. Numerous international scientific societies and research networks were contacted, with efforts made to ensure researchers from all continents and realms were reached (Table S2, Supplementary Material 1).

2.3. Data analyses

All data were analysed in R (v4.4; R Core Team, 2025). Raw survey data were first cleaned, harmonised and standardised before aggregation. Career stage was consolidated from free text and multiple option entries into six groups:

1) Student (Bachelor's and Master's students);
2) PhD candidate;
3) Postdoc;
4) Researcher (all non-postdoctoral researchers);
5) Professor (including assistant, associate, and full professors, as well as other faculty and academics); and,
6) Other (all remaining entries, such as university lecturers and independent consultants).

These career stage groupings were created following the survey and aimed to compile a wide variety of responses into a smaller list of categories. Variation in the initial responses is likely due, in part, to differences in career stage terminology used across the world. For example, the term "doctoral student" and "doctoral candidate" have different meanings in some countries but can be used interchangeably in others. As noted above, these career stages are not implied to follow a linear trajectory.

Gender was simplified to Man, Woman, or Other (aggregating non-binary and prefer-not-to-say responses). Scientific mobility was defined as a change in country between the respondent's origin and current location. The desired career path was recorded in three categories: Research (academic or non-academic), Undecided, and Other.

All analyses were descriptive. Categorical variables were summarised using frequencies and percentages of total respondents ($n = 147$), or of the relevant career-stage subgroup for stratified analyses. Multi-select responses were separated into individual entries before tabulation. To compare current research areas with future priorities, we calculated the proportion of mentions out of all mentions within the respective question (current research areas: unlimited choices; future priorities: up to three choices per respondent) and subtracted the current proportion from the future proportion. This normalisation was necessary because these two questions allowed up to three responses, making a direct comparison of raw respondent percentages invalid.

Responses to open-ended questions about the most significant knowledge gaps or unresolved questions within macrophyte research, and how ECRs envision the field of macrophyte research by 2040 (in terms of research focus, methods, collaborations, technologies, or the societal role of macrophyte research) were subjected to abductive thematic analysis with the assistance of ChatGPT 5.2 following the systematic thematic analysis framework proposed by Naeem et al. (2025). Unlike purely inductive approaches (deriving theory from data) or deductive approaches (testing pre-existing theory against data), this abductive approach consists of integrating both empirical data and existing theory to develop explanations that best account for observed patterns (Tavory and Timmermans, 2014). Using this abductive approach, responses were examined to identify meaningful keywords, which were synthesised into conceptual codes and subsequently grouped into broader themes representing recurring patterns related to the research questions (see Tables S3-S4 in Supplementary Material 1). Responses were assigned to one or more themes and quantified as percentages of total responses.

3. Results

3.1. Overview of survey participants

The survey included 147 participants from 51 countries across all continents except Antarctica, with Europe being the most represented region (51% of participants, Fig. 1A, see map in Figure S3−1 in Supplementary Material 3). Research in inland waters was the dominant realm across most regions, with coastal/marine researchers more prominent in Europe and North America (Fig. 1 A). A broad range of ecosystems, taxa and spatial scales were covered (Figure S3−2 in

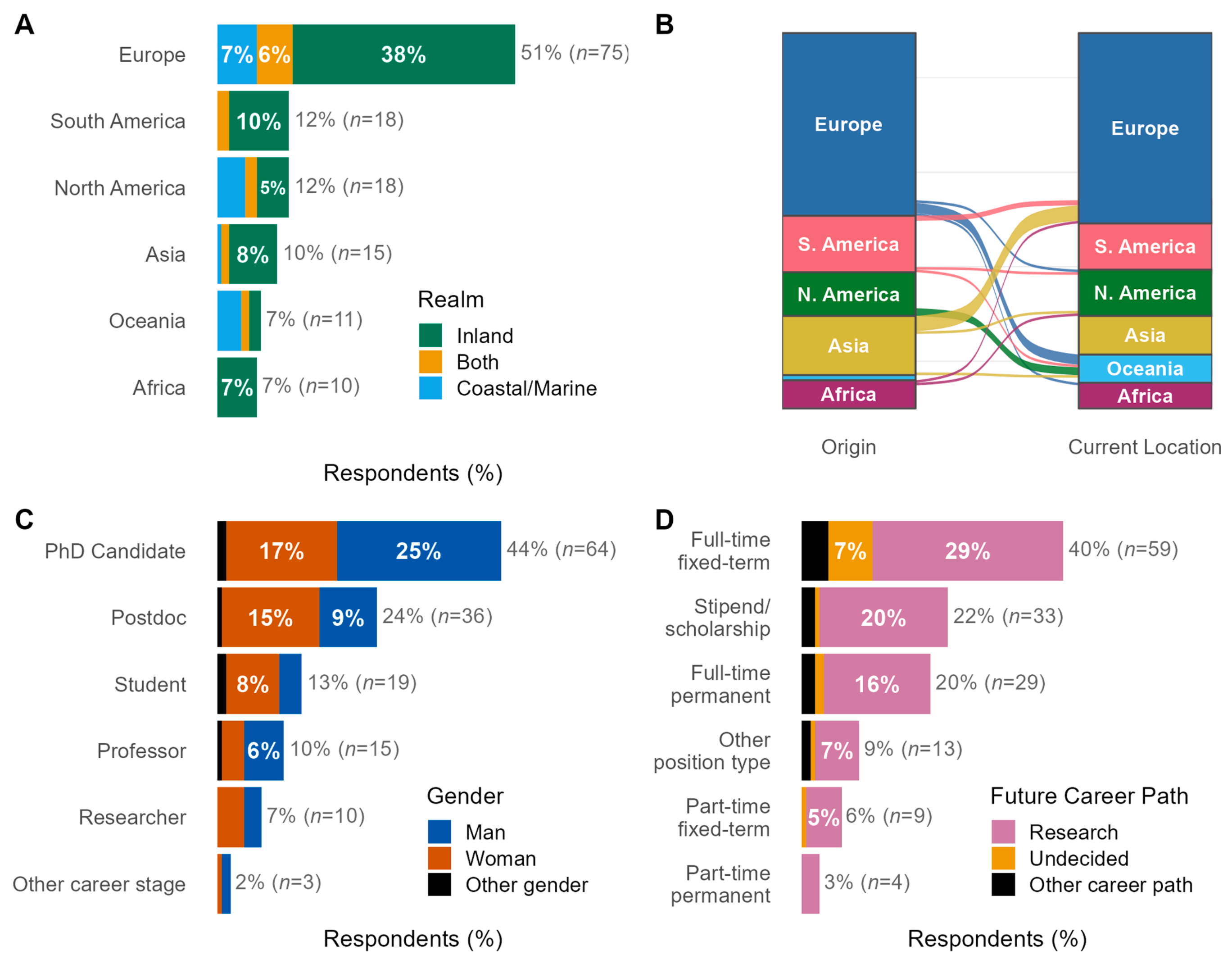

Fig. 1. Demographic and professional profile of survey participants in the macrophyte science community ($n = 147$). (A) Geographic distribution of respondents across six continents and their primary research realms (Inland, Coastal/Marine, or Both). (B) Scientific mobility showing the transition between continent of origin (left) and current professional location (right). (C) Distribution of career stages categorised by gender identification (Man, Woman, or Other). (D) Current employment status of respondents and their intended future long-term career paths.

Supplementary Material 3). The majority of respondents (84.2%) worked on the same continent as they were from, with only 6.3% having relocated to another continent (Fig. 1B). Among those who relocated, Europe and Australia/Oceania were the most common destinations. Gender distribution was near-equal among women (48.3%) and men (47.6%), with 4.1% of respondents identifying as non-binary or other (Fig. 1 C). Doctoral (PhD) candidates and postdocs together accounted for nearly two thirds of participants (Fig. 1 C). Most respondents held full-time fixed-term positions or stipends/scholarships, and the large majority intended to pursue a research career (Fig. 1D). The majority of respondents were aged 26–35 (Figure S3–3 in Supplementary Material 3).

3.2. Current research areas and methodologies

Early-career macrophyte researchers worked across a broad range of research areas (Fig. 2A) with biodiversity as the most commonly studied topic, followed by interactions between macrophytes, invasive species, (bio-)monitoring, and climate change. Applied and conservation-related topics, including restoration, ecosystem functioning, conservation, and other human impacts, were each reported by roughly a quarter of respondents. Topics at the interface of ecology and society, such as ecosystem services and nature-based solutions, management, and water treatment, were less common, as were remote sensing and phylogenetics/systematics.

The methodological approaches used by ECRs were centred around classical ecological techniques (Fig. 2B). Field work and statistics were near-universal, and experimental studies were common. In contrast, methodological approaches that are reliant on more modern technological advances, such as laboratory, spatial, and modelling approaches were each used by roughly a quarter to a third of respondents. Similarly, computational and remote sensing methods remained the least commonly used. Research areas and methods slightly diverge by continent and realm (Figures S–4 to S3–6 in Supplementary Material 3).

3.3. Perceived knowledge gaps in macrophyte research

The systematic thematic analysis revealed five major themes of knowledge gaps perceived by ECRs in the field as constraining the advancement of macrophyte research (Table S3, Supplementary Material 1). The most frequently mentioned theme was **Fundamental ecological knowledge of macrophytes**, reported in 56% of the responses, indicating limited understanding of biotic interactions, physiological and functional traits and their relationship with the

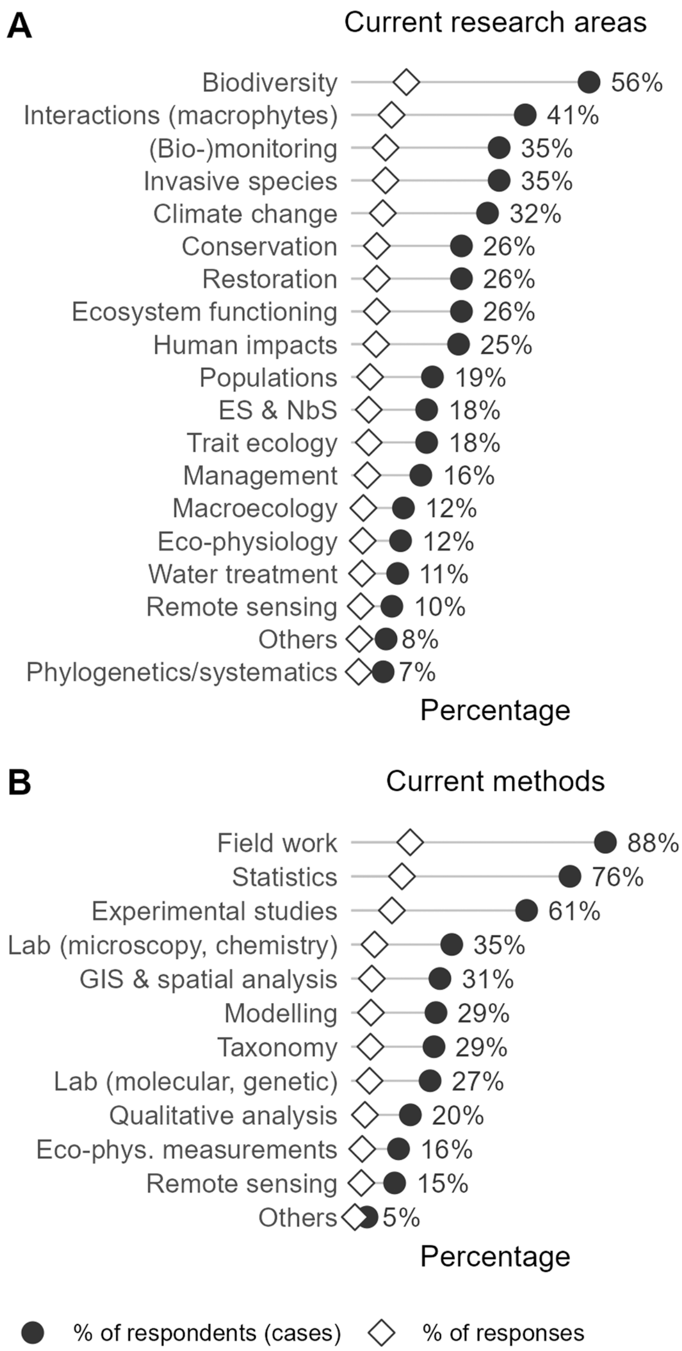

Fig. 2. Overview of research activities among early-career macrophyte researchers (n = 147 respondents). (A) Distribution of research areas. ES & NbS = Ecosystem Services and Nature-based Solutions. (B) Prevalence of methodologies and technical approaches utilised in current research projects. Eco-phys. meas. = Ecophysiological measurements. For both panels, multiple selections were permitted per question.

environment, species distributions, and community assembly. Respondents also identified important gaps in understanding the roles of macrophyte in key ecosystem processes such as nutrient and biogeochemical cycling, and biodiversity-ecosystem functioning relationships.

The second most common theme, **Methodological and data limitations** (37%), included a lack of macrophyte biodiversity data, particularly in understudied regions, and insufficient long-term monitoring. Taxonomic challenges, including the scarcity of trained specialists, were also frequently mentioned. Respondents further identified the need for improved and standardised sampling approaches, non-destructive estimation methods, and wider use of modern tools, such as remote sensing, molecular techniques, and artificial intelligence.

The **Impacts of multiple stressors** (33%) is the next theme most commonly highlighted by ECRs and refers to a lack of knowledge around the interacting and cumulative effects of both local and global environmental changes. Limited knowledge of the capacity of macrophyte communities to adapt to or mitigate environmental change over time was also emphasised.

The theme of **Ecosystem services and restoration** (30%) reflected limited understanding of macrophyte roles in ecosystem service provision and quantification, including carbon sequestration, and knowledge gaps answering questions related to invasive species management, effective restoration strategies, and ecosystem resilience under global change. The role of macrophytes as nature-based solutions and their limited recognition by the research community, society, policymakers, and environmental managers were also often highlighted.

Finally, **Understudied systems and cross-system comparisons** (23%) pointed to geographic and ecosystem biases, particularly in tropical regions and lotic systems. Respondents also indicated that comparative research across realms (i.e., aquatic, terrestrial), among aquatic systems (i.e., freshwater, brackish, marine), and across spatial scales, should be considered as research priorities. Lastly, 17% of respondents indicated that they were unsure about the most significant knowledge gaps in macrophyte research.

3.4. Future research areas and methodological developments

Respondents indicated a shift in research priorities, expressed as the change in relative share of topic mentions between the current research area and the future priority question (Fig. 3A). Topics expected to gain more importance were linked to global environmental challenges associated with human impacts and society's reliance on macrophytes for goods and services, listed in order of decreasing gain: climate change, ecosystem functioning, invasive species, human impacts, and ecosystem services and Nature-based Solutions. In contrast, topics such as (bio-)monitoring, macrophyte interactions, populations, and trait ecology are expected to lose relative share.

Next, ECRs identified a clear set of emerging methods they expect to shape the field (Fig. 3B). Modern methods such as DNA metabarcoding and eDNA were selected most often, followed by machine learning and open-access data platforms. Trait-based and functional ecology approaches and remote sensing, ecological modelling and forecasting, and citizen science and sensor networks were also frequently mentioned. The main research funding priority identified by ECRs is long-term macrophyte research programs (S3–7 in Supplementary Material 3).

3.5. Future vision of the field of macrophyte research

The systematic thematic analysis revealed seven major themes (Fig. 4) describing how ECRs envision the future of macrophyte research (Table S4, Supplementary Material 1). The most prominent theme, **Technological innovation and advanced analytical tools,** highlights strong expectations that advances in technology will transform the field (Fig. 4). Responses emphasised increasing use of remote sensing (drone-based and satellite imagery), automated monitoring systems, and molecular tools such as eDNA for biodiversity assessments. This is consistent with the emerging technologies identified by ECRs in Section 3.3. These advances are expected to improve early detection of invasive species, real-time monitoring of macrophyte distribution and health, and tracking of rapid environmental change. AI-assisted species identification, functional trait extraction from images, and predictive modelling were also anticipated to become central tools.

The second most common theme, **Advancing fundamental ecological knowledge of macrophytes**, reflects expectations for progress in addressing fundamental ecological knowledge gaps. Respondents expected substantial advances regarding several of the

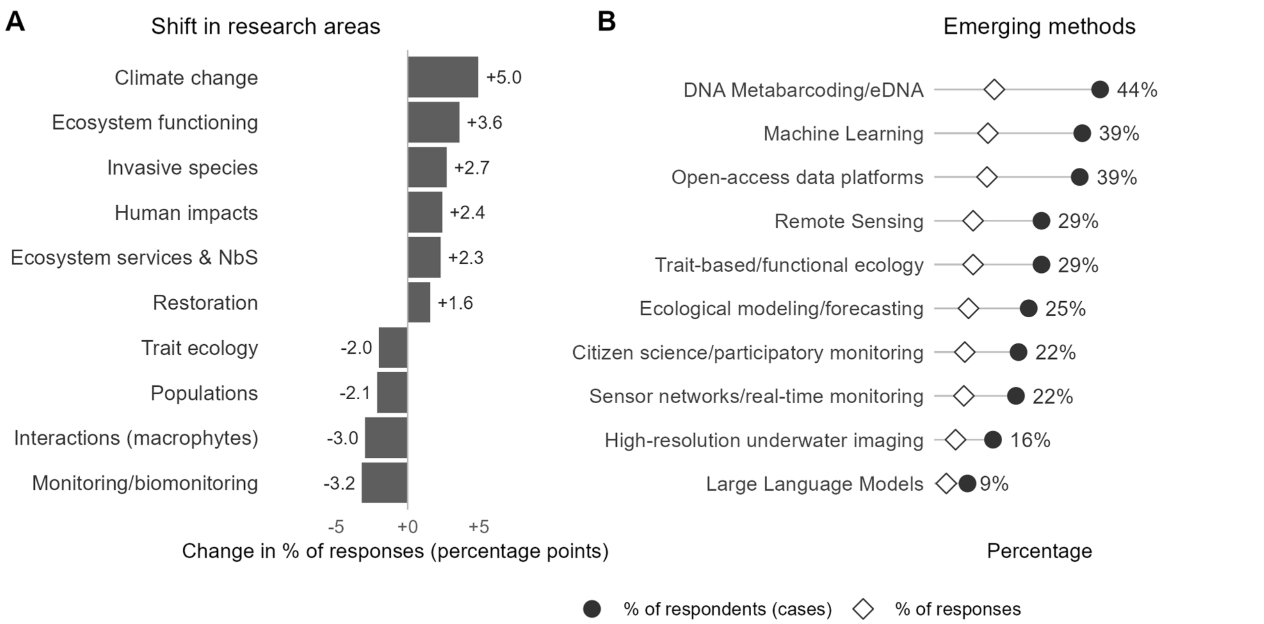

Fig. 3. Shifts in research areas and emerging methods among early-career macrophyte researchers (n = 147 respondents). (A) Change in the relative share of each topic between current research areas and future research priorities. Positive values indicate topics that gained relative share as a future priority, negative values indicate topics that lost relative share. Only the top ten with the largest absolute change are shown. (B) Top methods and technologies considered for future research. For panel B, multiple selections were permitted per question.

knowledge gaps identified in Section 3.2. These include advances in trait-based ecology and ecosystem functioning, species distributions, biodiversity patterns, and taxonomy, as well as clearer understanding of how multiple interacting stressors affect macrophyte communities and aquatic ecosystem functioning.

The third most mentioned theme, **Bridging science, society, and policy**, indicates that ECRs envision stronger connections between scientific research, society, and decision-making processes. Respondents emphasised improved communication between scientists, policymakers, and the public, leading to greater recognition of the ecological roles and services provided by macrophytes. Many ECRs highlighted the potential of macrophyte research to address pressing societal challenges such as climate change mitigation, water purification, biodiversity conservation, and sustainable ecosystem management, often identifying macrophytes as nature-based solutions. This third theme also emphasises the need for stronger engagement with local communities and stakeholders, including the integration of citizen science and traditional ecological knowledge into research and monitoring programs. Closely related to this is the fourth theme, **Macrophytes in conservation and ecosystem restoration**, which reflects the expectation that macrophytes will play a more central role in the protection and restoration of aquatic ecosystems.

The future of the field was also frequently envisioned as more connected and collaborative, reflected in themes four to six: **Global collaboration and research networks**, **Interdisciplinary and cross-system research**, and **Open science and data sharing culture**. Respondents highlighted stronger international research networks, interdisciplinary collaboration, and more open, transparent research practices, including shared global databases and open-access platforms. Additionally, 25% of the respondents indicated that they did not know what to expect for the future of the macrophyte research field.

These insights from the thematic analysis align closely with ECRs' preferred approaches to conducting their own research in the future (Fig. 5). Interdisciplinary and solution-oriented research were strongly favoured over intradisciplinary and theory-oriented work. Most respondents also preferred targeted and outcome-driven research, technology-driven methods, and stakeholder-engaged science. Preferences regarding study scale were more evenly balanced, with respondents split between global and comparative research, and local and contextual approaches.

3.6. Key challenges and support needs to secure funding across career stages

Survey results indicated that professional challenges do not diminish as careers progress but instead shift in nature (Fig. 6A). At the earliest career stages, job security, low remuneration, and funding availability were the most frequently reported professional challenges among students and PhD candidates. At the postdoctoral stage, job security becomes the most pressing concern, alongside funding availability, with work-life balance and publish-or-perish pressure and work-life balance each affecting around half of the respondents. Among researchers, funding availability and job security are jointly the top concerns, while publish-or-perish pressure drops notably. Among professors, work-life balance and publish-or-perish pressure become the leading challenges, while concerns over job security decrease. Funding availability remained a concern across all career stages. Most of the challenges are reported more frequently by women than men (Figure S3–8 in Supplementary Material 3) and slightly differ between continents (Figure S3–9 in Supplementary Material 3).

Support needs to secure research funding largely reflected the challenges reported at each career stage (Fig. 6B). Students most frequently reported needing information about available grants, collaboration opportunities, and mentorship. Dcotoral (PhD) candidates prioritized mentorship, grant information, collaboration opportunities, and training on grant writing. At the postdoctoral stage, information about available grants and collaboration opportunities were most prominent. Among researchers, the picture shifts: mentorship becomes the top need, followed by help with budget preparation and institutional support. Professors most frequently reported needing mentorship, grant information, and reduced administrative loads. However, the biggest share of ECRs (45%) are somewhat confident or not very confident (33%) about securing future funding (see Figure S3–10 in Supplementary Material 3).

Fig. 4. Thematic areas identified using abductive thematic analysis from the open-ended question *"Imagine the field of macrophyte research in the year 2040 — what do you envision it will look like?"* (Table S4, Supplementary Material 1). Bubble area is proportional to the number of responses assigned to each theme, and percentages indicate the share of all responses ($n = 147$). Multiple themes per response were possible, therefore percentages sum to > 100%. Selected responses of survey participants illustrating each theme are shown inside the bubbles.

4. Discussion

4.1. Who are the ECRs? Survey representation and limitations

This survey captured a diverse group of ECRs spanning a wide range of career stages, geographic regions, and research systems. Research interests reflected a broad range of themes across inland and coastal waters. Regardless of this diversity, current practices remained strongly centred on field-based and other classical ecological approaches, such as well-established statistical frameworks and laboratory and in situ experiments. Most respondents intended to remain in research, indicating high career commitment despite existing challenges. The survey, however, also revealed biases that must be considered when interpreting the results.

Despite considerable efforts to disseminate the survey, respondents were disproportionately based in Europe and focused on inland systems, with limited representation from biodiversity-rich regions such as Africa and Asia, as well as from coastal and marine research communities. While efforts were made to disseminate this survey via a geographically diverse list of societies/organizations (Table S2, Supplementary Material 1), we were unable to contact all potentially relevant organizations. Future surveys could improve geographic representation by contacting additional societies/organizations, such as the Aquatic Plant Management Society and the Society of Wetland Scientists.

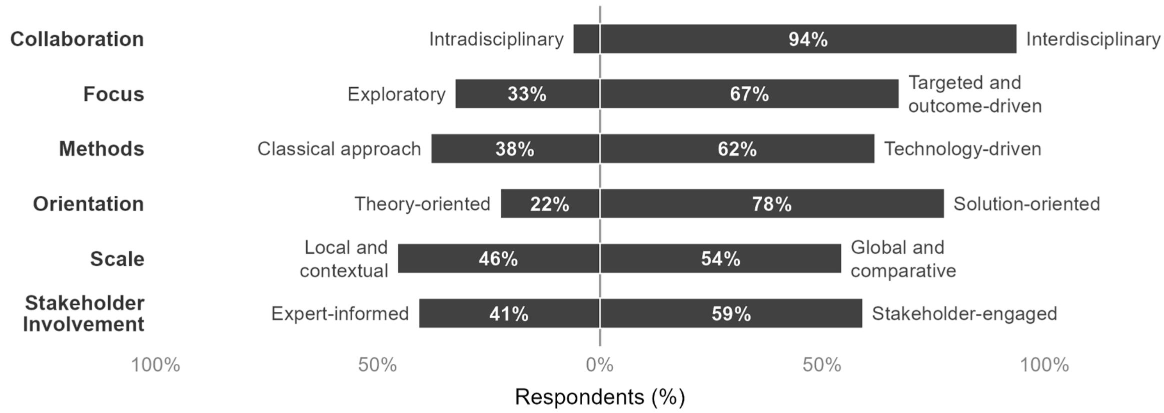

Fig. 5. Personal research aspirations of early-career macrophyte researchers. Respondents indicated how they would like to conduct their own research in the future across six dimensions: Collaboration (Intra- vs. Interdisciplinary), Focus (Exploratory vs. Targeted and outcome-driven), Methods (Classical vs. Technology-driven), Orientation (Theory- vs. Solution-oriented), Scale (Local and contextual vs. Global and comparative), and Stakeholder Involvement (Expert-informed vs. Stakeholder-engaged).

It is also important to note that the survey was conducted in English, which may have negatively influenced participation by ECRs whose first language is not English, despite the availability of translation and language support tools. Language of questionnaires remains an important topic among social scientists, with numerous "best-practices" for translating and conducting global (i.e., cross-cultural) surveys (Behr and Shishido, 2016; Survey Research Center, 2016). However, there appears to be a lack of consensus among experts on which method or approach is preferred, and a review of 31 different survey guidelines found that results across approaches are comparable (Epstein et al., 2015). Furthermore, survey response rates are not necessarily guaranteed to be increased through translation of the survey to multiple languages (Andersson, 2025; Lundmark et al., 2023). This survey therefore provides a valuable snapshot of ECR perspectives but does not claim to fully represent the global macrophyte early-career research community.

Gender distribution of survey respondents was near-equal, but female representation declined at more senior career stages, a pattern documented in academia more broadly (Huang et al., 2020; UNESCO, 2021; European Commission Directorate-General for Research and Innovation, 2021). We note that social media recruitment may have also introduced participation biases, as younger women are known to respond more often to online surveys and social media recruitment than other groups (Becker, 2022; Sanchez et al., 2020; Smith, 2008). These imbalances likely also reflect differences in access to funding, research infrastructure, and international networks. Gender differences lead not only to differences in challenges faced by individuals in academic settings (Casad et al., 2021), but can also lead to differences in their research agenda (capturing factors such as scientific ambition, preference for working on broad or a narrow range of topics, tolerance to conduct research with low funding, collaboration; (Santos et al., 2021). Despite this, we feel that the gender balance achieved by our survey is representative and should capture such differences.

4.2. *Knowledge gaps shaping future research priorities*

The collective perspective of ECRs outlines a clear research agenda for macrophyte science, driven not only by knowledge gaps and methodological advances, but also by how ECRs want to conduct their own research. Future research priorities closely align with the knowledge gaps currently perceived in the field. Persistent gaps in fundamental ecological knowledge, including interactions between macrophytes and animals, algae, and microbes, trait-based ecology, and ecosystem functions such as nutrient and biogeochemical cycling, indicate that the field still lacks a strong mechanistic foundation (Alahuhta et al., 2021; Dalla Vecchia et al., 2020; Nordlund et al., 2024). These gaps were consistently reflected in ECRs' visions of the future, where addressing fundamental ecological gaps emerged as a key priority. At the same time, ECRs aspire to conduct more targeted, outcome-driven, and solution-oriented research focused on global change impacts, management and restoration, that highlights how unresolved gaps are shaping future priorities. This reflects a transition from a field dominated by field-based and experimental studies focused on biodiversity, macrophyte interactions, and monitoring, toward research aimed at generating actionable knowledge and solutions. While future macrophyte research is expected to become more applied, its progress remains strongly dependent on addressing these knowledge gaps. Without considerable investment in fundamental research efforts to address current and future environmental challenges will remain limited.

Methodological and data limitations also shape future research priorities. The lack of biodiversity data, insufficient long-term monitoring, and taxonomic constraints expose persistent geographic and ecosystem biases, particularly in tropical and developing regions and understudied systems such as rivers, ponds and temporary waterbodies (Alahuhta et al., 2021; Hill et al., 2021). These limitations are reflected in opportunities for technological innovation, with ECRs anticipating increasing development and use of automated monitoring systems, remote sensing, molecular tools, and artificial intelligence. Emerging tools such as eDNA are promising non-invasive, sensitive, and cost-efficient approaches for biodiversity assessments, particularly in heterogeneous and difficult to access habitats (Revéret et al., 2023; Schenekar, 2023). While these approaches have strong potential to address existing biases and data limitations, ECRs recognise that they are not a silver bullet and cannot resolve all underlying gaps.

Despite this alignment, some mismatches between current gaps and future priorities remain. Taxonomic challenges are recognised as a major constraint, yet taxonomy is largely absent from the topics ECRs identify as priorities for their own research. Although taxonomy uses molecular and computational methods, and benefits from expanding online databases housing DNA and species-level descriptions and imagery (e.g., the Global Biodiveristy Information Facility; Fehrer et al., 2022; Padial et al., 2010), macrophyte species identification remains difficult due to reduced morphology and high phenotypic plasticity (Fehrer et al., 2022). While molecular tools such as eDNA can assist in detecting introduced species (Krueger-Hadfield et al., 2017) and hard-to-detect groups like mosses (Reinhart et al., 2025), reliable identification, especially to the species level, still depends heavily on trained taxonomists (Padial et al., 2010). Recent molecular approaches have revealed substantial genetic variation below the species level, such as distinct genotypes or strains. This underscores the importance of integrating taxonomic and genetic expertise, especially in research on

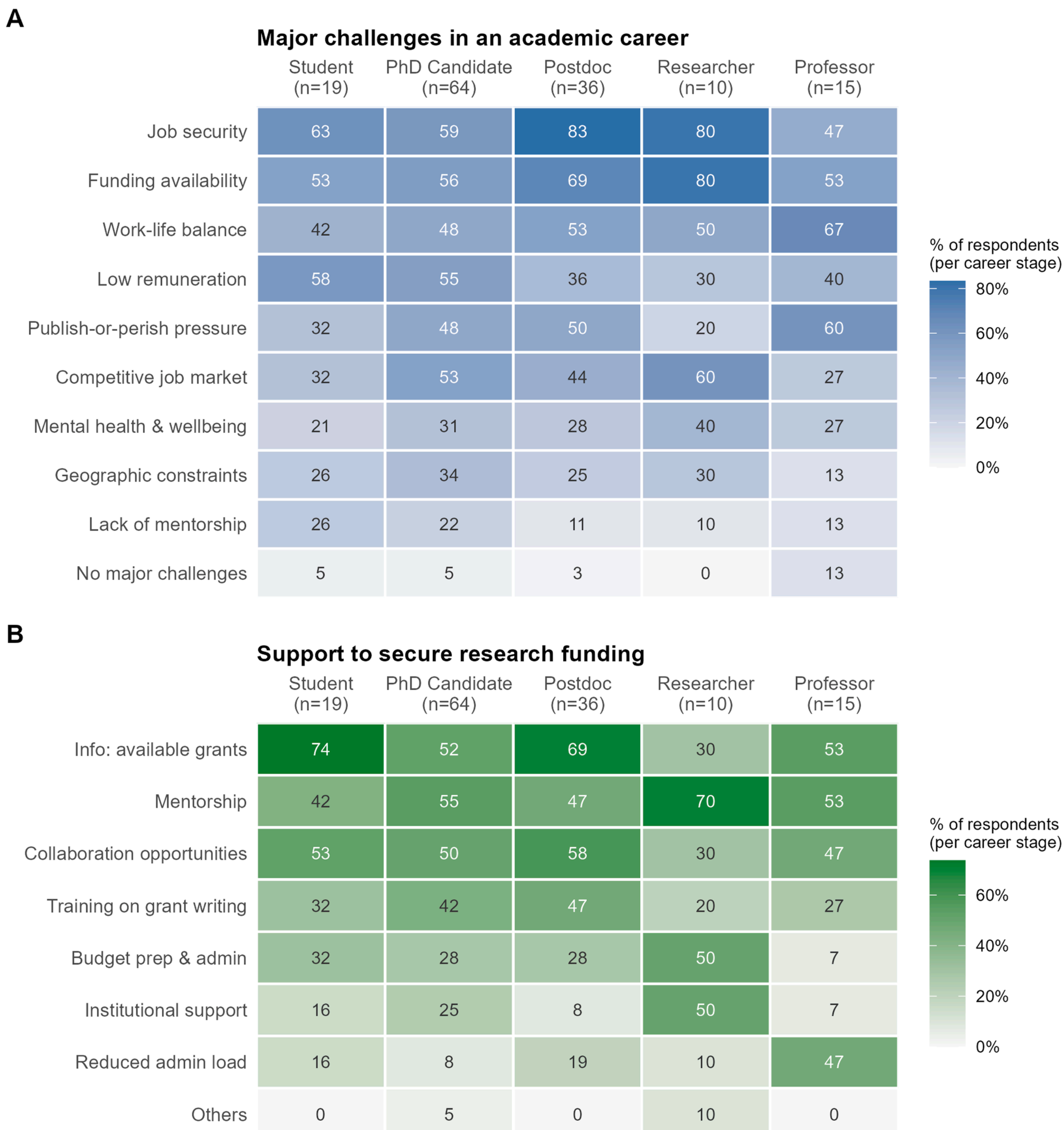

Fig. 6. Professional challenges and support needs to help secure research funding across career stages. (A) Prevalence of identified challenges reported by respondents at each career stage. (B) Types of support identified by respondents as most important to help secure research funding. Percentages are calculated within each career stage to allow for comparison across groups with different sample sizes (*n*).

invasive macrophytes and large-scale biogeographic comparisons. Furthermore, taxonomic descriptions and revisions are rarely cited, providing little academic incentive for taxonomic research (Agnarsson and Kuntner, 2007). The scarcity of taxonomic expertise is unlikely to be resolved with the identified emerging methods. Addressing this gap therefore requires recognition of taxonomy as a fundamental component of ecological research, alongside increased investment in training, infrastructure, and long-term institutional support for taxonomic expertise.

4.3. A shift toward integrative, predictive, and technology-driven research

Across all dimensions of the future development of macrophyte research, interdisciplinary collaboration emerges as a core theme. This is particularly important for addressing complex environmental problems, such as multiple interacting stressors, climate change, biological invasions, biodiversity loss, and environmental degradation, which cannot be effectively addressed within disciplinary boundaries alone (Dick et al., 2017; Mauser et al., 2013). Instead, they require holistic and integrative approaches that combine ecological, biogeochemical, hydrological, and computational methods alongside disciplines such as geography, chemistry, engineering, economics, and social sciences. Prioritising interdisciplinary work reflects a shift toward more integrative and collaborative science, where translating findings across systems and scales becomes essential for generating robust and broadly applicable solutions.

In this context, ECRs envision future macrophyte research focusing more on overcoming persistent geographic and ecosystem biases (Alahuhta et al., 2021; Pan et al., 2023; Smulders et al., 2025), and on conducting cross-realm macrophyte research (Botrel et al., 2026). This type of research is supported by stronger global research networks and open data platforms that facilitate collaboration and data integration across disciplines, regions, and realms. This also reflects a shift toward more integrative and technology driven research, where advances in remote sensing, molecular tools, and artificial intelligence enable ecological data to be collected, processed and analysed more efficiently and at larger temporal and spatial scales. However, many of these approaches are not yet fully developed or widely applied. For example, remote sensing technologies are opening up new possibilities for data collection across large spatial scales (Rowan and Kalacska, 2021). Advances in hyperspectral imaging may also support the detection of plant functional traits and improve ecosystem-level assessments (Dalla Vecchia et al., 2026). Remote sensing also enables non-destructive biomass estimations and facilitates the quantification of ecosystem functions such as carbon sequestration (Lu et al., 2024; Rowan and Kalacska, 2021). Increased collaboration, data integration and technological advances alone, however, are unlikely to resolve the persistent imbalance in research efforts in underrepresented areas and understudied systems. By expanding the scale and integration of ecological data, these developments are expected to increasingly support large scale and predictive studies.

Large-scale studies can also shape our understanding of ecological functioning and associated responses to global change, as revealed by long-term declines in submerged aquatic vegetation in lakes which indicates shifts toward turbid, phytoplankton-dominated states (Luo et al., 2025). At the same time, complementary local studies will remain critical for capturing ecological detail and understanding system-specific dynamics, as well as for providing validation data for larger scale analyses. The nearly even split between local and contextual, and global and comparative research approaches among ECRs points to the importance of combining both perspectives in future macrophyte research.

Advances in ecological modelling and forecasting, supported by increased computational power and the integration of large, multi-source datasets, are expected to enable robust predictions of macrophyte and whole-ecosystem responses to environmental change (Gsell et al., 2025; Lewerentz et al., 2023). Such forecasting can also inform management strategies and policy decisions under future environmental uncertainty (Campbell et al., 2024). These developments are closely linked to the increasing importance of open science. For example, data from publicly funded monitoring efforts are often inaccessible, limiting the access to long term datasets (van Rees et al., 2021). Addressing this will require improved data management based on FAIR principles (findable, accessible, interoperable, and reusable; Wilkinson et al., 2016), as well as the expansion of international, open-access platforms on aquatic biodiversity. Together, this reflects a cultural shift in how ECRs want to approach research, characterised by increased collaboration, data sharing, and open science practices. This cultural shift can be shaped both by ECRs who already have experience with such approaches and want to continue them, and by those who lack such experiences but their vision for the future is based on a desire to learn new approaches.

4.4. Bridging science and society: the growing relevance of macrophyte research

Taken together, our survey indicates that ECRs envision a future where macrophyte research focuses more on addressing pressing environmental challenges, with an emphasis on ecosystem functioning and services, Nature-based Solutions, and restoration. This aligns with a strong preference in ECRs to conduct solution-oriented and outcome-driven research. These priorities, however, are not developing in isolation and are shaped by broader policy frameworks and societal demands. European environmental policies, such as the Water Framework Directive and the Nature Restoration Regulation, and global agendas, such as the United Nations Sustainable Development Goals, increasingly prioritise applied research that can inform management and support sustainable resource use (Elfithri et al., 2025; Huss et al., 2022; Voulvoulis et al., 2017). Within this context, macrophyte research is positioned as key for addressing societal challenges including water quality degradation, climate change, and biodiversity loss, while delivering services such as nutrient regulation and carbon sequestration (Macreadie et al., 2017; Thomaz, 2023). However, achieving this shift will require overcoming existing gaps in communication and integration between science, policy, and society.

In this survey, ECRs emphasised the importance of stakeholder-engaged research, and identified improved communication between scientists, decision-makers, and the broader public as a key priority. Despite their applied value, the ecological importance of macrophytes remains insufficiently recognised both within the scientific community and across society. For example, only 1.75% of €745 million in European environmental grants were allocated to freshwater research in 2018, highlighting the limited funding available for these systems (Maasri et al., 2022). The integration of citizen science and traditional ecological knowledge into research and monitoring is also viewed as an important avenue for expanding data collection and increasing public engagement (Buldrini et al., 2015; De Freitas et al., 2015; Onwong'a et al., 2024; Vázquez-Delfín et al., 2024). Crucially, this also reflects a growing need to build and maintain social license (i.e., public understanding, acceptance, and support) for aquatic management which is essential for the successful implementation of management, conservation, and restoration actions (Kelly et al., 2019).

At the same time, this growing emphasis on the application of macrophytes in management is not fully matched by the current level of ecological understanding. Significant gaps remain in quantifying ecosystem services, understanding how macrophytes contribute to ecosystem functioning under changing environmental conditions, and determining how restoration strategies can be optimised across systems (Bennion et al., 2024; Schneider et al., 2024). Restoration success is often highly context-dependent, influenced by species composition, functional traits, and environmental conditions that remain poorly explored (Carlucci et al., 2020; Petruzzella et al., 2018). This highlights a central challenge for the future of the field; as societal demand for applied and solution-oriented research increases, the ecological foundations required to identify management and restoration decisions are still being developed. This shift reinforces the importance of basic ecological understanding as an essential component for solving applied problems.

4.5. Supporting the next generation: Structural barriers and needs

This survey found that job insecurity peaks at the postdoctoral stage and that funding constraints impact ECRs across all career stages, and both of these factors are known to contribute to poor mental health (Bacci et al., 2024; Jones, 2023; Marck et al., 2024; Nicholls et al., 2022). Among students and PhD candidates, barriers are centred on low remuneration, limited opportunities for collaboration, and inadequate training in grant writing and project design. As researchers advance to postdoctoral stages, barriers shift toward employment insecurity and limited access to long-term contracts. Short-term contracts and repeated mobility are well-known stressors (Bacci et al., 2024; Jones, 2023) and are particularly relevant to macrophyte research, where long-term observations often exceed contract durations.

As late-stage ECRs gain more independence, persistent funding limitations combined with high teaching and administrative loads, and pressures to establish research identity, constrain further progress. Moreover, the responsibilities of ECRs often extend beyond research activities, which can constrain their overall scientific contributions. Securing external funding through grants involves not only conceptual and research work but also time-consuming accounting and administrative duties. Increased institutional support for grant management is therefore necessary to allow researchers to focus more on their research objectives.

Beyond individual career stages, gender-related barriers such as caregiving responsibilities, fieldwork safety concerns, and restricted access to leadership and mentorship, contribute to the underrepresentation of women and slower career progression throughout their career (Brajdić Vuković et al., 2025; Cairo et al., 2026; Conesa Carpintero and González Ramos, 2018; Lomáscolo et al., 2024; Müller and Palmén, 2026; Podreka et al., 2024). Furthermore, funding constraints shape the broader research landscape in a manner that is not equal across the globe and may partially explain the greater abundance of ECRs from the Global North who participated in this survey. In more resource-limited systems, low mentorship, less funding, and insufficient infrastructure further restrict research time, publishing opportunities, career progression, and opportunities for collaboration (Shinkafi, 2020).

In addition to the general challenges faced by ECRs, those working in underrepresented fields often face further constraints regarding the visibility and recognition of their research. Macrophyte research, which includes studies on benthic primary producers, is less prominent than research on pelagic communities within aquatic ecology (Orr et al., 2024; Botrel et al., 2024). The historical focus on open-water processes in limnology has shaped the visibility of macrophyte research in scientific discourse, funding allocation, and career advancement. While the degree of topic-related bias among reviewers, hiring committees, or funding panels is difficult to assess, limited representation of a research field can restrict opportunities for networking, collaboration, and recognition, particularly for ECRs. Efforts to enhance the visibility of macrophyte research, such as organising dedicated conference sessions and workshops, are therefore essential for strengthening scientific communities and supporting ECR career development. These findings demonstrate that support needs, and resources required, change across ECR career stages. Students and PhD candidates would benefit from accessible training, scholarships, and mobility programs (Baker et al., 2025; Shettima et al., 2024). Postdoctoral researchers require longer contracts, structured mentorship, and institutional policies that support mental health and career development (Moraru et al., 2024). For later-stage ECRs, strengthening institutional infrastructure (including laboratories, technical staff, and administrative support) alongside reducing teaching burdens and ensuring access to long-term funding is critical (Raatikainen et al., 2021). Since these resources are provided via different channels (e.g., supervisors, departments, funders, etc.), multiple providers are implicated in the success of ECRs, and they each must take action. Addressing these challenges and providing more support for ECRs across career stages is essential for ensuring the long-term success of ECRs, and sustainability of their careers in macrophyte research.

At the same time, we cannot deduce from our survey results whether ECRs feel training and mentorship programs need to be created and improved because existing programs are ineffective or poorly promoted or because such programs do not exist. Regardless, ECRs are confident that their ability and preparedness to overcome barriers can be improved via access to training and mentorship programs. Mentoring practices also differ substantially, ranging from highly supportive supervision to prioritising researcher independence, which may itself explain why some ECRs report feeling unsupported even where formal programs do exist. Consequently, ECR preparedness is heterogeneous, not only with respect to grant writing and other research-associated tasks, but also in terms of broader professional needs such as work-life balance and career progression. Together, this underscores the need for equitable, accessible, and effective training, mentoring, and professional development opportunities across the macrophyte community.

4.6. What's next? How to advance the field

Not only are ECRs the next generation of macrophyte researchers, but they also actively shape the field through the questions they ask, the methods they develop and apply, and the challenges they prioritise. Early-career researchers envision the field of macrophyte research as increasingly integrative, solution-oriented, predictive, and technology-driven. They also recognise that achieving this vision requires stronger ecological foundations, more equitable access, and a research culture built upon openness and collaboration. Technological advances are expected to reshape the field by enabling more efficient data collection across scales, improved and standardised practices for data integration and sharing, and stronger predictive capacity to anticipate ecosystem responses to environmental change. The growing emphasis on the role of macrophytes in providing ecosystem services, acting as Nature-based Solutions, and serving as an integral part of aquatic systems offers an important opportunity to raise the societal profile of macrophyte research and improve recognition of macrophytes as environmental solutions and as key components of ecosystem resilience.

Moving this vision into practice requires coordinated action across funders, institutions, the broader macrophyte community, mentors, and ECRs themselves. Based on our survey findings and collective experience as ECRs, we have identified six areas for action, depicted in Fig. 7, that will ensure the field of macrophyte research advances in the directions ECRs deem most important, while also helping them overcome the barriers they face across the various early-career stages. These areas for action highlight a need to (a) strengthen and integrate existing networks, (b) invest in people, not only projects, (c) reduce geographic bias and enhance capacity, (d) support fundamental research, (e) encourage a cultural shift toward open science, and (f) foster relationships between science and society. Realising the potential of ECRs requires support and sustainable working conditions, which ultimately requires endorsement from all levels of the scientific community. Collectively, ECRs are optimistic that contemporary macrophyte research will grow into a more diverse and inclusive discipline that leverages emerging technologies to address critical issues affecting ecosystems and society.

CRediT authorship contribution statement

Benjamin Misteli: Writing – review & editing, Writing – original draft. **Anne Lewerentz:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yang Liu:** Writing – review & editing, Writing – original draft. **Lindsay Louise Trottier:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sonia Nadège Kenfack Voukeng:** Writing – review & editing, Writing – original draft. **Ashley Hoblyn:** Writing – review & editing, Writing – original draft. **Borislava Gyosheva:** Writing – review & editing, Writing – original draft. **Antonella Petruzzella:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abby Gilson:** Writing – review & editing, Writing – original draft. **Karina Anna Elisabeth van der Zon:** Writing – review & editing, Writing – original draft. **Alice Dalla Vecchia:** Writing – review & editing, Writing – original draft. **Fee O.H. Smulders:** Writing – review & editing, Writing – original draft. **Colin L. Burke:** Writing – review & editing, Writing – original draft. **Alexander Plakias:** Writing – review & editing, Writing – original draft. **Brito Letícia:** Writing – review & editing, Writing – original draft. **Lukas Petrulaitis:** Writing – review & editing, Writing – original draft. **Jhaydee Ann Pascual:** Writing –

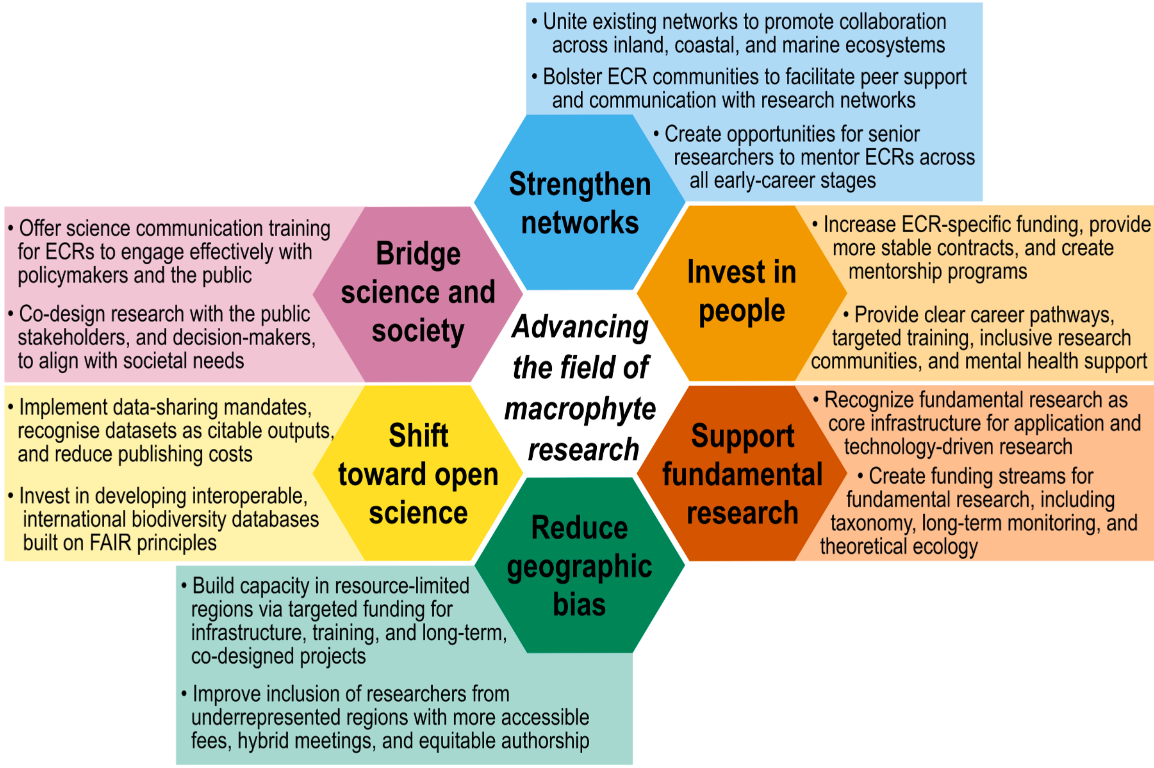

Fig. 7. The six areas for action identified by ECRs that must be prioritised for the field of macrophyte research to advance sustainably in the future.

review & editing, Writing – original draft. **Kerstin Bouma:** Writing – review & editing, Writing – original draft. **Athina Papatheodoulou:** Writing – review & editing, Writing – original draft. **Brzozowski Michał:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 5.2 in order to conduct a systematic thematic analysis of the open-ended survey responses. Furthermore, the authors used Claude Sonnet 4.6 and DeepL to improve readability and language. After using these tools, the authors reviewed and edited the content as needed, and the authors take full responsibility for the content of the published article.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have inappropriately influenced or biased the perspectives presented in this article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.aquabot.2026.104049.

Data availability

Code and data is available on GitHub: https://github.com/AnneLew/ECR_macrophytes_survey

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