EchoSystem: An Integrated Platform for Bioacoustic and Micrometeorological Monitoring

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Abstract. *Biodiversity loss driven by factors such as deforestation, wildfires, and urban expansion highlights the need for effective environmental monitoring strategies. This work presents EchoWeb, an open-source web platform for the processing and analysis of bioacoustic and micrometeorological data, and its integration within EchoSystem, a complete end-to-end monitoring ecosystem. EchoWeb supports acoustic index computation, spectrogram visualization, and structured organization of scientific results through a web-based interface. A case study conducted near the Federal University of Amazonas demonstrates its applicability in real-world conditions. Simulation experiments based on Poisson arrival processes and log-normal workload distributions show that the main system bottleneck lies in the audio processing stage. Results further indicate that scaling the number of audio-worker instances significantly reduces end-to-end response time and improves system throughput.*

Keywords: *Bioacoustic Monitoring, Environmental Monitoring, Integrated Hardware-Software Systems*

1. Introduction

Increasing anthropogenic disturbances, such as deforestation, urbanization, and climate change, have caused significant impacts on ecosystems, threatening the survival of numerous species [Pimm et al., 2014]. Among them, the pied tamarin (*Saguinus bicolor*) stands out, an endemic primate from the Manaus region whose population has been declining due to urban expansion and habitat fragmentation [Albernaz et al., 2026]. In response, a National Action Plan (PAN) was established, including guidelines to expand research on its acoustic communication, ecological interactions, and the creation of urban ecological corridors [ICMBio, 2025].

In this context, bioacoustic monitoring emerges as an important tool for understanding behavioral patterns and population dynamics, supporting more effective conservation strategies [Sugai et al., 2018]. While the EchoLogger field device was previously introduced as a standalone embedded system for acoustic recording and environmental sensing [Mendes et al., 2025], this article presents EchoWeb [1], the web platform that completes the EchoSystem ecosystem. It aims to provide the scientific community with an integrated and accessible online solution capable of supporting activities ranging from

[1]https://github.com/AlcirCastro/Echo_Web

field data collection to result sharing, thereby contributing to conservation efforts for endangered species.

The remainder of this paper is organized as follows. Section 2 discusses the related work that underpins this research. Section 3 presents the theoretical concepts. Section 4 describes in detail each component and module of the developed architecture, explaining their respective functions and interactions. Sections 5 and 6 present the use of the proposed solution and the simulation methodology. The results obtained are presented in Section 7. Finally, Section 8 discusses the main results and future directions.

2. Related Work

Bioacoustic monitoring has advanced with the development of autonomous recording devices and computational tools for soundscape analysis, generally organized into two main fronts: passive acoustic monitoring (PAM) devices and audio processing and analysis tools.

Among data acquisition devices, low-cost alternatives such as the AudioMoth [Hill et al., 2018] and Aurita [Beason et al., 2019] have contributed to increasing the accessibility of bioacoustic monitoring. However, they are primarily focused on audio capture and do not incorporate environmental variables, embedded audio processing, or customizable firmware. EchoLogger [Mendes et al., 2025] stands out by integrating acoustic recording with the collection of micrometeorological variables and onboard processing of acoustic indices, implemented on an ESP32 microcontroller with open MicroPython-based firmware.

In the field of audio data processing and analysis, tools such as BioSounds [Darras et al., 2020] and BiophonyAI [Joyce, 2025] offer relevant functionalities, although in isolation. A significant portion of existing solutions is proprietary or subject to licensing restrictions [Wood et al., 2024, Wildlife Acoustics, 2024, 2026], and integration with micrometeorological data remains fragmented.

Table 1 compares existing solutions according to the following criteria: integration with hardware (HW), configuration flexibility (Config.), audio playback (Audio), spectrogram visualization (Spectro.), acoustic index computation (Index), species detection (Species), micrometeorological data collection (Meteo.), and the ability to generate analytical reports and publish them directly on the platform for access and visualization by other users (Reports). The comparison shows that none of the evaluated solutions integrates all these capabilities simultaneously.

EchoSystem aims to fill this gap by bringing together, in a single open-source integrated platform, all stages of the bioacoustic monitoring workflow, from data acquisition to structured result publication, promoting traceability, reproducibility, and transparency.

3. Theoretical Foundations

3.1. Queueing Modeling

Computational systems can be modeled as queueing systems, in which requests arrive (potentially concurrently), wait in a queue, and are processed by one or more servers. Queueing theory provides analytical and probabilistic tools to evaluate performance metrics such as average waiting time, response time, and throughput.

Table 1. Comparison of bioacoustic monitoring solutions.

Solution	Access	HW	Config.	Audio	Spectro.	Index	Species	Meteo.	Reports
AudioMoth [Hill et al., 2018]	Free	Yes	Yes	Yes	Yes	No	No	No	No
BioSounds [Darras et al., 2020]	Free	No	N/A	Yes	Yes	No	No	No	Partial
BiophonyAI [Joyce, 2025]	Free	Yes	N/A	Yes	Yes	Yes	Partial	Partial	No
Ecoacoustic Bank [Giraldo-Forero et al., 2024]	Free	No	N/A	Yes	No	No	No	No	No
ecoPi + BirdNET [Wood et al., 2024]	Paid	Yes	Yes	Yes	Yes	No	Yes	No	No
Wildlife Acoustics [2026]	Paid	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Aurita [Beason et al., 2019]	Free	Yes	Yes	No	No	No	No	No	No
BirdNET [Kahl et al., 2021]	Free	No	N/A	Yes	Yes	No	Yes	No	No
EchoSystem	**Free**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Partial**	**Yes**	**Yes**

In deployed systems, requests often arrive independently and asynchronously, while service times exhibit variability associated with the workload. Therefore, both the arrival process and the service time can be described using appropriate probabilistic distributions [Harchol-Balter, 2013], as described below.

3.2. Poisson Process

The Poisson process is widely used to model events that occur randomly over time, assuming independence between occurrences and a constant average arrival rate. In this process, the number of events within a time interval follows a Poisson distribution, while the interarrival times follow an exponential distribution, $T \sim e^{\lambda}$, where λ represents the average arrival rate per unit of time and T corresponds to the time between two consecutive events.

This model is widely applied in computational systems, networks, and web servers, as it adequately represents scenarios in which multiple independent sources generate requests [Cheng, 2025].

3.3. Log-normal Distribution

The log-normal distribution is used to model positive random variables resulting from the multiplication of several independent factors. A random variable X follows a log-normal distribution when the natural logarithm of this variable is normally distributed. The probability density function is given by:

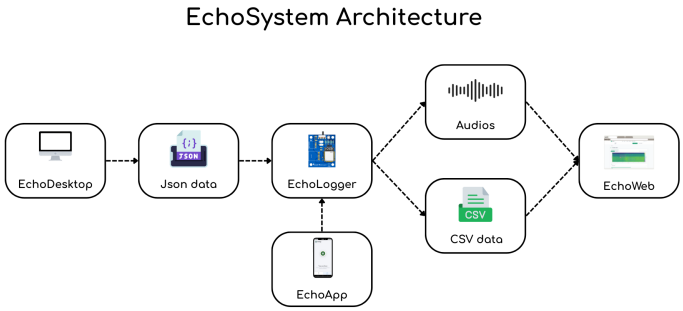
$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}}, \quad x > 0,$$

where μ and σ^2 represent the mean and variance of the $\ln(X)$.

Log-normal distributions are often used to model file sizes, processing times, and other quantities in computational systems, as they exhibit right-skewness. This characteristic allows representing scenarios in which most values are moderate, while a small number of events take significantly larger values [Mitzenmacher, 2004].

3.4. Factorial Experiments 2^k

Factorial experimental design is a simulation technique used to evaluate the effect of multiple factors on a system. In a full factorial experiment 2^k, k factors are considered, each evaluated at two levels, typically referred to as low and high levels.



(a) Communication diagram between modules.



(b) EchoLogger device inside the protection case.

Figure 1. EchoSystem architecture and the EchoLogger sensing/recording device.

This type of experiment allows the estimation of not only the main effects of each factor but also the interactions between them, making it possible to identify dependency relationships among system variables [Kandananond, 2013, Montgomery, 2017].

4. Proposed Solution

In light of the context presented in Section 2, we propose EchoSystem, a complete solution capable of integrating all functionalities required for bioacoustic monitoring. The proposed solution comprises two layers: (1) data acquisition, including micrometeorological measurements and audio recording; and (2) data processing, including feature extraction from audio and micrometeorological variables, audio playback, and spectrogram visualization for analysis.

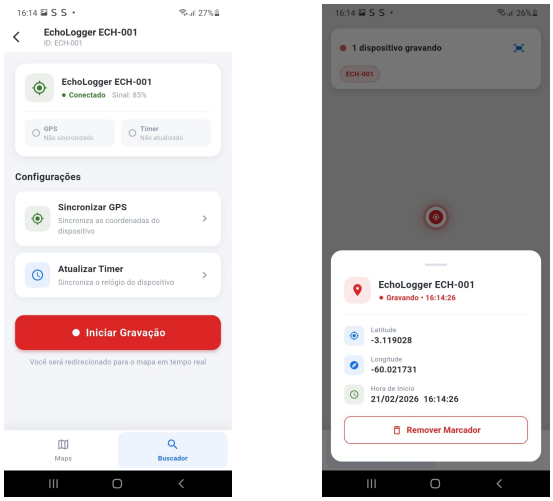
Figure 1(a) illustrates the solution implemented by EchoSystem, whose interactions between components are detailed as follows. The first step consists of configuring the recording and sensing device EchoLogger through EchoDesktop (a desktop application), which transfers a `.json` file to the device containing the audio quality settings and the duty cycle (i.e., recording intervals and sleep mode periods to save battery).

Next, we deploy the EchoLogger at the monitoring site. Using EchoAPP, we update the geographic coordinates and synchronize the ESP32 Real-Time Clock (RTC) using the smartphone's GPS. After this setup, audio recording starts in `.wav` format, and a `.csv` file containing micrometeorological data is also generated.

At the end of the monitoring period, the collected data is exported as a `.zip` file and uploaded to EchoWeb for further processing. In this second stage, bioacoustic features and micrometeorological metrics are computed, and it is also possible to play back the audio, generate spectrograms, and create bounding box annotations for analysis.

4.1. EchoSystem Components

EchoSystem is composed of four tools: EchoLogger, EchoApp, EchoDesktop, and EchoWeb. EchoLogger, illustrated in Figure 1(b), is a device designed for long-term field



(a) (b)

Figure 2. EchoApp: clock and GPS synchronization.

acoustic monitoring applications, based on the ESP32-WROOM-32S microcontroller. The system incorporates a BME680 sensor and an LDR, responsible for collecting environmental parameters such as temperature, humidity, atmospheric pressure, air quality, and luminosity. In addition, it uses an omnidirectional MEMS microphone capable of digital audio acquisition. The full hardware design and firmware are openly available in the project repository[2].

EchoApp, illustrated in Figure 2, allows remote updating of the device location by sending latitude and longitude from a smartphone, as well as synchronizing the EchoLogger RTC via BLE (Bluetooth Low Energy). EchoDesktop, shown in Figure 3, generates a `.json` file on the microSD card containing configuration parameters such as microphone gain, sampling rate, bit depth, AR index activation, and sleep and recording intervals, which are automatically loaded by EchoLogger during boot.

Finally, EchoWeb is an open-source web platform designed for bioacoustic and micrometeorological analysis of monitored sites. The application allows the upload of field recordings, automatic computation of bioacoustic indices, spectrogram visualization, annotation of acoustic events, and the automatic generation of PDF reports containing the analyzed data for easy sharing.

5. EchoSystem Use Case

The experiment was conducted in the Federal University of Amazonas (UFAM) campus, in Manaus, Brazil, at coordinates 3°05'19.1"S and 59°57'56.7"W (Figure 4). The region is characterized by dense non-flooded upland forest in an urban context, with significant fragments of native vegetation. The site was selected as it represents an important conservation area for the pied tamarin (*Saguinus bicolor*), an endemic and endangered species monkey, and due to its accessibility for installation and monitoring. Data collection took place from 13 February 2026 at 18:00 to 15 February 2026 at 13:00, totaling approxi-

[2] `https://github.com/juancolonna/EchoLogger`

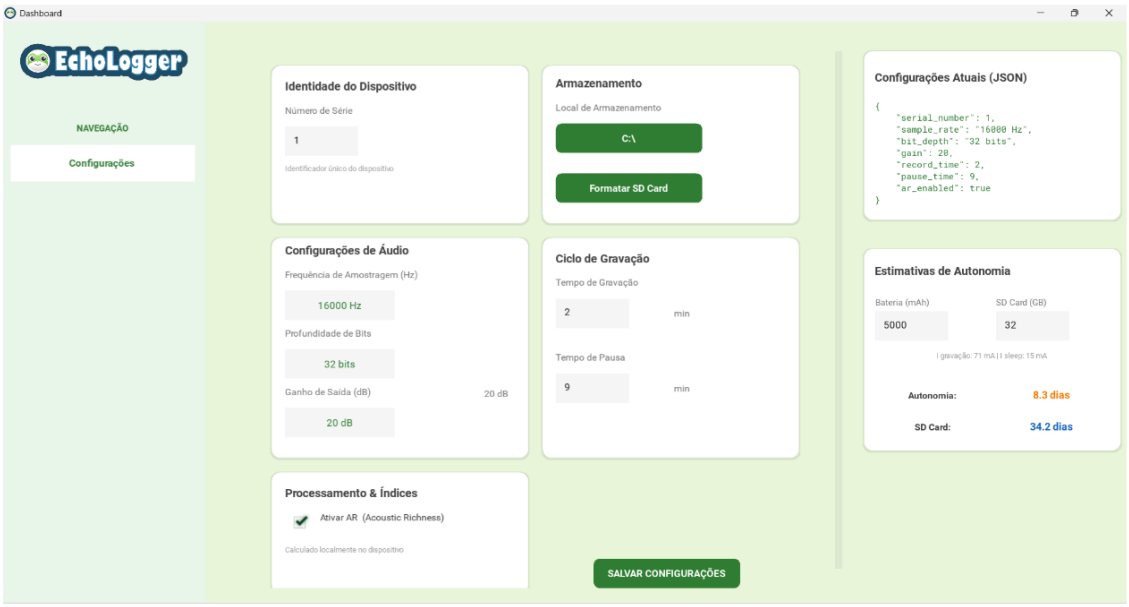


Figure 3. EchoDesktop.



Figure 4. Experiment locations. On the left, the recorder positioned on a tree; on the right, the geographic location within the forest conservation area.

mately 41.7 hours of continuous recording and 416 audio files.[3].

Prior to deployment, the EchoLogger was configured via EchoDesktop as described in Table 2 and updated using EchoAPP. At the end of the monitoring period, all data files were compressed and uploaded to EchoWeb, initiating a processing pipeline in which the *worker-coordinator* extracts the contents of the ZIP file, organizes the audio files and the CSV, and dispatches each audio file individually to the processing queue. Multiple instances of the *audio-worker*, responsible exclusively for computing acoustic indices, consume this queue in parallel, processing each recording independently and returning the corresponding index values. In parallel, the CSV file is forwarded to the *micro-worker*, responsible for micrometeorological analysis, including derived variables such as dew point [Lawrence, 2005], vapor pressure deficit [Acevedo-Romero et al., 2025], heat index [Anderson et al., 2013], implemented using MetPy [May et al., 2022], and daily temperature range.

[3]https://drive.google.com/drive/folders/1UPr9NfA5yynCR5ragqCzFt3scdPKWlmC?usp=sharing

Table 2. EchoLogger configuration.

Parameter	Value
Sampling rate (f_s)	$16\,\mathrm{kHz}$
Bit depth (n_b)	$16\,\mathrm{bit}$
Duty cycle (recording)	$1\,\mathrm{min}$
Sleep cycle (saving battery)	$5\,\mathrm{min}$
Acoustic Richness Index	Yes
Gain	$6\,\mathrm{dB}$
Storage (SD card)	$16\,\mathrm{GB}$

The EchoWeb platform provides an interactive dashboard with several bioacoustic indices, spectrograms synchronized with audio playback for visual inspection, noise filters, and tag-based annotations (Figures 5(a), 5(c)), as well as time series visualizations and correlation analysis between environmental variables (Figures 5(d), 5(b)). The computed bioacoustic indices include ACI (Acoustic Complexity Index), NDSI (Normalized Difference Soundscape Index), BI (Bioacoustic Index), H (Acoustic Entropy), and ADI (Acoustic Diversity Index). Automatic detection of pied tamarin vocalizations [Colonna et al., 2025] can also be performed using a dedicated *worker*. Additionally, this platform includes a dedicated section for writing and publishing technical reports, with support for exporting graphs and index values from the dashboard for further analysis, allowing researchers to document methodologies, record field observations, and publish results, thereby promoting traceability and scientific reproducibility.

6. Simulation Experiment

To evaluate the performance of the EchoWeb system under different workload conditions, a simulation experiment was conducted based on a Poisson arrival process and a log-normal distribution to model workload variability (*i.e.*, request arrival times and the sizes of files uploaded to the system). The simulations were executed on a computer equipped with an AMD Ryzen 5 3600XT processor (6 cores, 12 threads) and 24 GB of RAM.

Let X be the random variable representing the number of audio recordings contained in a ZIP file submitted to the system (*i.e.* the workload). Based on the acquisition protocol described in Table 2, with a duty cycle of recording followed by a sleep period, 10 recordings are generated per hour. Assuming continuous operation for up to $48\,\mathrm{h}$, the maximum value is $X_{\max} = 480$ recordings.

The variable X was modeled as a log-normal random variable, $X \sim \text{log-normal}(\mu, \sigma^2)$, truncated to the interval $[1, X_{\max}]$. The mean was set to $\mu = \ln(240)$, which is consistent with the 416 recordings obtained over approximately $41.7\,\mathrm{h}$ in the case study presented in Section 5. The 95th percentile was aligned with the physical limit by imposing $P(X \leq 480) = 0.95$, yielding $\sigma = \big(\ln(480) - \mu\big)/1.645$. These parameters were defined to represent typical system behavior and a high-load scenario.

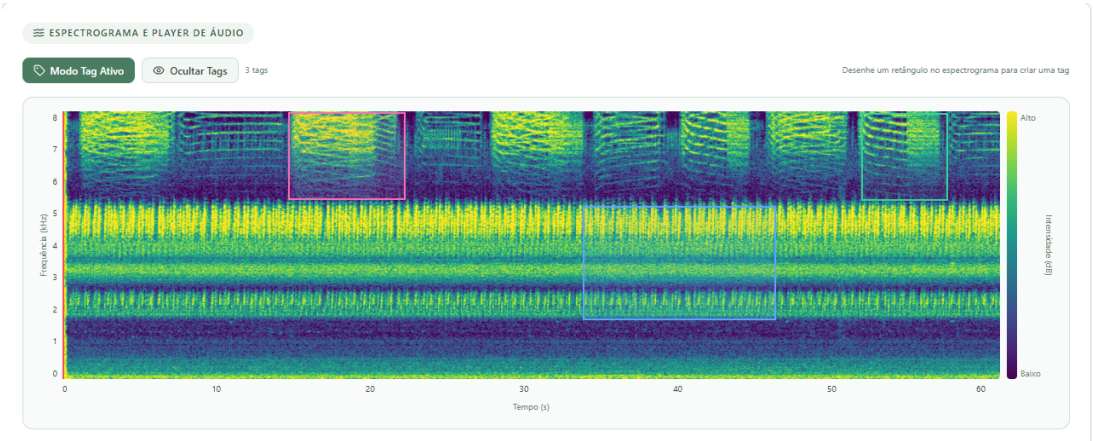
The experiments used real recordings that were resampled and recombined to compose the workloads. Five rounds were conducted using different random seeds (43 to 47). In each round, five synthetic ZIP files were generated, with the number of audio files defined by the log-normal distribution, resulting in the following sizes: 267, 163, 204, 191, and 344 audio files (round 1); 174, 417, 405, 122, and 129 (round 2); 242, 267, 203, 220, and 140 (round 3); 307, 403, 339, 171, and 285 (round 4); and 167, 416, 354, 314,



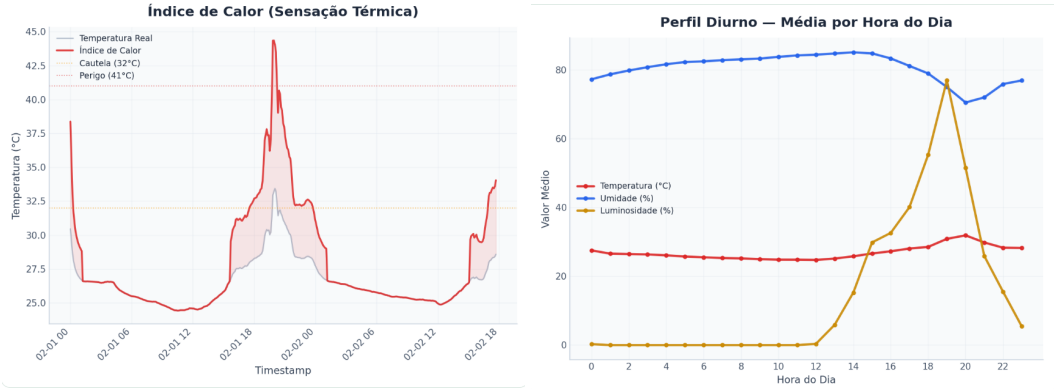
(a) Acoustic indices.



(b) Micrometeorological data.



(c) Spectrogram with annotations.



(d) Micrometeorological plots.

Figure 5. EchoWeb front end screens.

Table 3. Factors and levels of the experiment.

Factor	Service	Low level ($-$)	High level ($+$)
A	*worker-coordinator*	2 instances	8 instances
B	*audio-worker*	2 instances	8 instances

and 153 (round 5). Each round consisted of 50 simulated users (50 requests), with each user submitting one ZIP file selected uniformly at random from the five available in that round.

At the end of each round, two performance metrics were measured: end-to-end response time (*E2E*) and throughput. Lower values of *E2E* indicate higher processing efficiency. Throughput was evaluated relative to $\lambda = 0.1\,\mathrm{req/s}$, arbitrarily defined to simulate, on average, one new request every $10\,\mathrm{s}$, generating a moderate load. Values closer to λ indicate that the system keeps up with demand without congestion, considering only successfully completed requests.

To assess performance bottlenecks, a 2^2 factorial experiment was conducted, evaluating two factors with two levels each. The analyzed factors are the number of instances of the *worker-coordinator* service (A) and the *audio-worker* service (B), as presented in Table 3. Based on the mean values of *E2E* and throughput obtained for each configuration, $y_{(1)}, y_a, y_b, y_{ab}$, the main and interaction effects are estimated using linear contrasts as follows: $\hat{A} = \big((y_a+y_{ab})-(y_{(1)}+y_b)\big)/2$, $\hat{B} = \big((y_b+y_{ab})-(y_{(1)}+y_a)\big)/2$, and $\hat{AB} = \big((y_{(1)}+y_{ab})-(y_a+y_b)\big)/2$.

Statistical significance is evaluated using confidence intervals (CI) of $(1-\alpha)$, with $\alpha = 0.05$. An effect is considered statistically significant when the corresponding CI does not include zero, indicating that its contribution to performance is not attributable to randomness. The analysis of the estimated effects allows identification of system bottlenecks: if only $\hat{A}$ is significant, the performance limitation lies in the *worker-coordinator*; if only $\hat{B}$ is significant, the bottleneck is in the *audio-worker*. When both effects are significant, both services jointly contribute to performance degradation, with the one exhibiting the greatest absolute magnitude considered the dominant factor affecting the system.

The *micro-worker* was excluded from the factorial experiment because its processing runs in parallel, independently of the *worker-coordinator*, with negligible computational overhead.

7. Results

Table 4 presents the average metrics over five experimental rounds for each configuration of the 2^2 factorial design, along with the standard deviation, which indicates the dispersion of results across runs. High values suggest instability in performance between rounds. Configurations with only two *audio-worker* instances exhibited high variability, such as the baseline configuration (1), whose mean *E2E* of $101.926\,\mathrm{s}$ showed a standard deviation of $36.094\,\mathrm{s}$, indicating significant fluctuations across runs. In contrast, increasing the number of *audio-workers* (configuration b) not only substantially reduced *E2E* to $21.662\,\mathrm{s}$, but also stabilized system behavior, with a standard deviation of only $4.181\,\mathrm{s}$.

Table 5 presents the estimated effects and their 95% confidence intervals (CI). Factor A (*worker-coordinator*) was not significant for any metric: its CI for *E2E* ($[-53.27, +58.90]$) includes zero, indicating no statistically significant effect. In

Table 4. Mean and standard deviation per experimental configuration.

Config.	Coord.	Audio	*E2E* (s)	Throughput (req/s)
(1)	2	2	101.926 ± 36.094	0.0687 ± 0.0052
a	8	2	106.145 ± 38.167	0.0677 ± 0.0052
b	**2**	**8**	$\mathbf{21.662 \pm 4.181}$	$\mathbf{0.0861 \pm 0.0024}$
ab	8	8	23.068 ± 4.758	0.0857 ± 0.0021

Table 5. Estimated effects of the factorial experiment.

Effect	*E2E* (s)	Throughput (req/s)
$\hat{A}$ (*worker-coordinator*)	$+2.8125$ $[-53.27, +58.90]$	-0.0006 $[-0.0091, +0.0078]$
$\hat{B}$ (*audio-worker*)	$\mathbf{-81.6701}$ $[\mathbf{-137.75}, \mathbf{-25.59}]$	$\mathbf{+0.0177}$ $[\mathbf{+0.0092}, \mathbf{+0.0262}]$
$\hat{AB}$ (interaction)	-1.4066 $[-57.49, +54.68]$	$+0.0003$ $[-0.0082, +0.0088]$

contrast, factor B (*audio-worker*) was the only significant factor: its CI for *E2E* ($[-137.75, -25.59]$) is strictly negative, confirming a reduction in response time, while the CI for throughput ($[+0.0092, +0.0262]$) is entirely positive. The interaction effect $\hat{AB}$ was also not significant, indicating that the factors act independently, and that the system bottleneck lies exclusively in the *audio-worker*.

8. Conclusion

Passive acoustic monitoring has become an important approach for supporting biodiversity conservation over the past decade. In this context, EchoSystem proposes an integrated platform that combines low-cost field data acquisition devices with a web-based infrastructure to provide micrometeorological metrics, bioacoustic indices, and tools for organizing and disseminating scientific results.

The simulation results indicate that the main bottleneck in the pipeline lies in the audio processing stage (*audio-worker*), as this service performs computationally intensive acoustic index calculations. This bottleneck is associated with the high computational demand of acoustic index calculations.

Overall, EchoSystem demonstrates strong potential to support bioacoustic research by providing an integrated infrastructure for the collection, processing, and sharing of bioacoustic data along with micrometeorological variables. Future work includes the expansion of species detection capabilities and the incorporation of Large Language Models (LLMs) for automated report generation.

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