New technologies for biodiversity in environmental permitting for mining

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Abstract: Environmental permitting processes in Brazil require, both in the diagnosis for the environmental impact study (EIS) and the follow-up phase, the collection of primary data on fauna and flora. The rules for environmental permitting processes for the Mining sector recommend biodiversity sampling protocols with collections using traps and intensive sampling efforts, which represent high costs and risks intrinsic to fieldwork. Brazil overlaps the conditions of a megadiverse country with abundant reserves of critical and strategic minerals, especially those that support the energy transition to a more sustainable economy in the global context. These conditions point to the trend of mining expansion in the coming years, often in areas with unique or critical habitats, where impacts on biodiversity need to be adequately measured and monitored. In this context, the incorporation of new technologies for biodiversity studies, involving molecular methods (eDNA) and bioacoustics with artificial intelligence will be essential. This article presents a review of these new methodologies in comparison with conventional sampling techniques, as well as discussing examples of their applications in the specific context of exploration areas for different minerals. Examples of the use of applied technologies for the knowledge and conservation of species endemic to strategic mineral exploration environments are also discussed. As a result, there was great potential to improve biodiversity sampling, offering information to expand strategies for mitigating biodiversity loss.

Summary statement: Brazil is a megadiverse country and presents abundant reserves of minerals. This article discusses the use of new technologies for biodiversity assessment in environmental permitting for mining

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Introduction

The environmental permitting process in Brazil is three-phased and results in the issuance of three permits: the preliminary permit, installation permit and operating permit. The studies that support the request for the preliminary permit include diagnostics of the biotic, physical, and socioeconomic characteristics of the environment. Regarding biodiversity, the protocols require the collection of primary data on fauna and flora, even in extensively sampled areas. In the environmental impact monitoring studies carried out to obtain the installation and operating permits, periodic field samplings are again required, using traditional methods of collection and capture of animals and plants in the field.

In the nearly four decades since the environmental impact assessment process was regulated in Brazil (BRASIL, 1986), a small number of the technological innovations that have emerged during this period have been incorporated into environmental permitting procedures. Methodologies involving molecular data, bioacoustics, databases, and others are rarely accepted by the agencies responsible for issuing permits, which continue to require exhaustive field sampling while disregarding the knowledge produced in each region through previous studies, that often lack proper organization within structured databases.

The vast datasets generated from the environmental permitting processes of large infrastructure projects in Brazil, particularly in the Energy and Mining sectors, remain inaccessible to society at large, including the scientific community and consulting companies. This restricts the potential for utilizing these data to contribute to the cumulative knowledge of biodiversity.

Brazil is among the world's megadiverse countries, harboring between 15% and 20% of global biodiversity (UNEP, 2019). However, the rapid decline of global diversity demands scalable monitoring efforts and resource allocation based on strategies that ae consistent with the true conservation status of species, population and ecosystems (WREGE et al., 2017). In this regard, UNEP (2022) recommends the adoption of the Kunming-Montreal Global Biodiversity Framework (GBF), which includes, among its goals, the first one aimed at halting biodiversity loss by 2023.

In mining, there are initiatives aimed at "achieving at least no net loss of biodiversity at all mining sites relative to the 2020 baseline" (ICMM, 2024), indicating that the interface between biodiversity conservation and mining is crucial for achieving the global target of zero net loss.

Mining is a highly relevant sector in the Brazilian economy, accounting for 47% of the country's trade balance surplus (IBRAM, 2025) and holds reserves of critical and strategic minerals—particularly those that support the energy transition toward a more sustainable global economy (SILVA et al., 2024).

This condition indicates a trend of mining expansion in the coming years, often in areas with unique or critical habitats, where impacts on biodiversity must be properly measured and monitored. In this context, the incorporation of new technologies for biodiversity studies – such as molecular methods (eDNA) and bioacoustics integrated with artificial intelligence will be essential.

From this perspective, it is inevitable that there will be recurrences of diagnoses of biodiversity composition, especially in areas where there are already mining projects and other activities that require surveys of fauna and flora to be permitted. In the Quadrilátero Ferrífero, Minas Gerais, Brazil, where there is an abundance of mineral resources (FERREIRA, 2015), the high number of new environmental permitting requests (AMBIPAR, 2024) reflects the tendency for information redundancy when the diagnosis is based on traditional methods of fauna monitoring. In addition to the state of Minas Gerais, the state of Pará, in the Amazon region, has great potential for the advancement of mining, especially in the Carajás mountain range, with the exploitation of iron ore, copper, and nickel.

In this scenario, it is essential that biodiversity surveys be carried out efficiently, both in terms of representativeness of the species composition present in an area of interest and in terms of resource allocation. However, traditional strategies for biodiversity survey and monitoring have always been carried out using traditional methodologies, with the presence of specialists such as biologists in field activities. These methods may present several limitations, for example, difficulty in accessing the sampling sites, high application of material resources, and the need for a trained technical team. These barriers can hinder the understanding of the complexity of biological communities and ecosystems, preventing the structuring of truly effective conservation strategies (CHALMERS et al, 2017).

Thus, the use of new technologies and methods such as bioacoustics (KLEIN, 2015) and molecular analyses of eDNA (RUPPER et al., 2019) are important strategies to be incorporated into biodiversity assessments, especially in the context of mining projects, given the recurrence of surveys in areas that effectively present high biological diversity and the impacts that this activity generates on the biotic environment (SHANMUKHA, 2024).

The objective of this paper is to present a review of the uses of these new biodiversity sampling methodologies and to establish comparison with traditional methods currently used. These links will be structured based on case studies applied to mining, highlighting the main positive and negative aspects of using bioacoustics and eDNA, aligned with Artificial Intelligence (AI) technologies.

Method

A literature review was conducted on biodiversity surveys, covering both traditional methods and the use of indirect data collection methodologies that do not require the capture or collection of animals or reproductive material from flora, in conjunction with the use of artificial intelligence.

Based on the information from the bibliography, the potential application of bioacoustics and eDNA methodologies, coupled with artificial intelligence, was evaluated within the context of environmental permitting processes. This includes both the preliminary environmental diagnostic phase (baseline construction) and the biodiversity monitoring phase (follow-up), which facilitates the construction of knowledge for decision-making in the mitigation of biodiversity impacts.

Results

The use of bioacoustic methods has been well established since the beginning of avifauna studies using directional recorders. With the evolution of this methodology, automated and autonomous acoustic recorders are currently used, which continuously capture environmental sounds and, when combined with machine learning and other artificial intelligence tools, can be efficient in detecting and classifying animal sounds. This approach presents relevant potential for biodiversity conservation (TOLEDO, pers. com). This method can be applied to birds, amphibians, bats, and insects.

Klein et al. (2015) detailed, in their work, the diverse uses of acoustic sensors for biodiversity monitoring. The results presented demonstrate multiple applications, such as the identification and monitoring of threatened and rare species, detection and tracking of invasive exotic populations, and habitat monitoring. The authors also discuss that these methods generate a large amount of information and data that need to be stored and analyzed.

In this scenario, it is evident that the construction of databases is essential for the development of bioacoustic analyses. Several public acoustic databases can be used, such as the Macaulay Library (ML), Lab of Ornithology, Cornell University; Xenocanto; and Rainforest Connection (RFCX). The Australian organization The Terrestrial Ecosystem Research Network (TERN) has invested in bioacoustic sensors and the construction of automated and open databases, which currently maintain around 42,000 audio files from 21 distinct locations. This initiative has already demonstrated its utility in terms of species identification and resource allocation, as this method is less costly financially compared to traditional monitoring methods (TERN, 2017).

In Brazil, there are also significant initiatives related to biodiversity monitoring through the use of bioacoustics. The partnership between the Instituto de Desenvolvimento Sustentável Mamirauá (IDSM) and the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) monitors groups of amphibians, birds, insects, and mammals in the Serra do Cipó, an area of great interest for mining activities (MCTI, 2023; IBRAM, 2012). The monitoring of river dolphins (*Inia geoffrensis*) in the Amazon River is also carried out through bioacoustics, with analysis associated with recognition software (ERBS et al., 2023). Brazil also has the Fonoteca Neotropical Jacques Vielliard (FNJV), Museum of Biological Diversity, University of Campinas (Unicamp), with over 125,000 sound recordings deposited from 3,415 bird species; 1,181 amphibian species; 219 mammal species; 109 reptile species; 129 fish species; and 301 invertebrates (MUSEU DE ZOOLOGIA DA UNICAMP, 2025).

Bioacoustic sensors and their uses in monitoring offer significant advantages, mainly in terms of logistics, resource efficiency, increased species identification capacity, and reduced interference with the habitat (CHALMERS, 2021). Moreover, the passive acquisition of information generates a large amount of data that needs to be stored and analyzed. To optimize these analyses, the main approaches currently rely on machine learning to classify different animals from acoustic data (NANNIS, 2020; STOWELL, 2019).

For species identification to be feasible through AI, it is essential to have a considerable dataset for network learning. Chalmers (2021) discusses that it is crucial for sensors to be distributed across different habitats, capable of real-time data collection and inference. In a study conducted by Klein et al. (2015), it was found that, when meeting the information volume requirement, for certain species, there was a reduction of 100 to 1.000 times in the amount of data needed for manual review when integrated with AI.

The use of environmental DNA, or eDNA, refers to the genetic material present in environmental samples such as sediment, water, and air. Through molecular analysis of these samples, it is possible to identify species that have encoded genetic material. Although this technique is relatively new, eDNA shows great potential for biodiversity monitoring (RUPPERT, 2019). Deiner et al. (2017), through the use of this method, achieved higher taxonomic resolution by identifying a greater number of species compared to traditional methods, supporting previous studies that optimized results with the use of the eDNA technique (VALENTINI et al., 2016).

The main advantage of using eDNA for biodiversity monitoring is the identification of species that would be difficult to detect using traditional methods, such as threatened and rare species (RUPPERT, 2019). Feng et al. (2023) used the eDNA monitoring method to identify the occurrence of invasive and rare species in the middle and upper Yarlung Zangbo River, Tibet. The results obtained, in addition to identifying the presence of 30 species already recorded in the database, also allowed the identification of 12 additional fish species not yet listed in any previous captures, including a threatened species (*Oxygymnocypris stewartii*).

Another characteristic of this method, which makes it an important strategy for biodiversity monitoring, is the possibility of estimating the relative abundance of populations based on biomass (JARDER, 2011). Furthermore, eDNA has the potential to detect functional ecological interactions over larger spatial scales, through more rapid and efficient processes, due to the reduction in associated costs (YU et al., 2012).

Despite the advantages associated with biodiversity monitoring through eDNA, some challenges still need to be overcome, such as the standardization of sample collection to avoid contamination and the estimation of DNA molecule degradation rates, which may compromise the interpretation regarding species presence (RUPPERT, 2019). In addition to these challenges, it is important to highlight the need for the development of extensive reference databases to enable comparative eDNA analyses (OLIVEIRA et al., 2022). Nevertheless, efforts around the world have been undertaken to map the genetic code of different taxonomic groups and species.

In Brazil, there are initiatives dedicated to building species databases of anurans from the Amazon, based on mitochondrial DNA (mtDNA) (JEAN-PIERRE et al., 2020). In China, researchers have surveyed the genomic characteristics of nine species from the Sillaginidae family, also based on mtDNA. In addition to these cases, Denmark is conducting genome surveys of vertebrate species to develop a national database for biodiversity monitoring (MARGARYAN et al., 2020).

In the Carajás Mountains, in Eastern Amazonia, the plant community presents high endemism with rare species associated with a high incidence of mining. In traditional survey studies conducted over several years, Silva et al. (2023) identified 225 species; when added to previous long-term surveys, a total of 560 plant species were recorded in the region. In the same area, Vasconcelos et al. (2021), through the collection of young leaf tissues and eDNA extraction, assessed 1.179 specimens and identified 577 species, of which 344 were genetically coded for the first time, demonstrating that eDNA is a fast and effective tool for evaluating the genetic diversity of flora.

As in studies conducted using data obtained through bioacoustics, the information generated by eDNA on biodiversity can be better analyzed with the aid of AI. Machine learning, due to the volume of data, can optimize assessments and diagnoses when these systems are connected to robust databases containing the necessary information about species genomes (ZHANG, 2023). In this way, AI algorithms analyze genetic and acoustic data more efficiently and rapidly, enabling more consistent inferences about biodiversity, especially in identifying rare species and assessing the effects of environmental changes, allowing for early decision-making (ULLAH et al., 2025).

Comparing the use of traditional methodologies with bioacoustics and eDNA methodologies combined with AI, it is possible to apply these approaches to establish a baseline survey for 88 mining dams in the Quadrilátero Ferrífero area. The surveys were carried out in an optimized manner, focusing only on terrestrial fauna. A total of 192 sampling areas were surveyed, with sampling efforts for herpetofauna consisting of 1,536 hours of active search and 144,000 hours of pitfall sampling; for avifauna, 6,600 hours of mist-netting and 3,040 hours using Mackinnon lists and point counts; and for mammals, 1,536 hours of active search, 115,200 hours of live-trapping, 28,800 hours of camera-trapping, and 3,072 hours of mist-netting, with more than 150 field professionals and approximately 100 vehicles mobilized over one year of work (VALE, 2021/2022).

By applying bioacoustics methodologies for birds, amphibians, and bats, and eDNA for mammals—which have proven efficient for biodiversity sampling (BERRY et al., 2020; ZHANG et al., 2023; CHOWDHURY et al., 2024)—it would be possible to significantly reduce the number of professionals needed in the field, consequently decreasing accident risks, investment costs, and data analysis time. Moreover, these methodologies minimize the need for collecting live or deceased specimens, as they enable biodiversity assessments without direct physical sampling, while allowing for extended acoustic data collection durations, potentially tripling or more the time coverage, thus enhancing survey representativeness.

When analyzing studies based on traditional methodologies—alongside the findings of Tuia et al. (2022), Hoffmann (2022), Silvestro et al. (2022), and Volis (2019) (as cited in Ullah et al., 2025)—it becomes evident that manual tracking and the use of traps demand substantial human effort and time, are often prone to imprecision, and may result in an inefficient cost–benefit ratio. In stark contrast, the research conducted by Dauvergne (2020), Silvestro et al. (2022), Nagini et al. (2023), and Ditria et al. (2022) (as cited in Ullah et al., 2025) underscores the advantages of incorporating artificial intelligence into biodiversity monitoring. These advanced methodologies not only streamline data collection and enhance resource allocation for conservation efforts but also provide superior accuracy and speed in species detection, thus significantly improving the capacity to predict and mitigate threats to biodiversity.

Conclusion

The use and dissemination of new sampling methods for biodiversity monitoring present great potential for mitigating the environmental impacts of large projects, including mining, which is currently characterized as an important sector of the global economy. The main advantages of bioacoustic and eDNA methods enable more efficient use of resources employed in biodiversity monitoring, as they are capable of generating a larger volume of data, offering better cost-effectiveness.

For the implementation of these methodologies, it is essential that they be associated with Artificial Intelligence, particularly for the analysis of biodiversity data and information. In this context, it is crucial to establish robust databases containing information that enables identification through genomic and bioacoustic data. Despite the various ongoing initiatives to structure biodiversity information both in the public sector (SISBia) and the private sector, the effort for the development, strengthening, and unification of these databases must be continuous and growing.

The integration of these new methodologies does not dismiss the validity of the traditional methods already used, which provide data to corroborate the results obtained with the use of artificial intelligence. Thus, different methods should be employed for the construction of comprehensive knowledge about the current state of biological diversity. In this way, the appropriate use of the generated information can be directed towards the prevention and mitigation of biodiversity impacts, providing solid support for effective decision-making.

Finally, it is important that these databases be made available and managed by environmental public agencies for public access, thus preventing the recurrence of sampling and making the licensing process more efficient.

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