



REVIEW

Three Decades of Research on Passive Acoustic Monitoring in Bats: Systematic Review and Perspectives

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ABSTRACT

Introduction: Passive acoustic monitoring (PAM) has transformed bat research by enabling non-invasive, large-scale and long-term assessment of bat ecology and conservation status. Yet despite its rapid expansion, substantial methodological heterogeneity, pronounced geographic biases and fragmented taxonomic coverage continue to limit global synthesis and constrain the broader ecological and conservation value of PAM.

Aims: This review aims to: (1) map global geographic patterns and collaboration networks in PAM-based bat research; (2) characterise temporal trends and major developmental phases; and (3) evaluate methodological practices across detector technologies, survey designs, monitoring cycles and data-processing workflows. These objectives collectively provide a basis for identifying knowledge gaps, improving methodological coherence and guiding future monitoring and conservation efforts.

Methods: We systematically reviewed 935 peer-reviewed studies from 1992 to 2023, compiling associated bibliometric, methodological and thematic metadata. Keyword co-occurrence, thematic clustering, device-use profiles, methodological categorisation and temporal trends were analysed using bibliometric tools and descriptive statistics.

Results and Discussion: Our review revealed strong geographic biases, with PAM research heavily concentrated in a few well-studied regions. Research shifted from early detector-focused work to broader conservation applications. Methodologically, fixed surveys, seasonal sampling and manual call processing remained dominant, though automated tools are increasingly adopted. Research themes were heavily skewed towards movement and identification, with ecosystem-health and disturbance topics markedly underrepresented.

Synthesis and Recommendations: PAM research is advancing rapidly but remains geographically uneven and methodologically fragmented. Strengthening standardised yet flexible protocols and expanding capacity in under-represented regions will be essential to fully realise its value for global bat conservation.

1 | Introduction

Bats are one of the key components of global biodiversity owing to their vital ecological roles, including insect pest

suppression, pollination and seed dispersal, all of which significantly contribute to ecosystem stability and human well-being (Kunz et al. 2011; Russo et al. 2018). These ecological services provided by bats have considerable economic and

environmental implications in terms of agricultural productivity, forest regeneration and disease management (Gao et al. 2023; Voigt et al. 2024). However, global bat populations are being increasingly threatened by habitat fragmentation, urbanisation, agricultural intensification, climate change and emerging infectious diseases such as white-nose syndrome (Frick et al. 2020; Voigt, Russo, et al. 2021), which cumulate into serious conservation challenges, necessitating urgent and effective monitoring strategies to better understand bat population dynamics, habitat requirements and threats (Rodhouse et al. 2012).

Bat monitoring has traditionally relied on techniques such as visual observations, mist netting and radiotelemetry (Sugai et al. 2019). However, these methods are limited by their invasive nature, logistical complexity, ethical concerns, high labour intensity and restricted temporal and spatial coverage. The nocturnal activity patterns, elusive behaviours and highly vagile nature of bats further complicate the collection of reliable data when using conventional methods, resulting in significant gaps in ecological understanding and hindered conservation efforts (Russo et al. 2024). Passive acoustic monitoring (PAM) has emerged as a powerful, non-invasive approach to address the many limitations inherent to traditional bat monitoring approaches (Brinklov et al. 2023; Ross et al. 2023; Suter et al. 2017). Passive acoustic monitoring involves the use of automated acoustic recorders to detect and process bat echolocation calls. The widespread adoption of PAM technology has revolutionised the research on bat ecology by allowing continuous, large-scale and cost-effective monitoring of bat activities across diverse habitats. Recent advancements in acoustic sensors and recording devices, combined with significant progress in data processing technologies, particularly automated algorithms and machine learning approaches, have substantially enhanced the efficacy of PAM (Russo and Voigt 2016). These technological improvements have enabled detailed and precise processing of complex acoustic datasets, facilitating extensive insights into bat species identification, behavioural patterns, habitat utilisation and responses to environmental disturbances (Liu et al. 2024).

Passive acoustic monitoring has also generated substantial species-level ecological insights, demonstrating its value far beyond methodological innovation. Long-term acoustic datasets have enabled the early detection and quantification of population collapses in *Myotis lucifugus* and *M. septentrionalis* following the emergence of white-nose syndrome in North America (Dzal et al. 2011; Frick et al. 2010). In Europe, large-scale acoustic transects have revealed continental-scale migration routes and seasonal activity dynamics of *Pipistrellus pipistrellus* and *Nyctalus noctula* (Flaquer et al. 2007; Jones et al. 2009), providing key evidence for movement ecology. Passive acoustic monitoring has also become integral to applied conservation, including collision-risk assessments at wind-energy facilities – for example, acoustic activity data for *Tadarida brasiliensis* have been used to inform curtailment strategies (Weaver 2019) and the evaluation of habitat preferences in forest-dwelling species such as *Eptesicus fuscus* and *Rhinolophus ferrumequinum* across managed landscapes (Duchamp et al. 2006; Hermans et al. 2023). Integrated PAM and dietary evidence show that bats can dynamically track and

suppress agricultural pests – for example, intensifying activity during grape-pest outbreaks and exhibiting species-specific dietary shifts that reflect predator–prey ecological coupling (Baroja et al. 2021; Zhu et al. 2024). Collectively, these species-focused examples demonstrate how PAM directly supports ecological inference, population monitoring and conservation decision-making, and they underscore the need for a global synthesis of how acoustic methods are applied across taxa, biogeographic regions and research objectives.

However, despite the rapid advancement and growing popularity of PAM techniques worldwide, notable gaps and disparities remain in the application and methodological standardisation of these techniques (Browning et al. 2017). Research efforts employing PAM have been disproportionately concentrated in North America, Europe and Oceania, which have well-established research infrastructure, extensive funding and technological accessibility. Regions with rich biodiversity, such as Africa, South America and parts of Asia, however, witness a relatively scarce application of PAM in bat research, primarily due to infrastructural constraints, lack of funding and limited access to advanced technological tools (Gibb et al. 2019). Furthermore, the choice of acoustic monitoring devices, sampling protocols, survey methodologies (fixed, mobile, or mixed approaches), monitoring cycles (daily, monthly, or seasonal) and data processing strategies (manual, semi-automated, or automated) varies significantly across studies. At the same time, recent studies show that acoustic detectors capture only a small portion of the rotor-sweep zone due to signal attenuation and acoustic shadowing, suggesting that PAM alone may underestimate true turbine-related risks and should be complemented with additional monitoring tools (Voigt, Russo, et al. 2021). Therefore, as acoustic monitoring remains an emerging and rapidly advancing field, the development of universal standards is still ongoing and must ultimately be tailored to different research objectives and sampling contexts.

In order to address these critical gaps and methodological inconsistencies comprehensively, this review was conducted to systematically identify the global research trends and thematic evolution in the context of PAM-based studies on bats. The specific objectives were to: (1) quantify regional research distribution patterns, identify international collaboration networks and highlight geographical disparities; (2) delineate and analyse temporal research trends and thereby reveal the distinct developmental phases of PAM-based research, including foundational technological advancements and broad-scale monitoring periods; (3) critically evaluate the diversity and efficacy of the acoustic monitoring technologies, survey methodologies, monitoring cycles and data analysis practices currently employed in studies using PAM. This integration of multiple dimensions offered strategic insights and practical recommendations to promote methodological standardisation, strengthen international collaborations, facilitate technology transfer and ensure equitable access to monitoring resources. Ultimately, this review aims to inform about the global bat conservation strategies and thereby enhance these strategies and enable further effective responses to the ongoing ecological threats, ensuring the sustainability of vital ecosystem services provided by bats.

2 | Materials and Methods

The global research on the use of PAM in bat ecology was comprehensively assessed through a systematic review and bibliometric analysis approach, which included clearly defined stages of literature search, study screening and selection and bibliometric and thematic analyses.

2.1 | Data Collection

The peer-reviewed literature indexed in the Web of Science Core Collection (WoSCC) was systematically searched, covering all records published up to January 2024. Initial searches were conducted on the 20th of August 2023 and later updated on the 23rd of September 2023 to ensure the inclusion of recent literature. The search strategy employed was as follows: TS=(((sound* OR acoustic* OR call* OR vocal* OR echolocate* OR communicate) AND (monito OR passive OR record* OR detect* OR survey OR sample* OR automat* OR activity)) AND (bat OR bats OR chiropter)) NOT ('Brown adipose tissue'). The searches were restricted to 13 relevant WoS subject categories: biology, biodiversity conservation, environmental sciences, remote sensing, ecology, entomology, acoustics, behavioural sciences, zoology, ornithology and evolutionary biology. The WoS search was supplemented by including the potentially important articles not indexed in WoS, for which additional searches were performed using Google Scholar on the 15th September 2023 using the keyword combination 'bat acoustic' AND 'passive acoustic monitoring' to capture pertinent studies possibly omitted in WoS searches. All the retrieved records were exported to a bibliographic reference manager (EndNote X9) for duplicate study removal, record management and downstream screening. The final dataset was imported into CiteSpace (version 6.2. R6) for bibliometric and knowledge-mapping analyses.

2.2 | Study Screening and Selection Criteria

The methodological rigour and thematic relevance of the studies included in this review were ensured using predefined inclusion criteria. Eligible studies met at least one of the following conditions: (1) the use of PAM as a primary method for collecting all ecological or behavioural data on bats under field-based conditions, including natural, seminatural, or anthropogenically modified environments (e.g., forests, agricultural landscapes, urban areas, or protected reserves); (2) primary focus on the development, validation, or evaluation of PAM-related methodologies, such as acoustic detector hardware, signal processing techniques, or automated classification software, irrespective of field or controlled laboratory settings. These criteria allowed for the inclusion of both ecological applications and technical advancements relevant to PAM-based research on bats.

After defining the inclusion and exclusion criteria, the literature screening process was carried out in two phases. First, the titles and abstracts of all the retrieved publications were reviewed to eliminate irrelevant studies. In the second phase, the full texts of the remaining articles were assessed for

eligibility based on the detailed criteria above. Two reviewers independently conducted this screening to minimise bias, and any discrepancies were resolved through a discussion or consultation with a third reviewer (Foo et al. 2021). This rigorous screening process ensured that only high-quality, field-based studies that used PAM to address ecological or methodological queries related to bats were retained for the bibliometric and thematic analysis. In total, 935 peer-reviewed articles meeting the inclusion criteria were included in the final dataset used for analysis (Table S1).

2.3 | Bibliometric and Thematic Analysis

The selected studies were subjected to a bibliometric analysis using CiteSpace software (version 6.2. R6) (Chen and Leydesdorff 2014). The bibliometric analysis included the following steps: (1) The global distribution patterns of studies using PAM were conducted, identifying geographic hotspots and regional disparities in the research outputs. Additionally, international collaboration networks were identified to determine the central hubs and cooperative linkages among countries. Collaboration networks were constructed based on author affiliation information obtained from the C1 field of the Web of Science metadata. Each country listed in a publication was counted once, and all possible pairs of countries were connected to represent co-authorship relationships. For example, a paper with authors from the United States, the United Kingdom and Brazil generated three links (US–UK, US–Brazil and UK–Brazil). The resulting network thus reflects country-level collaboration patterns aggregated across all studies included in this review. (2) Citation burst detection analysis was employed to identify significant temporal shifts in research focus, using Kleinberg's burst detection algorithm as implemented in CiteSpace (Chen and Leydesdorff 2014; Kleinberg 2002), which allowed for the characterisation of developmental phases within PAM research over the study period (1992–2023). (3) A keyword co-occurrence network was constructed to elucidate the major research clusters and thematic relationships and identify coherent research topics, emerging research trends and their evolution over time.

Additionally, the technological advancements and methodological practices reported in the reviewed studies were summarised, categorising the commonly used acoustic devices, monitoring cycles (daily, monthly, or seasonal), data processing techniques (manual, automated or semi-automated) and survey methodologies. Survey methodologies were categorised as either fixed or mobile, with the latter including all transect-based recordings (walking, driving and boating). These mobile approaches differ in spatial coverage and accessibility, complementing fixed-point surveys to provide a more complete understanding of bat activity patterns. This comprehensive approach allowed for the systematic evaluation of research progress and methodological standards and the identification of critical knowledge gaps in global PAM studies related to bat ecology. This combined methodological approach provided a comprehensive and quantitative assessment of global research trends, thematic developments, methodological practices and research gaps in PAM studies related to bat ecology, facilitating robust review and critical discussion.

2.4 | Thematic Categorisation and Manual Annotation

A thematic categorisation process was also performed to qualitatively classify the included studies based on their research objectives, methodological focus and technological components. This step allowed for a more nuanced understanding of the diversity of topics and applications within PAM-based research on bats, which is unachievable through keyword co-occurrence or citation networks alone. Each study was manually reviewed and accordingly assigned to one or more thematic categories, including (1) species identification, (2) population or activity monitoring, (3) habitat use and ecological interactions, (4) behavioural ecology (e.g., foraging, roosting and commuting), (5) anthropogenic impacts (e.g., urbanisation, wind energy and artificial light), (6) methodological development (e.g., device performance and call classification tools) and (7) conservation applications. The classification was based on the stated aims, methods and analytical approaches described in each of the included articles. For studies involving multiple themes, all relevant categories were recorded. In order to improve consistency and reduce subjectivity, two independent reviewers conducted thematic coding, and any disagreements in category assignments were resolved through discussion and consensus. The results of this manual annotation were subsequently used for the cross-validation of the keyword co-occurrence clusters generated using CiteSpace, which identified the underexplored topics and examination of temporal trends across thematic domains. This dual quantitative-qualitative approach enhanced the interpretive depth of the bibliometric analysis and provided a better framework for structuring the results and discussion.

2.5 | Visualisation and Data Interpretation

All bibliometric and co-occurrence network visualisations were generated using CiteSpace (version 6.2. R6) (Chen and Leydesdorff 2014). Although early examples of acoustic monitoring appeared in the 1980s (e.g., Fenton & Bell 1981), these studies were rare and primarily exploratory, emphasising manual call recognition. Our analysis thus begins in 1992, marking the onset of systematically documented PAM research and representing the past three decades of methodological development. The term source was 'title, abstract, author keywords and keywords plus,' and the node types included author, country, institution, keyword, cited reference and cited journal. Pathfinder + Pruning sliced networks were used as the pruning algorithm to simplify network complexity while preserving the most meaningful structural information.

Knowledge structures such as keyword co-occurrence networks, timeline views and burst detection plots were utilised to interpret the temporal trends, thematic evolution and emerging research fronts in the PAM literature (Grames et al. 2019). Modularities (Q values) and silhouette scores were utilised to assess the clarity and cohesion of clusters, with $Q > 0.3$ and silhouette > 0.5 indicating significant and reliable structures (Neoh et al. 2023). In addition, the clusters were manually annotated and validated through a comparison

with the thematic categorisation results, allowing for the cross-validation of machine-generated and expert-informed interpretations. The resulting visualisations were refined using Adobe Illustrator for clarity and consistency and then utilised to identify the dominant themes, geographic patterns, research phases and technological trajectories within the field of PAM-based research on bats, as discussed in the Results and Discussion section.

3 | Results

3.1 | Regional Analysis of Bat PAM Studies

The global analysis conducted in this study revealed notable geographic disparities in the number of studies employing PAM for research on bats (Figure 1). The highest concentration of research output was noted for North America, especially the United States, followed closely by Europe, which are regions characterised by a substantial quantity of publications and significant interregional collaborations. In contrast, regions such as Africa and large areas of Asia presented considerably lower publication outputs, despite their high bat biodiversity. The analysis of international collaboration networks revealed that Europe serves as the central nexus connecting multiple global regions, exhibiting strong cooperative ties with North America and Asia. Conversely, the collaborative networks involving researchers from Africa and Oceania were relatively sparse and less interconnected, with fewer cross-regional links compared to other continents.

3.2 | Thematic Evolution and Keyword Network Structure in PAM Research in Bats

Keyword analysis of the studies from 1992 to 2023 revealed both temporal shifts in research focus and structural organisation of the thematic clusters in PAM-based studies on bats (Figure 2A). During the Foundational Phase (1992–2010), publication rates displayed a steady incremental increase, which is indicative of the early stages of PAM technology development and initial ecological exploration. A noticeable increase in the number of publications began in 2010, marking the onset of the technological advancement phase (2010–2018), during which the volume of research grew substantially and the use of advanced acoustic monitoring technologies became more common. The most recent phase, the Broad-Scale Monitoring Phase (2018–present), involved a rapid and sustained escalation in publication output, indicating extensive adoption of PAM methodologies and their application in diverse ecological contexts and broad spatial scales.

Citation burst analysis highlighted the prominent shifts in research focus across PAM studies on bats from 1992 to 2023 (Figure 2B). Early research primarily focused on ecological behaviour and habitat use, whereas the 2000s showed an increasing emphasis on methodological and analytical development, including the use of machine learning and automated processing. In recent years, keywords related to large-scale monitoring, ecosystem services and conservation threats have become dominant, showing a transition

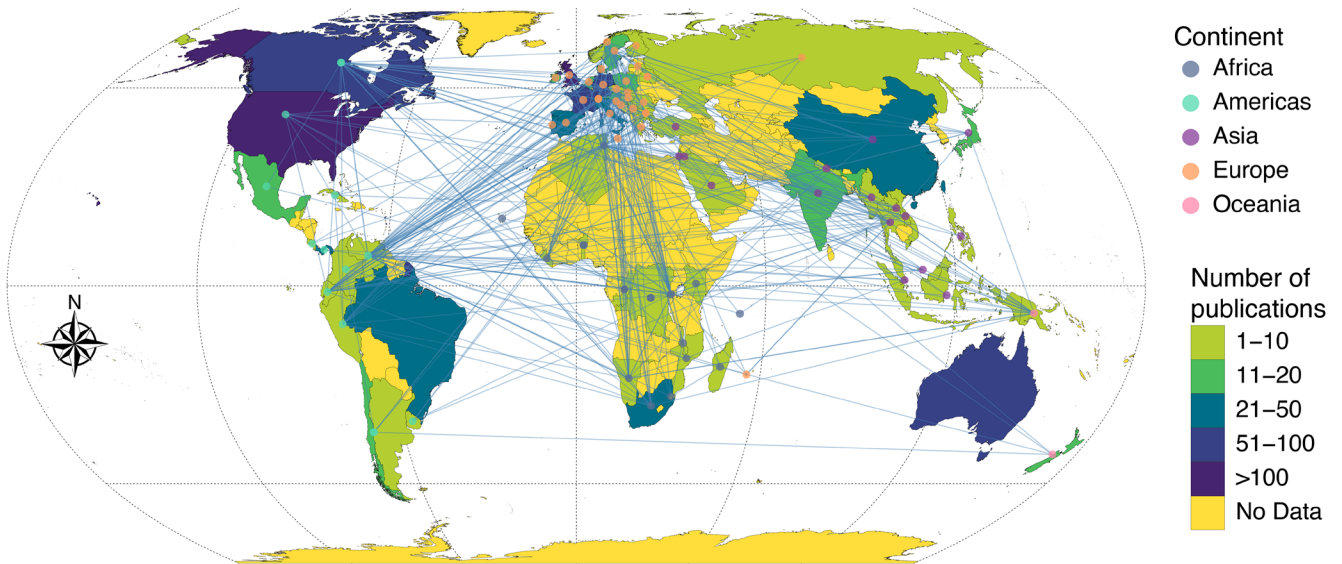


FIGURE 1 | Global distribution and collaboration in bat research based on passive acoustic monitoring. The coloured dots indicate country-level centroids that are coded by continental regions, and the blue lines represent international co-authorship or collaboration links derived from institutional affiliations. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

of PAM studies from ecological exploration to technology-driven and conservation-oriented applications.

3.3 | Keyword Co-Occurrence Network and Thematic Evolution

The keyword co-occurrence network analysis identified 11 major thematic clusters (#0–#10), each representing a coherent thematic focus within PAM-based bat research (Figure 3A,B). The network layout was generated with CiteSpace's standard algorithm and slightly adjusted to reduce overlap; thus, it serves as a qualitative visualisation of thematic relatedness rather than quantitative distance inference. Among these, habitat use (#0) formed the largest and most connected cluster, encompassing studies on spatial ecology and acoustic-based habitat assessment. Other major clusters included echolocation (#1), wind energy (#2), white-nose syndrome (#3) and species richness (#4), collectively representing a shift from behavioural and methodological studies towards biodiversity monitoring and conservation-oriented applications. Additional clusters such as light pollution (#5), habitat selection (#7) and bat activity (#9) demonstrate the diversification of PAM research into anthropogenic impacts and behavioural ecology. Conceptually, habitat use describes broader spatial patterns of species distribution and resource utilisation, whereas habitat selection refers to finer-scale preferences for specific roosting or foraging sites.

While new research themes have emerged, all thematic clusters have persisted and evolved over time, reflecting the gradual expansion of PAM-based bat studies from foundational acoustic identification to large-scale ecological monitoring and conservation integration (Figure 3B). Early PAM studies (1990s–2000s) were predominantly focused on habitat use, echolocation and the development of bat detectors (#6). This period represented the foundational stage of acoustic method development, during

which acoustic monitoring had not yet achieved broad acceptance within the conservation community. Accordingly, methodological reliability and confidence in acoustic data were still emerging, shaping the slower uptake of PAM approaches during this time. During the 2010s, clusters related to light pollution, wind energy and white-nose syndrome became increasingly prominent, coinciding with heightened attention to environmental change and conservation challenges. In recent years, themes such as habitat selection and ecosystem services (embedded within #4 and #5) have gained momentum, marking a transition towards large-scale ecological applications and policy-relevant research. Collectively, these patterns demonstrate the evolution of PAM-based bat studies through three major development phases: foundational (1992–2010), technological expansion (2010–2018) and broad-scale monitoring and conservation integration (2018–present).

3.4 | Acoustic Monitoring Devices and Methodological Preferences

An analysis of the devices used in PAM studies revealed significant variation in device preference (Figure 4A). The Anabat series (Titley Scientific, UK), particularly the SD1 and SD2 models, emerged as the most frequently used detectors, reflecting their widespread adoption in bat acoustic research. Other commonly used devices included the Song Meter series (Wildlife Acoustics, Maynard, MA, USA; e.g., SM2, SM3, SM4), the Batlogger (Elekon AG, Luzern, Switzerland) and Pettersson detectors (Pettersson Elektronik AB, Uppsala, Sweden; e.g., D500X, D1000X), indicating that researchers employ a diverse array of equipment tailored to specific study needs and field conditions. Across three decades of bat PAM studies, detector brand usage exhibited clear temporal and geographic heterogeneity (Figure 4B,C). The cumulative trend (Figure 4B) revealed a steady expansion in device adoption since the early 1990s, with marked acceleration

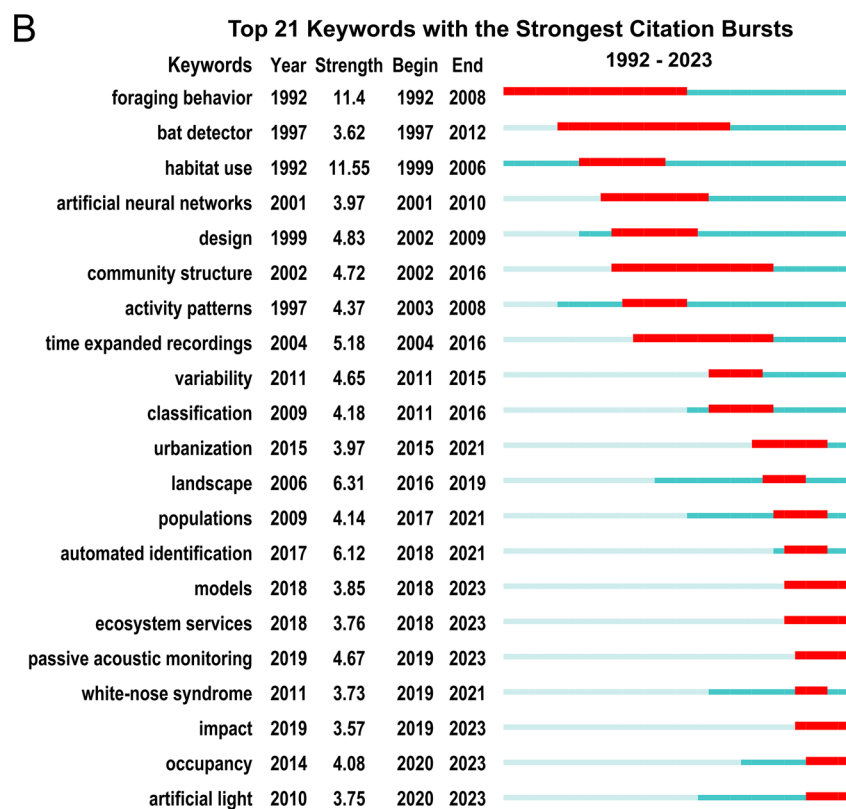
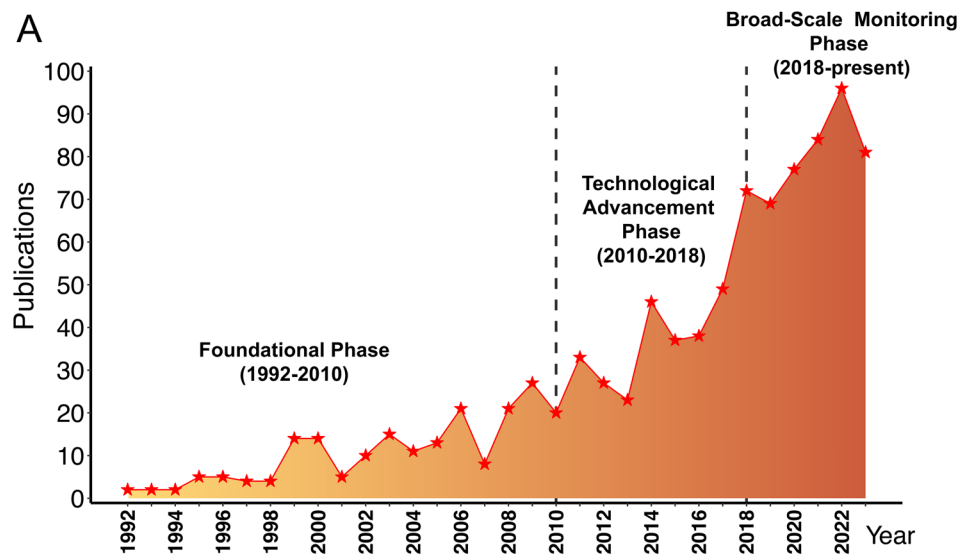


FIGURE 2 | Publication trends and thematic shifts in passive acoustic monitoring (PAM)-based studies on bats from the year 1992 to 2023. (A) Annual publication trends in PAM-related research on bats. (B) Top 21 keywords with the strongest citation bursts.

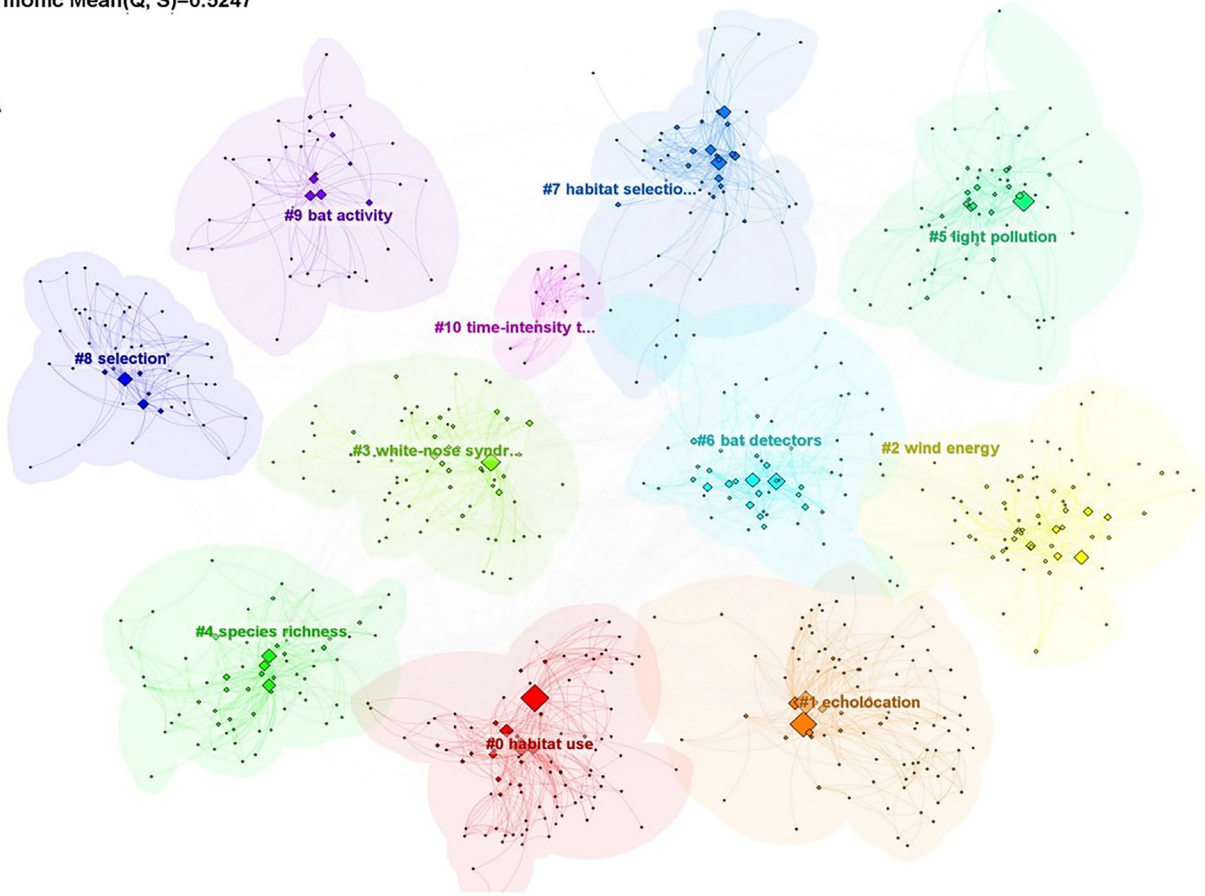
after 2010, coinciding with advances in automated recording and data-processing technologies. Among all brands, Anabat and Pettersson detectors dominated early applications, while SongMeter gained prominence in recent years, reflecting broader accessibility and versatility across research contexts. Geographically, detector use varied substantially among continents (Figure 4C). Anabat and SongMeter were predominantly employed in the Americas, whereas BatLogger and BatCorder were largely restricted to Europe, consistent with their regional manufacturing origins and distribution. In contrast, Asia, Oceania and Africa showed lower overall device use and narrower brand diversity. These spatial disparities

underscore how regional preferences and market availability shape methodological choices in PAM research, potentially influencing data comparability across continents.

The thematic analysis indicated a dominance of research focusing on bat movement patterns ($n = 436$), followed by species identification ($n = 252$) and habitat use ($n = 244$). The other less prevalent but notable themes included hardware and software developments ($n = 108$), human interference impacts ($n = 107$), monitoring optimisation ($n = 97$) and ecosystem health assessments ($n = 64$), which reflected a broad scope of interests in PAM research. In particular, studies grouped under 'hardware

CiteSpace, v. 6.4.R1 (64-bit) Advanced
 Timespan: 1992-2023 (Slice Length=1)
 Selection Criteria: g-index (k=25), LRF=2.5, L/N=10, LBY=5, e=1.0
 Network: N=712, E=4125 (Density=0.0163)
 Largest 1 CCs: 694 (97%)
 Nodes Labeled: 1.0%
 Pruning: None
 Modularity Q=0.409
 Weighted Mean Silhouette S=0.7314
 Harmonic Mean(Q, S)=0.5247

A



B

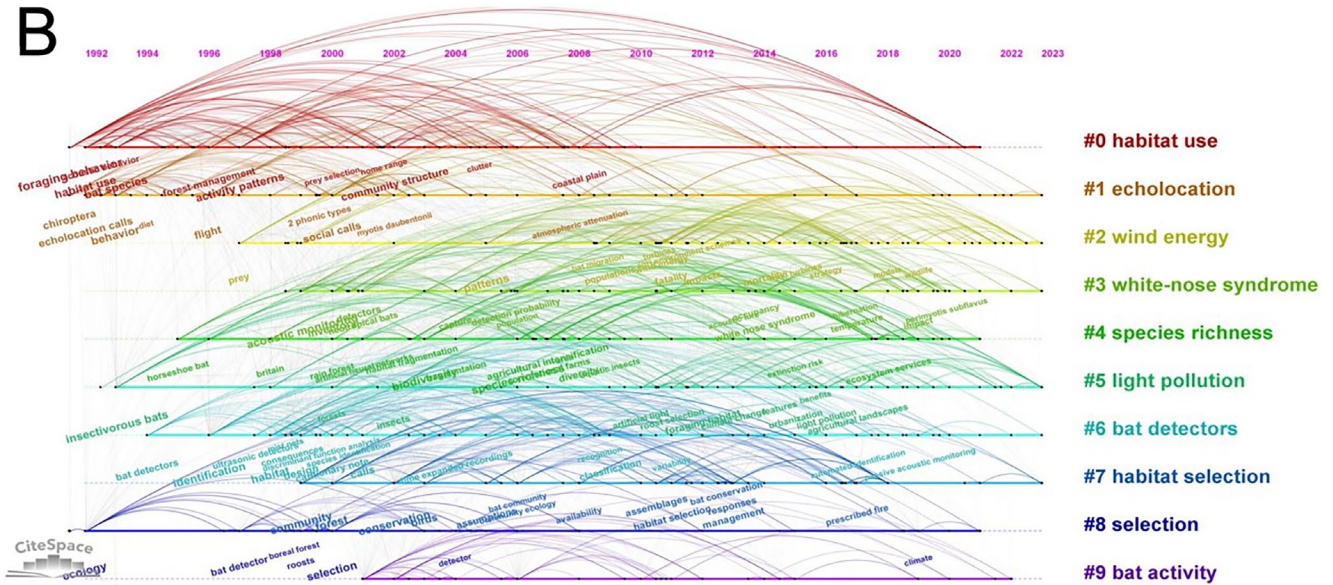


FIGURE 3 | Keyword co-occurrence network of bat-related PAM research. (A) Timeline view showing thematic evolution across time. (B) Clustered network view illustrating the structural organisation of major research topics.

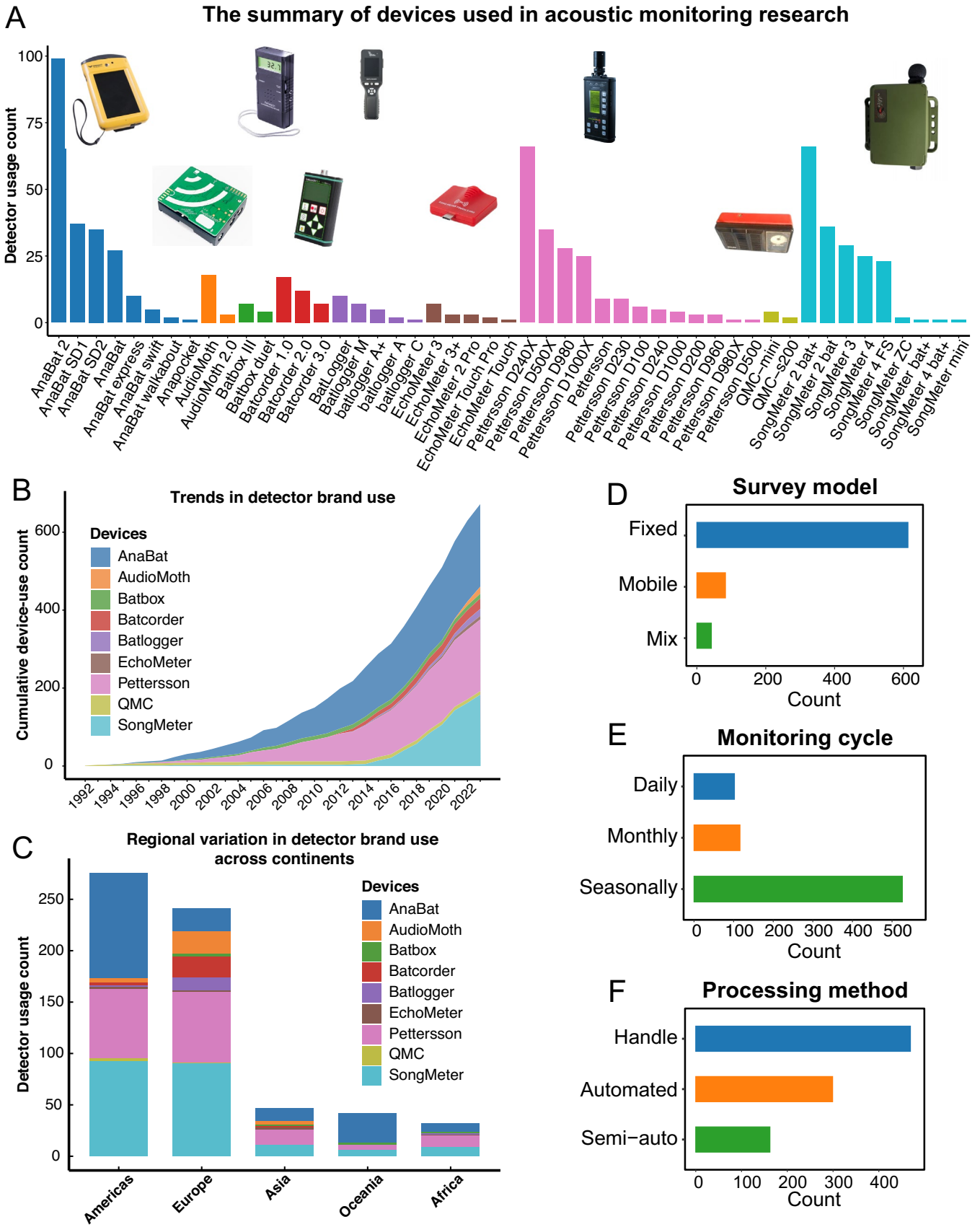


FIGURE 4 | Overview of the methodological characteristics of passive acoustic monitoring (PAM)-based studies on bats. (A) Frequencies of the acoustic recording devices used. (B) Cumulative growth in the use of acoustic detector brands. (C) Geographic variation in the use of acoustic detector brands across continents. (D) Survey models used. (E) Monitoring cycles applied. (F) Data processing methods used.

& software development' encompassed a wide range of technological innovations, including advances in detector recording modes (e.g., full-spectrum, zero-crossing, heterodyne and time-expansion systems), improvements in microphone and signal-processing performance and the development of automated and semi-automated call-analysis tools—each contributing to enhanced data quality and analytical efficiency. In terms of survey methodologies (Figure 4D), fixed-point surveys were mainly used and significantly outnumbered mobile and mixed survey methods. Analysis of the monitoring cycles (Figure 4E) revealed a preference for seasonal monitoring, followed by monthly and daily monitoring, suggesting an emphasis on capturing long-term ecological trends. The data processing methods (Figure 4F) revealed that manual analysis was the most commonly used approach, followed by automated and semi-automated methods.

4 | Discussion

This review provides a comprehensive analysis of the applications of PAM in bat ecology using a bibliometric approach. The findings highlighted the rapid growth and diversification of PAM research, along with the associated persistent gaps and challenges, which require targeted efforts for resolution. The analysis identified distinct developmental phases, which began with foundational studies focused on species identification and behavioural patterns, followed by a transition through technological advancements that facilitated automated and large-scale data collection, culminating in the current phase characterised by extensive conservation-oriented research across broader ecological and geographic contexts.

4.1 | Global Trends and Geographic Disparities in PAM-Based Bat Research

The substantial geographic disparity in the studies using PAM was a significant finding of this review. The regional disparities observed in PAM-based studies in bats could be attributed to differences in research infrastructure, availability of technological resources and funding mechanisms across different regions (Hofer et al. 2023). The dominance of North America and Europe in PAM-based studies is indicative of the advanced scientific facilities, extensive funding opportunities and robust research communities in these regions (Loeb et al. 2015). The dense international collaboration networks centred around Europe also reflect the leadership roles of these regions in standardising research methodologies and driving technological innovation (Michel et al. 2024). Another indicator of this leadership is the strong attraction of European research institutions for international scholars, as many researchers pursue postdoctoral training and advanced technical courses there, further consolidating Europe's central role in capacity building and methodological development. Conversely, the limited research output and weaker international collaboration noted in biodiversity-rich regions that had fewer such studies, for example, Africa and Oceania, are significant barriers to global bat conservation efforts in these regions (Gibb et al. 2019). Notably, in North America and parts of Europe, regulatory mandates for surveying protected bat species—such as requirements associated with federally listed species—have substantially accelerated the

development and widespread adoption of acoustic monitoring technologies. Therefore, targeted investment in research capacity building, technology transfer and stronger international collaboration are required in these regions to address the identified knowledge gaps. Enhancing research capabilities and fostering inclusive global research networks are, therefore, critical steps to be taken to achieve a comprehensive understanding of bat ecology and effective conservation management worldwide.

The identified phases reflected significant transitions in research emphasis and technological capacity within the PAM domain. The foundational phase represented initial attempts to establish acoustic methodologies and mainly included exploratory studies on bat ecology and behaviour. The subsequent acceleration observed in the technological advancement phase was aligned closely with the development of accessible and affordable acoustic devices and the incorporation of computational technologies, including artificial neural networks and automated classification algorithms (Bittle and Duncan 2013; Loeb et al. 2015). These technological advancements have significantly improved data accuracy, processing efficiency and the scope of possible research inquiries (Morales et al. 2022). The ongoing broad-scale monitoring phase was indicative of a growing emphasis on landscape-level ecological monitoring and conservation applications (Biffi et al. 2024). This most recent phase highlighted the recognition of PAM as a critical tool for addressing contemporary ecological challenges, such as habitat fragmentation, anthropogenic disturbances (e.g., urbanisation and artificial lighting) and disease emergence (e.g., white-nose syndrome) (Barré et al. 2023; López-Bosch et al. 2022).

However, the rapid increase in research outputs observed in this review underscores the need for standardised methodologies and open-access data repositories to ensure the comparability and scalability of research findings (Cañas et al. 2023). Future research should, therefore, focus on refining the established standardised PAM protocols, enhancing international collaboration and ensuring equitable technological access and training, particularly in the identified underrepresented regions, to facilitate comprehensive global bat conservation efforts. Interdisciplinary collaboration is another promising direction for PAM research in the context of bat ecology, particularly through integration with fields such as artificial intelligence, remote sensing, computer science and landscape ecology (Mann 2012; Sharma et al. 2023). Machine learning algorithms and automated classification technologies enable significantly advanced species identification accuracy and scalability (Bittle and Duncan 2013; Caruso et al. 2020). However, challenges such as species-rich environments, overlapping acoustic signals and regional variability in bat vocalisations remain, warranting rigorous validation and context-specific algorithm development (Wood et al. 2021). Therefore, interdisciplinary efforts should prioritise the development of robust, adaptable and validated analytical tools tailored to diverse ecological and geographical contexts (Ross et al. 2023).

Additionally, challenges such as species-rich environments, overlapping acoustic signals and regional variability in bat vocalisations remain, which significantly hinder the applicability of PAM, especially in biodiversity-rich regions. Additionally, the lack of reliable acoustic libraries in these regions exacerbates

these challenges, limiting the effective use of PAM (Wood et al. 2021). This biogeographical bias, alongside factors such as access to technology and researcher availability, contributes to the regional disparity in PAM studies. It is likely that the abundance of PAM studies is inversely correlated with the number of species locally present at study sites, especially in areas with high bat diversity. Therefore, interdisciplinary efforts should prioritise the development of robust, adaptable and validated analytical tools, as well as the creation of region-specific acoustic libraries, to enhance PAM's effectiveness across diverse ecological and geographical contexts (Ross et al. 2023).

4.2 | Technological Evolution and Thematic Shifts

Thematic evolution and keyword clustering observed in this review illustrate distinct shifts and expansions in the research scope and methodological sophistication of PAM applications in the field of bat ecology over the last three decades. Initial research in this field focused mainly on ecological fundamentals, such as habitat use, echolocation and foraging behaviours, thereby laying the groundwork crucial for future studies (Russo and Jones 2003; Russo et al. 2007). The emergence of conservation-oriented themes, such as wind energy impacts and white-nose syndrome, signalled a transition towards addressing the urgent global conservation issues encountered in bat populations (Coleman et al. 2014; Deeley et al. 2021). The emphasis on anthropogenic impacts (e.g., light pollution and wind energy) in the research underscored the increased awareness and prioritisation of studying bats in regions with human-dominated landscapes, reflecting broader ecological concerns and environmental management needs (Luo et al. 2021; Voigt, Dekker, et al. 2021). Notably, the integration of technological advancements highlighted by the clusters related to bat detectors and acoustic methodologies reflected increasing methodological rigour and the application of advanced analytical tools to address complex ecological issues. However, despite these advancements, significant opportunities for further research integration and thematic consolidation exist (Gibb et al. 2019). For example, acoustic monitoring approaches could be more closely linked with ecological network analysis or ecosystem service assessments, thereby strengthening the connection between methodological development and conservation applications. Moreover, enhanced interdisciplinary approaches, improved standardised monitoring protocols and international collaboration, particularly in regions and topics currently underrepresented, could substantially increase the impact and applicability of PAM research (Browning et al. 2017). Future research should, therefore, continue to leverage advanced acoustic technologies and expand the thematic scopes to address emerging ecological challenges and effectively support evidence-based conservation practices.

The dominance of movement patterns, species identification and habitat use themes in research highlighted the foundational importance of these themes within bat ecology studies, which aligned with the ongoing conservation efforts to understand the role of bat distributions and ecology. Conversely, emerging topics such as ecosystem health and human interference, although less represented, reflected the growing concerns about anthropogenic impacts and ecological integrity. However, despite

substantial progress, the absence of universally standardised protocols for PAM data collection and analysis remains a critical barrier (Kotila et al. 2023). Therefore, standardisation in equipment calibration, acoustic data handling and reporting practices could significantly enhance reproducibility, comparability and integrative analyses across global studies (Adams et al. 2012; Geay et al. 2020). Moreover, integrating PAM data with complementary methodologies, such as GPS telemetry, habitat modelling and environmental DNA analyses, could be a novel strategy for comprehensive ecological assessments (Dwyer et al. 2015). Such multifaceted approaches would allow researchers to understand complex ecological relationships, undertake informed predictive modelling decisions and devise more effective conservation and management strategies (Teixeira et al. 2024).

4.3 | Methodological Challenges and Standardisation Needs

The distinct preference for Anabat and Song Meter devices in bat acoustic monitoring reflected that these devices offer a balance of reliability, affordability and operational simplicity, rendering them well-suited for long-term ecological studies across various field conditions (Adams et al. 2012). The broad availability of these devices, their compatibility with standardised software, along with moderate storage and power requirements, has facilitated their widespread deployment in both temperate and tropical regions (Phinney 2020). These devices are often chosen for large-scale or multisite monitoring programs, in which logistical feasibility and consistency are paramount (Reichert et al. 2018). In contrast, more advanced detectors are typically employed in specialised research contexts requiring high-fidelity recordings (Adams et al. 2012; Wallis and Elmeros 2021), superior time expansion features and finer resolutions in echolocation call structure, especially the studies focused on species with overlapping call frequencies or subtle acoustic distinctions.

Recent advances in detector technology have also reshaped the potential of PAM-based monitoring. The diversification of detector types—from traditional passive ultrasonic detectors to active systems (e.g., EMT, M500) and open-source, low-cost devices such as AudioMoth—has expanded the accessibility and scope of acoustic surveys (Hill et al. 2018). These new platforms can record simultaneously in both acoustic and ultrasonic ranges, enabling the monitoring of multiple taxa, including bats, birds and insects, with a single device. Such technological convergence enhances cross-taxa conservation assessments and facilitates integrated biodiversity monitoring at landscape scales (Mi et al. 2021). The selection of a recording device is not merely a logistical decision but also one that can directly affect species detection accuracy and downstream data interpretation (Teixeira et al. 2024). Devices vary significantly in terms of sensitivity, frequency response, microphone quality and signal-to-noise ratio, all of which influence the detectability of low-intensity or high-frequency calls (Blumstein et al. 2011).

Another important factor shaping the adoption of PAM devices is cost. Although reliability and adaptability remain essential, economic constraints can substantially influence device selection, particularly in regions with limited research funding or technical infrastructure. In biodiversity-rich yet resource-limited

areas, the high price of advanced detectors often restricts their accessibility, thereby affecting the global distribution and frequency of PAM-based studies. Addressing this challenge will require prioritising cost-effective yet reliable solutions that maintain data quality. Future initiatives could focus on developing affordable but durable detectors or establishing shared equipment pools to enhance accessibility to advanced monitoring technologies across institutions and regions. Further, the compatibility of devices with automated or semiautomated analysis tools can vary, potentially affecting classification success and data processing efficiency (Heinicke et al. 2015). The continuous improvement in acoustic technologies warrants systematic cross-comparisons of detector performance under controlled field conditions (Goodwin et al. 2024; Perks et al. 2025). Such efforts would provide evidence-based recommendations for device selection tailored to different research objectives and ecological contexts, thereby improving the reproducibility, analytical comparability and methodological transparency of PAM-based studies on bats (Lara et al. 2020).

The strong preference for fixed-point sampling in PAM-based research on bats revealed in this review reflected both practical advantages and ecological suitability. Fixed survey models allow for continuous, standardised recordings at known locations, enabling direct comparisons over time and across sites (Perks and Goodenough 2021). This approach is particularly effective in detecting temporal activity patterns, habitat associations and responses to environmental change. Mobile transect methods, on the other hand, play a critical role in estimating relative abundance and detecting species occurrence across broader spatial gradients – capacities that stationary surveys cannot provide (Udell et al. 2024). These transects are typically conducted along accessible routes, such as public roads or established walking paths, though access permissions may still constrain where surveys can be implemented. Despite their value, mobile transects remain less frequently used, likely due to increased logistical requirements and their reduced ability to capture long-term temporal resolution (D'Acunto et al. 2018). The limited use of mixed survey strategies likely reflects not only underrepresentation in study design but also analytical challenges, as different survey approaches generate heterogeneous data types that are difficult to integrate within standard analytical frameworks. This gap highlights a potential direction for methodological innovation in future PAM designs (O'Shea and Bogan 2003).

Seasonal monitoring cycles were the most common, which likely reflects the practical constraints of field deployment and the ecological relevance of tracking seasonal patterns in bat activity, reproduction and migration (Hauer et al. 2023; Revilla-Martín et al. 2021). While monthly or daily monitoring provides finer-scale resolution, their limited adoption may be a result of cost, labour and data storage limitations. The predominant use of manual data processing in these studies highlighted persistent limitations in automated acoustic processing, including concerns regarding accuracy and species misclassification. However, the increasing use of automated and semiautomated approaches signals the progressive adoption of technological advancements, driven by developments in machine learning and artificial intelligence (Brinklov et al. 2023; Runkel et al. 2021). This trend was attributable to the perceived reliability of expert-based identification, especially in acoustically complex

communities or regions with poorly represented reference libraries (Dalton et al. 2021). However, the increasing use of automated pipelines has been increasing the confidence in their utility, especially for large datasets (Biffi et al. 2024). Future research should prioritise the standardisation and validation of both manual and automated processing workflows to enhance comparability, efficiency and accuracy in PAM-based studies (Brinklov et al. 2023). In particular, establishing clear and transparent criteria for manual vetting—widely used alongside automated pipelines—would help minimise subjective bias and substantially improve reproducibility across datasets.

4.4 | Integrating PAM With Interdisciplinary Technologies

The integration of PAM with other complementary technological and analytical approaches represents a critical frontier for advancing ecological research and conservation applications. Single-method monitoring often provides limited ecological resolution. Therefore, combining PAM with emerging technologies, such as environmental DNA (eDNA) analysis, high-resolution GPS telemetry, remote sensing and species distribution modelling, can offer a holistic understanding of bat ecology across spatiotemporal scales (Dalton et al. 2021; Mann 2012). For example, eDNA allows researchers to validate acoustic detections and assess broader community composition, particularly in environments in which call overlap or cryptic species reduce acoustic identifiability (Bell and Malerba 2025). Similarly, GPS tracking of individual bats can provide a fine-scale behavioural and spatial context for acoustic activity patterns, providing information about habitat use and roost-foraging dynamics in relation to landscape features.

Advances in artificial intelligence (AI) and machine learning have further enhanced the analytical capacity of PAM, enabling automated species identification in large, complex datasets (Haotian et al. 2024; Sharma et al. 2023). Deep learning models, particularly convolutional neural networks (CNNs), exhibit high accuracy in recognising bat echolocation calls, even under noisy field conditions or in species-rich acoustic environments (Duarte et al. 2024; Morales et al. 2022). However, the success of these models relies heavily on the availability of robust, geographically representative training datasets and expert validation (Görföl et al. 2022; Kath et al. 2024). Therefore, future research should focus on developing region-specific classification models to improve interoperability among software platforms and promote open-access annotated call libraries (e.g., ChiroVox). Moreover, integrating PAM-derived activity metrics into spatially explicit models that learn from remote sensing and climate data can improve the predictive power of conservation assessments, thereby supporting the identification of high-risk areas under environmental change (Gibb et al. 2019).

Recent advances demonstrate how technological miniaturisation and sensor integration are redefining acoustic monitoring paradigms. For instance, onboard multi-sensor systems combining GPS, microphones and accelerometers now enable real-time tracking of bat decision-making and flight behaviour in the wild (Goldshstein et al. 2025; Goldshstein and Yovel 2024). Similarly, thermal and acoustic imaging methods have expanded the

capacity for large-scale, non-invasive population monitoring (Ahlberg et al. 2025), supporting automated detection pipelines that improve population estimation accuracy and methodological standardisation. Collectively, these interdisciplinary integrations will significantly increase the ecological utility of PAM by enabling the capture of diverse biological signals, resolution of ecological uncertainties and real-time, scalable biodiversity assessments. For the full potential of PAM as an ecological indicator system, cross-disciplinary collaboration, particularly across acoustic ecology, computational science, landscape ecology and conservation policy, must be prioritised. These synergistic efforts will ultimately provide more accurate, context-specific and actionable insights into bat population dynamics and ecosystem health.

5 | Future Directions

As PAM continues to evolve from a specialised method to a foundational tool in ecological research and conservation, the future trajectory of PAM-based research must prioritise four interrelated aspects: methodological standardisation, technological integration, global inclusiveness and cross-disciplinary collaboration. Together, these efforts can expand the utility of PAM as a globally scalable, ecologically informative and policy-relevant approach for biodiversity monitoring and ecosystem assessment. Future studies could further explore temporal patterns in author numbers and international collaborations to better understand the expanding global network and interdisciplinary nature of PAM-based bat research.

The development of standardised PAM protocols is the foremost essential for improving comparability and reproducibility across studies and regions. The current methodological heterogeneity, including variations in the recording equipment, sampling rates, trigger settings, survey durations and data analysis pipelines, undermines the potential for large-scale meta-analyses and long-term trend detection. While standardisation is essential for improving comparability across studies, certain methodological parameters—such as sampling rates, trigger thresholds and survey duration—are inherently constrained by species-specific echolocation characteristics and local detection probabilities. Therefore, standardised protocols should be framed as flexible guidelines that allow scientifically justified adjustments based on the focal species and ecological context (Gibb et al. 2019). Community-driven guidelines should, therefore, be established for field deployment strategies, acoustic metadata reporting and device calibration procedures. Equally important is the expansion of open-access, expert-validated call libraries accounting for geographic, environmental and behavioural variability. These reference datasets will establish robust automated classification pipelines and facilitate consistent species identification across biomes. Prioritising contributions from the underrepresented taxa and regions will assist in closing the existing knowledge gaps and promote broader taxonomic and geographic coverage in global assessments.

In addition, PAM must be increasingly integrated with complementary tools and technologies to support multidimensional ecological inference. Combinations of PAM with environmental DNA (eDNA), GPS telemetry, remote sensing and habitat

suitability models would provide synergistic insights into species behaviour, population dynamics and environmental interactions. Moreover, the rapid growth of artificial intelligence, particularly deep learning and convolutional neural networks, has opened new frontiers in automated acoustic classification, thereby enabling high-throughput, real-time biodiversity assessments, even in acoustically complex environments. However, the accuracy and generalisability of these AI models depend highly on the availability of geographically representative training datasets and ecological validation. Future work should, therefore, focus on developing context-specific algorithms and improving interoperability across platforms and analytical tools.

Further, addressing global disparities in PAM-based studies and infrastructure is vital for equitable conservation science. This review highlights a concentration of PAM-based studies in North America and Europe, whereas ecologically critical bat-rich regions such as Africa, Southeast Asia and South America remain underrepresented in the literature. Bridging this gap will require targeted investment in local research capacity, regional collaboration and knowledge transfer initiatives. The incorporation of PAM in national and international biodiversity monitoring frameworks can also strengthen PAM's contribution to conservation policy, ensuring alignment between scientific inquiry and decision-making processes. Supporting inclusive and context-aware research practices will expand the global relevance of PAM and also increase its potential as a cost-effective and scalable tool for biodiversity surveillance in the Anthropocene.

These future directions outline a distinct pathway for advancing the next phase of PAM research. The acoustic monitoring community will foster methodological coherence, technological innovation, global equity and interdisciplinary synthesis, thereby unlocking the full potential of PAM in addressing contemporary ecological challenges, guiding evidence-based conservation actions and tracking ecosystem integrity across a rapidly changing world.

Author Contributions

Yang Geng: conceptualisation, software, data curation, formal analysis, visualisation and writing – original draft. **Hao Zeng:** methodology, data curation, resources. **Hanli Yin:** methodology, data curation. **Jing Lu:** methodology, visualisation. **Jiang Feng:** conceptualisation, writing – review and editing. **Peter John Taylor:** writing – review and editing. **Yingying Liu:** conceptualisation, funding acquisition, project administration and writing – review and editing. **Tinglei Jiang:** supervision, funding acquisition.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Summary of all studies included in the systematic review, with associated bibliometric and methodological metadata.