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Aquatic macrophytes in Amazon: review, knowledge and gaps

Macrófitas aquáticas na Amazônia: revisão, conhecimento e lacunas

Antônio Augusto de Souza Costa[1,2*], Nayara Louback Franco[1,3], Raimundo Luiz Morais de Sousa[1,2], Ana Luísa Biondi Fares[1,3], Flávia Alessandra Silva Nonato[1], Rayssa Silva Carmo[1,3], Marcelle Fernanda Oliveira Barbosa[1] and Thaisa Sala Michelan[1,2,3]

[1]Laboratório de Ecologia de Produtores Primários, Instituto de Ciências Biológicas, Universidade Federal do Pará – UFPA, Rua Augusto Correia, 1, CEP 66075-110, Belém, PA, Brasil

[2]Programa de Pós-graduação em Ciências Biológicas: Botânica Tropical, Museu Paraense Emílio Goeldi, Universidade Federal Rural da Amazônia – UFRA, Avenida Perimetral, 1901, CEP 66077-830, Belém, PA, Brasil

[3]Programa de Pós-graduação em Ecologia, Instituto de Ciências Biológicas, Universidade Federal do Pará – UFPA, Rua Augusto Correia, 1, CEP 66075-110, Belém, PA, Brasil

*e-mail: adryanufr@gmail.com

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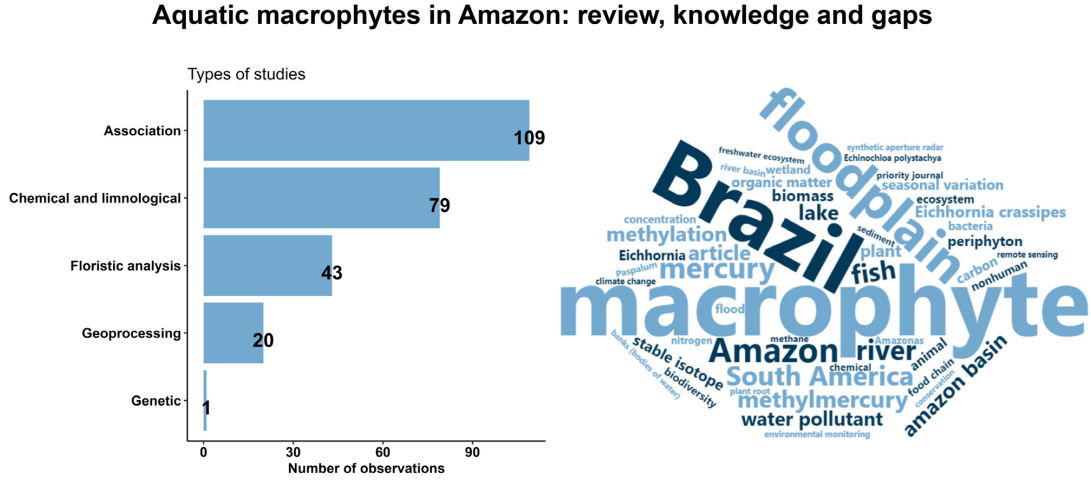
Abstract: Aim: The Amazon region presents peculiarities in its hydrology and vegetation, which are essential for climate balance. For this reason, the Amazon requires better sampling of its biodiversity, thus increasing knowledge of the organisms present in this area. In this study, through a systematic review, we evaluated to assess the advances in ecological theories research and we verified the stages of macrophyte biodiversity research in the Amazon. **Methods:** We used databases available on Web of Science and Scopus. The keywords used for the search were: amazon, macrophytes, and aquatic plant. The designated research period was between 1970 and 2022. The processed data were grouped into specific types according to the object of study. **Results:** Our results showed that the majority of studies addressed the influence of aquatic macrophytes on aquatic organisms (e.g., fish, insects, plankton, and manatees), as well as their influence on the abiotic characteristics of aquatic environments in the Amazon forest. Studies mostly focused on the relationship between macrophytes and other organisms or environmental variables. **Conclusions:** We identified research gaps in ecological and biological invasion studies with macrophytes in the Amazon and highlight the importance of international cooperation and scientific production for ecosystem conservation.

Keywords: aquatic plants; systematic review; neotropical region; bibliometrix; aquatic system.

Graphical Abstract



Types of studies involving aquatic macrophytes and their respective numbers of observations.

Keywords on aquatic macrophytes research in the Amazon that appear more frequently from 1970 to 2022.

Resumo: Objetivo: A região amazônica apresenta peculiaridades em sua hidrologia e vegetação, essenciais para o equilíbrio climático. Por esta razão, a Amazônia necessita de uma melhor amostragem de sua biodiversidade, aumentando assim o conhecimento dos organismos presentes nesta área. Neste estudo, por meio de uma revisão sistemática, avaliamos os avanços na pesquisa de teorias ecológicas e verificamos os estágios da pesquisa da biodiversidade de macrófitas na Amazônia. **Métodos:** Foram utilizadas bases de dados disponíveis na Web of Science e Scopus. As palavras-chave utilizadas para a busca foram: Amazônia, macrófitas e planta aquática. O período designado para a pesquisa foi entre 1970 e 2022. Os dados processados foram agrupados em tipos específicos de acordo com o objeto de estudo. **Resultados:** Nossos resultados mostraram que a maioria dos estudos abordou a influência das macrófitas aquáticas nos organismos aquáticos (por exemplo, peixes, insetos, plâncton e peixe-boi), bem como sua influência nas características abióticas dos ambientes aquáticos da floresta amazônica. A maioria dos estudos focou na relação entre macrófitas e outros organismos ou variáveis ambientais. **Conclusões:** Identificamos lacunas em relação a estudos ecológicos e de invasão biológica com macrófitas na Amazônia, e destacamos a importância da cooperação internacional e da produção científica para a preservação dos ecossistemas amazônicos.

Palavras-chave: plantas aquáticas; revisão sistemática; região neotropical; bibliometrix; sistema aquático.

1. Introduction

The neotropical region integrates abundant biomes and ecosystems diversity. Many ecosystems of this region are important to global process, and among them is the Amazon rainforest, that harbors approximately twenty-five percent of all species on the planet (Antonelli et al., 2018). The Amazon has hydrological and vegetal peculiarities essential for global climate balance and biodiversity (Piedade et al., 2010). Identifying biodiversity distribution and the threats leading to its extinction is fundamental for discussions on environmental conservation, especially given the high diversity and increasing numbers of threatened species, along with rising deforestation rates (Arantes et al., 2018; Fagua & Ramsey, 2019). The aquatic ecosystems of the Amazon, that harbors biggest river basin in the world, are particularly threatened by climate change and land-use conversion, especially because of their hydrological connectivity (Castello et al., 2013).

Survey and synthesis studies, such as systematic reviews, are important because they employ rigorous, transparent, and repeatable methods for cataloging and synthesizing documented evidence on a topic (Moher et al., 2009). The reviews support researchers in understanding the status of the research and identifying gaps and biases (Nakagawa et al., 2019). Several systematic review studies increased over the years, with a particular focus on aquatic ecosystems due to their sensitivity to anthropogenic and climatic

changes, which have intensified recently (Bora et al., 2019; Cabral et al., 2019; Goulas et al., 2020; Land et al., 2016; Luo et al., 2020). In the Amazon, environmental changes occur faster than the research capacity to evaluate their effect, especially regarding aquatic macrophytes (Córdova et al., 2024).

Macrophytes are herbaceous plants that grow in freshwater or wetlands (Weaner & Clements, 1938). To date, 539-709 aquatic macrophytes species have been identified, of which 48-90 are endemic to Brazil (Moura-Junior et al., 2015; Córdova et al., 2022). These plants play an essential role in structuring aquatic communities, influencing nutrient cycling and energy flow in the food web (Ma et al., 2021). However, excessive growth due to anthropic actions, especially in anthropized areas with increased light and nutrients, can threaten species and cause ecological and economic impacts (Blackburn et al., 2014; Hussner et al., 2017; Vilas et al., 2017; Wojciechowski et al., 2018).

Given the ecological importance of macrophytes, many studies on the Amazon region focus on floristic aspects to address ecological questions related to associated organisms, such as fish (Oliveira et al., 2022; Nonato et al., 2021), macroinvertebrates (Molina et al., 2011), insects (Brito et al., 2021), and algae (Leão et al., 2021). However, it is known that these plants have the potential to be used in scientific research for different purposes. For examples: improvement of soil properties (Song, 2019), phytoremediation (Tabinda et al., 2020), bioaccumulation (Zhang et al., 2020), ecological impact assessment (Sui et al., 2020), biological invasion effects (Bando et al., 2016; Michelan et al., 2018), biological indicators (Bytyqi et al., 2020), taxonomy (Arguelles, 2019), ecological restoration (Wu et al., 2020), geoprocessing (Cordeiro et al., 2020; Murphy et al., 2019). However, few of these studies have been conducted in the Amazon.

A systematic review carried out in 2008 for the Neotropical region found that most studies are mainly about the influence of aquatic macrophytes on organisms and abiotic characteristics (Padial et al., 2008). This systematic review pointed out gaps in the number of articles, the lack of cooperation between countries, and the low number of studies with a predictive approach (Padial et al., 2008). Eleven years have passed since this research was published and, thenceforward, the science in the region has advanced despite the few resources allocated to the Amazon in proportion to its biodiversity and conservation needs (Carvalho et al., 2023). Additionally, funding for research is often challenging to secure in Brazil (Angelo, 2019). Considering this, we propose to answer this question: what the current trend in macrophyte studies in the Amazon? Do they follow the same pattern found in Padial et al. (2008) research?

Therefore, recognizing the stages of current scientific production concerning aquatic macrophytes in the Amazon will allow us to understand in which steps are the scientific research efforts on this subject. Thus, one of our main objectives is to evaluate the already published aquatic macrophyte research and to identify trends and gaps in macrophyte research, particularly in the Amazon rainforest (Angelo, 2019). Considering this, we addressed the following questions: i) what is the type of the study (floristic, limnological, association, geoprocessing and biochemical and medicinal studies)? ii) What is the time trend for publication? And what are the most cited articles? iii) What are the countries of the Amazon where there is research? iv) What are the journals that most address the topic? v) What are the most frequent keywords? vi) What type of ecosystem (e.g. reservoir, river, stream, lake, pond, etc.) are most studied in the articles? And vii) What are the most studied species? By addressing these questions, we intend to find research gaps and biases and suggest solutions and new perspectives for the development of studies and provide a comprehensive understanding of the current research landscape and highlight areas for future investigation.

2. Material and Methods

2.1. Data collection

The general guidelines of a systematic review, proposed by "Preferred Reporting Items for Systematic reviews and Meta-Analysis" - PRISMA, 2020 (Page et al., 2021). The systematic review was developed using the Web of Science™ (WoS™) and Scopus™ databases (Elsevier, 2023; Clarivate Analytics, 2023). We evaluated a sample of studies related to aquatic macrophytes in the Amazon. The search time frame was between 1970 and 2022. For the WoS™ database, the following keywords were used to search: [amazon* (Topic) AND macrophyt* OR "aquatic plant*" (Topic)] and for the Scopus™ database: [Title-Abs -Key (amazon*) AND Title-Abs-Key (macrophyt* OR "aquatic plant*")] AND Pubyear > 1970. A well-chosen survey and word choices are required for complete control over the literature in the search process, as the quality of literature retrieved determines the accuracy of the knowledge map analysis. This is because excess brings irrelevant literature, thus causing pollution

of the results, while insufficient ranges filters the relevant literature and decreases the coverage of the results (Gao et al., 2015; Hu et al., 2019), so we used the search form above.

Duplicates of articles were removed using the Bibliometrix package (Aria & Cuccurullo, 2017) from the R environment (R Development Core Team, 2019). However, due to differences in the indexing of articles in the databases, the Bibliometrix package couldn't detect some duplicates, requiring greater attention from researchers in identifying the eligibility of articles to be included in the systematic review. Unrelated publications were excluded by title, abstract, or careful article reading when necessary. As exclusion criteria for the systematic review included: mangrove species with woody growth forms (trees – because they do not align with the focus on herbaceous macrophytes), articles in languages other than English (we included only articles in English to ensure consistency, comparability, and broad accessibility of data, as it is the predominant language in international scientific literature), and those in which the study area did not belong to the Amazon.

With the survey, we obtained 321 articles on the WoS™ platform and 324 on Scopus™ (Figure 1). After surveying the articles in the cited databases, duplicate articles were removed (159). Then, all articles were analysed, and the articles related to mangrove species, and/or that did not belong to the Amazon biome, and/or that were published in languages other than English, and/or duplicates not found by the Bibliometrix, were removed from the analysis. In the end, 238 articles remained and were used in the further analysis.

2.2. Data analysis

The article information was exported from the databases and subsequently imported into the R environment (R Development Core Team, 2019) using the Bibliometrix package (Aria & Cuccurullo, 2017). Then, through the Biblioshiny graphical interface, we

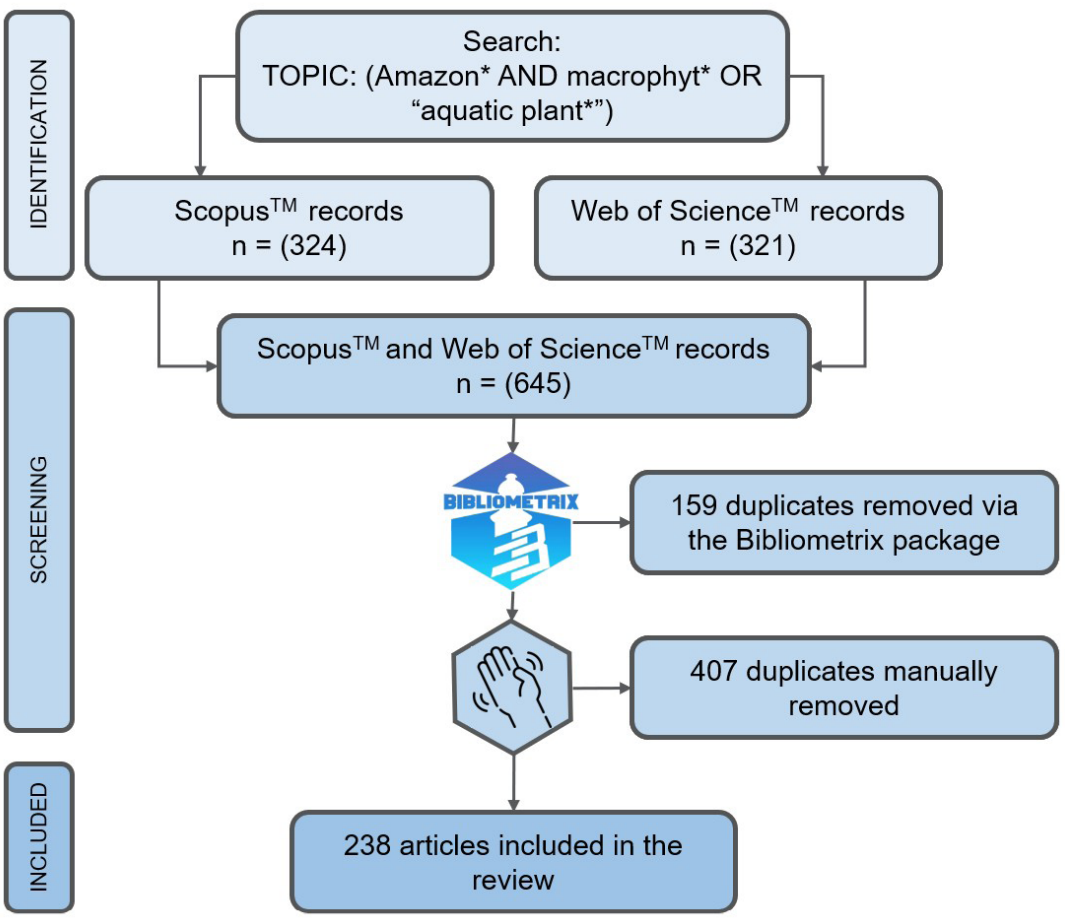


Figure 1. Flowchart showing the steps used for the selection of studies on aquatic macrophytes. The search found 645 articles, and of these, 407 were duplicates and therefore were removed, 159 were removed through the Bibliometrix package and 248 duplicates were removed after careful review.

visualized the main search results. Using the Bibliometrix package, we obtained the following information: year of publication of the article (question ii), number of citations of the article (question ii), journal and impact (h-index) in which the article was published (question iv) among other information described below.

Other aspects of the research were analysed by reading the article, such as: type of study (e.g., floristic analysis, limnological, association, geoprocessing) and type of associated organism (e.g., fish, plankton) (question i) (Table 1), geographic area of focus in the study (question iii), type of ecosystem (e.g., river, stream, lake, reservoir) (question vi), type of organism studied (macrophytes at family, genus and/or species level) (question vii) . A linear regression was performed to assess the increase in the number of publications. Linear regression was performed in the R environment itself, with the base package and the 'lm' function, which is used to fit linear models.

To create some graphs, we used the h-index (SCIMAGO), which is a metric for measuring the impact factor of a journal. Although originally conceived as an author-level metric, the h-index has been applied to higher-order aggregations of research publications, including journals. Publishing in a journal with a high h-index maximizes your chances of being cited by other authors and, consequently, can improve your personal h-index score (Google Scholar, 2024). All statistical analyses and maps were built in the R environment (R Development Core Team, 2019).

In studies exclusively on macrophytes, within studies categorized as floristic analysis, data were grouped into: (i) studied species; (ii) methodological approach, and (iii) variable tested, specifically within the context of floristic studies, with emphasis on types of ecological interactions involved. For the methodological approach, we categorize as research, experimental (*in situ* or in laboratory/greenhouse), taxonomic and modelling.

3. Results and Discussion

3.1. Types of studies

Our results showed that most studies addressed the influence of aquatic macrophytes on aquatic organisms, as well as their influence on the abiotic characteristics of aquatic environments in the Amazon rainforest. These results remain congruent with the conclusions found in the work by Padial et al. (2008). This alignment is further evidenced by the types of studies identified in our systematic review was the association with other organism(s) or with the place that they share (association of macrophytes with environmental variables) (95 articles, 39.92%). The other studies were distributed among chemical and limnological (79 articles, 33.19%), floristic analysis (43 articles, 18.07%), remote sensing (20 articles, 8.40%), and genetic (1 article, 0.42%) (Figure 2).

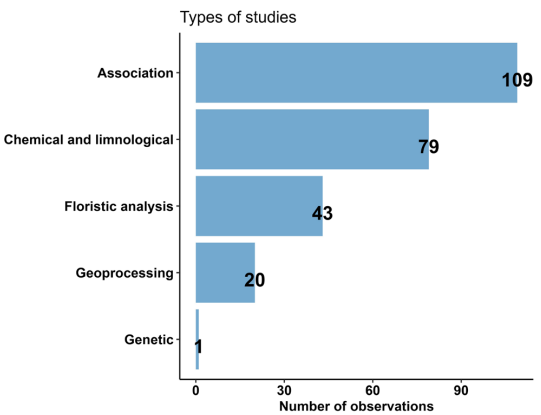


Figure 2. Types of studies defined for the review with their respective numbers of observations.

Table 1. Classification of articles according to the topics studied.

Categories	Classification	Themes Considered
1	ASSOCIATION STUDIES	Interaction of aquatic macrophytes with other organisms or with the environment (environmental variables).
2	FLORISTIC ANALYSIS STUDIES	Studies of terrestrial and aquatic vegetation, in addition to exclusive studies with aquatic macrophytes.
3	BIOCHEMICAL AND MEDICINAL STUDIES	Phytoremediation and/or ethnobotanical studies
4	CHEMICAL AND LIMNOLOGICAL STUDIES	Changes in the pH of water and sediments, concentrations of gases, nutrients and salts in relation to the flows of matter and energy linked to biotic communities.
5	GEOPROCESSING STUDIES	Remote sensing and modeling.

These results showed the role of aquatic macrophytes in freshwater ecosystem biodiversity but did not use them as the main organism in the studies, as Padial et al. (2008) found. Bączyk et al. (2018) reported the same trend in the European Union, where the number of articles dealing with various aspects has increased, which may be related to a growing scientific interest in the integrated analysis of the responses of aquatic ecosystems. Limnological studies were also quite frequent due to changes in ecosystems caused by the presence of aquatic macrophytes, in addition to the use of these organisms for the treatment of contaminated or polluted aquatic ecosystems (Dias et al., 2021a; Jabłońska et al., 2021; Kochi et al., 2020).

Studies involving floristic analysis, including taxonomic studies, are rarely observed in this systematic review. This may be related to methodological standards since these methodologies used for ecological and biological studies follow models designed for terrestrial plants and the use of this methodology in aquatic macrophytes can generate adverse results (Moura-Júnior et al., 2021). In addition, the studies in this field of research demand more expenditures to be carried out. This occurs due to the logistical difficulties of access in the Amazon region, as researchers generally use more than one mean of transportation to reach the sites and carry out their studies (such as car, boat and/or plane), a situation we face daily for research in the Amazon region.

Another important point observed in the analysed works, as well as in other reviews (Evangelista et al., 2017; Padial et al., 2008; Rocha et al., 2019), is that little or almost nothing is focused on ecological studies and the effects caused by the biological invasion of aquatic macrophytes, which is an essential subject and a global concern for biodiversity conservation. This probably occurs because the Amazon is still a region with scarce floristic and ecological surveys, and in many areas, the real biodiversity is still unknown, which makes invasive exotic species less evident (Fares et al., 2021). However, it is important to note that invasion is already happening in the Amazon, especially when studying macrophytes in anthropized areas within the deforestation arc (Fares et al., 2020). In Brazil, the lack of public policies focused on aquatic environments, especially regarding macrophytes, along with ineffective legislation simultaneously contribute to this knowledge gap concerning invasive exotic species.

3.2. Temporal analysis

The number of published articles related to aquatic macrophytes has increased following the worldwide trend of scientometrics performed with other organisms or subjects (Guerra et al., 2018; Gurevitch et al., 2018; Vaz et al., 2015), which corroborates the results of Padial et al. (2008) and Rocha et al. (2019). In general, the number of documents showed a growing trend, which is in line with the increasing number of scientific articles. In the first 20 years of research (1970-1990), only nine articles were published on the subject. The number of articles in this period was at least two per year. On the other hand, we believe that the first years of publication on the subject have few articles due to the difficult access to older articles, since online articles became more available from 1994, thus generating a publication gap (something that was also discussed by Pulzatto et al. (2018).

Then, from 1991 to 2008, the number of publications per year grew more, reaching 61 articles. However, the increase in the number of published articles was still not expressive. The number of publications began to rise in 2009, increasing progressively over the years. In 2016, it reached the number of 15, and 16 articles were published in 2018. The trend of publications in the last 12 years (2010–2022) increased in a considerable proportion (Figure 3, gray rectangle) after the publication of the article by Padial et al. (2008).

In recent years, the preservation of biodiversity in the Amazon is in evidence and therefore, a more significant number of research have been carried out in the area (Tollefson, 2022). Consequently, there has been a general increase in scientific publications and on macrophytes and their relationship with other organisms as well. Therefore, the field that concerns aquatic macrophytes continues to deepen, both in research of global scope and in research in the Amazon region (Córdova et al., 2022; García-Girón et al., 2020; Hofstra et al., 2020; O'Hare et al., 2018; Petruzzella et al., 2020; Song, 2019). In this way, it is

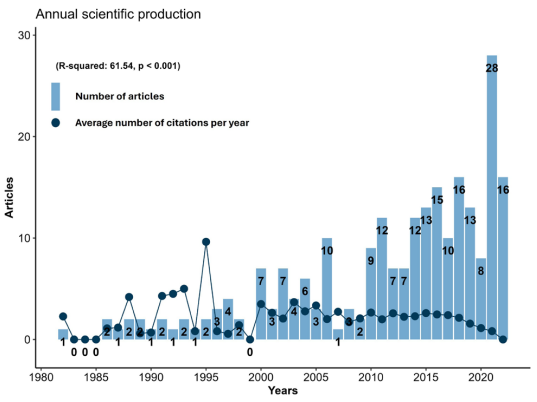


Figure 3. Number of publications about macrophytes in the Amazon per year.

possible to observe that the academic community has studied this group of plants in the region and, as interest about macrophytes became to grow, the number of publications.

Regarding the number of citations of publications on aquatic macrophytes in the Amazon, two articles from 1995 were the most cited and received an average of 260 citations. In the years following these two articles, the number of citations dropped sharply to an average of 27.83 citations per year. Although Brazil has the largest number of articles published on the subject, its articles had a low average of citations (Table 2). This pattern can be explained not only by the recent decrease in investment of resources in Science and Technology that Brazil has been facing in recent years (Angelo, 2019; Sills et al., 2019), but also by the historically limited investment in science in the country, which may have delayed the development of robust scientific infrastructure and continuity in research efforts.

3.3. Analysis of the main research country and journals

In some way, articles published in different countries reflect the importance of those countries regarding the topic, as well as the international cooperation between Brazilian research units and foreign ones (or the lack of them). The main countries contributing to the topic, as identified by the corresponding authors (Table 2), include one from Oceania (Australia), two from Asia (China and Lebanon), eleven from the Americas (e.g., Brazil, USA) and nine from Europe (e.g., France, United Kingdom). However, the contributions vary in scope and focus. The majority of countries publishing on the topic are developed countries. This indicates that developed countries have a greater presence in research on aquatic macrophytes (Table 2), and this applies to other research areas as well (Lobato-de Magalhães et al., 2024). The country with the highest number of published articles and indexed in the research databases is Brazil, with 192 articles cited 1743 times (Table 2). This number of citations establishes Brazil at a relatively high academic level. The USA is the second-largest country in publications on the topic (45 articles cited 1067 times); however, the number of publications is approximately four times smaller than the number of Brazilian publications. The fact that Brazil is the country with the highest number of publications and citations is mostly because most of the extension of the Amazon is located in this country. Thus, it is easier to go and perform studies in this area, which shows the interest of Brazilian research institutes and universities to understand the local biodiversity, and in collaborating with other institutions worldwide.

According to the statistics from the journals that published about aquatic macrophytes, the top three journals with the highest number of published articles are Hydrobiologia (13 articles), Science of the Total Environment (12 articles), and Acta Amazonica (nine articles) (Figure 4). The journal Hydrobiologia, which focuses on the biology of freshwater and marine environments, as well as anthropogenic impacts, remains the most important journal, just like in 2008 when Padial et al., addressed aquatic macrophytes in neotropical regions in general. However, our research was specifically focused on the Amazon region. The two leading journals are Dutch journals with high impact factors according to the Scimago classification of each journal, they are: Hydrobiologia and Science of the Total

Table 2. Publication status of the 15 main countries involved in research with aquatic macrophytes in the Amazon from 1970 to 2022.

Country	Articles	Total Citations	Average Article Citations
BRAZIL	192	1743	14.65
USA	45	1067	39.52
FRANCE	17	313	28.45
CANADA	15	426	47.33
COLOMBIA	15	32	8.00
UK	11	372	62.00
NETHERLANDS	8	25	12.50
GERMANY	7	313	31.30
BELGIUM	5	40	10.00
ARGENTINA	4	7	2.33
CHINA	4	3	3.00
SPAIN	4	92	23.00
BOLIVIA	2	98	24.50
FINLAND	2	19	19.00
LEBANON	2	3	1.50

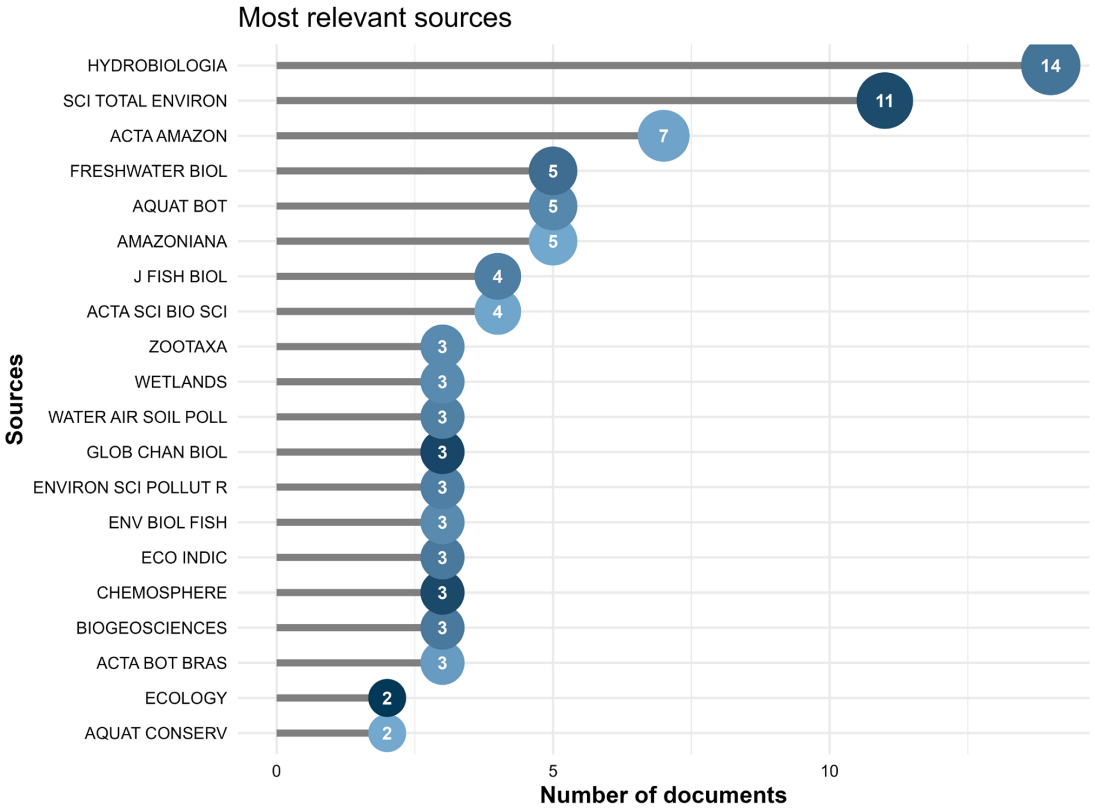


Figure 4. Distribution of articles by relevant sources from 1970 to 2022. The size of the bubbles refers to the number of articles and the color gradient is proportional to the h index of the journal according to SCIMAGO. ("SCI TOTAL ENVIRON" = Science of the Total Environment; "ACTA AMAZON" = Acta Amazonica; "AQUAT BOT" = Aquatic Botany; "FRESHWATER BIOL" = Freshwater Biology; " ACTA SCI BIO SCI" = Acta Scientiarum - Biological Sciences; "J FISH BIOL" = Journal of Fish Biology; "ENVIRON SCI POLLUT R" = Environmental Science and Pollution Survey; "WETL ECO MANAG" = Wetlands Ecology and Management; "WATER AIR SOIL POLL" = Water, Air and Soil Pollution; "REV BRAS ENTOMOL" = Revista brasileira de Entomologia; "GLOB CHAN BIOL" = Global Change Biology; "ENVIRON RES" = Environmental Research; "ENV BIOL FISH" = Environmental Biology of Fish; "ECO FRESHW FISH" = Ecology of Freshwater Fish; ; "ECO INDIC" = Ecological Indicators; "BIO NEO" = Biota Neotropica; "AQUAT CONSERV" = Aquatic Conservation: Marine and Freshwater Ecosystems); "ACTA BOT BRAS" = Acta Botanica Brasilica.

Environment (H-index: 141 and 244, respectively). The third journal in terms of publications is Brazilian, Acta Amazonica, which has a much lower Scimago impact factor (30) compared to the top-ranked journals.

3.4. Analysis of the most studied aquatic ecosystem, species, type of study and tested variable

The majority of studies focus on the following ecosystems: lakes or lagoons (183) with approximately 57% of the observations. The following were rivers (90) and streams/creeks (23) with 28.04% and 7.17% of the observations, respectively (Figure 5). This fact occurred because lentic habitats generally exhibit higher diversity of macrophytes compared to lotic habitats due to the favourability generated by abiotic factors, such as

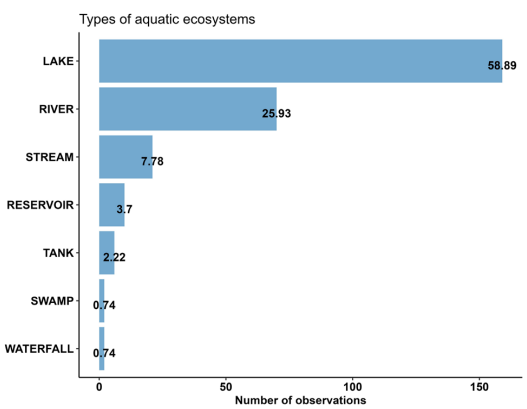


Figure 5. Types of aquatic ecosystems with number of observations in bars and percentage presented numerically. We include lagoon in lake, and creek in stream.

higher light incidence, low water flow, and nutrient abundance (Fares et al., 2021). But the number of publications on macrophytes is quite small considering the enormous variety of environments, as well as the immense biodiversity that the region carries (Baker et al., 2014; Cardoso et al., 2017).

Regarding fast-flowing ecosystems such as waterfalls, which appear with the lowest number of observations in this research, it is possible that they are species of macrophytes from the family Podostemaceae, a particular group of aquatic plants that have been suggested to be under-sampled due to their highly modified phenotypes and the challenging access to extreme aquatic environments where these plants occur (e.g. waterfalls) (Bedoya & Olmstead, 2022). Therefore, a significant effort is required to investigate their distribution (Tsukamoto et al., 2021).

Our results showed a higher number of publications on species from the Poaceae family (352), followed by the families Cyperaceae (165) and Pontederiaceae (112) (Figure 6C). This is because these families have many representatives that are considered aquatic species, with many genera that developed specific adaptations to inhabit freshwater ecosystems (e.g. *Eleocharis* – Cyperaceae and the entirety of the Pontederiaceae family) (Moura-Junior et al., 2015). Thus, they are often

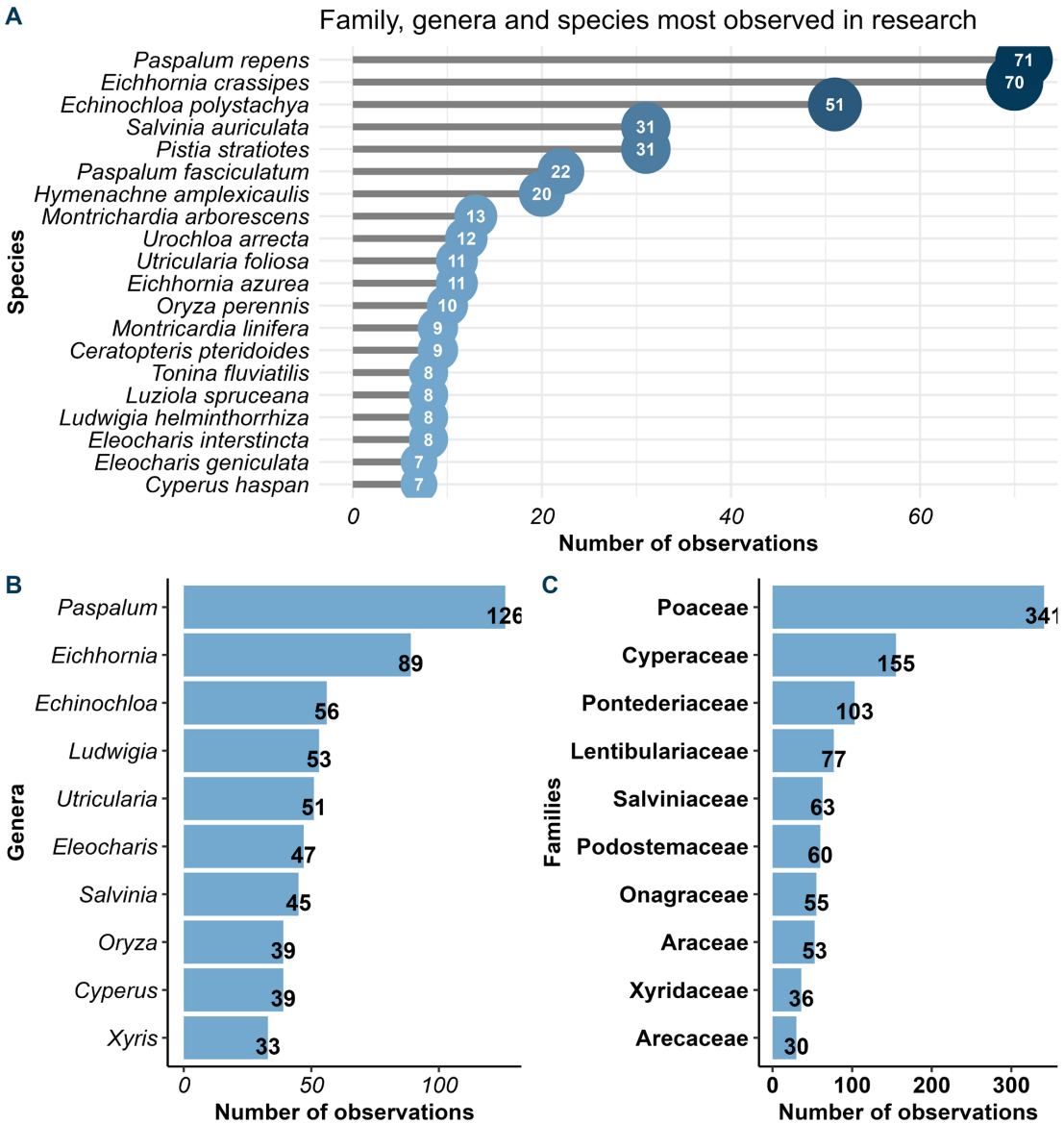


Figure 6. Species of macrophytes most studied in the Amazon. The graph shows the 20 most studied species in (A), the 10 most studied genera in (B), and the 10 most studied botanical families in (C).

very representative in aquatic plant surveys in the Amazon (Moura-Junior et al., 2015; Fares et al., 2021). At the genus level, the most studied genera were *Paspalum* (123), *Pontederia* (99), and *Echinochloa* (63) (Figure 6B). The 25 most studied species in the Amazon, with *Pontederia crassipes* being the most studied species with 79 observations, followed by *Paspalum repens* and *Echinochloa polystachya* with 75 and 53 observations, respectively (Figure 6A). The genus with the highest number of observations was the genus *Paspalum*, which is consistent with the number of species.

Regarding the association of organisms with aquatic macrophytes, fishes were the most studied organisms, with a total of 38 observations (34.86% of association articles) (Figure 7). Next, the Insecta Class appeared with 27 associations with macrophytes (24.77%), and in the third place in the association ranking, we have the Manatees (mammals) with 10 observations (9.17%). Within the Insecta Class, we highlight the contribution of the Orders Odonata and Diptera, both with 8 associations with macrophytes, accounting for 7.34% of the associations each.

The majority of articles investigated at the community level (188), followed by population-level investigations (61). When examining studies at the genus, species, and individual levels, we found 5, 3, and 1 article, respectively. Most articles employed experimental approaches (162), of which 92 were in situ experiments and 70 were laboratory experiments. Among these, only 33 articles tested ecological hypotheses. Observational studies accounted for the second-largest group of articles, adding 78 to the count. Other types of topics addressed were taxonomic and modelling studies, contributing 24 and 20 articles, respectively. This result indicates there is a need for more ecological studies with macrophytes in this region, as well as the urge for more studies with an ecological approach (e.g. species and ecological niche modelling investigating future scenarios with increasing climate and land-use change).

The limited emphasis on ecological studies and biological invasions by aquatic macrophytes in the analysed works and other reviews (Evangelista et al., 2017; Padial et al., 2008; Rocha et al., 2019) is concerning, as invasions represent a significant challenge for global conservation. This trend may be related to the scarcity of floristic and ecological surveys in the Amazon, leaving local biodiversity underexplored and potentially masking invasive exotic species (Fares et al., 2021).

Notably, invasions are already occurring, especially in anthropized regions along the deforestation arc (Fares et al., 2020). The introduction of invasive

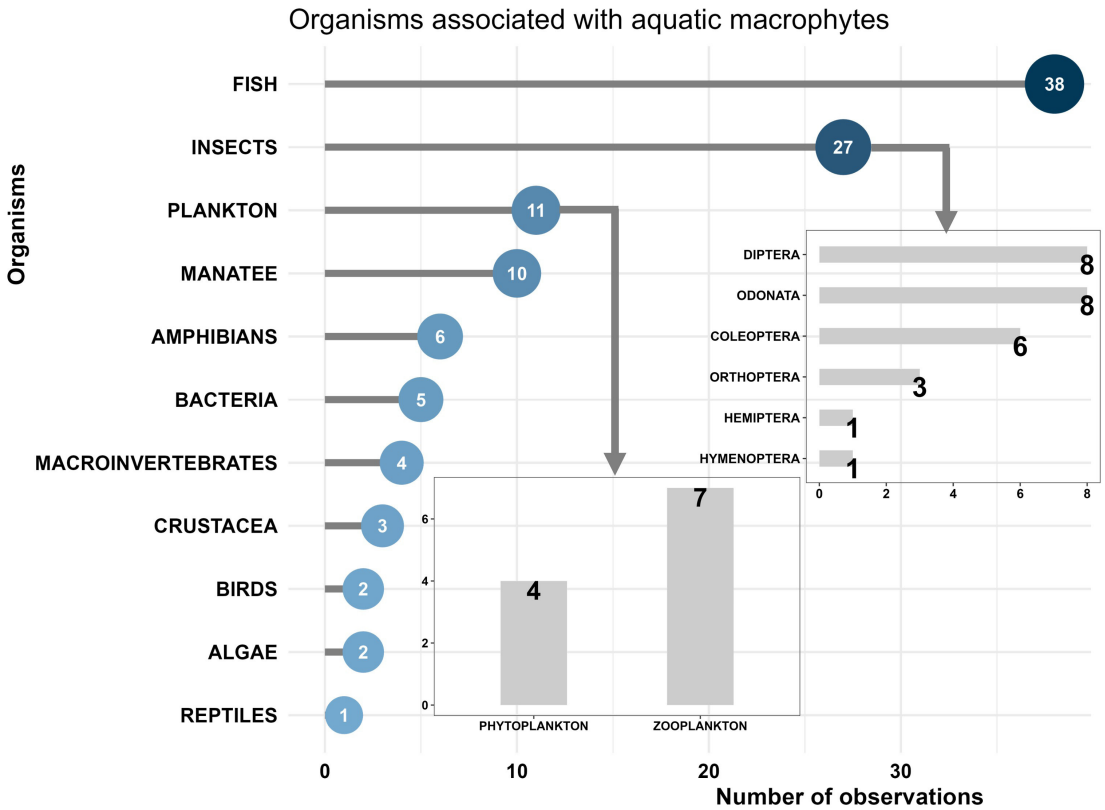


Figure 7. Association of organisms with aquatic macrophytes.

macrophytes, such as *Hydrilla verticillata* (hydrilla), exemplifies the potential for ecological disturbance, as these species can transform local habitats by altering hydrology, reducing light penetration, and changing nutrient dynamics, leading to the displacement of native species (Villamagna & Murphy, 2010; Michelan et al., 2010; Miller et al., 2023). Moreover, the density and richness of native macrophytes can affect the invasiveness of exotic species, as observed by Michelan et al. (2013), highlighting the importance of studying interactions between native and invasive species.

Another example is *Salvinia molesta*, an invasive species that has impacted freshwater biodiversity and ecosystem functionality globally, creating management challenges in invaded regions (Holt et al., 2023). Studies indicate that invasive species, such as *Urochloa arrecta*, can reduce native species richness and functional diversity (Michelan et al., 2010), reinforcing the need for specific policies for aquatic ecosystem management.

In Brazil, the lack of public policies and weak legislation for managing aquatic ecosystems, particularly concerning macrophytes, exacerbates these challenges, increasing knowledge gaps about invasive exotic species (Azevedo-Santos et al., 2021; Dias et al., 2021b). Integrating local and international research could, therefore, assist in creating effective strategies for controlling invasive species in Amazonian aquatic systems (Fricke & Olden, 2023).

In conclusion, this review highlights significant gaps in the current understanding of aquatic macrophytes in the Amazon, emphasizing the need for more targeted research to advance aquatic sciences in this region. Despite the considerable number of publications, we identified that: (1) the ecological roles of aquatic macrophytes remain underexplored, particularly regarding their contributions to ecosystem functioning; (2) certain topics, such as biological invasions and their impacts, are poorly addressed; and (3) there is a notable lack of studies integrating limnological data with macrophyte diversity and distribution. Addressing these gaps will require increased financial investment, funding opportunities focused specifically on the Amazon and enhanced national and international scientific collaborations. These efforts are crucial for fostering a deeper understanding of aquatic macrophytes, ensuring the conservation of freshwater ecosystems, and supporting sustainable management practices in the Amazon.

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Data availability

The dataset is available in ALB DATAVERSE. Access is free. It can be accessed in https://doi.org/10.48331/scielodata.W1A1IL

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