12. Vollmer, E. et al. Enhancing UAV-based multispectral semantic segmentation through feature engineering. *IEEE J. Select. Top. Appl. Earth Observ. Remote Sens.* https://doi.org/10.1109/JSTARS.2025.3537330 (2025).
13. Ahanger, T. A., Tariq, U. & Ullah, I. UAV-based intelligent vehicular network: Blockchain perspective. *Ad Hoc Netw.* **173**, 103827 (2025).
14. Aydin, I. & Sefercik, U. G. Multispectral UAV-based LULC mapping performance improvement by integrating precise NDSM data and machine learning algorithms. *Earth Sci. Inf.* **18**(2), 326 (2025).
15. Detsikas, S. E., Petropoulos, G. P., Kalogeropoulos, K. & Faraslis, I. Combining low-cost UAV imagery with machine learning classifiers for accurate land use/land cover mapping. *Earth* **5**(2), 244–254 (2024).
16. Lv, Z. et al. Novel adaptive region spectral-spatial features for land cover classification with high spatial resolution remotely sensed imagery. *IEEE Trans. Geosci. Remote Sens.* **61**, 1–12 (2023).
17. Liu, J. et al. Integrated 1D, 2D, and 3D CNNs enable robust and efficient land cover classification from hyperspectral imagery. *Remote Sens.* **15**(19), 4797 (2023).
18. Supreeth, A., & Subash, N., An Integrated learning model for land use classification and prediction. In *2025 International Conference on Multi-Agent Systems for Collaborative Intelligence (ICMSCI)* 659–664. IEEE (2025).
19. Wang, Y., Wang, Q., Su, Y., Jing, B. & Feng, M. Detection of kidney bean leaf spot disease based on a hybrid deep learning model. *Sci. Rep.* **15**(1), 11185 (2025).
20. Pathipati, H., Ramisetti, L.N.B., Reddy, D.N., Pesaru, S., Balakrishna, M., & Anitha, T. Optimizing cancer detection: swarm algorithms combined with deep learning in colon and lung cancer using biomedical images. *Diyala J. Eng. Sci.*, pp.91–102 (2025).
21. Kaur, M., Valderrama, C. E. & Liu, Q. Hybrid vision transformer framework for efficient and explainable SEM image-based nanomaterial classification. *Mach. Learn. Sci. Technol.* **6**(1), 015066 (2025).
22. Raman, R. & Jayaraman, S. Artificial intelligence for sustainable farming with dual branch convolutional graph attention networks in rice leaf disease detection. *Sci. Rep.* **15**(1), 10595 (2025).
23. Sivasakthi, B., Preetha, K. & Selvanayagi, D. Osteoporosis disease detection using optimized Elman recurrent neural network based on hybrid bacterial colony optimization and tabu search algorithm. *Int. Res. J. Multidiscipl. Tech.* **7**(1), 1–16 (2025).
24. Diab, A. A. Z. et al. Various optimization algorithms for efficient placement and sizing of photovoltaic distributed generations in different networks. *PLoS ONE* **20**(4), e0319422 (2025).
25. https://www.kaggle.com/datasets/dhoogla/cictoniot
26. https://www.kaggle.com/datasets/apollo2506/eurosat-dataset
27. Özer, E., Iskefiyeli, M. & Azimjonov, J. Toward lightweight intrusion detection systems using the optimal and efficient feature pairs of the Bot-IoT 2018 dataset. *Int. J. Distrib. Sens. Netw.* **17**(10), 15501477211052202 (2021).
28. Wei, M., Rong, C., Liang, E. & Zhuang, Y. An intrusion detection mechanism for IPv6-based wireless sensor networks. *Int. J. Distrib. Sens. Netw.* **18**(3), 15501329221077922 (2022).
29. Olmo, M., Cos, P., Campos, D., Munoz, A.G., Altava-Ortiz, V., Barrera-Escoda, T., Jury, M., Loosveldt-Tomas, S., Bretonniere, P.A., Doblas-Reyes, F.J., & Soret, A. Filtering Cmip6 models in the euro-Mediterranean based on a circulation patterns approach. *Available at SSRN 5012413*.
30. Alamgeer, M. et al. Improving remote sensing scene classification using dung Beetle optimization with enhanced deep learning approach. *Heliyon* **10**(18), e37154 (2024).


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## Author contributions

S. Nagadevi: Conceptualization, Formal analysis, Writing-original draftG. Abirami: Investigation, Software, Visualization R. Brindha: Resources, Investigation, Software T. Prabhakara Rao: Data Curation, Methodology, ValidationGyanendra Prasad Joshi: Validation, supervision, writing-review & editingWoong Cho: Funding acquisition, project administration, Supervision.

## Declarations

## Competing interests

The authors declare no competing interests.

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This article contains no studies with human participants performed by any authors.

## Consent to participate

Not applicable.

## Informed consent

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## Additional information

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