

- [15] D. G. Dietlein, "A method for remote monitoring of activity of honeybee colonies by sound analysis," *J. Apicultural Res.*, vol. 24, no. 3, pp. 176–183, 1985.
- [16] A. Zgank, "Bee swarm activity acoustic classification for an IoT-based farm service," *Sensors*, vol. 20, no. 1, 2019, Art. no. 21.
- [17] H. Eren, L. Whiffler, and R. Manning, "Electronic sensing and identification of queen bees in honeybee colonies," in *Proc. IEEE Instrum. Meas. Technol. Conf. Sens., Process., Network.*, vol. 2, 1997, vol. 2, pp. 1052–1055.
- [18] W. H. Kirchner, "Acoustical communication in honeybees," *Apidologie*, vol. 24, no. 3, pp. 297–307, 1993, doi: [10.1051/apido:19930309](https://doi.org/10.1051/apido:19930309).
- [19] I. Rigakis, I. Potamitis, N.-A. Tatlas, G. Psirofonia, E. Tzagaraki, and E. Alissandrakis, "A low-cost, low-power, multisensory device, and multi-variable time series prediction for beehive health monitoring," *Sensors*, vol. 23, no. 3, 2023, Art. no. 1407.
- [20] A. Robles-Guerrero, T. Saucedo-Anaya, C. A. Guerrero-Mendez, S. Gómez-Jiménez, and D. J. Navarro-Solís, "Comparative study of machine learning models for bee colony acoustic pattern classification on low computational resources," *Sensors*, vol. 23, no. 1, 2023, Art. no. 460.
- [21] A. Terenzi, N. Ortolani, I. Nolasco, E. Benetos, and S. Cecchi, "Comparison of feature extraction methods for sound-based classification of honey bee activity," *IEEE/ACM Trans. Audio, Speech, Lang. Process.*, vol. 30, pp. 112–122, Dec. 2021.
- [22] A. Robles-Guerrero, T. Saucedo-Anaya, E. González-Ramírez, and J. I. De la Rosa-Vargas, "Analysis of a multiclass classification problem by lasso logistic regression and singular value decomposition to identify sound patterns in queenless bee colonies," *Comput. Electron. Agriculture*, vol. 159, pp. 69–74, 2019.
- [23] L. Barbisan, G. Turvani, and R. Fabrizio, "Audio-based identification of queen bee presence inside beehives," in *Proc. IEEE Conf. AgriFood Electron.*, 2023, pp. 70–74.
- [24] I. Nolasco, A. Terenzi, S. Cecchi, S. Orcioni, H. L. Bear, and E. Benetos, "Audio-based identification of beehive states," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process.*, Brighton, UK, 2019, pp. 8256–8260, doi: [10.1109/ICASSP.2019.8682981](https://doi.org/10.1109/ICASSP.2019.8682981).
- [25] L. Barbisan and F. Riente, "Machine learning framework for the acoustic detection of the queen bee presence," in *Proc. 10th Conv. Eur. Acoustics Ass.*, Turin, Italy, 2023, pp. 4347–4350, doi: [10.61782/fa.2023.1309](https://doi.org/10.61782/fa.2023.1309).
- [26] A. Žgank, "Acoustic monitoring and classification of bee swarm activity using MFCC feature extraction and HMM acoustic modeling," in *Proc. ELEKTRO*, 2018, pp. 1–4.
- [27] W. Kirchner, "Acoustical communication in honeybees," *Apidologie*, vol. 24, no. 3, pp. 297–307, 1993.
- [28] A. Terenzi, S. Cecchi, S. Orcioni, and F. Piazza, "Features extraction applied to the analysis of the sounds emitted by honey bees in a beehive," in *Proc. IEEE 11th Int. Symp. Image Signal Process. Anal.*, 2019, pp. 03–08.
- [29] N. Inês, T. Alessandro, C. Stefania, O. Simone, B. H. L., and B. Emmanouil, "Audio-based identification of beehive states," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process.*, 2019, pp. 8256–8260.
- [30] S. Cecchi, A. Terenzi, S. Orcioni, P. Riolo, S. Ruschioni, and N. Isidoro, "A preliminary study of sounds emitted by honey bees in a beehive," in *Proc. Audio Eng. Soc. Conv.*, 2018, Art. no. 9981.
- [31] G. Iglesias, E. Talavera, Á. González-Prieto, A. Mozo, and S. Gómez-Canaval, "Data augmentation techniques in time series domain: A survey and taxonomy," *Neural Comput. Appl.*, vol. 35, no. 14, pp. 10123–10145, 2023.
- [32] L. Nanni, G. Maguolo, and M. Paci, "Data augmentation approaches for improving animal audio classification," *Ecological Informat.*, vol. 57, 2020, Art. no. 101084.
- [33] Z. K. Abdul and A. K. Al-Talabani, "Mel frequency cepstral coefficient and its applications: A review," *IEEE Access*, vol. 10, pp. 122136–122158, 2022.
- [34] T. Baba, "Time-frequency analysis using short time Fourier transform," *Open Acoust. J.*, vol. 5, no. 1, pp. 32–38, 2012.
- [35] F. Chollet et al., "Keras," 2015. [Online]. Available: <https://keras.io>
- [36] F. Pedregosa et al., "Scikit-learn: Machine learning in python," *J. Mach. Learn. Res.*, vol. 12, pp. 2825–2830, 2011.
- [37] H. Xu, C. Caramanis, and S. Mannor, "Robustness and regularization of support vector machines," *J. Mach. Learn. Res.*, vol. 10, pp. 1485–1510, Dec. 2009.



**Luca Barbisan** (Student Member, IEEE) received the bachelor's degree in electronics and telecommunication engineering from the University of Trento, Trento, Italy, in 2017, and the master's degree in electronics engineering in 2021 from Politecnico di Torino, Turin, Italy, where he is currently working toward the Ph.D. degree in electronics and telecommunications engineering.

His current research interests include digital signal processing and modern machine learning techniques, mainly applied to audio signals.



**Giovanna Turvani** received the master's degree (magna cum laude) in electronic and telecommunication engineering and the Ph.D. degree in electronics and telecommunications from the Politecnico di Torino, Turin, Italy, in 2016.

In 2015, she went to the Technical University of Munich, Munich, Germany, for research on nanocomputing. After that, she worked as a Postdoctoral Researcher with the Politecnico di Torino, focusing on microwave imaging systems for biomedical use and food safety. Currently, she is a Professor Assistant

with the Politecnico di Torino, researching low-power embedded systems for environmental monitoring, quantum computing, and digital architectures based on the logic-in-memory paradigm.



**Fabrizio Riente** (Member, IEEE) received the M.Sc. degree (magna cum laude) in electronic engineering and the Ph.D. degree in electronics and telecommunications from the Politecnico di Torino in 2012 and 2016, respectively.

He was a Postdoctoral Research Associate with the Technical University of Munich, Munich, Germany, in 2016. He is currently an Assistant Professor with the Department of Electronics and Telecommunications, Politecnico di Torino, Turin, Italy. His primary research interests include device modeling,

circuit design for nano-computing, with particular interest on field-coupled nanotechnologies, the development audio processing systems, and low-power IoT devices.