

AI-AGRI FOOD 2026

Book of Abstract

**International Scientific Congress on
Artificial Intelligence in the Agri-Food System**

19th and 20th March, 2026 . Cordoba, Spain

UCOPress
Editorial Universidad de Córdoba

Book of Abstracts. International Scientific Congress on Artificial Intelligence in the Agri-Food System. – Córdoba: UCOPress, University of Córdoba Press, 2026.

21 x 29,7 cm, 137 pages

THEMA: KJMV, TV, GP

Editors: Rosa Gallardo Cobos, Adolfo Peña Acevedo, Joaquín Olivares Bueno, Carlos Parra López & Pablo J. Zarco Tejada



This volume is part of the International ENIA Chair on Agriculture - University of Cordoba (TSI-100921-2023-3), funded by the Secretary of State for Digitalisation and Artificial Intelligence and by the European Union - Next Generation EU, within the framework of the Recovery, Transformation and Resilience Plan.

© Editors: Rosa Gallardo Cobos, Adolfo Peña Acevedo, Joaquín Olivares Bueno, Carlos Parra López & Pablo J. Zarco Tejada

© Authors

© Published by: UCOPress, University of Córdoba Press, 2026

Campus Universitario de Rabanales
Ctra. Nacional IV, Km 396. 14071 Córdoba (España)
Tel.: (+34) 957 218 126
<https://ucopress.uco.es> · ucopress@uco.es

e-ISBN: 978-84-1072-018-3

DOI: <https://doi.org/10.21071/000137>



This press is a member of the Spanish Association of University Presses (UNE), ensuring the nationwide and international dissemination and distribution of its publications.

Typesetting: UCOPress, University of Córdoba Press

Figures: Sabina Andreu Bustos & María Teresa Hidalgo Velasco

This book has been published under a quality management system certified to ISO 9001:2015



This publication is licensed under the Creative Commons Attribution–NonCommercial–ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence. You are free to copy, distribute, adapt and build upon the material in this publication, provided that appropriate credit is given to the original authors and the material is not used for commercial purposes. Any derivative works must be distributed under the same licence.



AI-AGRI FOOD 2026

Book of Abstract

**International Scientific Congress on
Artificial Intelligence in the Agri-Food System**

19th and 20th March, 2026 . Cordoba, Spain



**UNIVERSIDAD
DE
CÓRDOBA**



Instituto Andaluz de Investigación y
Formación Agraria, Pesquera, Alimentaria y
de la Producción Ecológica
Consejería de Agricultura,
Pesca, Agua y Desarrollo Rural



UCOPress

Editorial Universidad de Córdoba

Contenido

AI-AGRIFOOD 2026	8
Rationale.....	8
Target Audience	8
Main Objectives.....	8
Organising Committee.....	9
Scientific Committee.....	9
Plenary Session 1: Sensing and Data Intelligence	10
Real-time biosensing and ai-driven decision-making for regenerated water safety in agricultural systems: The Water Biosense® Platform.....	11
Deep learning for olive counting under field conditions: Object detection vs instance segmentation	14
Development and validation of an image dataset for automatic recognition of the olive fruit fly (bactrocera oleae) using Machine Learning	17
Artificial Intelligence-driven characterization of evaporation losses in brandy barrel ageing using highfrequency environmental sensing	19
Machine Learning enabled soil erosion risk assessment in a large olive-producing area of southern Spain	21
Portable NIR spectroscopy and Machine Learning for on-farm classification of somatic cell content in sheep milk	24
Measuring tree sap flow using artificial neural networks	26
Integrating proximal soil sensing and remote sensing to assess soil–crop interactions in reclaimed saline marshlands.....	28
Operational skill assessment of ECMWF-IFS forecasts in complex terrain: Spatial precipitation verification and thermal bias in southern Spain	30
Making global forecasts local: Improving ECMWF-IFS temperature extremes downscaling with Machine-Learning	32
AI-Driven 3D digital twins for precision pruning and decision support in mediterranean olive groves.....	35
Scalable NDVI-based methods for Agri-intelligence: Recurrence plots for vegetation classification.....	38

AI-Driven probabilistic instability monitoring of agricultural gullies using UAV Lidar Geometry and in-field soil moisture sensing.....	40
Temporal information vs. architectural complexity in AI-Based multitemporal crop segmentation: Evidence from an irrigated agricultural area.....	43
High-resolution stem water potential estimation in vineyards using UAV-Based multispectral imagery and lasso regression: A case study in Mendoza, Argentina	45
Machine Learning for agroecological design: Automated shrub identification and functional biodiversity assessment in the Argentine Monte	47
Accounting for physical barriers in insect pest modeling: A spatially explicit simulation-based approach	49
Machine-Learning–Driven analysis of stage-dependent sensitivity of plant functional traits to water stress dynamics in almond	52
Plenary Session 2: Services and utilities for an intelligent agriculture	55
Development and deployment of a grapevine downy mildew decision support model for the Montilla-Moriles PDO (Cordoba, Spain) within a FIWARE-based data platform	56
Digital twin of olive groves integrating GIS, 3D visualization and realtime IoT data for precision agriculture	59
Digital twin of a mediterranean forest for dynamic scenario simulation and GIS-Based 3D visualization	61
Automated live weight monitoring of feedlot calves using computer vision	63
Climatic Intelligence for pest early warning machine learning identification of environmental drivers of <i>ceratitis capitata population maxima</i> in mediterranean citrus systems	65
Sizing of large-scale photovoltaic irrigation systems. Model for environmental and economic optimisation of Grid-Hybrid Systems	68
Multi-modal retrieval-augmented generation for agricultural technical support integrating visual evidence into large language models	70
Document-Adapted metaprompting in agricultural RAG systems differential effects on explanatory and factoid queries	72
Estimation of the evolution of soil organic carbon in citrus orchards in Andalusia within the framework of the Citridata Project	74
Hierarchical multi-agent system based on generative AI for a virtual assistant focused on operations and information retrieval	76
Classification and early detection of new citrus plantations using an ensemble XGBOOST–YOLOV9 Model	78

Plenary Session 3: Innovation Systems and Socioeconomic Implications	80
Digital transformation in Agri-Food Systems: Emerging technologies, scaling challenges, and pathways for sustainable futures	81
Is blockchain a one-size-fits-all for agriculture? A systematic review across ecosystem domains	84
Beef 4.0 and the transformation of work and social relations in beef production	86
Bridging the mediterranean digital divide: Integrating AI and ICT into local urban markets for smallholders.....	88
Artificial Intelligence as a socio-technical enabler in agribusiness innovation systems evidence from agtech-based value chain	91
Market Intelligence through FIWARE open-source platform – applied cases in the study of citrus supply and price data in the european single market	93
35 Years of climate and agricultural research: AI reveals a structural shift from impact assessment to active intervention.....	95
Behavioural configurations and AI-Sensitive design of sustainable innovation systemsevidence from mediterranean viticulture	97
How Agrifood research connects digital technologies to socio-productive challenges: A global evidence map (2015-2025)	99
Influence of policies on agricultural digitalisation uptake in the European Union.....	101
Plenary Session 4: Industry 4.0 and Sustainable Food Systems.....	103
AI and blockchain as enablers of circular economy in brazilian agribusiness: Models, barriers, engagement strategies, and tax implications from solution providers' perspective.....	104
Technological solutions of Agro 4.0 and its implications on performance in agricultural production units	106
Leveraging industry 4.0 technologies in augmenting circular and sustainable agro-processing for food loss and waste reduction in Agri-Food Systems	109
A Cost-Intelligence dashboard for benchmarking olive oil mill cooperatives: An industry 4.0 approach for strategic decision support.....	110
Stakeholder engagement as a driver of circular economy adoption in brazilian agtechs	112
AI adoption and industry 4.0 bundles in the European Agri-Food business ecosystem ..	114
Development and implementation of a digital twin for the optimization of postharvest processes in the citrus industry	116
AI application for tomato-based product classification via electronic nose	118

Artificial Intelligence in agri-food systems: Transforming food safety, quality, and sustainability across the supply chain.....	120
The potential of digital technologies for climate change adaptation and mitigation in agriculture	123
Artificial Intelligence in melissopalynology: Validation of an automated microscopy system for pollen quantification in honey.....	126
Design of a multisensory AI-Powered device for ripeness monitoring and early detection of botrytis cinerea in tomatoes.....	128
Compact multisensory platform integrating electronic nose and electronic eye for tomato paste analysis.....	130
AI-Driven drought forecasting in dehesa grasslands using LSTM.....	133
Twin olive: A digital twin framework to identify climatic drivers of olive yield	135

AI-AGRIFOOD 2026

AI-AGRIFOOD 2026: International Scientific Congress on AI in the Agri-Food System organised by the University of Cordoba, through its International Chair in Artificial Intelligence and Agriculture (CI-IAA), the Instituto Andaluz de Investigación y Formación Agraria, Pesquera, Alimentaria y de la Producción Ecológica (IFAPA) and the Instituto de Agricultura Sostenible IAS-CSIC.

The CI-IAA is a university–industry chair comprising the University of Cordoba and its partner companies Hispatec, Fertinagro Biotech, xFarm Technologies and Deuser Indra Group.

Rationale

The digital transition of the agri-food sector holds immense promise for enhancing productivity and resilience. However, technology is not an end in itself. To ensure a truly sustainable digital transition, we must look beyond technical optimisation. This Congress seeks to address the dual challenge: building the infrastructure, such as data, algorithms, and hardware, necessary for AI to optimize farming and food supply chains; and creating policies and resources that empower stakeholders to accelerate both agricultural innovation and AI development, improving food system resilience, and bringing technological advances closer to the sector and markets to solve real problems. We aim to bridge the gap between data science and systemic sustainability, ensuring that the future of farming and food processing is not only smart but also wise, inclusive and market-ready.

Target Audience

- Researchers in agricultural sciences, food engineering and technology, economics, social sciences and computer sciences.
- PhD students and postdoctoral researchers.
- R&D managers in the agri-food industry.
- Executives and technicians from technology companies (AgriTech and agri-food companies).
- Policy makers.

Main Objectives

- To consolidate a leading international scientific forum for the advanced analysis of Artificial Intelligence application across the entire agri-food system (agriculture and food industry).
- To present and debate the latest scientific and methodological advances, from precision farming to Industry 4.0 in food processing.
- To promote interdisciplinary research that explores the synergies and trade-offs inherent in the digital transformation of the supply chain.
- To guide the development of a future research agenda ensuring a robust, sustainable, and ethical application of AI in the agri-food sector.
- To bridge the gap between scientific advances and the market, facilitating the transfer of AI solutions to the productive sector to solve real-world problems.

Organising Committee

Presidency (Co-Chairs)

- Prof. Rosa Gallardo Cobos (University of Cordoba, Spain)
- Dr. Leire Molinero-Ruiz (IAS-CSIC, Spain)
- Dr. Carlos Parra-López (IFAPA, Spain)

Technical Secretariat

- External Event Management Company

Members (Vocals)

- Dr. Montserrat Jurado-Expósito (IAS-CSIC, Spain)
- Prof. Joaquín Olivares Bueno (University of Cordoba, Spain)
- Prof. Adolfo Peña Acevedo (University of Cordoba, Spain)
- Dr. Samir Sayadi (IFAPA, Spain)
- Dr. Pablo Zarco-Tejada (IAS-CSIC, Spain)

Scientific Committee

- Dr. Carlos Parra-López (IFAPA, Spain) – Presidency
- Dr. Federico Bert (Instituto Interamericano de Cooperación para la Agricultura, Argentina)
- Dr. Ignacio Antonio Ciampitti (Purdue University, USA)
- Prof. Spyros Fountas (Agricultural University of Athens, Greece)
- Prof. Rosa Gallardo Cobos (University of Cordoba, Spain)
- Dr. Raffaele Giaffreda (Bruno Kessler Foundation-Trento, Italy)
- Prof. María José de la Haba de la Cerda (University of Cordoba, Spain)
- Dr. Abdo Hassoun (SAFIR, France)
- Dr. José Antonio Jiménez Berni (IAS-CSIC, Spain)
- Prof. Laurens Klerkx (Wageningen UR, Netherland/ Univ. Talca, Chile)
- Dr. Ignacio Lorite Torres (IFAPA, Spain)
- Prof. Francisco Javier Mesas Carrascosa (University of Cordoba, Spain)
- Prof. Joaquim João Moreira de Sousa (INESC TEC, Portugal)
- Prof. Joaquín Olivares Bueno (University of Cordoba, Spain)
- Prof. Adolfo Peña Acevedo (University of Cordoba, Spain)
- Prof. Dolores C. Pérez Marín (University of Cordoba, Spain)
- Prof. Tom Vanwallegghem (University of Cordoba, Spain)
- Dr. Pablo Zarco-Tejada (IAS-CSIC, Spain)

Plenary Session 1: Sensing and Data Intelligence

Theme: From raw data acquisition to actionable agronomic intelligence

REAL-TIME BIOSENSING AND AI-DRIVEN DECISION-MAKING FOR REGENERATED WATER SAFETY IN AGRICULTURAL SYSTEMS: THE WATER BIOSENSE® PLATFORM

Cabeo, Mónica; Iglesias-Baena, Iván; López-Robles, María Dolores;
López-Escalona, Antonio Junior; Procupetz, Gabriel

Department of R&D, Sensactive technology S.L., Granada, Spain

mcabeo@sensactivetech.com, iglesias@sensactivetech.com, mdlopez@sensactivetech.com

Background

Recurrent drought periods and climate emergencies have positioned regenerated water as an essential resource for agriculture. However, regulatory frameworks (EU Regulation 2020/741, Royal Decree 3/2023, Royal Decree 1085/2024) demand continuous and reliable microbiological monitoring of *Escherichia coli*, *Enterococcus* spp., and *Legionella* spp. to ensure water safety for irrigation. Traditional laboratory methods, based on selective culture (membrane filtration, ISO standards 9308-1, 7899-2, 11731), suffer critical limitations: delayed results, inability to detect viable non-culturable cells (VBNC), and poor sensitivity to biofilms and biofouling. This creates a technological gap where early detection and automated real-time monitoring could substantially reduce operational uncertainty, prevent microbiological risks to crops, and strengthen confidence in regenerated water use.

Design/Methodology

Water biosense® is an automated smart platform integrating: (1) nanoparticle-based biosensors activated with specific antibodies for optical detection of target microorganisms; (2) a hydraulic module for sample capture and conditioning; (3) embedded real-time processing and edge computing; and (4) multiprotocol IoT connectivity (NB-IoT, LoRaWAN, 4G) designed for underserved rural areas. The system architecture incorporates a Lakehouse-based data platform that performs time-series ingestion under Quality Assurance and Quality Control (QA/QC) protocols, maintains data lineage, and hosts operational dashboards. AI algorithms employ multiparametric sensor data combined with supervised and unsupervised machine learning (still under validation) to: (a) distinguish precisely between pathogens and compensate for matrix-dependent variables (pH, temperature, turbidity); (b) enable predictive anomaly detection and maintenance planning; and (c) support intelligent sampling frequency optimization.

Findings

Field deployment in regenerated water applications within the agrifood sector demonstrates technical viability and continuous data availability across multi-sector irrigation networks. The system achieves detection limits ≤ 2 CFU/L and enables: (1) real-time microbial level quantification across multiple sampling points in a single monitoring network, reducing blind zones between laboratory analysis; (2) automated alerts triggering sector-specific irrigation purges and treatment adjustments before crop impact occurs, reducing the detection-decision-action cycle from days to minutes; (3) temporal traceability of all measurements; (4) significant reduction in manual sampling requirements and associated human error, improving operational safety and resource efficiency; and (5) remote diagnostics, firmware-over-the-air updates, and predictive maintenance, minimizing unplanned downtime.

Conclusions

Water biosense® represents a disruptive shift toward proactive rather than reactive biological surveillance, strengthening water safety in agriculture. Real-time monitoring, combined with multi-protocol IoT and AI-driven analytics, builds trust in regenerated water reuse, addresses regulatory compliance systematically, and enables objective risk prioritization in field operations. The solution facilitates efficient water resource management under water-stress scenarios, supports the transition to sustainable digital agriculture, and scalable expansion to additional pathogens and chemical contaminants such as pesticides and microplastics.

Keywords

biosensors, real-time, smart-monitoring, water-quality, regenerated-water

References

- Bonilla, V., Campoverde, B., & Yoo, S. G. (2023). A systematic literature review of LoRaWAN: sensors and applications. *Sensors*, 23(20), 8440.
- Essamlali, I., Nhaila, H., & El Khaili, M. (2024). Advances in machine learning and IoT for water quality monitoring: A comprehensive review. *Heliyon*, 10(6)
- European Union (2020) Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on minimum requirements for water reuse (OJ L 177, 5.6.2020)
- Jabbar, W. A., Ting, T. M., Hamidun, M. F. I., Kamarudin, A. H. C., Wu, W., Sultan, J., ... & Ali, M. A. (2024). Development of LoRaWAN-based IoT system for water quality monitoring in rural areas. *Expert systems with applications*, 242, 122862.
- Janik-Karpinska, E., Ceremuga, M., Niemcewicz, M., Podogrocki, M., Stela, M., Cichon, N., & Bijak, M. (2022). Immunosensors—The future of pathogen real-time detection. *Sensors*, 22(24), 9757.
- Mesas Gómez, M., Molina-Moya, B., de Araujo Souza, B., Boldrin Zanoni, M. V., Julián, E., Domínguez, J., & Pividori, M. I. (2024). Improved biosensing of *Legionella* by integrating filtration and immunomagnetic separation of the bacteria retained in filters. *Microchimica Acta*, 191(2), 82.
- Oon, Y. L., Oon, Y. S., Ayaz, M., Deng, M., Li, L., & Song, K. (2023). Waterborne pathogens detection technologies: advances, challenges, and future perspectives. *Frontiers in Microbiology*, 14, 1286923.

- Reino de España. (2024). Real Decreto 1085/2024, de 22 de octubre, por el que se aprueba el Reglamento de reutilización del agua. Boletín Oficial del Estado (BOE-A-2024-21701).
- Reino de España. (2023). Real Decreto 3/2023, de 10 de enero, por el que se establecen los criterios técnico-sanitarios de las aguas de consumo y su control. Boletín Oficial del Estado (BOE-A-2023-628).
- Screpis, G. A., Aleo, A., Privitera, N., Capuano, G. E., Farina, R., Corso, D., ... & Coniglio, M. A. (2024). Biosensing Technologies for Detecting Legionella in Environmental Samples: A Systematic Review. *Microorganisms*, 12(9), 1855.

DEEP LEARNING FOR OLIVE COUNTING UNDER FIELD CONDITIONS: OBJECT DETECTION VS INSTANCE SEGMENTATION

Cristian Quevedo-Villalta^a, Jorge Torres-Sánchez, Javier^a Jesús Hidalgo-Moya^b, Susana Cantón-Martínez^a, Francisco Javier Mesas-Carrascosa^a, Fernando Pérez-Porras^a

^a Department of Graphic Engineering and Geomatics, Campus de Rabanales, Universidad de Córdoba, Córdoba

g92quvic@uco.es, o22tosaj@uco.es, fjmesas@uco.es, z52camas@uco.es, o12pepof@uco.es

^b Instituto de Investigación y Formación Agraria y Pesquera (IFAPA), Center "Alameda del Obispo", Córdoba

javierj.hidalgo@juntadeandalucia.es

Background

Automated yield estimation in olive production is a critical tool for designing production strategies that mitigate optimise labour costs, and improve the precision of harvest forecasting [1]. Although computer vision has advanced significantly in other fruit crops for the counting of well-differentiated fruits (such as citrus, apple, or vineyards) [2,3], precise olive detection remains a challenge due to variable lighting conditions, foliage occlusion, the small size of the fruit, and background complexity [4,5]. Currently, there is no established model capable of detecting olives with the necessary precision to perform a reliable yield prediction under real field conditions. Consequently, the objective of this work is to develop a deep learning model for accurate olive counting using two different approaches: object detection, and instance segmentation.

Design/methodology/approach

In this study, 4K-resolution videos were captured using a conventional RGB camera in an olive grove. From these videos, frames were extracted to build a robust dataset comprising 10,000 manually annotated olive instances. Each olive was labelled in two ways: (i) with bounding boxes for object detection tasks, and (ii) with instance segmentation masks to capture pixel-level fruit contours. This dual annotation strategy enabled a direct comparison between detection-based and segmentation-based architectures. Subsequently, two model variants—YOLOv11x (object detection) and YOLOv11x-seg (instance segmentation) based on the Ultralytics framework [6]—were trained under equivalent conditions, following established protocols for on-ground agricultural imagen detection [7], to evaluate which approach provided higher reliability in standard performance metrics.

Findings

The object detection model (YOLOv11x) outperformed the segmentation model across all evaluated performance metrics. The detection model achieved an F1-score of 0.76, Precision of 0.83, Recall of 0.70, a mAP50 of 0.80, and a mAP50-95 of 0.42. In contrast, the instance segmentation model (YOLOv11x-seg) showed inferior performance, with an F1-score of 0.70, Precision of 0.75, Recall of 0.66, a mAP50 of 0.72, and a mAP50-95 of 0.28. These data indicate that, for the specific task of identifying small individual fruits complex backgrounds, the bounding box approach offers greater robustness against visual noise and background complexity than the pixel-level segmentation of olive contours.

Conclusions

This work demonstrates that the YOLOv11x object detection model is currently more effective than instance segmentation for the identification of olives in the field. Although segmentation provides detailed morphological information, the results suggest that bounding box detection is more precise for fruit counting and localisation—essential preliminary steps for yield estimation. Anyway, segmentation allows the number of pixels per olive to be determined, thus providing a size-related variable that is likely to be highly correlated with yield. As future research directions, a comparison with other computer vision models is proposed to advance towards a system capable of accurately predicting yield, thereby supporting the sustainability and economic viability of the olive sector.

Keywords

Computer Vision, Yolov11, Object Detection, Instance Segmentation, digitalization of agriculture, Olives, Deep Learning

References

- [1] Aquino, A., Ponce, J. M., Noguera, M., & Andújar, J. M. (2023). "Olive-fruit yield estimation by modelling perceptual visual features". *Computers and Electronics in Agriculture*, vol. 214, 108361. <https://doi.org/10.1016/j.compag.2023.108361>
- [2] Koirala, A., Walsh, K. B., Wang, Z., & McCarthy, C. (2019). "Deep learning for real-time fruit detection and orchard fruit load estimation: benchmarking of 'MangoYOLO'". *Precision Agriculture*, 20(6). <https://doi.org/10.1007/s11119-019-09642-0>
- [3] Bargoti, S., & Underwood, J. P. (2017). "Deep fruit detection in orchards." 2017 IEEE International Conference on Robotics and Automation (ICRA), pp. 3626-3633. <https://doi.org/10.1109/ICRA.2017.7989417>
- [4] Osco-Mamani, E., Santana-Carbajal, O., Chaparro-Cruz, I., Ochoa-Donoso, D., & Alcazar-Alay, S. (2025). "The Detection and Counting of Olive Tree Fruits Using Deep Learning Models in Tacna, Perú". *AI*, 6(2), 25. <https://doi.org/10.3390/ai6020025>
- [5] Musić, J., Bonković, M., Sikora, T., & Papić, V. (2025). "Evaluation of Deep Neural Network Architectures and Image Datasets for Olive Fruit Detection". 2025 International Conference on Software, Telecommunications and Computer Networks (SoftCOM). <https://doi.org/10.23919/SoftCOM66362.2025.11197389>
- [6] Jocher, G., Qiu, J., & Chaurasia, A. (2023). "Ultralytics YOLO" (Version 8.0.0). [Software]. Available: <https://github.com/ultralytics/ultralytics> [7] Pérez-Porras, F. J., Torres-Sánchez, J.,

López-Granados, F., & Mesas-Carrascosa, F. J. (2023). "Early and on-ground image-based detection of poppy (*Papaver rhoeas*) in wheat using YOLO architectures". *Weed Science*, 71(1), pp. 50–58. <https://doi.org/10.1017/wsc.2022.64>

DEVELOPMENT AND VALIDATION OF AN IMAGE DATASET FOR AUTOMATIC RECOGNITION OF THE OLIVE FRUIT FLY (BACTROCERA OLEAE) USING MACHINE LEARNING

Flora Moreno-Alcaide^a, Meelad Yousef-Yousef^a, Juan Manuel Díaz-Cabrera^b, Luis Miguel CámaraDíaz^b, Enrique Quesada Moraga^a, José Cristóbal Ramírez-Faz^b

^aDepartamento de Agronomía, Unidad de Excelencia María de Maeztu DAUCO, ETSIAM, Universidad de Córdoba, Campus de Rabanales, Edificio C4 Celestino Mutis, 14071 Córdoba, España.

^bDepartamento de Ingeniería Eléctrica y Automática Área de Ingeniería Eléctrica Universidad de Córdoba. España. Campus de Rabanales. Leonardo Da Vinci, 14071 Cordoba, Spain.

Background

The olive fruit fly (*Bactrocera oleae* Rossi; Diptera: Tephritidae) is the most important pest affecting olive cultivation worldwide, causing significant economic losses and directly compromising fruit and oil quality. Current monitoring and control strategies within Integrated Pest Management (IPM) programs rely primarily on manual field inspections, which hinder early and accurate detection of population increases and often result in delayed decision-making. In this context, recent advances in computer vision and deep learning provide new opportunities for the development of automated population monitoring systems. However, the effectiveness of these systems largely depends on the availability of robust, representative datasets specifically designed for the detection of *B. oleae* under real-world conditions.

Design/methodology/approach

This study presents the development and validation of an image dataset aimed at the automated detection of the olive fruit fly using artificial intelligence techniques. A total of 2,440 images were generated from two complementary sources: images acquired under real field conditions using yellow chromotropic sticky traps, and images captured under controlled laboratory conditions designed to simulate the visual variability of field environments. All images were manually annotated using bounding boxes following a rigorous and consistent labeling protocol. Data augmentation techniques were subsequently applied to increase training set diversity and enhance model robustness. Object detection models based on convolutional neural networks were trained using the YOLOv5 algorithm, evaluating different model configurations and training epochs. Model performance was assessed using standard metrics, including precision, recall, F1score, and inference accuracy on independent datasets.

Findings

All trained models achieved precision values exceeding 90%. Models trained exclusively on field or laboratory images showed high performance when evaluated on similar data but exhibited reduced accuracy when applied to images from unseen environments. In contrast, the model trained on the combined dataset (field and laboratory images) demonstrated superior generalization capability, achieving an average inference accuracy of approximately 94%. The optimal configuration corresponded to the YOLOv5-s model trained for 300 epochs, which provided the best trade-off between accuracy, robustness, and computational efficiency, making it suitable for deployment on low-cost, resource-limited platforms.

Conclusions

The results demonstrate that combining field and laboratory images is essential for developing robust and generalizable detection models for the olive fruit fly. The validated dataset and optimized model provide a solid foundation for automated monitoring systems, enabling earlier pest detection and improving decision-making within IPM programs. This approach represents a significant step toward the practical integration of artificial intelligence in olive cultivation, contributing to more sustainable production systems and reduced chemical input use.

Keywords

Bactrocera oleae, Deep Learning, IPM, Precision agriculture, automated monitoring

References

- Kalamatianos, R., Kermanidis, K.L., Karydis, I., Avlonitis, M., 2017. Treating stochasticity of olive-fruit fly's outbreaks via machine learning algorithms. *Neurocomputing* 280, 135–146. <https://doi.org/10.1016/j.neucom.2017.07.071>.
- Malheiro, R., Casal, S., Baptista, P., Pereira, J.A., 2015. A review of *Bactrocera oleae* (Rossi) impact in olive products: From the tree to the table. *Trends Food Sci. Technol.* 44, 226–242. <https://doi.org/10.1016/j.tifs.2015.04.009>.
- Rustia, D.J.A., Chao, J.-J., Chiu, L.-Y., Wu, Y.-F., Chung, J.-Y., Hsu, J.-C., Lin, T.-T., 2020. Automatic greenhouse insect pest detection and recognition based on a cascaded deep learning classification method. *J. Appl. Entomol.* 145, 206–222. <https://doi.org/10.1111/jen.12834>.

ARTIFICIAL INTELLIGENCE-DRIVEN CHARACTERIZATION OF EVAPORATION LOSSES IN BRANDY BARREL AGEING USING HIGHFREQUENCY ENVIRONMENTAL SENSING

Olivares Joaquín^a, León-García Fernando^a, García-Velasco Manuel^a, Ruiz-de-Adana Manuel^b

^a*Department of Electronic and Computer Engineering, University of Cordoba*
el1olbuj@uco.es, fernando.leon@uco.es, i72gavem@uco.es

^b*Department of Applied Thermodynamics, University of Cordoba*
manuel.ruiz@uco.es

Background

The ageing of brandy in oak barrels is a critical stage that strongly influences product quality, economic performance, and sustainability in the spirits industry. This process is governed by complex mass and energy transfer phenomena between the barrel, the spirit, and the surrounding environment, leading to unavoidable volume losses commonly referred to as the “Angel’s share”. In traditional industrial warehouses with natural ventilation and without active climate control systems, environmental variability introduces significant uncertainty into ageing dynamics. Despite extensive research on barrel ageing mechanisms, there remains a lack of high-resolution, data-driven studies integrating continuous environmental sensing with advanced analytical methods to characterize microclimatic effects and their impact on volume loss under real industrial conditions.

Methodology

This study analyzes the natural ageing of brandy in oak barrels stored in an industrial warehouse operating under passive ventilation and without climatization. Within the BRANELOR project framework, a multi-sensor monitoring system was deployed, combining physical sensors and automated data logging at a 15-minute temporal resolution. Measured variables include brandy temperature inside the barrel, barrel weight loss, indoor air temperature, relative humidity and ethanol concentration, as well as outdoor temperature and relative humidity. From these measurements, derived indicators such as vapor pressure deficit (VPD) and equilibrium moisture content (EMC) were computed. The analytical methodology integrates advanced statistical analysis, artificial intelligence (AI) and machine learning techniques, together with the development of a data-driven digital twin to capture non-linear relationships, temporal delays, and operational states associated with ventilated and non-ventilated conditions.

Findings

The results demonstrate a strong and consistent correlation between VPD and barrel volume loss, confirming the dominant role of the thermo-hygrometric microenvironment in driving evaporation during ageing. Distinct operational regimes linked to natural ventilation events were successfully identified and classified, revealing significant differences in moisture and ethanol exchange dynamics. Indoor air ethanol concentration emerged as a valuable indirect indicator of ventilation intensity and mass transfer conditions. Artificial intelligence models, particularly machine learning approaches incorporating environmental variables and time-lagged features achieved a substantial improvement in predictive accuracy compared to conventional linear approaches, highlighting the importance of non-linearity and delayed responses in the ageing process.

Conclusions

The proposed sensing and data intelligence framework provides a robust and scalable approach for characterizing and managing brandy ageing in non-conditioned industrial environments. By integrating high-frequency environmental sensing with advanced analytics and digital twin concepts, the methodology enhances process transparency, predictive capability, and decision support. The study advances the state of the art by moving beyond static or averaged environmental descriptors, offering a dynamic, data-driven understanding of barrel ageing. This approach supports process optimization, reduction of economic losses, and the implementation of intelligent control strategies, aligning with Industry 4.0 principles and sustainable food systems.

Keywords

Artificial Intelligence (AI), Machine Learning, Digital Twin, Environmental Sensing, Vapor Pressure Deficit, Barrel Ageing.

Acknowledgement

Thanks to Almudena Marrufo and Bodegas Fundador for their enthusiasm and inestimable collaboration. Branelor project is supported by Bodegas Fundador (Grant 12022137).

References

- Ruiz de Adana, S. M. (2002). Aplicación de la Dinámica de Fluidos Computacional al Control de las mermas de vino en naves de Crianza Climatizadas. Ingeniería Mecánica. Tesis Doctoral. Universidad de La Rioja, La Rioja.
- Ruiz de Adana, M., Lopez, L. M., and Sala, J. M. (2005). A Fickian model for calculating wine losses from oak casks depending on conditions in ageing facilities. *Appl. Therm. Eng.* 25:709–718.
- Leon-Garcia F, Palomares J, Olivares J. D2R-TED: Data–Domain Reduction Model for Threshold-Based Event Detection in Sensor Networks. *Sensors*. 2018;18: 3806. doi:10.3390/s18113806
- León-García F, Rodríguez-Lozano FJ, Olivares J, Palomares JM. Data Communication Optimization for the Evaluation of Multivariate Conditions in Distributed Scenarios. *IEEE Access*. 2019;7: 123473–123489. doi:10.1109/ACCESS.2019.2936918
- Martínez-Sánchez IR, Cuellar-Padilla J, Olivares J, Palomares JM, León-García F. Context-aware adaptive Send-on-Delta for traffic saving in sensor networks. *Ad Hoc Networks*. 2025;178: 103967. doi:10.1016/j.adhoc.2025.103967

MACHINE LEARNING ENABLED SOIL EROSION RISK ASSESSMENT IN A LARGE OLIVE-PRODUCING AREA OF SOUTHERN SPAIN

Domenech-Carretero Ignacio^a, Guzmán Gema^b, Gómez José Alfonso^a

^a *Institute for Sustainable Agriculture (IAS-CSIC), Agronomy Department,
Av. Menéndez Pidal s/n, 14004 Cordoba. Spain*
i.domenech.carretero@csic.es; joseagomez@ias.csic.es

^b *Andalusian Institute of Agricultural and Fisheries Research and Training
(IFAPA), Camino de Purchil s/n, Ronda, 18004 Granada, Spain*
mariag.guzman@juntadeandalucia.es

Background

Soil erosion is a major environmental and agronomic threat in Mediterranean olive-growing regions, yet its assessment at operational scales is limited by the difficulty of mapping soil management practices consistently across large areas. Remote sensing has proven effective for characterising vegetation and surface conditions, but its application to soil-related variables in woody crops remains scarce [1,2]. Artificial intelligence (AI) offers new opportunities to automate the detection of management practices and integrate them into erosion modelling frameworks. This study presents an AI-enabled approach to identify soil management practices in olive orchards and to assess soil erosion risk over a 56,000-ha area in Southern Spain.

Design/methodology/approach

The identification of soil management practices was performed through a supervised classification framework using multi temporal Sentinel 2 Level 2A imagery. Reflectance data (spectral bands) and vegetation indexes (ARVI, AVI, GNDVI, MBI, EVI, MCARI, NDVI, SAVI) were extracted from 34 commercial olive orchards with known management practices, using two dates chosen to maximise reflectance response between green vegetation and bare surfaces. Five machine learning algorithms were evaluated: Linear Discriminant Analysis (LDA), Linear Support Vector Machines, Random Forests, Boosted Regression Trees and a Dense Neural Network. To ensure robust model development, a two-stage random sampling strategy was applied. In each of 50 iterations, 25% of the dataset was reserved for validation, while the remaining 75% was split into training (two thirds) and calibration (one third). This procedure was repeated for all algorithms and input configurations (spectral bands and vegetation indexes). Model performance was assessed using accuracy, sensitivity, specificity, F1-score and Cohen's kappa, complemented by an analysis of variable importance and classifier coefficients of the algorithm with the greatest discriminatory power. Additional validation

was conducted using 39 orchards within the study area whose management had previously been verified through field visits. The final classification (bare soil vs. cover crops) was then used to assign spatially distributed C-factor values derived from ORUSCAL [3], which were integrated with R, K and LS layers from publicly available information to compute parcel-scale erosion risk using RUSLE [4] within a GIS environment.

Findings

The supervised classification methodology achieved very high accuracy identifying the soil management practices under study, with vegetation index dataset clearly outperforming spectral-bands dataset. LDA and SVM reached validation accuracies close to 99%, F1-scores near 1.00, and kappa values of 0.99-1.00. Subsequent analysis of index importance identified ARVI as the most discriminative variable. LDA was then rerun using three datasets (comprehensive, reduced, and single-index), all showing strong discriminatory capacity. The best-performing configuration (LDA using solely ARVI) achieved 79.5% accuracy in extra validation. Preliminary RUSLE-based estimations indicated that 83% of orchards exhibit erosion rates below $10 \text{ t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$, and 6.1% below $1 \text{ t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$.

Conclusions

This study demonstrates the value of combining AI based classification, multi-temporal remote sensing and GIS based modelling to support large scale soil erosion assessment in Mediterranean olive systems. This integrated approach illustrates how AI can enhance digital soil monitoring in the agrifood sector and strengthen decision making processes aimed at improving soil conservation and long-term sustainability.

Keywords

Soil conservation, Mediterranean agriculture, Geospatial analysis, Woody crops, Soil management practices.

Acknowledgments

This work has been supported by the projects SCALE (EJP Soil Horizon 2020 GA 862695), TUDI (Horizon 2020, GA 101000224), GOPO-SE-20-0002 (EIP-Agri), ECOMED (AVA23-INV202301.035), PID2019-105793RB-I00 (Spanish Ministry of Science and Innovation), and grants PID2023-146177OB-C21 and PID2023146177OB-C22 funded by MICIU/AEI/10.13039/501100011033.

References

- Durigon, V.L., Carvalho, D., Antunes, M., Oliveira, P., & Fernandes, M. (2014). NDVI time series for monitoring RUSLE cover management factor in a tropical watershed. *International Journal of Remote Sensing*, 35(2), 441-453. DOI: 10.1080/01431161.2013.871081
- Guzmán, G., Boumahdi, A., & Gómez, J. (2022). Expansion of olive orchards and their impact on the cultivation and landscape through a case study in the countryside of Cordoba (Spain). *Land Use Policy*, 116, 106065. DOI: 10.1016/j.landusepol.2022.106065
- Gómez Calero, J. A., Biddoccu, M., & Guzmán, G. (2020). ORUSCAL: RUSLE calculator for orchards. <https://digital.csic.es/handle/10261/216656>.

- Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., & Yoder, D. C. (1997). Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Department of Agriculture. Washington, DC: U.S.

PORTABLE NIR SPECTROSCOPY AND MACHINE LEARNING FOR ON-FARM CLASSIFICATION OF SOMATIC CELL CONTENT IN SHEEP MILK

Marín-Méndez Juan-Jesús^a, Rodríguez Ajamil Daniel^a, Freire Fernández Fernando^b, Esquíroz Herreros Paula^a, Suárez Rubio Vanesa^a, Sáiz Abajo M.^a José^a

^a *Nuevas Aplicaciones Analíticas - Calidad y Seguridad Alimentaria 4.0,
Centro Nacional de Tecnología Alimentaria*

jmarin@cnta.es, drodriguez@cnta.es, pesquiroz@cnta.es, vsuarez@cnta.es, mjsaiz@cnta.es

^b *Departamento de proyectos, Genovis S.C.
ventas@genovis.es*

Abstract

Somatic cell count (SCC) is a key quality indicator in the dairy sector, directly influencing milk value and farmer profitability. In sheep farming, the economic penalties associated with elevated SCC levels are becoming increasingly relevant, with thresholds varying across Spanish regions. Near-Infrared (NIR) spectroscopy enables rapid and non-destructive assessment of samples, providing a near real-time tool for decision-making. The rise of portable NIR devices offers new opportunities for implementing these technologies directly in agricultural environments.

This study evaluated the capacity of a portable NIR spectrometer to classify sheep milk based on SCC using artificial intelligence algorithms. The methodological approach followed the OSEMN workflow (Obtain, Scrub, Explore, Model, iNterpret). First, milk samples were collected from three dairy farms together with their reference SCC values. The analysis of SCC, was carried out by an official dairy control organization in accordance with ICAR (International Committee for Animal Recording) standards, which set the standards for dairy control, animal identification, and genetics (<https://www.icar.org/>). A threshold of 500×10³ somatic cells/mL was established based on literature to enable binning into two classes. All samples were scanned with a portable NIR device (643–1050 nm), generating their spectral fingerprints. In the data scrubbing stage, spectral trimming and common pre-processing techniques—such as smoothing, normalization, and noise reduction—were applied, generating several datasets for modelling. Exploratory analysis included line plots and scatter plots (after PCA) for spectral inspection, and descriptive statistics, density plots, boxplots, and barplots for SCC distribution before and after binning.

For modelling, several algorithms were tested following a systematic procedure: dataset splitting into train and test sets, normalization, raw algorithm fitting, cross-validation for performance assessment using appropriate metrics, and hyperparameter tuning to obtain the best-performing model. Final evaluation was conducted on the test set.

The most accurate results were obtained using a combination of Standard Normal Variate, Savitzky–Golay smoothing, and Mean Centering preprocessing, together with a Random Forest classification model. Based on 200 milk samples, the resulting classifier successfully distinguished samples above the 500×10³ somatic cells/mL threshold. In the test set, the model achieved an accuracy of 0.75, sensitivity of 0.789, specificity of 0.714, a positive predictive value of 0.714, and a negative predictive value of 0.789.

These results demonstrate that combining portable NIR devices with artificial intelligence algorithms enables non-destructive identification of milk according to SCC. In addition, the SCC threshold could be adjusted to meet specific requirements of different autonomous communities. This approach offers farmers a real-time decision-making tool that does not require the destruction of samples. Although the current results were obtained using a relatively small dataset, improvements are expected as larger datasets become available.

Keywords

IA, quality control, NIR, portable sensors, Somatic cell count (SCC)

MEASURING TREE SAP FLOW USING ARTIFICIAL NEURAL NETWORKS

Jurado-Jimenez Gabriel^a, Testi Luca^a, López-Bernal Alvaro^b,
Vinagre Blas M.^c, Tejado Inés^c, Villalobos Francisco J.^{a,b}

^a *Instituto de Agricultura Sostenible, Consejo Superior de Investigaciones Científicas, 14004 Córdoba, Spain*

gjurado@ias.csic.es, lucatesti@ias.csic.es

^b *Departamento de Agronomía, Universidad de Córdoba, 14071 Córdoba, Spain*

g42lobea@uco.es, ag1vimaf@uco.es

^c *Escuela de Ingenierías Industriales, Universidad de Extremadura, 06006 Badajoz, Spain*

bvinagre@unex.es, itejbal@unex.es

Background

Sap flow measurements are usually based on the insertion of needles in the sapwood that allow applying heat and measuring temperatures curves. The calculations are typically based on analytical solutions of the heat transfer equation for conduction and convection (Swanson, 1972). This has historically restricted the possible configurations and measurement methods used to estimate sap flow velocities. Furthermore, these configurations have presented significant limitations regarding available measurement ranges. For instance, the Heat Ratio Method (HRM) cannot be used for high sap velocity. On the other hand, the compensated heat pulse method (CHP) fails for low velocities. One important problem of heat pulse methods is the correct installation of needles in the sapwood, as correct alignment is required. This study tests the use of artificial neural networks (ANN) to analyse temperatures curves obtained using standard CHP sensors, bypassing the need for analytical solutions.

Design/methodology/approach

The study was conducted between May and October 2025 at the Instituto de Agricultura Sostenible (IAS-CSIC) in Cordoba, Spain (37.859 °N, 4.797 °W, 93 m a.s.l.). Four seven-year-old 'Arbequina' olive trees (*Olea europaea* L.) were instrumented. The trees were planted in 50-litre pots containing a substrate of 60 % sand, 30 % silt, and 10 % peat, and were placed inside a shade house with 71 % transmissivity and irrigated with drippers.

Standard CHP sensors consist of two needles housing several thermocouples and located asymmetrically from a central heater inserted in the xylem. Temperature curves are obtained after applying a 2-second heat pulse. We evaluated a symmetrical probe configuration, using sensors designed and built at IAS (Testi and Villalobos, 2009). An ANN was trained in silico using a finite element model that simulated temperatures curves for a range of velocities (0–100 cm h⁻¹, 0.5 cm h⁻¹ resolution). We

compared different ANN configurations using the root mean square error (RMSE) and the corrected Akaike Information Criterion (AICc). The selected ANN model was validated using tree transpiration data (E_p) measured by high precision (1 g) scales serving as lysimeters for each pot. Transpiration data were converted to sap velocity taking into account the area of the stems.

Findings

The ANN method showed a good performance (RMSE 3.6 cm h⁻¹) despite the use of only 6 features. It showed high precision across the entire range of velocities exhibited by the trees in the experiment, highlighting its versatility for both very low and medium-to-high flows—a common limitation in existing methodologies. Further research may explore alternative machine learning models (e.g. random forest) and analyse the impact of wounds in the sapwood on errors of sap velocity.

Conclusions

The integration of artificial intelligence (AI) into sap flow sensing eliminates the requirement for restrictive analytical solutions and complex hardware systems. This paves the way for the development of new sensors that are simpler, easier to install (potentially avoiding or auto-correcting probe misalignment), and more cost-effective due to reduced technical requirements. Ultimately, this will assist in monitoring water consumption and optimising the management of water resources in agriculture.

Keywords

Artificial Neural Networks, Sap Flow, Machine Learning, Sensor Innovation, Evapotranspiration.

Acknowledgments

This work was funded by grant PID2023-153178OB-I00 (MCIN/AEI, Spain).

References

- Swanson, R. H. (1972). Water transpired by trees is indicated by heat pulse velocity. *Agricultural Meteorology*, 10, 277-281.
- Testi, L., & Villalobos, F. J. (2009). New approach for measuring low sap velocities in trees. *Agricultural and Forest Meteorology*, 149(3-4), 730-734.

INTEGRATING PROXIMAL SOIL SENSING AND REMOTE SENSING TO ASSESS SOIL–CROP INTERACTIONS IN RECLAIMED SALINE MARSHLANDS

Mario Ramos-Rodríguez^a, José Luis Gómez-Flores^a, M. Farzamian^b, G. Martínez García^c, Karl Vanderlinden^a

^a IFAPA - Centro Alameda del Obispo, 14004, Córdoba, Spain

mario.ramos.r@juntadeandalucia.es, josel.gomez@juntadeandalucia.es, karl.vanderlinden@juntadeandalucia.es

^b Instituto Nacional de Investigação Agrária e Veterinária, Avenida da República, Quinta do Marquês, 2780-157 Oeiras, Portugal

mohammad.farzamian@iniav.pt

^c Departamento de Física Aplicada, Radiología y Medicina Física, Universidad de Córdoba, Campus de Rabanales, Edificio Albert Einstein (C-2), 14071, Córdoba, Spain

gonzalo.martinez@uco.es

Background

Managing spatial variability is essential for optimizing agricultural practices, particularly in salinization-prone agroecosystems influenced by shallow saline water tables. In these environments, soil apparent electrical conductivity (ECa) is a powerful variable for delineating homogeneous management zones, as it reliably identifies subsurface salinity hotspots where rootzone salinization may develop during the cropping season (Gómez-Flores *et al.*, 2022). Complementary to ECa, freely available remote sensing imagery—especially vegetation indices (VIs) such as NDVI—supports both improved zoning (Dogar *et al.*, 2025) and high-frequency monitoring of crop development. This temporal dimension enhances understanding of soil–crop dynamics, which is critical for more sustainable and adaptive management. Linking ECa and VI datasets in space and time can reveal how soil constraints emerge and evolve during the season, providing opportunities for timely adjustments in agricultural practices.

Design/methodology/approach

This work presents a spatiotemporal correlation framework that integrates proximal soil sensing (ECa) with remote sensing imagery (NDVI) to identify within-field areas where soil conditions either support or limit crop growth in salinization-prone fields of southwestern Spain. Geographically weighted regression is used to quantify the spatial relationship between the time-stable ECa pattern and each available NDVI image throughout the season. Positive Spearman correlations are interpreted as favourable soil conditions, while negative correlations signal constraints such as salinity or water scarcity.

Findings

The methodology was applied to irrigated fields cultivated with cotton, tomato, and sugar beet. Results indicate that correlation patterns vary markedly during the growing season and depend on crop type and irrigation strategies. At the start of the season, correlations tend to be positive because higher soil water content in ECa hotspots enhances early crop growth. As the irrigation season progresses, however, correlations frequently shift to negative values. This reflects the increasing detrimental effect of ECa hotspots on crop performance, particularly under high atmospheric evaporative demand. In such conditions, rootzone salinization is triggered earlier in these areas due to the upward movement of the saline water table, driven by intensive irrigation to meet crop water requirements. This process imposes a clear constraint on crop development.

Conclusions

This integrative workflow demonstrates the potential of combining proximal and remote sensing to diagnose soil-driven spatiotemporal crop variability and support more informed management decisions. The sign reversal of the Spearman correlation coefficient can be interpreted as an indicator of rootzone salinization onset, with decreasing positive correlations serving as an early warning signal. Such anticipatory insights allow practitioners to adjust irrigation management before significant crop damage occurs. Overall, merging proximal and remote sensing technologies enhances the capacity to monitor, interpret and manage soil-crop interactions in complex, salinization-prone agroecosystems.

Keywords

ECa, Electromagnetic induction, NDVI, Reclaimed marshland, Salinity

Acknowledgements

This work is supported by grant PID2023-149609OR-I00, funded by MICIU/AEI/10.13039/501100011033 and FEDER, EU, grant PRE2020-095133, funded by MICIU/AEI/10.13039/501100011033 and by ESF Investing in Your Future, and PREP2023-001917, funded by MICIU/AEI/10.13039/501100011033 and FSE+.

References

- Gómez Flores, J. L., Ramos Rodríguez, M., González Jiménez, A., Farzamian, M., Herencia Galán, J. F., Salvatierra Bellido, B., Cermeño Sacristan, Vanderlinden, K. (2022). Depth-specific soil electrical conductivity and NDVI elucidate salinity effects on crop development in reclaimed marsh soils. *Remote Sensing*, 14, 3389.
- Dogar, S. S., Brogi, C., O'Leary, D., Hernández-Ochoa, I. M., Donat, M., Vereecken, H., Huisman, J. A. (2025). Combining electromagnetic induction and satellite-based NDVI data for improved determination of management zones for sustainable crop production. *Soil*, 11, 655-679.

OPERATIONAL SKILL ASSESSMENT OF ECMWF-IFS FORECASTS IN COMPLEX TERRAIN: SPATIAL PRECIPITATION VERIFICATION AND THERMAL BIAS IN SOUTHERN SPAIN

Alcalá-Espinosa, Estrella; Peña-Acevedo, Adolfo

*Department of Rural Engineering, Civil Constructions and Engineering Projects,
Higher Technical School of Agricultural and Forestry Engineering (ETSIAM), University
of Córdoba, Rabanales University Campus, 14071 Córdoba, Spain*

q12alese@uco.es

Background

The digital transformation of the agrifood sector relies heavily on the accuracy of medium-range weather forecasts to feed Decision Support Systems (DSS) for critical tasks such as irrigation scheduling and pest management. However, operational global models like the ECMWF-IFS often exhibit systematic biases in regions with complex topography. This discrepancy between grid-scale predictions and farm-scale reality limits the effectiveness of digital tools, particularly in high-value Protected Designation of Origin (DOP) zones. This study presents a comprehensive audit of the operational forecast skill of the ECMWF model, evaluating both spatial displacement errors in precipitation and specific orographic thermal biases.

Design/methodology/approach

We conducted a high-resolution validation of ECMWF-IFS forecasts over a two-year period (March 2024-February 2026) using an extensive and representative network of 229 agrometeorological stations (AEMET/SiAR) distributed across Andalusia, Spain. To evaluate thermal skill, we calculated the Mean Absolute Error (MAE) and Mean Bias Error (MBE) for each station point. These metrics were then analysed using Kruskal-Wallis tests to assess the significance of performance across different altitudes and population densities. For precipitation, we compared standard point-to-point metrics against a “Spatial Rescue” algorithm. This method reclassifies point-based “False Alarms” as “Displaced Hits” if rain is observed within a 10 km radius, allowing us to differentiate between non-existent precipitation events (hallucinations) and spatial positioning errors.

Findings

The results reveal a distinct contrast in forecast utility for both variables. Thermally, the model performs well in lowlands ($MAE < 2.5^{\circ}C$) but struggles in mountain rural systems due to a systematic “Cold Bias”. Specifically, in the DOP Sierra Mágina, maximum temperature is underestimated by up

to 5°C because the model smoothes the topography. Conversely, minimum temperature predictions improve in dense urban areas, suggesting the model captures heat islands better than rural cold pools. Regarding precipitation, standard verification shows a high False Alarm Ratio (FAR) of 56.4%, creating a “Cry Wolf” effect. However, the spatial verification reveals that 55.4% of these errors are actually “Displaced Hits”, events that occurred but were spatially mislocated by the model (<10km). This indicates that while the model correctly predicts the atmospheric instability, it suffers from precision errors regarding the exact impact zone.

Conclusions

The ECMWF-IFS model demonstrates high reliability for general weather patterns but requires statistical correction to be actionable at the farm level. Operational validation must go beyond simple pointbased metrics, which often mask the model's true utility for detecting rainfall events. The identified biases in mountain DOP zones highlight the need for specific downscaling techniques for both temperature and precipitation. Furthermore, the high representativeness of the Andalusian station network proves to be an invaluable asset for “ground-truthing” global models, providing a necessary benchmark for calibrating future AI-driven forecasting systems in complex terrain.

Keywords

Spatial Verification, ECMWF, Precision Agriculture, Weather Bias, Agrometeorology

Acknowledgments

This research is part of the ENIA International Chair in Agriculture, University of Córdoba (TSI-100921-2023-3), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union - Next Generation EU. Recovery, Transformation and Resilience Plan.

References

- Cogato, A., Meggio, F., De Antoni Migliorati, M., & Marinello, F. (2019). Extreme Weather Events in Agriculture: A Systematic Review. *Sustainability*, 11(9), 2547. <https://doi.org/10.3390/su11092547>
- Ebel, P., Schneider, R., Bonavita, M., *et al.* (2024). 2024 ESA-ECMWF workshop report: current status, progress and opportunities in machine learning for Earth system observation and prediction. *Npj Climate and Atmospheric Science*. <https://doi.org/10.1038/s41612-024-00757-4>
- Estévez, J., Gavilán, P., & García-Marín, A. P. (2011). Data validation procedures in agricultural meteorology - a prerequisite for their use. *Advances in Science and Research*, 6(1), 141–146. <https://doi.org/10.5194/asr-6141-2011>
- Li, J., Chen, H., Li, P., & Jiang, X. (2023). Evaluating the Precipitation Biases over the Western Periphery of the Sichuan Basin with the ECMWF Operational Forecast Model. *Weather and Forecasting*, 38(8), 14811496. <https://doi.org/10.1175/WAF-D-22-0218.1>
- Montané, G., & Codina, B. (2021). Global high-resolution models vs. limited-area models: Verification of HRES-IFS WRF-ARW forecasts over Catalonia. *Tethys*, 2021(18), 14–22. <https://doi.org/10.3369/tethys.2021.18.02>

MAKING GLOBAL FORECASTS LOCAL: IMPROVING ECMWF-IFS TEMPERATURE EXTREMES DOWNSCALING WITH MACHINE-LEARNING

Alcalá-Espinosa, Estrella^a; Peña-Acevedo, Adolfo^a; Mesas-Carrascosa, Francisco Javier^b

^aDepartment of Rural Engineering, Civil Constructions and Engineering Projects,
Higher Technical School of Agricultural and Forestry Engineering (ETSIAM), University
of Córdoba, Rabanales University Campus, 14071 Córdoba, Spain

q12alese@uco.es

^bDepartment of Graphic Engineering and Geomatics, University of
Cordoba, Campus de Rabanales, 14014 Córdoba, Spain

Background

Local-scale weather forecasts often show systematic limitations in regions with high agroclimatic complexity, particularly for extreme events that drive agricultural risk. In Mediterranean landscapes such as Andalusia, complex orography and rural microclimates can amplify representativeness errors between grid-scale numerical weather prediction outputs and station-scale conditions. This study assesses the performance of the ECMWF Integrated Forecasting System (ECMWF-IFS) for near-surface temperature over rural Andalusia and develops a machine learning (ML) statistical downscaling framework to improve forecast skill for agronomically relevant extremes.

Design/methodology/approach

ECMWF-IFS forecasts were evaluated against observations from 229 meteorological stations across Andalusia, from March 2024 to February 2026. Forecast accuracy and bias were quantified across lead times (D+1 to D+7) using MAE, RMSE, bias, and goodness-of-fit diagnostics, with specific attention to the representation of thermal extremes. Based on the verification results, an ML-based statistical downscaling model (IFS-SDM) was developed for a representative mountain olive-growing site (Santo Tomás-Torre Vinagre, Jaén; 537 m). Predictors combined ECMWF-derived variables (e.g., 2 m temperature, wind, precipitation, radiation) with lagged local observations and derived temporal features. Seven ML algorithms spanning tree-based methods, kernel approaches, and neural networks were trained and validated under time-aware procedures to prevent leakage and to ensure operational realism.

Findings

Verification indicates marked spatial heterogeneity of forecast error and bias, consistent with terrain-driven representativeness limitations in rural and mountainous areas. The IFS-SDM framework

substantially improves station-scale forecasts relative to raw ECMWF-IFS, with gains that are most pronounced for high-temperature extremes. For daily maximum temperature, Gradient Boosting provides the strongest correction at the case-study site: at D+5, MAE decreases from 9.13 °C (ECMWF-IFS) to 2.18 °C (IFS-SDM) and RMSE from 9.47 °C to 2.83 °C; skill remains high through medium lead times ($R^2 \geq 0.86$ up to D+6). For daily minimum temperature, Random Forest yields consistent improvements: at D+5, MAE decreases from 5.46 °C to 1.64 °C and RMSE from 5.93 °C to 2.04 °C, with $R^2 \geq 0.87$ up to D+6. Distributional diagnostics indicate improved representation of warm and cold tails, and case-study evaluation during a July 2024 heat episode shows a marked reduction of cold bias in the corrected forecasts.

Conclusions

The proposed ML-based statistical downscaling framework bridges the gap between global forecasts and local agroclimatic needs in rural, topographically complex environments. By reducing systematic bias and improving the skill of temperature extremes at decision-relevant lead times, the approach supports earlier and more reliable agroclimatic warnings and risk-informed planning. The single-site calibration demonstrates feasibility under strong-error conditions and provides a foundation for subsequent scaling to multi-station or regionalized implementations for operational agricultural decision support in Mediterranean climates.

Keywords

Statistical downscaling, machine learning, ECMWF-IFS, temperature extremes, rural agroclimate

Acknowledgments

This research is part of the ENIA International Chair in Agriculture, University of Córdoba (TSI-100921-2023-3), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union - Next Generation EU. Recovery, Transformation and Resilience Plan.

References

- Ben Bouallegue, Z., Clare, M. C. A., Magnusson, L., Gascon, E., Maier-Gerber, M., Janousek, M., Rodwell, M., Pinault, F., Dramsch, J. S., Lang, S. T. K., Raoult, B., Rabier, F., Chevallier, M., Sandu, I., Dueben, P., Chantry, M., & Pappenberger, F. (2024). The rise of data-driven weather forecasting: A first statistical assessment of machine learning-based weather forecasts in an operational-like context. *Bulletin of the American Meteorological Society*, 105(6). <https://doi.org/10.1175/BAMS-D-23-0162.1>
- European Centre for Medium-Range Weather Forecasts. (2020). IFS documentation CY47R3: Part II-Data assimilation. <https://www.ecmwf.int/en/elibrary/81269-ifs-documentation-cy47r3-part-ii-data-assimilation>
- Haiden, T., Janousek, M., Vitart, F., Ben Bouallegue, Z., Ferranti, L., & Prates, F. (2021). Evaluation of ECMWF forecasts, including the 2021 upgrade (ECMWF Technical Memorandum No. 884). European Centre for Medium-Range Weather Forecasts. <https://www.ecmwf.int/en/elibrary/81235-evaluation-ecmwf-forecasts-including-2021-upgrade>
- Gutierrez, J. M., Maraun, D., Widmann, M., Huth, R., Hertig, E., Benestad, R., Roessler, O., Wibig, J., Wilcke, R., Kotlarski, S., San Martin, D., Herrera, S., Bedia, J., Casanueva, A., Manzananas, R., Iturbide, M., Vrac, M., Dubrovsky, M., Ribalaygua, J., & Page, C. (2019). An intercomparison of a

large ensemble of statistical downscaling methods over Europe: Results from the VALUE perfect predictor cross-validation experiment. *International Journal of Climatology*, 39(9), 3750-3785. <https://doi.org/10.1002/joc.5462>

- Hernanz, A., Correa, C., Dominguez, M., Rodriguez-Guisado, E., & Rodriguez-Camino, E. (2023). Comparison of machine learning statistical downscaling and regional climate models for temperature, precipitation, wind speed, humidity and radiation over Europe under present conditions. *International Journal of Climatology*, 43(13), 6065-6082. <https://doi.org/10.1002/joc.8190>

AI-DRIVEN 3D DIGITAL TWINS FOR PRECISION PRUNING AND DECISION SUPPORT IN MEDITERRANEAN OLIVE GROVES

Francisco Jiménez Jiménez^a, Francisco José Castillo Ruiz^b, Fernando Aragón Rodríguez^a, Sergio Bayano Tejero^c, Gregorio L. Blanco Roldán^b, Antonio Rodríguez Lizana^d.

^aDepartment of Engineering, Universidad Miguel Hernández, Orihuela, 03312 Alicante, Spain
francisco.jimenezj@umh.es

^bDepartment of Rural Engineering, E.T.S. de Ingeniería Agronómica y de Montes, Universidad de Córdoba, Campus de Rabanales, ctra. N-IV, km 396, 14014 Córdoba, Spain
g62caruf@uco.es, ir3blrog@uco.es

^cDepartment of Electronic and Computer Engineering, Universidad de Córdoba, Campus de Rabanales, ctra. N-IV, km 396, 14014 Córdoba, Spain
p52bates@uco.es

^dDepartment of Aerospace Engineering and Fluid Mechanics. ETSIA, University of Seville, Ctra. de Utrera, Km. 1, 41013 Seville, Spain
arodriguez2@us.es

Background

Olive cultivation dominates Mediterranean agroecosystems, accounting for more than 85% of global olive oil production (FAO, 2025). However, precision pruning remains largely dependent on empirical expertise, generating structural variability that affects biomass estimation, mechanization efficiency, and long-term soil sustainability. Recent research demonstrates that canopy architecture and branching patterns can be quantified using 3D sensing technologies (Castillo-Ruiz *et al.*, 2016; Méndez *et al.*, 2016; (Rodríguez-Lizana *et al.*, 2023)), while pruning residues significantly influence soil protection, erosion control and carbon dynamics (Rodríguez-Lizana *et al.*, 2008; Repullo *et al.*, 2012; Taguas *et al.*, 2021). Within the Erasmus+ KA220-VET OliVR project (<https://www.olivr.org/>), a transnational consortium has developed an AI-ready methodology to generate 3D digital twins of olive trees (Arbequina, Arbosana, Koroneiki, Memecik and Turkish local cultivars) to support precision pruning, biomass prediction and sustainable orchard management.

Design/methodology/approach

The proposed framework integrates standardized smartphone-based photogrammetry using high-resolution images and video sequences, where embedded metadata (camera parameters, focal length, exposure settings, and geolocation) are leveraged to enhance geometric consistency in

3D canopy reconstruction. Tree capture follows harmonized protocols including 360° circular orbit acquisition (60–80% overlap), constant radial distance (1–3 m), RAW/DNG imaging, and export in .PLY/.LAS/.PCD formats for AI processing.

The AI workflow comprises: (1) point-cloud preprocessing and canopy–trunk segmentation; (2) high-resolution 3D reconstruction; (3) structural metric extraction (canopy volume, branching hierarchy, trunk diameter); and (4) supervised machine learning models to predict pruning biomass and classify structural balance. Branching reconstruction incorporates quantitative structure models and L-systems (Morales & MacFarlane, 2025; Méndez *et al.*, 2016), supported by allometric relationships derived from biological energy minimization principles (Rinaldo *et al.*, 2014; Pelletier & Turcotte, 2000).

Spatial variability is addressed through sequential simulation and co-simulation algorithms (Horta & Soares, 2010; Soares *et al.*, 2017), enabling probabilistic mapping of pruning biomass and mulch distribution at farm scale. The framework builds upon previous research in canopy volume modelling and spatial optimization in olive orchards (Miranda-Fuentes *et al.*, 2015; Sola-Guirado *et al.*, 2017; Samuel-Rosa *et al.*, 2015).

Findings

Preliminary results confirm strong correlations between canopy volume, branching metrics, and pruning biomass, supporting previous evidence on spatial modelling in olive orchards (Rodríguez-Lizana *et al.*, 2017). AI-assisted 3D models enable automated structural quantification and improve biomass prediction compared to traditional field measurements. RAW imaging enhances geometric fidelity under variable Mediterranean light conditions

Conclusions

This study proposes a scalable AI-driven digital twin ecosystem for perennial crops, integrating low-cost sensing, machine learning, and spatial uncertainty modelling. Combining 3D reconstruction, branching analysis, and stochastic geostatistics, the framework advances data intelligence in Mediterranean olive systems. The methodology strengthens precision pruning standardization, supports carbon-oriented soil management, and contributes to sustainable digital transformation aligned with EU Green Deal objectives. Its transferability to other woody crops enhances broader agri-food innovation potential.

Keywords

Artificial Intelligence, Olive Trees, Digital Twin, Precision Pruning, Virtual Reality

References

- Castillo-Ruiz, F., Castro-Garcia, S., Blanco-Roldan, G., Sola-Guirado, R., & Gil-Ribes, J. (2016). Olive Crown Porosity Measurement Based on Radiation Transmittance: An Assessment of Pruning Effect. *Sensors*, 16(5), 723. <https://doi.org/10.3390/s16050723>
- Horta, A., & Soares, A. (2010). Direct Sequential Co-simulation with Joint Probability Distributions. *Mathematical Geosciences*, 42(3), 269–292. <https://doi.org/10.1007/s11004-010-9265-x>
- Méndez, V., Rosell-Polo, J. R., Pascual, M., & Escolà, A. (2016). Multi-tree woody structure reconstruction from mobile terrestrial laser scanner point clouds based on a dual neighbourhood

connectivity graph algorithm. *Biosystems Engineering*, 148, 34–47. <https://doi.org/10.1016/j.biosystemseng.2016.04.013>

- Miranda-Fuentes, A., Llorens, J., Gamarra-Diezma, J., Gil-Ribes, J., & Gil, E. (2015). Towards an Optimized Method of Olive Tree Crown Volume Measurement. *Sensors*, 15(2), 3671–3687. <https://doi.org/10.3390/s150203671>
- Morales, A., & MacFarlane, D. W. (2025). Reducing tree volume overestimation in quantitative structure models using modeled branch topology and direct twig measurements. *Forestry: An International Journal of Forest Research*, 98(3), 394–409. <https://doi.org/10.1093/forestry/cpae046>
- Pelletier, J. D., & Turcotte, D. L. (2000). Shapes of river networks and leaves: are they statistically similar? *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 355(1394), 307–311. <https://doi.org/10.1098/rstb.2000.0566>
- Repullo, M. A., Carbonell, R., Hidalgo, J., Rodríguez-Lizana, A., & Ordóñez, R. (2012). Using olive pruning residues to cover soil and improve fertility. *Soil and Tillage Research*, 124, 36–46. <https://doi.org/10.1016/j.still.2012.04.003>
- Rinaldo, A., Rigon, R., Banavar, J. R., Maritan, A., & Rodriguez-Iturbe, I. (2014). Evolution and selection of river networks: Statics, dynamics, and complexity. *Proceedings of the National Academy of Sciences*, 111(7), 2417–2424. <https://doi.org/10.1073/pnas.1322700111>
- Rodríguez-Lizana, A., Espejo-Pérez, A. J., González-Fernández, P., & Ordóñez-Fernández, R. (2008). Pruning Residues as an Alternative to Traditional Tillage to Reduce Erosion and Pollutant Dispersion in Olive Groves. *Water, Air, and Soil Pollution*, 193(1–4), 165–173. <https://doi.org/10.1007/s11270-008-9680-5>
- Rodríguez-Lizana, A., Ramos, A., Pereira, M. J., Soares, A., & Ribeiro, M. C. (2023). Assessment of the Spatial Variability and Uncertainty of Shreddable Pruning Biomass in an Olive Grove Based on Canopy Volume and Tree Projected Area. *Agronomy*, 13(7), 1697. <https://doi.org/10.3390/agronomy13071697>
- Soares, A., Nunes, R., & Azevedo, L. (2017). Integration of Uncertain Data in Geostatistical Modelling. *Mathematical Geosciences*, 49(2), 253–273. <https://doi.org/10.1007/s11004-016-9667-5>
- Sola-Guirado, R., Castillo-Ruiz, F., Jiménez-Jiménez, F., Blanco-Roldan, G., Castro-Garcia, S., & Gil-Ribes, J. (2017). Olive Actual “on Year” Yield Forecast Tool Based on the Tree Canopy Geometry Using UAS Imagery. *Sensors*, 17(8), 1743. <https://doi.org/10.3390/s17081743>
- Taguas, E. V., Marín-Moreno, V., Díez, C. M., Mateos, L., Barranco, D., Mesas-Carrascosa, F.-J., Pérez, R., García-Ferrer, A., & Quero, J. L. (2021). Opportunities of super high-density olive orchard to improve soil quality: Management guidelines for application of pruning residues. *Journal of Environmental Management*, 293, 112785. <https://doi.org/10.1016/j.jenvman.2021.112785>

SCALABLE NDVI-BASED METHODS FOR AGRI-INTELLIGENCE: RECURRENCE PLOTS FOR VEGETATION CLASSIFICATION

Rosa Gutiérrez-Cabrera^{a,b}, Javier Borondo^b, Ana M. Tarquis^{a,c},

^a Grupo de Sistemas Complejos, Universidad Politécnica de Madrid, 28040 Madrid, Spain

^b AgrowingData, 04001 Almería, Spain

^c CEIGRAM, Universidad Politécnica de Madrid, 28040 Madrid, Spain

Background

High-mountain pastures are key components of livestock systems and are highly exposed to climate variability. Yet, they are often represented by simple spatial averages of vegetation indices, which fail to capture the diversity of temporal dynamics within a region. NDVI time series from satellite sensors provide long-term, spatially explicit information on vegetation activity, but most applications use only aggregated indicators or basic seasonal metrics. There is a need for methods that exploit the dynamical structure of NDVI time series to identify distinct vegetation regimes, which is essential for understanding production stability, climate risk and the design of index-based insurance schemes.

Design/methodology/approach

We develop an unsupervised framework based on recurrence plots (RPs) and Recurrence Quantification Analysis (RQA) to classify high-mountain pastures according to the dynamics of their NDVI time series. We use 10-day MODIS NDVI data from 2002 to 2018 for a mountainous catchment in northern Spain. After quality control and temporal interpolation, each pixel's NDVI series is standardised and reconstructed in phase space using time-delay embedding. We develop an unsupervised framework based on **recurrence plots (RPs)** and **Recurrence Quantification Analysis (RQA)** to classify high-mountain pastures according to the dynamics of their NDVI time series. We use 10-day MODIS NDVI data from 2002 to 2018 for a mountainous catchment in northern Spain. After quality control and temporal interpolation, each pixel's NDVI series is standardised and reconstructed in phase space using time-delay embedding.

Findings

The RQA-based clustering reveals pasture classes that differ not only in mean NDVI level, but also in **temporal regularity, persistence of high or low NDVI states** and **frequency of anomalies**, such as unusually low or delayed greening. These clusters show clear spatial structure and systematic, but not trivial, relationships with altitude and topography. The image-based clustering of recurrence plots identifies similar groups, highlighting distinct RP textures (e.g. long diagonal structures, laminar bands, fragmented patterns) that correspond to different types of seasonal behaviour and

inter-annual variability. Compared with clustering directly on NDVI trajectories, recurrence-based methods provide a more nuanced dynamical stratification of pastures.

Conclusions

Recurrence plots and RQA offer a powerful framework to move beyond simple NDVI summaries towards a **dynamical classification** of high-mountain pastures. By grouping pixels according to the structure of their recurrence patterns, the proposed methods generate information layers that are directly relevant for understanding vegetation stability and climate sensitivity. These layers can be integrated into decision-support tools for grazing management and can inform the design of index-based insurance products by identifying areas with distinct risk profiles. More broadly, recurrence-plot-based analysis provides a physically interpretable bridge between NDVI time series and AI workflows for unsupervised pattern discovery in agricultural landscapes.

Keywords

NDVI, recurrence plots, Recurrence Quantification Analysis, unsupervised clustering

AI-DRIVEN PROBABILISTIC INSTABILITY MONITORING OF AGRICULTURAL GULLIES USING UAV LIDAR GEOMETRY AND IN-FIELD SOIL MOISTURE SENSING

González-Garrido, Paula^a, Peña-Acevedo, Adolfo^a, Mesas-Carrascosa, Francisco Javier^b

^aDepartment of Rural Engineering, Civil Construction and Project Engineering, University of Cordoba, Campus de Rabanales, Crta. IV, km. 396, E-14071 Córdoba, Spain

^bDepartment of Graphic Engineering and Geomatics, University of Cordoba, Campus de Rabanales, Crta. IV, km. 396, E-14071 Córdoba, Spain

Background

Gully erosion threatens soil sustainability in Mediterranean olive orchards, accelerating soil loss, reducing field accessibility and increasing sediment delivery to downstream infrastructure. Despite growing deployment of on-farm weather stations and soil-moisture probes, these data streams are typically used descriptively and rarely converted into operational instability indicators for gully banks. Artificial Intelligence (AI) and UAV-borne LiDAR enable automated, extraction of gully geometry and its fusion with real-time hydroclimatic observations, supporting early warning, prioritised inspections and evidence-based maintenance (Stöcker *et al.*, 2015).

Design/methodology/approach

We developed an AI-driven data-fusion pipeline combining: (i) UAV LiDAR point clouds processed into a classified terrain model (DTM) and cross-sections every 5 cm to compute gully bank slopes, relief, curvature and along-gully morphological variability; (ii) in-field soil-moisture sensing on both margins (four probes installed 15 cm from the rim; depths 20, 40, 60 and 80 cm); and (iii) an on-site meteorological station (hourly rainfall, air temperature and relative humidity). Data engineering steps include automated quality control (spikes/resets), gap handling, time-zone normalisation and feature generation (antecedent rainfall indices, rolling moisture metrics and geometry descriptors). By using AI tools, it is possible to standardize/align flows from multiple sources and translate LiDAR geometry into features relevant to gully stability. A probabilistic stability surrogate (infinite-slope) was driven by deep soil moisture (80 cm) as a proxy for antecedent wetness and pore-pressure evolution (Iverson, 2000), consistent with stochastic storage/threshold concepts (Laio *et al.*, 2001; Gioia *et al.*, 2008, 2012). Parameter uncertainty (mobilised depth, strength parameters and unit weight) was propagated via Monte Carlo (N=2500) to estimate Factor of Safety (FS) distributions and probability of failure Pf. Outputs were produced per margin and aggregated into event-based summaries and operational alert levels, aligned with rainfall-triggered threshold reasoning (Frattoni *et al.*, 2009).

Findings

The monitoring system revealed a strong asymmetry between the margins: the steepest slope derived from LiDAR concentrated the greatest sensitivity to instability. Under conservative assumptions P_f approached 1, whereas under realistic field conditions (reduced effective slope from LiDAR profiles, partial saturation and apparent vegetation reinforcement) P_f decreased to 0.20 on the critical margin while remaining near zero on the opposite side. Deep soil moisture captured rainfall memory and explained risk evolution better than rainfall peaks alone, indicating that sustained subsurface wetness is the dominant control on short-term susceptibility. The framework produced interpretable time series of FS and P_f , highlighting windows for targeted field inspection after wet periods.

Conclusions

Geometry generated using UAV LiDAR technology and continuous soil moisture detection can be integrated through AI workflows into probabilistic and interpretable instability indicators suitable for field operations. The approach facilitates prioritized inspections, scenario testing (vegetation management, drainage improvement and slope reshaping) and transfer to other areas, contributing to scalable AI-based soil risk monitoring and decision support for sustainable land management in agricultural landscapes.

Keywords

UAV LiDAR, data fusion, soil moisture, gully erosion, early warning

Acknowledgement

This research is part of the research project “CARCAVA. Climatic and Agronomic Influence on the Formation and Evolution of the Gully Network in the Andalusian Countryside,” funded by the Ministry of University, Research, and Innovation of Government of Andalusia.

References

- Iverson, R. M. (2000). Landslide triggering by rain infiltration. *Water Resources Research*, 36(7), 1897–1910. <https://doi.org/10.1029/2000WR900090>
- Laio, F., Porporato, A., Ridolfi, L., & Rodríguez-Iturbe, I. (2001). Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress. *Advances in Water Resources*, 24(7), 707–723. [https://doi.org/10.1016/S0309-1708\(01\)00004-5](https://doi.org/10.1016/S0309-1708(01)00004-5)
- Gioia, A., Iacobellis, V., Manfreda, S., & Fiorentino, M. (2008). Runoff thresholds in derived flood frequency distributions. *Hydrology and Earth System Sciences*, 12, 1295–1307. <https://doi.org/10.5194/hess-12-1295-2008>
- Gioia, A., Iacobellis, V., Manfreda, S., & Fiorentino, M. (2012). Influence of infiltration and soil storage capacity on the skewness of the annual maximum flood peaks in a theoretically derived distribution. *Hydrology and Earth System Sciences*, 16, 937–951. <https://doi.org/10.5194/hess-16-937-2012>
- Frattini, P., Crosta, G. B., & Sosio, R. (2009). Approaches for defining thresholds and return periods for rainfall-triggered shallow landslides. *Hydrological Processes*, 23(10), 1444–1460. <https://doi.org/10.1002/hyp.7269>

- Stöcker, C., Eltner, A., & Karrasch, P. (2015). Measuring gullies by synergetic application of UAV and close range photogrammetry—A case study from Andalusia, Spain. *Catena*, 132, 1–11. <https://doi.org/10.1016/j.catena.2015.04.004>

TEMPORAL INFORMATION VS. ARCHITECTURAL COMPLEXITY IN AI-BASED MULTITEMPORAL CROP SEGMENTATION: EVIDENCE FROM AN IRRIGATED AGRICULTURAL AREA

López Juana María, Barraza Gabriela Alejandra,
Gómez Néstor Augusto, Angella Gabriel Augusto

*Instituto Nacional de Tecnología Agropecuaria (INTA) Estación
Experimental Agropecuaria Santiago del Estero (Argentina)*

lopez.juana@inta.gob.ar, barraza.gabriela@inta.gob.ar, gomez.nestor@inta.gob.ar, angella.gabriel@inta.gob.ar

Background

Accurate crop maps are essential for food security management and precision agriculture in irrigated systems, as they support area estimation, yield forecasting, and in-season decision-making. Remote sensing is the primary data source for monitoring land use and cover. Despite advances in deep learning, optimizing multitemporal crop segmentation remains challenging, and it is unclear whether improvements mainly depend on temporal depth or on increased architectural complexity.

Design/methodology/approach

The study was conducted in the SUD I district of the Río Dulce Irrigation System (Santiago del Estero, Argentina), focusing on winter crops. Six classes were segmented: alfalfa, wheat, onion, carrot, barley, and no crop. Four Planet Scope images (3 m spatial resolution) acquired on July 2, 14, 24, and August 11, 2024, were used. For each date, a 15-band product was generated, including spectral bands, vegetation indices, and textural statistics (mean, correlation, variance, dissimilarity) from the Gray-Level Co-occurrence Matrix (GLCM). Data were collected from 281 georeferenced field plots.

Three deep learning architectures of increasing complexity were evaluated to assess the relative impact of temporal depth versus architectural complexity: (1) CNN_LSTM_simple (Convolutional Neural Network–Long Short-Term Memory, reduced convolutional block), (2) CNN_LSTM+ (greater convolutional depth with intermediate normalization), and (3) CNN_LSTM_QC, a hybrid quantum-classical model based on Quantum Machine Learning. Configurations using 2–4 dates were analyzed. Performance metrics included overall accuracy, macro F1-score, and macro IoU at global and class levels, with statistical differences tested via McNemar's test.

Findings

With four dates, CNN_LSTM_simple achieved the highest performance (accuracy = 0.998; F1_macro = 0.997; IoU_macro = 0.995), outperforming CNN_LSTM+ (F1_macro = 0.976; IoU_macro = 0.954)

and CNN_LSTM_QC (F1_macro = 0.971; IoU_macro = 0.945), with significant differences ($p < 0.01$). Increasing temporal depth improved performance in all architectures: CNN_LSTM_simple F1_macro rose from 0.981 (2 dates) to 0.994 (3 dates) and 0.997 (4 dates); CNN_LSTM+ from 0.958 → 0.966 → 0.976; CNN_LSTM_QC from 0.901 to 0.971 (2 to 4 dates).

Class-level analysis showed spectrally similar crops, like wheat and barley, benefited most from additional dates (F1 > 0.998), while distinct classes (alfalfa, carrot) were already high with fewer dates. Overall ranking: CNN_LSTM_simple > CNN_LSTM+ > CNN_LSTM_QC, confirming temporal depth has greater impact than architectural complexity.

Conclusions

Temporal depth exerts a substantially stronger influence on multitemporal crop segmentation than increased architectural complexity. The simplest architecture with full temporal input achieved the highest metrics, outperforming more complex models. Adding temporal information reduces confusion among spectrally similar crops, highlighting the importance of phenological dynamics for class discrimination. Prioritizing high-quality multitemporal data is more efficient and cost-effective than adopting complex architectures. This work provides empirical evidence to guide AI-based decision-support tools in precision agriculture, balancing accuracy, interpretability, and operational feasibility.

Keywords

Multitemporal Crop Segmentation, Deep Learning, Remote Sensing, Precision Agriculture, Irrigation Systems

HIGH-RESOLUTION STEM WATER POTENTIAL ESTIMATION IN VINEYARDS USING UAV-BASED MULTISPECTRAL IMAGERY AND LASSO REGRESSION: A CASE STUDY IN MENDOZA, ARGENTINA

Henriquez-Dole, Lenin^a; Miner, Anahi^a; Calderón, Facundo^b;
Puertas, Carlos^b; Mateo, Daiana^b; Contreras, Octavio^b

^aEcoAgsus: Interdisciplinary Network for Ecosystem Sustainability, Mendoza, Argentina

l.henriquez@ecoagsus.com, a.miner@ecoagsus.com

^bEstación Experimental Agropecuaria Junín (Instituto Nacional de
Tecnología Agropecuaria), Mendoza, Argentina

calderon.facundo@inta.gob.ar, puertas.carlos@inta.gob.ar,
mateo.daiana@inta.gob.ar, contreras.octavio@inta.gob.ar

In semi-arid regions like Cuyo, Argentina, water scarcity necessitates high-precision irrigation management to maintain crop quality and yield. Traditional methods for monitoring grapevine (*Vitis vinifera* L.) water status, such as Stem Water Potential (SWP) measurements using pressure chambers, are accurate but labour-intensive and lack spatial representativeness. This study aims to evaluate the capacity of high-resolution multispectral signals captured by Unmanned Aerial Vehicles (UAVs) to identify and spatialize variations in the SWP of *grapevine*. The research was conducted during the 2024-2025 and 2025-2026 seasons at an experimental field of grapevine cv. Bonarda in INTA Junín, Mendoza, featuring different irrigation frequencies. A DJI Mavic 3M equipped with a multispectral sensor (Red, Green, NIR, Red-Edge) performed 15 flights across 14 dates. Concurrently, SWP data was collected from 36 selected plants across 7 dates. Image processing involved generating orthomosaics, radiometric correction, and extracting 8 statistical metrics per plant for 11 multispectral indices (including NDVI, GNDVI, NDRE, and OSAVI). Data analysis was performed using LASSO (Least Absolute Shrinkage and Selection Operator) regression to correlate spectral signatures with SWP and identify the most universal predictors. The LASSO regression models successfully explained over 80 % of the SWP variability across all evaluated dates, with deviance percentages (% Dev) ranging from 80.15 % to 90.21 %. A specific verification of the model (Nov 22, 2024) yielded an R^2 of 0.7817. Feature importance analysis identified the NDVI mode and NDRE median as the most influential and universal variables for predicting water status. The results also demonstrated that while models remain robust, the highest accuracy is achieved when UAV flights are synchronized with field measurements. This study demonstrates that UAV-based multispectral sensing, combined with machine learning techniques like LASSO, provides a reliable and scalable alternative for monitoring plant water status in vineyards. The methodology allows for the spatialization of SWP from a

limited number of field samples to an entire plot level, effectively capturing the response to different irrigation treatments. These findings offer a high-resolution decision-making tool for optimizing water use efficiency in precision viticulture within water-stressed environments.

Keywords

Precision Viticulture, Unmanned Aerial Vehicles (UAV), Stem Water Potential, Multispectral Imagery, Machine Learning

References

- Giannico, V., Garofalo, S. P., Brillante, L., Sciusco, P., Elia, M., Lopriore, G., Camposeo, S., Lafortezza, R., Sanesi, G., & Vivaldi, G. A. (2024). Temporal Vine Water Status Modeling Through Machine Learning Ensemble Technique and Sentinel-2 Multispectral Images Under Semi-Arid Conditions. *Remote Sensing*, 16(24), 4784. <https://doi.org/10.3390/rs16244784>.
- Laroche-Pinel, E., Casteran, G., Clenet, A., Gée, C., & Jenhaoui, A. (2021). Monitoring vineyard water status using Sentinel-2 images: Qualitative survey on five wine estates in the south of France. *OENO One*, 55(1), 227-241. <https://doi.org/10.20870/oeno-one.2021.55.4.4752>.
- Nowack, J. C., Atencia-Payares, L. K., Tarquis, A. M., & Gomez-del-Campo, M. (2024). Application of Unmanned Aerial Vehicle (UAV) Sensing for Water Status Estimation in Vineyards under Different Pruning Strategies. *Plants*, 13(10), 1350. <https://doi.org/10.3390/plants13101350>

MACHINE LEARNING FOR AGROECOLOGICAL DESIGN: AUTOMATED SHRUB IDENTIFICATION AND FUNCTIONAL BIODIVERSITY ASSESSMENT IN THE ARGENTINE MONTE

Miner Vega, Anahí J.^a, Del Barrio, Lucía^b, Alemanno, Valeria^a

^aEcoAgsus: Interdisciplinary Network for Ecosystem Sustainability, Mendoza, Argentina

a.miner@ecoagsus.com

^bDepartment, University/ Research Institute

delbarriolu@gmail.com

^bDepartment, University/ Research Institute

valemanno.91@gmail.com

The expansion of viticulture into the fragile arid ecosystems of the Argentine Monte requires robust biodiversity baselines to ensure long-term sustainability and the conservation of ecosystem services. Traditional botanical surveys, such as Point Quadrat and phytosociological analysis, are labor-intensive and lack the spatial continuity needed for large-scale landscape management. This study addresses this gap by integrating Remote Sensing and Artificial Intelligence to automate biodiversity monitoring, providing essential data for “rational land clearing” and the design of functional green infrastructure in newly developed vineyards.

Design/methodology/approach

Research was conducted during the 2024–2025 season across a 20hectare area in the Mendoza piedmont. We combined field-based vegetation surveys (450 georeferenced sampling points) with multispectral imagery acquired via UAV at an altitude of 60 meters. The sensor captured visible, near-infrared, and short-wave infrared bands, which were used to derive vegetation indices and a Digital Elevation Model (DEM). A supervised Random Forest (RF) classification model was implemented in RStudio, utilizing 70% of the field data for training and 30% for validation. To complement the structural mapping, a Potential Habitat Index for Functional Biodiversity (PHIFB) was calculated across ten sites, integrating species richness, total cover, and functional plant groups to identify high-value ecological patches.

Findings

The Random Forest model successfully identified 17 native shrub species with a Kappa coefficient of 0.77, demonstrating high reliability for automated mapping in semi-arid environments. The results

revealed that six dominant species account for over 80% of the total vegetative cover, allowing for a simplified yet effective management focus. The integration of spatial analysis and the PHIFB index highlighted specific “hotspots” of biodiversity, particularly Site 10, and validated the role of native corridors in maintaining ecological connectivity. While the automated segmentation significantly improved the exclusion of bare soil and annual species, observed differences between spectral outputs and manual field surveys emphasize the importance of iterative calibration in high-diversity landscapes.

Conclusions

The integration of UAV-based multispectral imaging and Machine Learning provides a scalable and efficient tool for biodiversity assessment in viticultural agroecosystems. This methodology not only reduces fieldwork time and costs but also provides 100% spatial coverage, enabling producers to implement evidence-based agroecological designs. By identifying priority conservation areas and functional patches, this approach supports sustainable viticulture and informs rational land-use decisions in arid regions. Future research will focus on expanding the model to include spontaneous herbaceous species and refining spectral signatures for complex Mediterranean-style shrublands.

Keywords

Remote sensing, Random Forest, Biodiversity mapping, Agroecology, Ecosystem services.

References

- Breiman, L. (2001). Random Forests. *Machine Learning*, 45(1), 5-32.
- García, L., *et al.* (2020). Remote sensing applications in monitoring biodiversity in agricultural landscapes. *Journal of Arid Environments*.
- Garibaldi, L. A., Pérez-Méndez, N., Garratt, M. P., Gemmill-Herren, B., Miguez, F. E., Dicks, L. V., & Samnegård, U. (2017). Policies for ecological intensification of crop production. *Trends in Ecology & Evolution*, 32(8), 497–510. <https://doi.org/10.1016/j.tree.2017.03.002>
- Viliotti, *et al.* (2023). Indices of functional biodiversity in semi-arid agroecosystems: A review of field-to-map integration.

ACCOUNTING FOR PHYSICAL BARRIERS IN INSECT PEST MODELING: A SPATIALLY EXPLICIT SIMULATION-BASED APPROACH

Requena-Mullor Juan Miguel^{1,2}, Rodríguez Estefanía³,
González Mónica⁴, Castro Antonio J.^{1,2}, Garau Enrica^{1,2},
Pérez-Ramírez Irene⁵, Peláez-Pérez Álvaro^{1,2}, Barranco Pablo^{1,6}.

¹ *Department of Biology and Geology, Universidad de Almería, La
Cañada de San Urbano, 04120 Almería, Spain*

juanmir@ual.es, acastro@ual.es, egarau@ual.es, alvaro.pelaez@ual.es, pbvega@ual.es

² *Centro Andaluz para el Cambio Global - Hermelindo Castro (ENGLOBA),
Universidad de Almería, La Cañada de San Urbano, 04120 Almería, Spain*

juanmir@ual.es, acastro@ual.es, egarau@ual.es, alvaro.pelaez@ual.es

³ *Department of Sustainable Crop Protection, IFAPA, La Mojonera-Centre, Almería, Spain*

mestefania.rodriguez@juntadeandalucia.es

⁴ *Agrobio S.L. Ctra Nacional 340, Km 419, n.º 81, 04746 La Mojonera, Almería, Spain*

mgonzalez@agrobio.es

⁵ *Social-Ecological Systems Laboratory, Department of Ecology,
Universidad Autónoma de Madrid, Madrid, Spain*

ip.ramirez@fct.unl.pt

⁶ *CECOUAL, Universidad de Almería, La Cañada de San Urbano, 04120, Almería, Spain*

pbvega@ual.es

Background

AI-enabled sensing and data intelligence systems are transforming pest monitoring and decision support in agri-food systems. However, the predictive performance of AI models depends critically on the quality, representativeness, and spatial structure of field data used for training and inference. In greenhouse-dominated agricultural landscapes, pest dispersal is strongly influenced by built infrastructure that simultaneously acts as both habitat and physical barrier, generating non-stationary spatial patterns that conventional monitoring designs and stationary models fail to capture (Bakka *et al.*, 2019; Cendoya *et al.*, 2022). This limitation constrains the development of reliable early-warning systems and spatially optimized sensing networks for Integrated Pest Management. To address this challenge, we develop a spatially explicit simulation-based framework that integrates landscape structure, pest dispersal processes, and sampling design to optimize data acquisition and improve predictive modeling in barrier-rich agroecosystems (Requena-Mullor *et al.*, 2026).

Design/methodology/approach

We propose a workflow that combines spatial simulation, Bayesian inference, and sampling optimization to evaluate pest monitoring strategies. Pest abundance was simulated in peri-greenhouse landscapes using high-resolution land-use data from southeastern Spain. Non-stationary Gaussian random fields were implemented through a Bayesian Barrier Stochastic Partial Differential Equation model estimated via Integrated Nested Laplace Approximation, allowing explicit representation of physical barriers and heterogeneous spatial dependence (Rue *et al.*, 2009; Bakka *et al.*, 2019). Three realistic landscape configurations, scarcely, moderately, and densely greenhouse-dominated, were modeled under varying levels of dispersal resistance. We compared cluster sampling and simple random sampling across multiple sample sizes (10–40 observations) to assess their impact on model accuracy and predictive reliability. Model performance was evaluated using mean absolute error and posterior predictive p-values against independent test datasets, providing a quantitative assessment of data efficiency and predictive uncertainty.

Findings

Results show that greenhouse spatial configuration strongly shapes pest aggregation patterns, dispersal pathways, and the effectiveness of sensing strategies. Cluster sampling consistently improved predictive accuracy and model calibration in sparsely and densely fragmented landscapes, where pest populations exhibited strong spatial continuity or compartmentalization. These conditions enabled spatially targeted sampling to capture localized hotspots and improve Bayesian model performance. In contrast, moderately fragmented landscapes produced dispersed pest distributions that reduced cluster sampling efficiency, leading to comparable performance between sampling methods. The framework also revealed that greenhouse density and permeability govern hotspot formation and movement constraints, demonstrating that monitoring design must be adapted to landscape structure to maximize information gain and predictive power.

Conclusions

This study introduces a scalable AI-enabled framework for optimizing pest sensing and monitoring strategies in complex agricultural environments. By integrating spatial simulation, advanced Bayesian modeling, and sampling evaluation, the proposed approach enhances data intelligence pipelines for early-warning systems and adaptive pest management. Explicitly accounting for physical dispersal barriers improves predictive reliability, reduces sampling effort, and supports the design of spatially informed monitoring networks. The framework provides a transferable methodology for AI-driven decision support in agri-food systems, advancing sustainable pest management through optimized data acquisition and landscape-scale ecological forecasting (Requena-Mullor *et al.*, 2026).

Keywords

Greenhouse agriculture, Pest monitoring, Conservative pest control, Bayesian modeling, Spatial analysis.

References

- Bakka, H., Vanhatalo, J., Illian, J.B., Simpson, D., Rue, H. (2019). Non-stationary Gaussian models with physical barriers. *Spatial Statistics*, 29, 268–288.

- Cendoya, M., Hubel, A., Conesa, D., Vicent, A. (2022). Modeling spatial distribution with dispersal barriers. *Phytopathology*, 112, 1036–1045.
- Requena-Mullor, J.M., *et al.* (2026). Accounting for physical barriers in insect pest modeling: A spatially explicit simulation-based approach. *Ecological Informatics*, 94, 103629.
- Rue, H., Martino, S., Chopin, N. (2009). Approximate Bayesian inference for latent Gaussian models using integrated nested Laplace approximations. *Journal of the Royal Statistical Society B*, 71, 319–392.

MACHINE-LEARNING-DRIVEN ANALYSIS OF STAGE-DEPENDENT SENSITIVITY OF PLANT FUNCTIONAL TRAITS TO WATER STRESS DYNAMICS IN ALMOND

Na Wang^{a,b}, Victoria Gonzalez-Dugo^b, Anirudh Belwalkar^c, Tomas Poblete^a, Paula Peña^b, Peiqi Yang^{d,e}, Wonseok Choi^{f,g}, Alessio Scalisi^h, Mark O'Connell^{h,a}, Youngryel Ryu^{f,g,i}, Pablo J. Zarco-Tejada^b

^a School of Agriculture, Food and Ecosystem Sciences (SAFES), Faculty of Science, and Faculty of Engineering and Information Technology (IE-FEIT), University of Melbourne, Melbourne, VIC, Australia
wangna1516@gmail.com; tomas.pobletecisterna@unimelb.edu.au

^b Institute for Sustainable Agriculture (IAS), Spanish Council for Scientific Research (CSIC), Cordoba, 14004, Spain
pablo.zarco@csic.es; victoria.gonzalez@ias.csic.es

^c Precision Agriculture Lab, School of Life Sciences, Technical University of Munich, Freising 85354, Germany
anirudh.belwalkar@tum.de

^d Key Laboratory of Virtual Geographic Environment, Ministry of Education, Nanjing Normal University, Nanjing, China
p.yang@njnu.edu.cn

^e Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing, China

^f Interdisciplinary Program in Landscape Architecture, Seoul National University, Seoul, South Korea
jackie6396@snu.ac.kr; ryuyr77@gmail.com

^g Integrated Major in Smart City Global Convergence, Seoul National University, Seoul, South Korea

^h Tatura SmartFarm, Agriculture Victoria Research, Tatura, VIC 3616, Australia
alessio.scalisi@agriculture.vic.gov.au; Mark.OConnell@agriculture.vic.gov.au

ⁱ Department of Landscape Architecture and Rural Systems Engineering, Seoul National University, Seoul, South Korea

Background

Limited water supply alters plant physiological, biochemical, and structural traits, reducing transpiration and photosynthesis and ultimately constraining yield (Atzberger, 2013). Because these responses vary with stress severity and recovery stage (Flexas and Medrano, 2002), irrigation management requires functional traits that remain diagnostically useful across growth stages and water-stress levels. Remote sensing provides spatiotemporal observations of water-stress-driven trait dynamics (Zarco-Tejada *et al.*, 2012).

Design/methodology/approach

We acquired airborne hyperspectral and thermal imagery in Victoria, Australia, and Cordoba, Spain, over well-watered and water-stressed almond orchards near solar noon under mild and high-level water stress, and during rehydration recovery. Physiological responses were quantified using the canopy–air temperature difference ($T_c - T_a$) and the Crop Water Stress Index (CWSI) (Gonzalez-Dugo and Zarco-Tejada, 2024) from thermal imagery, as well as sun-induced chlorophyll fluorescence at O2A (SIFA) and O2B (SIFB) spectral features (Wang *et al.*, 2023) from hyperspectral imagery as indicators of photosynthetic function. Leaf chlorophyll content (Cab) and canopy structural traits (leaf area index (LAI) and leaf angle distribution (LAD)) were retrieved from hyperspectral data through radiative transfer model (RTM) inversion using numerical optimization (Yang *et al.*, 2021). We then applied machine-learning models (Random forest) (Menze *et al.*, 2009) to assess the stage-dependent contribution of each trait to water-stress monitoring.

Findings

Feature-importance analysis revealed a pronounced shift in dominant drivers across stages. Under mild stress, CWSI and SIFA jointly explained 93.5% of model sensitivity (56.6% and 36.9%, respectively), with a smaller contribution from LAI (6.1%) and negligible effects from Cab and LAD (0.4% and 0%). Under high stress, CWSI became the dominant predictor, as expected. Nevertheless, during the recovery stage, sensitivity shifted toward photosynthetic and RTM-derived biophysical traits after transpiration levels recovered. SIFA contributed 67.4%, Cab and LAI each contributed 12.1%, and LAD contributed 8.5%, while thermal (i.e. CWSI or $T_c - T_a$) had negligible contribution. These results demonstrate that water-stress detection and irrigation decision rules are stage-dependent, and that the importance of physiological traits related to photosynthesis are critical to understand the effects of water stress, even after rehydration.

Conclusions

These results demonstrate that thermal metrics are most informative during mild and high-level of water stress, whereas fluorescence and pigmental/structural traits are more diagnostic of recovery dynamics. Overall, the combined RTM–ML framework highlights the value of AI-driven algorithms for identifying critical, stage-specific traits and advancing precision irrigation strategies in orchards.

Keywords

water stress, remote sensing, plant functional traits, machine learning, radiative transfer model.

References

- Atzberger, C., 2013. Advances in remote sensing of agriculture: Context description, existing operational monitoring systems and major information needs. *Remote sensing*, 5(2), 949–981.
- Flexas, J., Medrano, H., 2002. Drought-inhibition of photosynthesis in C3 plants: stomatal and non-stomatal limitations revisited. *Annals of botany*, 89, 183–189.
- Gonzalez-Dugo, V., Zarco-Tejada, P., 2024. Assessing the impact of measurement errors in the calculation of CWSI for characterizing the water status of several crop species. *Irrigation Science*, 42, 431–443.

- Menze, B. H., Kelm, B. M., Masuch, R., Himmelreich, U., Bachert, P., Petrich, W., Hamprecht, F. A. 2009. A comparison of random forest and its Gini importance with standard chemometric methods for the feature selection and classification of spectral data. *BMC bioinformatics*, 10(1), 213.
- Wang, N., Yang, P., Clevers, J.G., Wieneke, S., Kooistra, L., 2023. Decoupling physiological and non-physiological responses of sugar beet to water stress from sun-induced chlorophyll fluorescence. *Remote Sensing of Environment*, 286, 113445.
- Yang, P., Prikaziuk, E., Verhoef, W., & van Der Tol, C., 2021. SCOPE 2.0: A model to simulate vegetated land surface fluxes and satellite signals. *Geoscientific Model Development*, 14(7), 4697-4712.
- Zarco-Tejada, P.J., González-Dugo, V., Berni, J.A.J., 2012. Fluorescence, temperature and narrow-band indices acquired from a UAV platform for water stress detection using a micro-hyperspectral imager and a thermal camera. *Remote Sensing of Environment*, 117, 322-337.

Plenary Session 2: Services and utilities for an intelligent agriculture

Theme: Service-centric intelligent agriculture powered by virtual assistants, digital twins, and trusted data spaces- turning farm data into real-time, actionable operations.

DEVELOPMENT AND DEPLOYMENT OF A GRAPEVINE DOWNY MILDEW DECISION SUPPORT MODEL FOR THE MONTILLA-MORILES PDO (CORDOBA, SPAIN) WITHIN A FIWARE-BASED DATA PLATFORM

López-de la Fuente Alejandro^a, Palma-López Jesús^b, Checa
Caudel José^c, Torres-González Pedro J.^d

^a AgrifoodTEF, Córdoba University

g12lofua@uco.es

^b ENIA International Chair of Artificial Intelligence and Agriculture, Córdoba University

g72paloj@uco.es

^c Córdoba FIWARE Digital Transformation LAB, Córdoba University

jcheca@uco.es

^d CitriData, Córdoba University

z32togop@uco.es

Background

Plasmopara viticola (Peronosporales: Peronosporaceae) is a major grapevine pathogen that can cause severe damage under favourable environmental conditions. Its management traditionally relies on cultural practices, tolerant cultivars and phytosanitary applications. The integration of predictive models, particularly decision support systems (DSS), can optimise these strategies by helping to prevent severe yield losses through the anticipation of periods of high infection risk, while also reducing the number of phytosanitary treatments required. In this study, we aimed to develop and adapt the UR-model, designed for Mediterranean conditions, to the specific agroclimatic context of the Montilla-Moriles PDO (Córdoba, Spain), and integrate it into a FIWARE-based data and alert platform.

Design/methodology/approach

The epidemiological model is structured in successive modules describing the main stages of the disease cycle: (i) oospore maturation, (ii) primary infection, (iii) crop susceptibility, (iv) incubation, and (v) secondary infections and is driven by hourly and daily meteorological variables (air temperature, relative humidity and rainfall) collected from automatic weather stations located near the PDO by the SIAR network. For operational deployment, the model was integrated into a FIWARE-based data and decision support platform. Meteorological observations and predictions are ingested into the

FIWARE Context Broker using NGSiv2 protocol and entities based on Smart Data Models, which provide a harmonised representation of predictions, stations and their time series. These model outputs are then consumed by a web-based dashboard that provides growers and advisers with near real-time maps and time series of downy mildew risk, together with warning messages highlighting periods of high infection probability.

Findings

Model performance was evaluated by comparing simulated infection and high-risk periods with a historical record of downy mildew symptom appearance (first oil spots) spanning 17 years in the Montilla-Moriles PDO. The adapted model showed a very good agreement with the historical observations, yielding a mean absolute error of approximately 4 days in predicting the onset of visible symptoms over the 17-year dataset.

Conclusions

The adapted grapevine downy mildew model, integrated into a FIWARE-based decision support platform, showed satisfactory performance, reproducing the timing of first symptoms with a mean error of about 4 days over a 17-year historical record. A key limitation is that symptom records were not collected at the same locations as the meteorological stations, so microclimatic variability may partially explain mismatches between simulated and observed onset dates. Future work will therefore focus on installing additional, more locally representative stations and IoT sensors within vineyards to improve data quality, calibration and validation. Overall, the system is conceived as an operational tool to address a major phytosanitary challenge and to support the long-term viability and sustainability of vineyards in the PDO Montilla-Moriles.

Keywords

Plasmopara viticola, FIWARE, Vineyard, Epidemiological Model, Data Platform.

References

- Dubuis, P. H., Viret, O., Bloesch, B., Fabre, A., Naef, A., Bleyer, G., Kassemeyer, H., & Krause, R. (2012). Lutte contre le mildiou de la vigne avec le modèle VitiMeteo-Plasmopara. *Revue Suisse de Viticulture, Arboriculture et Horticulture*, 44(3), 192–198. FIWARE Foundation. (n.d.).
- FIWARE: Open-source platform for the smart digital future. <https://www.fiware.org>
- FIWARE Foundation. (n.d.). Smart Data Models. <https://www.fiware.org/smart-data-models/>
- FIWARE-Orion. (n.d.). NGSiv2 Implementation Notes – User & Programmers Manual. https://fiwareorion.readthedocs.io/en/latest/user/ngsiv2_implementation_notes.html
- Gehmann, K. (1987). Untersuchungen zur Epidemiologie und Bekämpfung des Falschen Mehltaus der Weinrebe, verursacht durch *Plasmopara viticola* (Berk. & Curt. ex de Bary) Berl. & de Toni (Doctoral dissertation). Universität Hohenheim, Germany.
- Gessler, C., Pertot, I., & Perazzolli, M. (2011). *Plasmopara viticola*: A review of knowledge on downy mildew of grapevine and effective disease management. *Phytopathologia Mediterranea*, 50 (1), 3–44.
- Goidanich, G. (1964). Le Peronosporales. In G. Goidanich (Ed.), *Manuale di patologia vegetale* (Vol. II, pp. 315–346). Edizioni Agricole.

- Koledenkova, K., Esmaeel, Q., Jacquard, C., Nowak, J., Clément, C., & Ait Barka, E. (2022). *Plasmopara viticola*, the causal agent of downy mildew of grapevine: From its taxonomy to disease management. *Frontiers in Microbiology*, 13, 889472. <https://doi.org/10.3389/fmicb.2022.889472>
- Puelles, M., Arbizu-Milagro, J., Castillo-Ruiz, F. J., & Peña, J. M. (2024). Predictive models for grape downy mildew (*Plasmopara viticola*) as a decision support system in Mediterranean conditions. *Crop Protection*, 175, 106450. <https://doi.org/10.1016/j.cropro.2023.106450>
- Rossi, V., Caffi, T., Giosuè, S., & Bugiani, R. (2008). A mechanistic model simulating primary infections of downy mildew in grapevine. *Ecological Modelling*, 212 (3–4), 480–491. <https://doi.org/10.1016/j.ecolmodel.2007.10.046>
- Velásquez-Camacho, L., Otero, M., Basile, B., Pijuan, J., & Corrado, G. (2023). Current trends and perspectives on predictive models for mildew diseases in vineyards. *Microorganisms*, 11 (1), 73. <https://doi.org/10.3390/microorganisms11010073>

DIGITAL TWIN OF OLIVE GROVES INTEGRATING GIS, 3D VISUALIZATION AND REALTIME IOT DATA FOR PRECISION AGRICULTURE

Palma-López Jesús^a, García-Velasco Manuel^a, Gómez Giménez Antonio^a, Checa Claudel José^b, González Perea Rafael^a, Martínez-Ruedas Cristina^a, Olivares Joaquín^a

^a ENIA International Chair of Artificial Intelligence and Agriculture, Córdoba University

g72paloj@uco.es, i72gavem@uco.es, i72gogia@uco.es, g72goper@uco.es, z42maruc@uco.es, el1olbuj@uco.es

^b Córdoba FIWARE Digital Transformation LAB, Córdoba University

jcheca@uco.es

Background

The management of olive groves is increasingly challenged by climate variability, soil heterogeneity, and the need for efficient use of natural resources. Traditional decision-support tools often fail to integrate spatial analysis, real-time sensor data, and immersive visualization within a single coherent framework. Digital Twin technology offers a promising solution by enabling the virtual representation of agricultural systems, allowing continuous monitoring, analysis, and interaction with real-world processes.

Design/methodology/approach

This work presents the development of a Digital Twin for olive groves that integrates geospatial analysis, 3D modeling, and real-time data visualization. The system is built upon three complementary components. First, QGIS is used to process spatial data derived from shapefiles and digital terrain models (DTM), generating thematic layers such as slope, orientation, soil characteristics, and real-time sensor location and information, all implemented in a 2D control panel. Real-time sensor data (environmental and soil parameters) are integrated via FIWARE. Second, Blender is employed as a middleware to transform geospatial outputs into optimized 3D assets, preserving spatial accuracy while enabling efficient rendering. Finally, Unity is used to deploy an interactive 3D environment compatible with immersive visualization through virtual reality headsets.

Findings

The resulting Digital Twin enables accurate spatial representation of olive groves and seamless integration of real-time IoT data. The combined 2D–3D approach allows users to analyze terrain constraints, soil variability, and sensor behavior simultaneously, both through conventional map interfaces and immersive VR visualization. Initial use cases demonstrate improved situational awareness,

easier interpretation of complex spatial patterns, and enhanced monitoring capabilities compared to traditional GIS-only or dashboard-based systems.

Conclusions

The proposed Digital Twin framework demonstrates the potential of integrating GIS, 3D visualization, and real-time IoT data for precision agriculture in olive groves. By combining analytical rigor with immersive interaction, the system supports more informed decision-making and offers a scalable and adaptable methodology for other woody crops. This approach contributes to advancing digital agriculture tools toward more intuitive, interoperable, and sustainable farm management solutions.

Keywords

Precision Agriculture, Geospatial Analysis, Virtual Reality Visualization, Smart Farming Systems, FIWARE

Acknowledgement

This work has been supported by the ENIA International Chair in Agriculture, University of Córdoba (TSI100921-2023-3), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union – Next Generation EU, Recovery, Transformation and Resilience Plan.

References

- Martínez-Ruedas, C., Flores-Arias, J.-M., Moreno-García, I. M., Linan-Reyes, M., & Bellido-Outeiriño, F. J. (2024). A Cyber–Physical System Based on Digital Twin and 3D SCADA for Real-Time Monitoring of Olive Oil Mills. *Technologies*, 12(5), 60. <https://doi.org/10.3390/technologies12050060>
- Pylianidis, C., Osinga, S., & Athanasiadis, I. N. (2021). Introducing digital twins to agriculture. *Computers and Electronics in Agriculture*, 184, 105942. <https://doi.org/10.1016/j.compag.2020.105942>
- Subeesh, A., & Chauhan, N. (2025). Agricultural digital twin for smart farming: A review. *Green Technologies and Sustainability*, 4(2), 100299. <https://doi.org/10.1016/j.grets.2025.100299>
- Vargas, J. M., Castrillon, O. D., & Giraldo, J. A. (2025). Implementation and Field Validation of a Digital Twin Methodology to Enhance Production and Service Systems in Waste Management. *Applied Sciences*, 15(12), 6733. <https://doi.org/10.3390/app15126733>

DIGITAL TWIN OF A MEDITERRANEAN FOREST FOR DYNAMIC SCENARIO SIMULATION AND GIS-BASED 3D VISUALIZATION

García-Velasco Manuel^a, Palma-López Jesús^a, Gómez-Giménez Antonio^a,
Palacios-Rodríguez Guillermo^b, Lara-Gómez Miguel Ángel^b, González
Perea Rafael^a, Martínez-Ruedas Cristina^a, Olivares Joaquín^a

^a *ENIA International Chair of Artificial Intelligence and Agriculture, Córdoba University*

i72gavem@uco.es, g72paloj@uco.es, i72gogia@uco.es, g72goper@uco.es, z42maruc@uco.es, el1olbuj@uco.es

^b *Department of Forestry Engineering, Córdoba University*

gpalacios@uco.es, g82lagom@uco.es

Background

Mediterranean forest ecosystems are highly sensitive to climate change effects, land management practices, and disturbance regimes, requiring tools that support the exploration of alternative management scenarios and their potential impacts. Traditional GIS-based analyses are often static and limited in their ability to represent temporal dynamics and spatial complexity. Digital Twin approaches provide a suitable framework to integrate spatial analysis, simulation, and realistic visualization, enabling a deeper understanding of forest variables behaviour under different conditions.

Design/methodology/approach

This work presents the development of a Digital Twin of a Mediterranean forest that integrates geospatial analysis, dynamic scenario simulation, and 3D visualization. The analytical core is implemented in QGIS, where an interactive panel allows users to define and simulate multiple scenarios by modifying key parameters related to forest structure, management and environmental conditions. The system dynamically generates graphical outputs that summarize spatial distributions and class-based indicators for both current and simulated future states. The results of the GIS-based simulations are transferred to a 3D environment developed in Unity, where realistic forest scenes are generated based on the simulated scenarios.

Findings

The Digital Twin enables dynamic comparison of multiple scenarios, linking quantitative GIS outputs with realistic 3D environments. The interactive panel facilitates the analysis of current and future forest states, while the Unity visualization enhances the interpretation of structural changes and spatial

patterns. The generation of scenario-dependent 3D environments allows users to intuitively assess the impact of different conditions and management strategies for decision-making.

Conclusions

The proposed Digital Twin demonstrates the potential of combining GIS-based simulation and 3D visualization for the evaluation and management of Mediterranean forest ecosystems. By enabling dynamic scenario exploration and realistic visual representation, the system supports improved understanding and communication of complex forest dynamics. The system could support informed decision-making in forest management by enabling the evaluation and comparison of alternative scenarios under changing environmental and management conditions. The framework is extensible and provides a solid basis for future integration of immersive virtual reality technologies.

Keywords

Forest Digital Twin, Forest Ecosystem Modelling, Geospatial Decision Support, Dynamic Environmental Simulation, Interactive 3D Environments

Acknowledgement

This work has been supported by the ENIA International Chair in Agriculture, University of Córdoba (TSI100921-2023-3), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union – Next Generation EU, Recovery, Transformation and Resilience Plan.

References

- Martínez-Ruedas, C., Flores-Arias, J.-M., Moreno-García, I. M., Linan-Reyes, M., & Bellido-Outeiriño, F. J. (2024). A Cyber–Physical System Based on Digital Twin and 3D SCADA for Real-Time Monitoring of Olive Oil Mills. *Technologies*, 12(5), 60. <https://doi.org/10.3390/technologies12050060>
- Pylianidis, C., Osinga, S., & Athanasiadis, I. N. (2021). Introducing digital twins to agriculture. *Computers and Electronics in Agriculture*, 184, 105942. <https://doi.org/10.1016/j.compag.2020.105942>
- Subeesh, A., & Chauhan, N. (2025). Agricultural digital twin for smart farming: A review. *Green Technologies and Sustainability*, 4(2), 100299. <https://doi.org/10.1016/j.grets.2025.100299>
- Vargas, J. M., Castrillon, O. D., & Giraldo, J. A. (2025). Implementation and Field Validation of a Digital Twin Methodology to Enhance Production and Service Systems in Waste Management. *Applied Sciences*, 15(12), 6733. <https://doi.org/10.3390/app15126733>

AUTOMATED LIVE WEIGHT MONITORING OF FEEDLOT CALVES USING COMPUTER VISION

Cristian Quevedo-Villalta^a, Manuel Jesús García-García^b, Eseró Padrón-Tejera^b, María Pilar Torralbo-Muñoz^b, Francisco Maroto-Molina^b

^aENIA International Chair of Artificial Intelligence and Agriculture, University of Cordoba, Cordoba, Spain

g92quvic@uco.es

^bResearch Group on Engineering of Agri-Livestock Systems, School of Agricultural and Forestry Engineering (ETSIAM), University of Cordoba, Cordoba, Spain

g42gagam@uco.es, z12pateee@uco.es, g92tomum@uco.es, g02mamof@uco.es

Background

Monitoring live body weight (BW) in beef cattle feedlots enables optimisation of ration formulation, improved pen uniformity, and more accurate slaughter timing decisions, supporting precision feedlot management [1]. However, routine weighing using conventional scales is labour-intensive, time-consuming and may induce stress responses in animals, limiting the frequency of weighing under commercial conditions [2-3]. This study evaluates whether overhead two-dimensional images of fattening calves captured at the drinking trough can estimate BW, providing a practical and non-invasive alternative to conventional weighing systems.

Methodology

The monitoring system consisted of a 5-MP overhead IP camera installed above the drinking trough, where an automatic weighing scale was integrated, enabling simultaneous acquisition of body weight (BW) records and calf images. The camera recorded 19,916 videos (maximum duration: 5 min) at 4.01 frames per second (fps). A quality-control protocol retained only video clips ≥ 30 s that corresponded to timestamps with an associated reference BW from the scale. After filtering, 1,257 valid videos were retained for further analysis. A subset of frames was sampled from these videos to maximise variability in animal posture, occlusion, and lighting conditions, and was manually annotated using Roboflow. A twostage computer vision pipeline was developed. First, an object detection and instance segmentation model was trained to detect calves and classify each instance into two categories: CSW (Calf Suitable for Weighing) and non-CSW (Calf Not Suitable for Weighing), according to whether the animal was correctly positioned on the scale. The annotated dataset was split into 70% for training and 30% for validation. A YOLOv11m-Seg model was trained to segment CSW calves and delineate their dorsal body perimeter. From each predicted segmentation mask, the projected dorsal area (in pixels) was extracted and paired with the corresponding BW recorded by the scale. The mean dorsal area per video was then regressed against live weight using both linear

and second-order polynomial models. Finally, residualbased outlier filtering ($|\text{residual}| > 3 \text{ SD}$) was applied, and the regression models were refitted to improve robustness.

Findings

The YOLOv11m-Seg model demonstrated strong performance, achieving a mean average precision at 50% IoU (mAP50) of 94.5% for bounding boxes and 94.6% for segmentation masks. Under more stringent thresholds (mAP50–90), performance remained robust at approximately 89%, maintaining a balanced trade-off between precision (91.4%), recall (92.3%), and F1-score (91.9%). For live weight estimation, the polynomial model significantly outperformed the linear approach after outlier removal. The second-degree regression achieved an R^2 of 0.81, reducing the mean absolute error (MAE) to 19.3 kg and yielding a mean absolute percentage error (MAPE) of 5.3%.

Conclusions

This study demonstrates that overhead RGB imaging at the drinking trough, combined with instance segmentation, represents a feasible and contactless alternative to conventional weighing for beef calves under feedlot conditions. The proposed approach enables more frequent and low-labour body weight monitoring, supporting data-driven feeding management and batch-level decision-making while reducing the need for animal handling. Future research should focus on validating the system across different pens, seasons, and weight ranges, as well as benchmarking its performance against other automated weighing solutions currently implemented in practice.

Keywords

cattle fattening, weight monitoring, precision livestock farming, computer vision

References

- [1] Guarnido-Lopez P, Pi Y, Tao J, Mendes EDM, Tedeschi LO. Computer vision algorithms to help decision-making in cattle production. *Animal Frontiers*. 2024; 14(6): 11-22. doi:10.1093/af/vfae028.
- [2] Cominotte A, Fernandes AFA, Dorea JRR, *et al.* Automated computer vision system to predict body weight and average daily gain in beef cattle during growing and finishing phases. *Livestock Science*. 2020; 232: 103904. doi:10.1016/j.livsci.2019.103904.
- [3] Norton T, Chen C, Larsen MLV, Berckmans D. Precision livestock farming: building 'digital representations' to bring the animals closer to the farmer. *Animal*. 2019; 13(12): 3009-3017. doi:10.1017/S175173111900199X

CLIMATIC INTELLIGENCE FOR PEST EARLY WARNING MACHINE LEARNING IDENTIFICATION OF ENVIRONMENTAL DRIVERS OF *CERATITIS CAPITATA* POPULATION MAXIMA IN MEDITERRANEAN CITRUS SYSTEMS

Barlin Orlando Olivares Campos^a; Juan Muñoz-Lorite^a, Pedro J. Torres-González^a; Flora Moreno-Alcaide^b, Inmaculada Garrido-Jurado^b, José Checa Claudel^a, Adolfo Peña-Acevedo^a

^a *CitriData Project. Rabanales Campus, University of Cordoba, Carretera Nacional IV, km 396, 14014, Córdoba, Spain*
ep2olcab@uco.es

^b *Department of Agronomy, DAUCO, ETSIAM, University of Cordoba, Carretera Nacional IV, km 396, 14014 Córdoba, Spain.*

The Mediterranean fruit fly, *Ceratitis capitata* Wied. is a major phytosanitary constraint in Mediterranean citrus systems, where population outbreaks are strongly modulated by climatic conditions. However, most studies rely on mean abundance or average climate metrics, potentially obscuring the specific environmental factors driving outbreak-level population pressure. This study aimed to identify and characterize the climatic conditions associated with the annual maximum population levels of *C. capitata* in Andalusian citrus systems (Spain) during the 2023–2024. Weekly trapmonitoring data (flies per trap per day, FTD) from 169 citrus polygons were integrated with high-resolution climatic datasets to extract the environmental context associated with annual population maxima. Polygons were categorized into high- and low-population-pressure classes based on an operational threshold of 0.5 flies·trap⁻¹·day⁻¹. An integrated analytical framework was applied, including univariate screening (Fold Change and Wilcoxon tests), Orthogonal Partial Least Squares Discriminant Analysis (OPLS-DA), and Random Forest (RF) classification.

Univariate analyses revealed significant contrasts primarily associated with temperature-related variables and shortwave radiation. The OPLS-DA model showed robust discrimination between pressure classes ($R^2Y = 0.47$; $Q^2 = 0.46$), supported by permutation testing, and identified shortwave radiation and temperature variables as the main contributors to class separation. The RF model achieved an overall outof-bag error of 0.166 (83% accuracy), with substantially lower classification error for the high-pressure class, indicating a more coherent climatic signature associated with high population pressure. Variable importance rankings consistently identified shortwave radiation and temperature metrics as dominant drivers.

Accordingly, these findings support the interpretation that population maxima emerge under consistently favorable thermal regimes rather than sporadic heat events. This distributional pattern mirrors field observations in Mediterranean citrus systems, where fly abundance peaks coincide with prolonged warm periods rather than isolated temperature extremes (Sciarretta & Trematerra, 2011). Similar seasonal peak dynamics have been reported in Mediterranean citrus groves in Spain, where population maxima rather than mean abundance drive management decisions (Martínez-Ferrer *et al.*, 2006, 2010).

Beyond temperature, our results highlight the role of the energy balance environment (captured by shortwave radiation) as a key component of the climatic signature associated with maximum population pressure events. This is consistent with field evidence indicating that *C. capitata* phenology and seasonal peaks are strongly influenced by environmental gradients that covary with temperature and landscape context.

For instance, a trap-based study in Mediterranean agroecosystems by Rodovitis *et al.* (2024) reported clear seasonal peaks and altitudinal shifts, with captures in coastal areas preceding those in highlands by approximately 15 days, underscoring that warmer and earlier conditions can advance population build-up and peak timing. Findings by Szyniszewska *et al.* (2024) on invasion dynamics and ecophysiology further support that climatic suitability for *C. capitata* is highly seasonal and spatially heterogeneous, an important parallel to our polygon-level contrasts based on annual maxima.

Overall, the results demonstrate that maximum *C. capitata* population pressure occurs under recurrent, well-defined climatic configurations rather than under average conditions. This analytical framework provides a robust basis for climate-informed surveillance, early warning systems, and integrated pest management, particularly when combined with automated trapping and biodigital monitoring networks in Mediterranean agroecosystems.

Keywords

Diptera, citrus, shortwave radiation, temperature, Random Forest.

Acknowledgments

This research is part of CITRIDATA Project: “Federated space for data, models, and services across the citrus value chain in the Autonomous Community of Andalusia”, University of Córdoba (TSI-100121-2024-107), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union - Next Generation EU. Recovery, Transformation and Resilience Plan.

References

- Martínez-Ferrer, M. T., Campos, J. M., & Fibla, J. M. (2006). Population dynamics of *Ceratitis capitata* on citrus in northeastern Spain: influence of adjacent host fruit trees. *IOBC-WPRS Bulletin*, 29(3), 7784.
- Martínez-Ferrer, M. T., Navarro, C., Campos, J. M., Marzal, C., Fibla, J. M., Barguès, L., & García-Marí, F. (2010). Seasonal and annual trends in field populations of Mediterranean fruit fly, *Ceratitis capitata*, in Mediterranean citrus groves: comparison of two geographic areas in eastern Spain. *Spanish Journal of Agricultural Research*, 8(3), 757–765. <https://doi.org/10.5424/sjar/2010083-1275>
- Rodovitis, V. G., Verykoui, E., Zarpas, K. D., Papanastasiou, S. A., Moraiti, C. A., Patronis, N., & Papadopoulos, N. T. (2024). Mediterranean fruit fly population phenological patterns are strongly

affected by elevation and host presence. *Scientific Reports*, 14(1), 6010. <https://doi.org/10.1038/s41598-024-56714-x>

- Sciarretta, A., & Trematerra, P. (2011). Spatio-temporal distribution of *Ceratitis capitata* population in a heterogeneous landscape in Central Italy. *Journal of Applied Entomology*, 135(4), 241-251. <https://doi.org/10.1111/j.1439-0418.2010.01515.x>
- Szyniszewska, A. M., Bieszczak, H., Kozyra, K., Papadopoulos, N. T., De Meyer, M., Nowosad, J., ... & Kriticos, D. J. (2024). Evidence that recent climatic changes have expanded the potential geographical range of the Mediterranean fruit fly. *Scientific Reports*, 14(1), 2515. <https://doi.org/10.1038/s41598024-52861-3>

SIZING OF LARGE-SCALE PHOTOVOLTAIC IRRIGATION SYSTEMS. MODEL FOR ENVIRONMENTAL AND ECONOMIC OPTIMISATION OF GRID-HYBRID SYSTEMS

Julián Alfonso Flores Cayuela^a, Irene Fernández García^b, Juan Antonio Rodríguez Díaz^c

^a*Department of Agronomy, University of Córdoba, Campus Rabanales, Edif. Da Vinci, 14071, Córdoba, Spain*
g12flcaj@uco.es

^b*Department of Electrical Engineering and Automatic Control, University of Córdoba, Campus Rabanales, Edif. Da Vinci, 14071, Córdoba, Spain*
g52fegai@uco.es

^c*Department of Agronomy, University of Córdoba, Campus Rabanales, Edif. Da Vinci, 14071, Córdoba, Spain*
ma2rodij@uco.es

The modernisation of irrigation systems towards pressurised networks has significantly increased energy demand in the agricultural sector, raising operational costs and environmental concerns. While large-scale photovoltaic (PV) systems offer a sustainable alternative, current sizing methodologies often rely on simple annual net energy balances, neglecting the high seasonality of irrigation demand, life cycle costs (LCC), and environmental impacts (LCA). This study addresses the need for a comprehensive multi-objective optimisation tool specifically designed for large-scale, grid-connected hybrid PV irrigation systems.

A novel model was developed using the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to simultaneously minimise LCC and LCA. The model optimises key design variables: PV panel type, installation configuration (fixed vs. single-axis tracking), and peak installed power. Environmental impacts were assessed using the Ecoinvent v3.9.1 database and the Environmental Footprint 3.0 methodology. The methodology was applied to a real-world case study in the Valle Inferior del Guadalquivir Irrigation District (VIGID) in southern Spain, comparing the algorithm's optimal solutions against an existing 6 MWp installation under two scenarios: with and without the sale of surplus energy.

The results demonstrated that single-axis tracking systems generally offer a better balance between economic and environmental performance compared to fixed installations, as they maximise daytime generation to match irrigation schedules. In the scenario allowing surplus energy sales, the Pareto front expanded significantly, identifying solutions that improved the LCC by 7.53% and the LCA by 5.67% compared to the actually installed system. Conversely, fixed installations, while economically viable when surplus sales are permitted due to higher peak power density, resulted in higher environmental burdens due to increased material requirements. The proposed model proves to be a robust decision-making tool, adaptable to different geographical contexts and consumption

profiles. It successfully identifies optimal trade-offs between conflicting economic and environmental objectives, outperforming traditional design methods. The study concludes that maximising installed power is not always the most efficient strategy, particularly without feed-in tariffs, and highlights the superior sustainability of tracking systems for high-demand irrigation profiles.

Keywords

Photovoltaic system, NSGA-II, Life cycle cost, Life cycle assessment, Irrigation District.

Acknowledgments

This research is part of CITRIDATA Project: “Federated space for data, models, and services across the citrus value chain in the Autonomous Community of Andalusia”, University of Córdoba (TSI-100121-2024-107), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union - Next Generation EU. Recovery, Transformation and Resilience Plan.

MULTI-MODAL RETRIEVAL-AUGMENTED GENERATION FOR AGRICULTURAL TECHNICAL SUPPORT INTEGRATING VISUAL EVIDENCE INTO LARGE LANGUAGE MODELS

Herrera-Poch, Fernando^a, Espejo-Santofimia, Antonio
Francisco^a, García-Martínez, Carlos^{a, b}

^aENIA International Chair of Artificial Intelligence and Agriculture, Córdoba University

a52hepofj@uco.es, i72gavem@uco.es, cgarcia@uco.es

^bDepartment of Computer Science and Artificial Intelligence, Córdoba University

Background

Agricultural decision-making relies heavily on visually rich technical documentation, such as pest identification guides, machinery handbooks, and fertilization protocols, where critical information is embedded in images, diagrams, and tables essential for field interpretation. Text-only RAG pipelines often lose this visual evidence, reducing interpretability and trust for technicians and farmers (Yu *et al.*; Tanaka *et al.*). Recent “vision-first” multimodal RAG approaches preserve layout by embedding full-page images but incur high storage and computational costs when scaling to large document collections (Faysse *et al.*). Our system addresses these challenges by generating semantic descriptions of images, figures, and tables during ingestion and integrating them into searchable textual chunks, enabling efficient retrieval without runtime vision encoding or large vector storage overhead. Additionally, the system presents the original images and tables alongside answers to reinforce credibility and support evidence-based interpretation.

Design/methodology/approach

This work presents an evidence-grounded multimodal RAG framework for agricultural knowledge management with four stages: (1) Structural parsing enables layout-aware extraction of text, tables, and figures while preserving document hierarchy (Hoang *et al.*). (2) Semantic enrichment filters, stores, and captions relevant tables and images using Vision-Language Models to make visual content searchable via embeddings (Luo *et al.*) (3) Indexing builds multimodal chunks combining text, file paths, and semantic descriptions, which are embedded and stored in a vector database. (4) Grounded generation produces answers linked to original images and tables with their captions, ensuring faithful visual grounding while keeping query-time retrieval textual and rendering linked evidence in the interface (Hoang *et al.*).

Findings

The approach improves usability and credibility for agronomic expert systems by linking explanations to original visual evidence. It scales effectively to large corpora, maintaining low online latency through standard embedding retrieval while performing OCR and captioning offline

Conclusions

By converting images into retrievable semantics through offline captioning while preserving original figures as evidence, the proposed architecture provides a practical path toward trustworthy agricultural knowledge assistants. Compared with end-to-end vision-first RAG pipelines, it offers a more deployment-friendly solution for large document collections, enabling low-latency retrieval with reduced storage and infrastructure overhead while maintaining traceable visual grounding. Storage and infrastructure costs remain lower than vision multi-vector indexes, which can substantially increase resource requirements at scale (Faysse *et al.*). Vision-first methods, however, may provide higher fidelity on dense graphical layouts (Yu *et al.*; Tanaka *et al.*). Further investigation is needed to systematically compare these results with alternative approaches.

Keywords

Multimodal RAG, Agricultural Knowledge Systems, Visually-Rich Documents, Efficient Retrieval, Document Images

Acknowledgement

This work has been supported by the ENIA International Chair in Agriculture, University of Córdoba (TSI100921-2023-3), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union – Next Generation EU, Recovery, Transformation and Resilience Plan.

References

- Luo, H., *et al.* (2023). Unifying Text, Tables, and Images for Multimodal Question Answering (UniMQA). Findings of EMNLP 2023.
- Yu, S., *et al.* (2024). VisRAG: Vision-based Retrieval-augmented Generation on Multi-modality Documents. arXiv:2410.10594.
- Faysse, M., *et al.* (2024). ColPali: Efficient Document Retrieval with Vision Language Models. arXiv:2407.01449.
- Tanaka, R., *et al.* (2025). VDocRAG: Retrieval-Augmented Generation over Visually-Rich Documents. arXiv:2504.09795.
- Hoang, T. T. U., *et al.* (2025). PDF Retrieval Augmented Question Answering. arXiv:2506.18027.

DOCUMENT-ADAPTED METAPROMPTING IN AGRICULTURAL RAG SYSTEMS DIFFERENTIAL EFFECTS ON EXPLANATORY AND FACTOID QUERIES

Herrera-Poch, Fernando^a, Espejo-Santofimia, Antonio Francisco^a,
García-Martínez, Carlos^{a, b}

^aENIA International Chair of Artificial Intelligence and Agriculture, Córdoba University
a52hepofj@uco.es, i72gavem@uco.es, cgarcia@uco.es

^bDepartment of Computer Science and Artificial Intelligence, Córdoba University

Background

Retrieval-Augmented Generation (RAG) systems are increasingly used to provide access to agricultural knowledge contained in technical manuals, scientific literature, and operational guidelines (Vizniuk *et al.*). In agricultural practice, questions often include both short explanatory requests and highly precise factseeking queries, such as product dosages, operational parameters, or instructions described in equipment manuals. These factoid queries are strategically important because inaccurate answers can directly affect field operations and decision-making. Prompt design plays a critical role in how RAG systems address these needs, and recent research highlights the value of incorporating contextual signals such as metadata and document structure to improve retrieval and grounding (Yousuf *et al.*). In this work, we study metaprompting as a strategy to generate document-adapted prompts that inject summaries, keywords, and representative agricultural question patterns to guide the model in selecting relevant context and evidence for grounded answer generation.

Design/methodology/approach

We evaluate a RAG pipeline where queries are enriched through a metaprompt constructed from document characteristics and representative agricultural question patterns. Experiments compare conventional prompting with metaprompt configurations across datasets categorized into factoid and short explanatory question types. Evaluation is conducted using an LLM-as-judge framework based on RAGAS and extended with RACAR-inspired criteria to assess answer relevance, grounding, and semantic alignment (Es *et al.*; Wan, Y. *et al.*; Zheng *et al.*). This setup enables systematic analysis of performance differences associated with prompt adaptation across query categories.

Findings

Results show that metaprompting improves performance by 15% for short explanatory questions, indicating that document-aware contextualization helps the model generate more coherent

responses when synthesis is required. However, performance decreases for factoid questions. Given that factoid queries in agriculture often correspond to critical operational information – including quantities of products, dosage recommendations, and step-by-step instructions – this reduction highlights an important limitation. The findings suggest that additional contextual signals may introduce ambiguity or reduce precision when concise answers are required.

Conclusions

These observations suggest that prompting strategies should be explicitly adapted to question type when deploying RAG systems in agricultural settings, where both interpretative and precision-critical queries coexist. Enriched metaprompting can support more effective handling of short explanatory questions, while the behavior observed in factoid queries indicates that additional contextual signals introduced by the metaprompt may act as noise and hinder precise answer generation in scenarios involving operationally critical information such as quantities, dosages, and procedural instructions. These implications highlight the need for careful prompt design to balance contextual richness and precision. Future work will extend the analysis to questions involving tables, broader information needs, and reasoning across multiple documents.

Keywords

Metaprompting, Retrieval-Augmented Generation, Agricultural Decision Support, LLM-based Evaluation, Question Type Adaptation

Acknowledgement

This work has been supported by the ENIA International Chair in Agriculture, University of Córdoba (TSI100921-2023-3), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union – Next Generation EU, Recovery, Transformation and Resilience Plan.

References

- Vizniuk, A., Diachenko, G., Laktionov, I., Siwocha, A., Xiao, M., & Smolağ, J. (2025). A comprehensive survey of retrieval-augmented large language models for decision making in agriculture: Unsolved problems and research opportunities. *Journal of Artificial Intelligence and Soft Computing Research*, 15.
- Yousuf, R. B., *et al.* (2026). Utilizing Metadata for Better Retrieval-Augmented Generation.
- Es, S., *et al.* (2023). RAGAS: Automated Evaluation of Retrieval Augmented Generation.
- Wan, Y., Liu, Y., Ajith, A., Grazian, C., Hoex, B., Zhang, W., Kit, C., Xie, T., & Foster, I. (2024). SciQAG: A framework for auto-generated scientific question answering dataset with fine-grained evaluation. *arXiv*. <https://doi.org/10.48550/arXiv.2405.09939>
- Zheng, L., Chiang, W.-L., Sheng, Y., Zhuang, S., Wu, Z., Zhuang, Y., Lin, Z., Li, D., Li, E., Zhang, H., Gonzalez, J., & Stoica, I. (2023). Judging LLM-as-a-judge with MT-Bench and Chatbot Arena. *arXiv*. <https://arxiv.org/abs/2306.05685>

ESTIMATION OF THE EVOLUTION OF SOIL ORGANIC CARBON IN CITRUS ORCHARDS IN ANDALUSIA WITHIN THE FRAMEWORK OF THE CITRIDATA PROJECT

Gómez Ariza Manuel^a, Yáñez Ávila Juan de Dios^b, González Sánchez Emilio^c.

^a *Departament of Rural Engineering. University of Córdoba, Campus Rabanales, Leonardo da Vinci bldg*
am2goarm@uco.es

^b *Departament of Rural Engineering. University of Córdoba, Campus Rabanales, Leonardo da Vinci bldg*
z42yaavj@uco.es

^c *Departament of Rural Engineering. University of Córdoba, Campus Rabanales, Leonardo da Vinci bldg*
emilio.gonzalez@uco.es

Background

According to the Survey on Areas and Crop Yields (ESYRCE) [1] conducted by the Spanish Ministry of Agriculture, Fisheries and Food (MAPA), the citrus-growing area in Spain in 2025 was 298,939 ha, representing 5.52% of the total área under permanente crop (5,411,982 ha). Andalusia, with 90,939 ha (30.4%), constitutes the second largest citrus-growing region after the Valencian Community. In terms of production, the Annual Crop Area and Production Report (MAPA) [2] indicates that Spain produced 5,953,382 tonnes of citrus in 2024, 57.8% of which was destined for export.

In recent years, the implications of climate change for agricultural systems have gained increasing relevance. Combined with soil degradation and declining organic matter levels, these processes pose significant challenges to the long-term sustainability of agricultural production. The adoption of good agricultural practices—such as the use of cover crops in Andalusian citrus orchards—contributes to CO₂ sequestration. The biomass generated by these covers, when retained on the soil surface, promotes organic matter dynamics analogous to those observed in natural ecosystems, thereby enhancing total soil organic matter.

Within the framework of the Common Agricultural Policy (CAP), several interventions have been established through direct payments linked to climate- and environment-oriented schemes (Eco-schemes). Some of these are associated with carbon farming or agroecological practices aimed at improving soil structure, increasing soil carbon content, reducing erosion and desertification, and mitigating greenhouse gas emissions. In parallel, an additional opportunity is emerging through carbon credits under Regulation (EU) 2024/3012, which promotes activities that enhance carbon sequestration in soils.

Design/methodology/approach

Using open data provided by the Andalusian Environmental Information Network (REDIAM) [3], together with a characterization of parameters associated with good agricultural practices, we propose the use of soil carbon models such as RothC and related derivatives to estimate the evolution of soil organic carbon under different soil management scenarios.

Findings

The application of these models and methodologies requires the availability of a set of parameters at plot or farm scale. Based on existing datasets, it is possible to characterize citrus-growing parcels and obtain the key input variables needed to estimate soil carbon dynamics over time.

Conclusions

The use of these tools enables the estimation of soil organic carbon dynamics and the quantification of CO₂ removals associated with the implementation of good agricultural practices in citrus systems.

Keywords

Soil organic carbon, ground cover, sustainable agriculture, soil management, citrus.

Acknowledgments

This research is part of CITRIDATA Project: “Federated space for data, models, and services across the citrus value chain in the Autonomous Community of Andalusia”, University of Córdoba (TSI-100121-2024-107), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union - Next Generation EU. Recovery, Transformation and Resilience Plan.

References

- [1] ESYRCE. Encuesta sobre superficies y rendimientos. MAPA. <https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce/>
- [2] MAPA, Informe interactivo del comercio exterior. <https://www.mapa.gob.es/es/ministerio/servicios/analisis-y-prospectiva/comercio-exterior/powerbi-comex.aspx>
- [3] REDIAM. Portal Ambiental de Andalucía. Junta de Andalucía. <https://www.juntadeandalucia.es/medioambiente/portal/acceso-rediam>
- [4] Coleman, K.; Jenkinson, D.S. RothC-26.3—A Model for the Turnover of Carbon in Soil. In Evaluation of Soil Organic Matter Models; Powlson, D.S., Smith, P., Smith, J.U., Eds.; Springer: Berlin/Heidelberg, Germany, 1996; pp. 237–246, ISBN 978-3-642-64692-8.

HIERARCHICAL MULTI-AGENT SYSTEM BASED ON GENERATIVE AI FOR A VIRTUAL ASSISTANT FOCUSED ON OPERATIONS AND INFORMATION RETRIEVAL

Espejo-Santofimia Antonio Francisco^a, Herrera Poch Fernando^a,
Bergillos Navarro Cristóbal^b, García-Martínez Carlos^{a,c}

^a*ENIA International Chair of Artificial Intelligence and Agriculture, Córdoba University*

i72gavem@uco.es, g72paloj@uco.es, i72gogia@uco.es, g72goper@uco.es, z42maruc@uco.es, el1olbuj@uco.es

^b*Department of Forestry Engineering, Córdoba University*

gpalacios@uco.es, g82lagom@uco.es

^c*Department of Computer Science and Artificial Intelligence, Córdoba University*

cgarcia@uco.es

Background

In business environments, generative AI-based virtual assistants enable more natural access to corporate applications, improving human-machine interaction. This is particularly relevant in the agri-food sector due to its continuous technological advancement. However, when different operational tasks and information queries coexist, monolithic approaches tend to degrade performance because of context accumulation, ambiguity in intent routing, and higher inference costs (Wu *et al.*). To address these limitations, a hierarchical multi-agent architecture based on generative AI has been developed that translates requests into explicit, reusable responsibilities, prioritizing efficiency, flow control, and robustness to intent shifts (Hou *et al.*).

Design/methodology/approach

The system is implemented with LangGraph using hierarchical nodes. A first node (router) classifies the user message and dispatches execution to a main domain (operations, information querying, or document retrieval via RAG). Within each domain, a second supervisory level selects the appropriate sub-flow (e.g., standard execution, recommendation-guided execution, and associated optional modules). To reduce latency and cost, the state stores the last node that handled the user's request, so that, for consecutive coherent messages, the system can skip intermediate decisions and continue directly within the active subflow. Nodes also include topic-verification agents that check whether the intent has changed and force rerouting if necessary. The system additionally includes an agent that interacts with the user and another that guides incremental data capture. Information is collected from the message history (without persisting intermediate structures). Once the action is confirmed, an agent consolidates fields from the conversation and invokes tools accessible via

MCP, which encapsulate integration with corporate APIs for both querying and updating information (Model Context Protocol).

For validation, an LLM-assisted testing framework is incorporated, where a test agent executes defined scenarios (e.g., completing an operational process with all mandatory fields) and compares expected data with what is recorded in the output. Additionally, metrics such as the number of iterations and token consumption are logged to compare efficiency across tests and flow variants (Acikgoz *et al.*).

Findings

The hierarchical multi-agent approach improves efficiency by restricting reasoning to specialized contexts, reduces redundant decisions when intent remains stable, and increases robustness to deviations through explicit verification within nodes. Modularity makes it easier to extend capabilities by adding new domains and sub-flows without degrading existing behavior. In goal-oriented tasks, such as order creation, the system achieves a success rate above 90%.

Conclusions

The hierarchical multi-agent approach provides a practical balance between control, scalability, and cost for process-oriented assistants. The architecture is reusable across different functional domains through the addition of nodes, the configuration of parameterized instructions, and specialized tools, while preserving routing and validation logic. The proposed architecture has been used as the basis for developing an internal system at Hispatec (an AgTech solutions company for the agri-food sector), adapted to its needs and workflows.

Keywords

Generative AI, multi-agent systems, LangGraph, hierarchical routing, virtual assistants, MCP, LLM-based testing, RAG

Acknowledgement

This work has been supported by the ENIA International Chair in Agriculture, University of Córdoba (TSI100921-2023-3), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union – Next Generation EU, Recovery, Transformation and Resilience Plan.

References

- Model Context Protocol. (2025, November 25). Specification (Protocol Revision: 2025-11-25). [ModelContextProtocol.io](https://modelcontextprotocol.io/specification/2025-11-25). <https://modelcontextprotocol.io/specification/2025-11-25>
- Wu, Q., Bansal, G., Zhang, J., Wu, Y., Li, B., Zhu, E., Jiang, L., Zhang, X., Zhang, S., Liu, J., Awadallah, A. H., White, R. W., Burger, D., & Wang, C. (2024). AutoGen: Enabling next-gen LLM applications via multi-agent conversations. OpenReview. <https://openreview.net/forum?id=BAakY1hNKS>
- Hou, Z., Tang, J., & Wang, Y. (2025). HALO: Hierarchical autonomous logic-oriented orchestration for multi-agent LLM systems (arXiv:2505.13516). arXiv. <https://arxiv.org/abs/2505.13516>
- Acikgoz, E. C., Guo, C., Dey, S., Datta, A., Kim, T., Tur, G., & Hakkani-Tür, D. (2025). TD-EVAL: Re-visiting task-oriented dialogue evaluation by combining turn-level precision with dialogue-level comparisons (arXiv:2504.19982). arXiv. <https://arxiv.org/abs/2504.19982>

CLASSIFICATION AND EARLY DETECTION OF NEW CITRUS PLANTATIONS USING AN ENSEMBLE XGBOOST–YOLOV9 MODEL

Juanma Muñoz-Lorite^{a-b}; Fernando Pérez-Porras^a; Pedro J. Torres-González^b;
José Checa-Claudel^b; Francisco Javier Mesas-Carrascosa^a; Adolfo Peña-Acevedo^b

^a Universidad de Córdoba. Departamento de Ingeniería Gráfica y Geomática. Edif. Gregor Mendel
(C5) 2.ª Planta. Campus de Rabanales Crta. N-IV km. 396 C.P. 14071, Córdoba, Spain

g92muloj@uco.es

^b CitriData Project. Rabanales Campus, Universidad de Córdoba,
Carretera Nacional IV, km 396, 14071, Córdoba, Spain.

Citrus orchards in Mediterranean regions have expanded significantly in recent years, creating the need for recurrent and automated approaches to quantify these increases. Artificial intelligence enables the exploitation of geospatial information for the early detection of new plantations and the assessment of structural changes in orchard systems (Bordas *et al.*, 2012). In Spain, citrus production reaches 5.95 Mt according to the Ministry of Agriculture, Fisheries and Food (MAPA, 2025), with Andalusia accounting for 40% of national output (2.29 Mt) and 87,322 ha registered in the SIGPAC system. Within this context, multitemporal analysis of citrus plantation dynamics is essential to support data-driven decision-making at regional scale.

This study presents an integrated workflow combining Machine Learning and Deep Learning models, following methodological approaches previously reported in the literature (Ishengoma & Lyimo, 2024), and using open geospatial data to classify citrus orchards into three developmental stages: newly established plantations, young orchards, and mature orchards. The objective is to support planning and evidence-based decision-making (Santos *et al.*, 2019). The proposed framework merges structural information derived from LiDAR data with individual tree-crown detection from high-resolution RGB orthophotography to enhance early identification of new plantations.

New citrus plantations were identified using an XGBoost classifier trained on metrics derived from a 2.5 m normalized Digital Surface Model (nDSM) generated from LiDAR data provided by the Spanish National Aerial Orthophotography Plan (PNOA), following procedures similar to those described by Zhu *et al.* (2021). Complementarily, tree-crown detection and tree counting were performed using a pretrained YOLOv9 model (Aszkowski *et al.*, 2023) applied to high-resolution PNOA RGB orthophotographs.

The study area corresponds to the Guadalquivir Valley in the provinces of Córdoba and Seville, where 12,456 parcels (38,800 ha) were analyzed and classified as new plantations (1.93%), young orchards (7.99%), and mature orchards (90.07%). The XGBoost model achieved an overall accuracy of 96.4%, with a recall of 96.38% and an F1-score of 96.37%. The ensemble approach, incorporating

YOLOv9-based individual tree detection, enabled cross-verification between models, requiring corrections in only 0.83% of parcels initially classified as new plantations by XGBoost.

Planting-density analysis, based on individual tree counts and geostatistical calculations, revealed an increase from an average of 323 trees/ha (approximate spacing 5 × 6 m) in mature orchards corresponding to the LiDAR acquisition year to 386 trees/ha (approximate spacing 5 × 5 m) in newly established plantations detected in the subsequent RGB orthophotograph. Furthermore, the proportion of orchards with densities exceeding 500 trees/ha increased from 5.6% to 17.7%, indicating a clear shift towards high-density production systems in the study region.

The proposed workflow enables automated detection of new citrus plantations and individual tree counting, facilitating the assessment of intensification trends in comparison with consolidated orchards. The observed increase of approximately 65 trees/ha reflects a structural transition towards more intensive production models. This methodology provides operational value for the agricultural sector by enabling temporal monitoring of orchard evolution and supporting future studies on water consumption, input requirements (Muñoz-Lorite *et al.*, 2026), and the development of yield-prediction models.

Keywords

Ensemble model; XGBoost, YOLOv9, citrus plantations, territorial analysis.

Acknowledgments

This research is part of CITRIDATA Project: “Federated space for data, models, and services across the citrus value chain in the Autonomous Community of Andalusia”, University of Córdoba (TSI-100121-2024-107), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union - Next Generation EU. Recovery, Transformation and Resilience Plan.

References

- Aszkowski, P., Ptak, B., Kraft, M., Pieczyński, D., & Drapikowski, P. (2023). Deepness: Deep neural remote sensing plugin for QGIS. *SoftwareX*, 23. <https://doi.org/10.1016/j.softx.2023.101495>
- Bordas, M., T. J., A. F. J. and H. A. (2012). HIGH DENSITY PLANTATION SYSTEM OF THE SPANISH CITRUS INDUSTRY. *Acta Hort.* 965. 10.17660/ActaHortic.2012.965.15
- Ishengoma, F. S., & Lyimo, N. N. (2024). Ensemble model for grape leaf disease detection using CNN feature extractors and random forest classifier. *Heliyon*, 10(12). <https://doi.org/10.1016/j.heliyon.2024.e33377>
- MAPA. (2025). ESYRCE. <https://www.mapa.gob.es/es/estadistica/temas/estadisticasagrarias/agricultura/esyrce/>
- Muñoz-Lorite, J., Torres-Sánchez, J., Cantón-Martínez, S., Mesas, F. J., & Pérez Porras, F. (2026). Automatic detection of olive grove planting systems using Deep Learning algorithms. <https://doi.org/10.2139/ssrn.6183764>
- Santos, F., Graw, V., & Bonilla, S. (2019). A geographically weighted random forest approach for evaluate forest change drivers in the Northern Ecuadorian Amazon. *PLoS ONE*, 14(12). <https://doi.org/10.1371/journal.pone.0226224>
- Zhu, Y., Sun, G., Ding, G., Zhou, J., Wen, M., Jin, S., Zhao, Q., Colmer, J., Ding, Y., Ober, E. S., & Zhou, J. (2021). Large-scale field phenotyping using backpack LiDAR and CropQuant-3D to measure structural variation in wheat. *Plant Physiology*, 187(2), 716–738. <https://doi.org/10.1093/plphys/kiab324>

Plenary Session 3: Innovation Systems and Socioeconomic Implications

Theme: Economics, governance, ethics, and the
institutional context of digitalisation.

DIGITAL TRANSFORMATION IN AGRI-FOOD SYSTEMS: EMERGING TECHNOLOGIES, SCALING CHALLENGES, AND PATHWAYS FOR SUSTAINABLE FUTURES

Tarek Ben Hassen^a and Hamid El Bilali^b

^a*Department of International Affairs, College of Arts and Sciences, Qatar University, Doha PO Box 2713, Qatar*
thassen@qu.edu.qa

^b*International Centre for Advanced Mediterranean Agronomic Studies
(CIHEAM-Bari), via Ceglie 9, 70010 Valenzano, Italy*
elbilali@iamb.it

Background

Agri-food systems face intertwined challenges—productivity constraints, environmental pressures, market inefficiencies, and equity gaps—that require transformational change rather than incremental fixes. Digital technologies (AI/ML, IoT and smart sensors, drones/remote sensing, robotics/automation, blockchain, cloud/data analytics, and CEA/vertical farming) are reshaping production and supply chains by enabling precision management, traceability, and data-driven decisions. This paper synthesizes emerging trends and future perspectives to answer the following question: How can digitalization be scaled and governed to enhance sustainability, resilience, and inclusivity across agri-food systems? It situates the research question within the broader transition to sustainable food systems and examines benefits, barriers, ethical considerations, and regulatory requirements for responsible deployment.

Design/methodology/approach

The paper undertakes an integrative review of recent scholarship and practice on agricultural digitalization, drawing on multi-disciplinary sources (agronomy, engineering, computer science, policy). Evidence spans applications using satellite imagery and UAVs, field and livestock sensors, and socio-economic interventions such as digital marketplaces and extension. Analytical coverage includes AI/ML models for yield prediction and pest/disease detection; IoT-based irrigation and greenhouse control; blockchain traceability and smart contracts; autonomous tractors and harvesting/weeding robots; and systems approaches such as CEA/vertical farming.

Findings

1. **Efficiency and sustainability:** Precision tools consistently improve the use of inputs (water, fertilizers, pesticides), cut waste, and raise yields, with AI/ML and robotics enabling hyper-personalized

- plant/animal management and adaptive field decisions. CEA/vertical farming and smart greenhouses demonstrate high resource efficiency in controlled environments.
2. Transparency and market access: Blockchain-enabled traceability and digital marketplaces enhance food safety, reduce fraud, and connect farmers directly to consumers, strengthening pricing and logistics. Digital twins offer real-time supply-chain optimization.
 3. Inclusive potential via data-driven services: Digital extension and open data platforms can lower information asymmetries and support smallholders' decision-making, climate insurance, and carbon programs.
 4. Scaling barriers: Infrastructure deficits (connectivity, power), high upfront costs, fragmented/interoperable systems, digital illiteracy, and limited skills across the food chain impede adoption—especially for smallholders. Data governance concerns (ownership, privacy, misuse), cybersecurity risks, and unclear liability for autonomous systems further constrain trust. Policy gaps and uneven regulations compound these hurdles.
 5. Ethical risks: Algorithmic opacity/bias, power asymmetries and corporate concentration, rebound environmental effects (e.g., intensification from efficiency gains), and potential job displacement necessitate deliberate safeguards and just transition measures.

Conclusions

Implications for the Agri-Food System: A sustainable and just digital transition depends on pairing innovation with governance: farmer-centric data rights (ownership, access/portability, consent), secure and interoperable data infrastructures, and trustworthy AI (transparency, accountability, bias mitigation) are foundational to legitimacy and scaling. Targeted public investment in rural connectivity and skills, fit-for-purpose finance (subsidies/credit), and standards that mandate interoperable, safe traceability can unlock system-level benefits while protecting vulnerable actors. Environmental regulation should align digital optimization with climate and biodiversity goals, avoiding efficiency-driven externalities and rebound effects. National strategies and international coordination (standards, PPPs) are critical to harmonize rules across borders and prevent vendor lock-in. Ultimately, the paper argues that digitalization can advance productivity, resilience, and equity *only* when ethical design, inclusive policies, and adaptive regulation co-evolve with technology. It offers a roadmap that centers farmers and workers, safeguards data, and balances innovation with societal well-being—so digital agri-food genuinely contributes to feeding a growing world sustainably.

Keywords

Agriculture 4.0; Digital agriculture; Digital technologies; Ethics; Policy; Precision agriculture.

References

- Ben-Daya, M., Hassini, E., Bahroun, Z., & Banimfreg, B. H. (2021). The role of internet of things in food supply chain quality management: A review. *Quality Management Journal*, 28(1), 17–40. <https://doi.org/10.1080/10686967.2020.1838978>
- Ben Hassen T., El Bilali H., Baya Chatti C. (2024). Acceptance and adoption of emerging digital technologies by agribusinesses in low and middle-income countries. In: Galati, A., Vrontis, D., Thrassou, A., Fiore, M. (eds), *Agribusiness Innovation and Contextual Evolution*, Volume II. Palgrave Macmillan, Cham. pp. 25–54 https://doi.org/10.1007/978-3-031-45742-5_2

- Benos, L., Tagarakis, A. C., Dolias, G., Berruto, R., Kateris, D., & Bochtis, D. (2021). Machine learning in agriculture: A comprehensive updated review. *Sensors*, 21(11), 3758. <https://doi.org/10.3390/s21113758>
- Birner, R., Daum, T., & Pray, C. (2021). Who drives the digital revolution in agriculture? A review of supply-side trends, players and challenges. *Applied Economic Perspectives and Policy*, 43(4), 1260–1285. <https://doi.org/10.1002/aepp.13145>
- El Bilali, H., & Allahyari, M. S. (2018). Transition towards sustainability in agriculture and food systems: Role of information and communication technologies. *Information Processing in Agriculture*, 5(4), 456–464. <https://doi.org/10.1016/j.inpa.2018.06.006>
- FAO. (2024). Scaling up digital solutions for the sustainable transformation of agri-food systems. Food and Agriculture Organization of the United Nations.
- Ferrag, M. A., Shu, L., Yang, X., Derhab, A., & Maglaras, L. (2020). Security and privacy for green IoT-based agriculture: Review, blockchain solutions, and challenges. *IEEE Access*, 8, 32031–32053. <https://doi.org/10.1109/ACCESS.2020.2973178>
- Kamilaris, A., & Prenafeta-Boldú, F. X. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, 147, 70–90. <https://doi.org/10.1016/j.compag.2018.02.016>
- OECD. (2020). Issues around data governance in the digital transformation of agriculture. *OECD Food, Agriculture and Fisheries Papers*, No. 146. <https://doi.org/10.1787/53ecf2ab-en>
- Parra-López, C., Ben Abdallah, S., Garcia-Garcia, G., Hassoun, A., Sánchez-Zamora, P., Trollman, H., Jagtap, S., & Carmona-Torres, C. (2024). Integrating digital technologies in agriculture for climate change adaptation and mitigation: State of the art and future perspectives. *Computers and Electronics in Agriculture*, 226, 109412. <https://doi.org/10.1016/j.compag.2024.109412>
- World Bank. (2023). Data-driven digital agriculture. World Bank Group.

IS BLOCKCHAIN A ONE-SIZE-FITS-ALL FOR AGRICULTURE? A SYSTEMATIC REVIEW ACROSS ECOSYSTEM DOMAINS

Mehreen Tahir^{a,b}, Cataldo Pulvento^b

^a School of Advanced Studies, University of Camerino, Italy

mehreen.tahir@unicam.it

^b Department of Soil, Food and Plant Sciences, University of Bari, Italy

cataldo.pulvento@uniba.it

Background

Blockchain technology has attracted growing attention in agriculture due to its potential to enhance transparency, traceability, trust, and coordination across agri-food systems. Much of the existing literature portrays blockchain as a broadly applicable digital solution capable of addressing long-standing challenges related to food safety, fraud, sustainability, and information asymmetries. However, agriculture is characterized by heterogeneous domains involving diverse actors, data types, governance structures, and technological capabilities. Despite a rapidly expanding body of research, it remains unclear whether blockchain delivers comparable benefits across different agricultural domains or whether its effectiveness is context dependent. Addressing this gap is important for guiding research priorities, digital investment, and policy decisions in the agri-food sector.

Design/methodology/approach

This study employs a systematic literature review to examine how blockchain and distributed ledger technologies have been studied and applied across agricultural ecosystem domains. The review is based on 1,593 peer-reviewed publications indexed in Scopus and Web of Science and published between 2016 and 2025. Following a structured multi-step protocol, duplicate records were removed and metadata were analyzed using bibliometric and network analysis techniques. Keyword cooccurrence, bibliographic coupling, and thematic clustering were used to map the evolution of blockchain research and identify dominant application areas. A domain-based classification was then applied to distinguish between agri-food supply chains, farm-level resource management, livestock systems, land governance, agricultural finance, and sustainability-related applications such as carbon farming.

Findings

The analysis shows a highly uneven distribution of blockchain research across agricultural domains. Agri-food supply chains dominate the literature, where blockchain's strengths in traceability,

transparency, and certification align closely with sector needs. In contrast, domains such as soil and water management, livestock systems, land governance, and carbon farming remain relatively underexplored and are often discussed at a conceptual or pilot stage. Across these domains, blockchain's contribution is strongly conditioned by the availability of reliable data and the presence of complementary digital technologies, including IoT sensors, analytics, and artificial intelligence. Where upstream data infrastructures are weak or fragmented, blockchain's added value is limited, and its role tends to be supportive rather than transformative.

Conclusions

The findings demonstrate that blockchain is not a one-size-fits-all solution for agriculture. Its effectiveness varies across ecosystem domains and depends on technological readiness, institutional arrangements, and integration with other digital systems. By adopting a domain-based perspective, this review contributes to more understanding of blockchain's role in agricultural digital transformation. The results highlight the need for selective, context-sensitive implementation strategies and caution against uniform adoption approaches. The study also identifies directions for future research, particularly in underexplored domains and in relation to the combined role of blockchain and AI within layered agricultural digital ecosystems.

Keywords

Blockchain, Agriculture, Agri-food systems, Ecosystem domains, Digital transformation.

References

- Casino, F., Dasaklis, T. K., & Patsakis, C. (2019). A systematic literature review of blockchain-based applications: Current status, classification and open issues. *Telematics and informatics*, 36, 55-81.
- Galvez, J. F., Mejuto, J. C., & Simal-Gandara, J. (2018). Future challenges on the use of blockchain for food traceability analysis. *TrAC Trends in Analytical Chemistry*, 107, 222-232.
- Kamilaris, A., Fonts, A., & Prenafeta-Boldú, F. X. (2019). The rise of blockchain technology in agriculture and food supply chains. *Trends in food science & technology*, 91, 640-652.
- Kouhizadeh, M., Saberi, S., & Sarkis, J. (2021). Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers. *International journal of production economics*, 231, 107831.
- Lin, Q., Wang, H., Pei, X., & Wang, J. (2019). Food safety traceability system based on blockchain and EPCIS. *IEEE access*, 7, 20698-20707.
- Mambile, C., Mwangakala, H. A., Chali, F., Julius, B., Shao, D., Mongi, H., & Ishengoma, F. (2025). Evaluating Blockchain Technology for Contract Farming in Tanzania: A Task-Technology Fit Analysis. *Sustainable Futures*, 100905.
- Mbadlisa, G., & Jokonya, O. (2024). Factors affecting the adoption of blockchain technologies in the food supply chain. *Frontiers in Sustainable Food Systems*, 8, 1497599.
- Tian, F. (2016, June). An agri-food supply chain traceability system for China based on RFID & blockchain technology. In *2016 13th international conference on service systems and service management (ICSSSM)* (pp. 1-6). IEEE.

BEEF 4.0 AND THE TRANSFORMATION OF WORK AND SOCIAL RELATIONS IN BEEF PRODUCTION

Bruno Capdevielle^a

^a *Interdisciplinary Centre of Agrarian Studies (CIEA), Faculty of Economic Sciences, University of Buenos Aires, Argentina*

Capdbruno@gmail.com

The development of digitalization and artificial intelligence has become one of the main challenges in beef production, particularly in Latin America and Argentina. While technical and infrastructural limitations are the most visible barriers, the central tensions surrounding Beef 4.0 sustainability lie in social relations of production and the people involved in them. Since technology is ultimately adopted and used in everyday work practices, understanding these social dimensions is crucial to assessing the long-term viability of digital transformations (Capdevielle, 2024; Klerkx et al., 2022; Prause, 2021).

This article examines the changing dimensions of work associated with Beef 4.0 from a social science perspective. The analysis focuses on five key aspects: the reproduction of knowledge and know-how; consent and job satisfaction (Burawoy, 1989); employment personalization (Newby, 1983); autonomy, surveillance, and task control (Payne, 2008); and labour and living conditions. It is argued that sustainability must incorporate social dimensions in order to enable effective and equitable technological adoption. Otherwise, innovations risk clashing with existing social practices, territorial dynamics, and forms of rural life.

The study draws on ongoing PhD research combining fieldwork and analysis of contemporary digital and AI-based market technologies. Empirical data include semistructured interviews with more than 80 beef farmers, rural workers, and technicians conducted between 2022 and 2023, as well as field visits to 21 rural towns and 18 farms in Buenos Aires Province, Argentina's main beef-producing region.

The findings highlight three major trends. First, digitalization and AI increasingly replace tasks and practical knowledge traditionally acquired through experience. While this may facilitate knowledge transmission for younger generations, it generates tensions with experienced workers, who perceive a loss of autonomy and decision-making capacity.

Second, the mediation of work through digital tools contributes to the depersonalization of labour relations, affecting interactions among workers as well as relationships with animals, tasks, and the landscape. This is particularly significant in a sector where occupational identity and affective engagement with work remain central. Third, digital technologies offer potential improvements in working and living conditions by reducing physical strain, occupational risks, rural isolation, and barriers to education.

The article argues that Beef 4.0 sustainability cannot be assessed solely through productivity and efficiency gains. Digital innovation may conflict with established socio-territorial dynamics if social dimensions are not adequately considered. Policies promoting agricultural digitalization should therefore integrate labour and social considerations to ensure that technological change contributes not only to increased production but also to improved quality of work and rural life.

Keywords

Beef 4.0, Digitalization in agriculture, Labour relations, Social sustainability, Rural work

References

- Burawoy, M. (1989). El consentimiento en la producción. Los cambios del proceso productivo en el capitalismo monopolista. Ministerio de Trabajo y Seguridad Social.
- Capdevielle, B. (2024). Tecnologías de la información y la comunicación, digitalización y trabajo en la ganadería bovina argentina del siglo XXI. *Revista Latinoamericana de Estudios Rurales*, 9(17).
- Klerkx, L., Jakku, E., & Labarthe, P. (2022). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS: Wageningen Journal of Life Sciences*, 90–91, 1–16. <https://doi.org/10.1016/j.njas.2019.100315>
- Newby, H. (1983). La sociología rural institucionalizada. In H. Newby & E. SevillaGuzmán, *Introducción a la Sociología Rural*. Alianza.
- Payne, J. (2008). 'Put Your Hands Where My Eyes Can See': An Analysis of Workplace Surveillance, Resistance and Consent [Tesis de Maestría en Sociología, North Carolina State University]. <http://www.lib.ncsu.edu/resolver/1840.16/593>
- Prause, L. (2021). Digital agriculture and labor: A few challenges for social sustainability. *Sustainability*, 13(11), 5980.

BRIDGING THE MEDITERRANEAN DIGITAL DIVIDE: INTEGRATING AI AND ICT INTO LOCAL URBAN MARKETS FOR SMALLHOLDERS

Saker Ben Abdallah^a, Meriem Oueslati^a, Nedia Ounalli^a,
Mohamed Zied Dhraief^a, Takwa Oueslati^a, Ghada Ferchichi^a, Mustapha Jouili^{a,b}

^a *Laboratory of Rural Economy, National Institute of Agronomic Research of Tunisia (INRAT)*

saker.benabdallah@inrat.ucar.tn

^b *Département Sciences Economiques. Faculté des Sciences Économiques et de Gestion de Nabeul.*

Background

The Mediterranean agri-food sector faces a critical convergence of climate change, water scarcity, and socio-economic fragmentation. These factors disproportionately impact the resilience of smallholder farmers (Ahmed *et al.*, 2025). While Agriculture 4.0 and artificial intelligence (AI) offer transformative potential, these technologies have traditionally favoured large-scale industrial farming. Smallholders often encounter substantial obstacles to adopting these innovations due to limited capital and technical training (Bonet *et al.*, 2026; Tabe-Ojong, 2023). This bypasses the critical networks of local urban markets that define the region's food security. Conducted within the framework of the BLUMI-Med project, this study addresses the urgent need to adapt digital technologies – ranging from advanced sensors to frugal mobile solutions – to scale up these local markets and enhance their sustainability.

Design/methodology/approach

A systematic literature review was conducted to analyse the current state of digital adoption within the Mediterranean agri-food system. The analysis categorised empirical studies based on a conceptual framework that distinguished between producer-oriented ICT, such as precision agriculture using UAVs (Greco *et al.*, 2025), and food system-oriented ICT, including traceability and waste management. A comparative approach was then employed to evaluate the deployment of technology in the northern, southern and eastern Mediterranean regions, focusing on the roles of AI, the Internet of Things (IoT) and blockchain.

Findings

The review reveals a distinct technological divergence. In the Northern Mediterranean, AI and the Internet of Things (IoT) are used to improve efficiency and enhance quality. For example, blockchain technology is used to certify Protected Designation of Origin products (Scuderi *et al.*, 2020), while IoT systems quantify food waste in the hospitality sector (Markides *et al.*, 2025) and optimise urban

irrigation (Gasser *et al.*, 2024). In the Southern and Eastern Mediterranean, however, the focus is on resilience. Here, machine learning ensembles predict crop yields in water-scarce conditions (Eddamiri *et al.*, 2024) and deep learning mobile apps help farmers diagnose plant diseases accurately, filling in knowledge gaps (Buchailot *et al.*, 2024). Evidence suggests that low-cost sensors and smartphone-based AI are economically viable even for farms under 50 hectares (Loures *et al.*, 2020; Sánchez Millán *et al.*, 2023). However, a critical gap remains, as current applications predominantly target either production or consumption, largely ignoring the market hub itself as a centre for social exchange and logistics.

Conclusions

A context-sensitive approach is required for digital transformation. While technologies such as AI have reached a level of technical maturity, success in local urban markets hinges on ‘frugal innovation’ that transcends digital literacy barriers and acknowledges indigenous knowledge (Abdulhamid *et al.*, 2025). Future policy must shift its focus from agronomic metrics alone to market-centric digital ecosystems that reinforce locavore principles and short supply chains (Nikhitha and Prasanth, 2025; Dos Santos *et al.*, 2021). By fostering inclusive digital solutions, stakeholders can transform local markets into optimised hubs that ensure food security.

Keywords

Local Urban Markets, Artificial Intelligence, ICT, Frugal Innovation, Smallholders, BLUMI-Med.

References

- Abdulhamid, N. G., Ogunyemi, A., Perry, M., Bauters, M.L., Rephisti, J., Sam, S., Maina, S.C., Ocheing, M., Nyairo, S., Gandhi, R., O'Neill, J., 2025. Advancing Sustainable Agricultural Practices in Africa with AI: Interdisciplinary Approaches to Inclusivity and Resilience. *Proceedings of the 5th Biennial African Human-Computer Interaction Conference (AfriCHI 2025)*, 415–418.
- Ahmed, O., Faiz, M., Abdelali, L., Khoali, S., Pulvent, C., Mohamed, S., Mbaye, M.S., Glauben, T., 2025. Unlocking climate change resilience: socioeconomic factors shaping smallholder farmers' perceptions and adaptation strategies in Mediterranean and Sub-Saharan Africa regions. *Regional Sustainability*, 6(1), 100195.
- Bonet, L., Thomas, F., Martínez-Gimeno, M. A., Tasa, M., Badal, E., Pérez-Pérez, J.G., Werban, U., 2026. A user-friendly decision support tool for irrigation scheduling in smallholder olive orchards. *Agricultural Water Management*, 324, 110131.
- Buchailot, M. L., Fernandez-Gallego, J. A., Mahmoudi, H., Thushar, S., Aljanaahi, A.A., Kosimov, S., Hammami, Z., Al Jabri, G., La Cruz Puente, A., Akl, A., Trillas, M.I., Araus, J.L., 2024. Framework for deep learning diagnosis of plant disorders in horticultural crops: From data collection tools to user-friendly web and mobile apps. *Ecological Informatics*, 84, 102900.
- Dos-Santos, M. J. P. L., Machado-Santos, C., Batista, N., 2021. Smart and sustainable cities in the Mediterranean region: The contribution of short supply chains of food. *Ecocycles*, 7(2), 8–17.
- Eddamiri, S., Bassine, F. Z., Ongoma, V., Epule, T.E., Chehbouni, A., 2024. An automatic ensemble machine learning for wheat yield prediction in Africa. *Multimedia Tools and Applications*, 83, 66433–66459.

- Greco, C., Gaglio, R., Settanni, L., Sciurba, L., Ciulla, S., Orlando, S., Mammano, M.M., 2025. Smart Farming Technologies for Sustainable Agriculture: A Case Study of a Mediterranean Aromatic Farm. *Agriculture*, 15, 810.
- Loures, L., Chamizo, A., Ferreira, P., Loures, A., Castanho, R., Panagopoulos, T., 2020. Assessing the Effectiveness of Precision Agriculture Management Systems in Mediterranean Small Farms. *Sustainability*, 12(9), 3765.
- Markides, C., Pericleous, S., Achilleos, A., Hamrouni, H., Philippou, P., 2025. FoodFlow-1.0: A Smart IoT System for Manual Food Waste Logging for Hotels in the Med Region. *IOP Conference Series: Earth and Environmental Science*, 1558, 012064.
- Nikhitha, K. K., Prasanth, A. P., 2025. Artificial intelligence for climate-adaptive agriculture: supporting locavore principles and small-scale farmers. *Journal of Enabling Technologies*, 1–16.
- Sánchez Millán, F., Ortiz, F. J., Mestre Ortuño, T. C., Frutos, A., Martínez, V., 2023. Development of Smart Irrigation Equipment for Soilless Crops Based on the Current Most Representative Water-Demand Sensors. *Sensors*, 23(6), 3177.
- Scuderi, A., Foti, V., Timpanaro, G., 2020. The Supply Chain Value of POD and PGI Food Products Through the Application of Blockchain. *Quality - Access to Success*, 20(S2), 580–587.
- Tabe-Ojong, M. P., 2023. Climate-smart Agriculture and Food Security in the MENA. *Orient*, 64(1), 24–35.

ARTIFICIAL INTELLIGENCE AS A SOCIO-TECHNICAL ENABLER IN AGRIBUSINESS INNOVATION SYSTEMS EVIDENCE FROM AGTECH-BASED VALUE CHAIN

Elisete Aparecida Ferreira Stenger^a, Simone Sehnem^b

^a Postgraduate Program in Administration, Unoesc - University of Western Santa Catarina

elisete.stenger@gmail.com

^b Postgraduate Program in Administration, - Unoesc - University of Western Santa Catarina

simone.sehnem@unoesc.edu.br

Background

The diffusion of Industry 4.0 enabling technologies has significantly reshaped innovation dynamics in agribusiness, particularly through the increasing role of technology-based startups acting as intermediaries within innovation systems. Commonly referred to as AgTechs, these startups develop and deploy digital solutions that mediate interactions among farmers, technical advisors, cooperatives, input suppliers, and other actors across agribusiness value chains. Within this technological landscape, artificial intelligence (AI) has assumed a central, though non-exclusive, role by enabling data-driven processes, advanced analytical capabilities, and new coordination and decision-making mechanisms. While digital transformation in agribusiness is often associated with efficiency gains and operational improvements, its broader socioeconomic implications remain insufficiently explored. In particular, limited attention has been given to understanding how Industry 4.0 technologies reshape innovation systems, stakeholder relationships, and patterns of resource use through socio-technical arrangements, especially in emerging economy contexts characterized by decentralized and relational innovation processes.

Design/methodology/approach

This study adopted a qualitative multiple-case study approach to analyze AgTechs that develop and implement digital technologies applied to productive, operational, and managerial activities in agribusiness. The investigated startups deployed a combination of Industry 4.0 enabling technologies—including artificial intelligence, data analytics, digital platforms, and automation tools—to support production management, process optimization, operational control, and data-driven decision-making. Empirical data were collected through in-depth semi-structured interviews with founders and senior managers, complemented by document analysis. The empirical material was examined using qualitative content analysis conducted with the support of the MAXQDA software, enabling the identification of recurring patterns related to innovation processes, stakeholder coordination, and technology-mediated practices within agribusiness innovation systems.

Findings

The findings indicated that artificial intelligence played a central role in structuring innovation processes by enabling coordination, information sharing, and data-driven decision-making among multiple stakeholders. Digital solutions supported improvements in operational efficiency, monitoring, and resource management, contributing to loss reduction and more informed managerial decisions across agribusiness activities. However, these outcomes were not primarily driven by formal innovation strategies or explicit sustainability-oriented objectives articulated by the AgTechs. Instead, innovation effects emerged from the ways in which stakeholders appropriated digital tools to adjust practices, coordinate actions, and respond to operational challenges within the broader innovation system.

Conclusions

The study shows that the socioeconomic implications of Industry 4.0 in agribusiness extend beyond firm-level technological adoption and are better understood through a systems perspective that accounts for socio-technical interactions and networked decision-making processes. In this context, artificial intelligence operated as a socio-technical enabler, linking technological capabilities with stakeholder practices and facilitating emergent patterns of innovation across agribusiness value chains. By integrating insights from Industry 4.0 and innovation systems literature, this research contributes to a deeper understanding of how AgTechs function as intermediaries of innovation and how digital technologies reshape coordination, learning, and value creation in agribusiness, particularly in emerging economy settings.

Keywords

Industry 4.0, Artificial Intelligence, Innovation Systems, Agribusiness, AgTechs.

References

- Agrawal, R., Wankhede, V. A., Kumar, A., Luthra, S., & Huisingh, D. (2022). Progress and trends in integrating Industry 4.0 within the circular economy. *Business Strategy and the Environment*, 31(4), 1736–1762. <https://doi.org/10.1002/bse.3203>.
- Bertoglio, O., & Sehnem, S. (2024). Industry 4.0 in the context of agribusiness: A systematic literature review. *Procedia Computer Science*, 232, 107–116. <https://doi.org/10.1016/j.procs.2024.01.011>.
- Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and Agriculture 4.0. *NJAS – Wageningen Journal of Life Sciences*, 90–91, 100315. <https://doi.org/10.1016/j.njas.2019.100315>.
- Reitano, M., Segovia, M. S., & Nayga, R. M. Jr. (2025). A systematic review on the impact of artificial intelligence in the agri-food supply chain. *Food Policy*, 137, 102983. <https://doi.org/10.1016/j.foodpol.2025.102983>.
- Taddei, E., Sassanelli, C., Rosa, P., & Terzi, S. (2022). Circular supply chains in the era of Industry 4.0. *Computers & Industrial Engineering*, 168, 108097. <https://doi.org/10.1016/j.cie.2022.108097>.

MARKET INTELLIGENCE THROUGH FIWARE OPEN-SOURCE PLATFORM – APPLIED CASES IN THE STUDY OF CITRUS SUPPLY AND PRICE DATA IN THE EUROPEAN SINGLE MARKET

Luis Villanueva Gandul^a, Pedro Sánchez-Zamora^{a,b}, Rosa Gallardo-Cobos^{a,b}

^a CitriData Project, Rabanales Campus, Universidad de Córdoba/
ETSIAM, Ctra. N-IV, km 396, 14014, Córdoba, Spain
sc2vigal@uco.es; pedro.sanchez@uco.es; rosagallardo@uco.es

^b Department of Agricultural Economics, Universidad de Córdoba/
ETSIAM, Ctra. N-IV, km 396, 14014, Córdoba, Spain
pedro.sanchez@uco.es; rosagallardo@uco.es

Background

The global citrus market has experienced significant growth driven by steady demand and a profound production sector transformation. This evolution has fostered the emergence of new production hubs, while traditional regions face severe impacts. Within the specific context of the European Union (EU), detailed knowledge of the interaction between imported supply and local production is crucial for understanding market status and trends in price discovery (European Commission, n.d.-a, n.d.-b). These dynamics directly affect consumer prices and the profitability of European farmers, who must navigate strict production standards, rising costs, and high volatility caused by climate fluctuations and phytosanitary risks, in a market increasingly contested by competition from Southern Mediterranean.

Design/methodology/approach

This study presents a market intelligence tool developed within the CITRIDATA project (CITRIDATA, 2025) using the FIWARE open-source platform (Cátedra de Transformación Digital y FIWARE, n.d.), whose methodology integrates the ingestion and processing of large-scale datasets from official national and international sources—e.g., UN Comtrade, MERCASA, Observatorio de Precios de la Junta de Andalucía, BLE, or FranceAgrimer. The technical stack leverages programming language-based scripts for automated Data Ingestion and ETL (Extract, Transform, Load) processes, ensuring data harmonization. Furthermore, Apache Superset is utilized for advanced data visualization and business intelligence (BI), enabling the correlation of monthly trade flows (fresh citrus—namely oranges, soft citrus or lemons—alongside their industrial derivatives) with market prices across strategic European locations.

Findings

Preliminary results demonstrate that the market intelligence tool developed upon the FIWARE framework architecture facilitates the identification of seasonal patterns and key determinants influencing price-setting mechanisms within the EU. The integration of a robust analytical backend for automated data processing allows for the detection of anomalies and correlations between import volumes and local price drops. Furthermore, the tool's computational capabilities and data-driven architecture successfully demonstrate the technical feasibility of developing predictive models tailored to the specificities of the agrifood chain.

Conclusions

The implementation of this tool enables a deeper understanding of the citrus market as an international phenomenon, accounting for both long-term evolution and sudden disruptions. The use of interoperable data management standards and open-source visualization tools (BI, Apache Superset) contributes to a more transparent and complex ecosystem analysis. Ultimately, this framework enhances the resilience of the European citrus sector, providing the necessary intelligence to foster sustainability and informed strategic decision-making in a volatile international landscape.

Keywords

Citrus Market, FIWARE, third-country competition, Price discovery mechanisms, food security.

Acknowledgments

This research is part of CITRIDATA Project: "Federated space for data, models, and services across the citrus value chain in the Autonomous Community of Andalusia", University of Córdoba (TSI-100121-2024-107), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union - Next Generation EU. Recovery, Transformation and Resilience Plan.

References

- Cátedra de Transformación Digital y FIWARE. (n.d.). Transformación digital y ecosistema FIWARE. Universidad de Córdoba. Retrieved February 20, 2026, from <https://www.uco.es/atdfiware/>
- CITRIDATA (2025). CITRIDATA: Inteligencia de mercado para el sector citrícola mediante estándares interoperables. Universidad de Córdoba. <https://www.uco.es/citridata/>
- European Commission. (n.d.-a). Agri-food Data Portal. Retrieved May 22, 2024, from <https://agri-data.ec.europa.eu/extensions/DataPortal/home.html>
- European Commission. (n.d.-b). Citrus fruit statistics: Market observatories. Directorate-General for Agriculture and Rural Development. https://agriculture.ec.europa.eu/data-and-analysis/markets/overviews/market-observatories/fruit-and-vegetables/citrus-fruit-statistics_en

35 YEARS OF CLIMATE AND AGRICULTURAL RESEARCH: AI REVEALS A STRUCTURAL SHIFT FROM IMPACT ASSESSMENT TO ACTIVE INTERVENTION

Alcalá-Espinosa, Estrella; Peña-Acevedo, Adolfo

*Department of Rural Engineering, Civil Constructions and Engineering Projects,
Higher Technical School of Agricultural and Forestry Engineering (ETSIAM), University
of Córdoba, Rabanales University Campus, 14071 Córdoba, Spain*

q12alese@uco.es

Background

The exponential growth of scientific literature on climate change and agriculture hinders the identification of established research questions, emerging topics, and critical evidence gaps. As the corpus expands, traditional bibliometric methods often overlook latent thematic structures or the complex “coframing” of technologies and risks. This information overload creates potential blind spots regarding whether global research priorities align with urgent adaptation needs. This study addresses the need for a comprehensive, data-driven map of the global agricultural innovation system. By decoding the latent semantic topology of the field, the aim is to understand how scientific priorities have shifted over the last three decades and to detect structural misalignments between academic research and socio-economic resilience.

Design/methodology/approach

A scalable unsupervised Artificial Intelligence pipeline was implemented to mine 219,261 Scopus-indexed documents published between 1990 and 2025. The workflow integrated Term Frequency-Inverse Document Frequency (TF-IDF) vectorization with Latent Semantic Analysis (LSA) to generate a 60-dimensional semantic space. Subsequently, Uniform Manifold Approximation and Projection (UMAP) was applied for non-linear dimensionality reduction and HDBSCAN for density-based clustering, autonomously identifying 18 distinct macro-themes. To distinguish structural thematic shifts from the general exponential growth of the field, topic evolution was monitored using normalized intensity indicators (z-scores). Furthermore, cross-theme “co-framing” was quantified to assess how technical concepts, such as biotechnology or energy, are inextricably paired with socio-economic challenges within the literature.

Findings

Results reveal a structural shift in the innovation system: a transition from an “Impact Assessment” paradigm (1990s) to an “Intervention Engineering” paradigm (post-2010). This shift is driven by the

rapid rise of biotechnology and genomic resilience research, signalling a shift from observing climate impacts to actively developing biological resilience. A distinct “Social Turn” emerges, where socio-economic vulnerability has evolved from a peripheral topic to a consolidated research theme, increasingly co-framed with sustainability and economic analysis. The analysis also identifies a “Soil Carbon Turn”, where soil research has shifted focus from local soil quality to global carbon sequestration strategies. Significantly, the study uncovers deep epistemic asymmetries: Western research agendas (e.g., UK, Canada) prioritize mitigation and Net-Zero policies, whereas major Asian economies (China, India) focus heavily on crop production and biotechnology. Additionally, the temporal analysis detects that “Heat Stress” has recently overtaken “Drought” as the dominant stressor signal in the corpus (post-2021), indicating a growing concern with thermal biological limits.

Conclusions

The global climate-agriculture knowledge system is expanding but shows signs of fragmentation. While technological capabilities (AI, modelling, biotech) are growing, they often develop separately from social vulnerability assessments. The disconnect between technical and policy domains risks creating solutions that are technically viable but socially inequitable. It is suggested that future research strategies should encourage a “convergence” approach, better integrating biophysical innovations with socio-economic frameworks. This semantic map provides evidence to help policymakers connect mitigation-focused and production-focused research agendas more effectively.

Keywords

Science Mapping, NLP, Climate Adaptation, Semantic Clustering, Topic Evolution

Acknowledgments

This research is part of the ENIA International Chair in Agriculture, University of Córdoba (TSI-100921-2023-3), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union - Next Generation EU. Recovery, Transformation and Resilience Plan. Also, this research was supported by “CARCAVA. Climatic and Agronomic Influence on the Formation and Evolution of the Gully Network in the Andalusian Countryside”, funded by the Ministry of University, Research, and Innovation of Government of Andalusia.

References

- Deerwester, S., Dumais, S. T., Furnas, G. W., Landauer, T. K., & Harshman, R. (1990). Indexing by Latent Semantic Analysis. *Journal of the American Society for Information Science*, 41(6), 391-407. [https://doi.org/10.1002/\(SICI\)1097-4571\(199009\)41:6](https://doi.org/10.1002/(SICI)1097-4571(199009)41:6)
- Li, C., Yao, H., Li, Z., Wu, F., Liu, B., Wu, Y., Chun, K. P., Octavianti, T., Cui, X., & Xu, Y. (2024). A Bibliometric Analysis of Global Research on Climate Change and Agriculture from 1985 to 2023. *Agronomy*, 14(11), 2729. <https://doi.org/10.3390/agronomy14112729>
- McInnes, L., Healy, J., & Astels, S. (2017). hdbscan: Hierarchical density based clustering. *The Journal of Open Source Software*, 2(11), 205. <https://doi.org/10.21105/joss.00205>
- Nalau, J., & Verrall, B. (2021). Mapping the evolution and current trends in climate change adaptation science. *Climate Risk Management*, 32. <https://doi.org/10.1016/j.crm.2021.100290>

BEHAVIOURAL CONFIGURATIONS AND AI-SENSITIVE DESIGN OF SUSTAINABLE INNOVATION SYSTEMS EVIDENCE FROM MEDITERRANEAN VITICULTURE

Teresa Latorre-Carrascosa^a, Verónica Piñeiro^b, Victor Martinez-Gomez^a, Raúl Compés López^c

^aDepartamento de Economía y Ciencias Sociales. Universitat Politècnica de València (Valencia)

telacar@upv.es, vicmargo@esp.upv.es

^bDepartamento Agronomía, Universidad Nacional del Sur (Bahía Blanca, Argentina)

veronica.pineiro@uns.edu.ar

^cInstituto Agronómico Mediterráneo de Zaragoza (CIHEAM ZARAGOZA)

raul.compes@iamz.ciheam.org

Background

Sustainability transitions in agriculture are increasingly understood as systemic and behavioural transformations with significant socioeconomic implications (Ofosu-Ampong *et al.*, 2025). Advancing sustainable farming remains a strategic priority within the EU agri-environmental agenda, where policy frameworks combine mandatory regulations and voluntary instruments. However, the effectiveness of voluntary measures depends not only on financial incentives or technological availability, but also on a comprehensive understanding of farmers' behaviour (Latorre-Carrascosa *et al.*, 2025). Behavioural approaches highlight non-monetary factors such as social norms, environmental attitudes, innovation orientation, heuristics, trust, and values (Kahneman, 2003; Thaler & Sunstein, 2008; Wuepper *et al.*, 2023). These factors interact with structural and institutional conditions, generating heterogeneous adoption pathways. In digitally evolving agri-food systems, such behavioural heterogeneity is particularly relevant, as the performance of data-driven and AI-enabled solutions depends on farmers' social embeddedness and cognitive readiness (Camaréna, 2020). This study examines which configurations enable the transformative adoption of sustainable viticulture practices in the Valencian Community (Spain).

Design/methodology/approach

Structured interviews were conducted with 60 professional winegrowers in the Valencian Community (Spain). The survey captured dispositional, social, and cognitive drivers following Dessart *et al.*'s (2019) integrated framework of behavioural factors. The outcome—a weighted adoption index of environmentally sustainable practices—was analysed with fuzzy-set Qualitative Comparative Analysis

(fsQCA) (Ragin, 2008). This method is suited to medium-N studies and uses Boolean algebra to obtain combinations of conditions, represented by simplified expressions that lead to the outcome of interest (the adoption of more environmentally sustainable practices). It allows equifinality: diverse, mutually non-exclusive pathways can lead to the same phenomenon (Legewie, 2013).

Findings

Necessity analysis indicates that environmental concern (0.890), social influence (0.992), and cognitive adoption capacity (0.663) constitute necessary conditions for high levels of sustainable practice adoption. The near-perfect consistency of social influence underscores the systemic character of sustainability transitions, revealing adoption as deeply embedded within peer networks and governance structures. Sufficiency analysis identifies two distinct configurational pathways. The first, a system-embedded adaptive trajectory, combines environmental concern, cognitive readiness, and strong social influence with favourable structural conditions (vineyard size). This pathway aligns with the Innovation Systems perspective, emphasising collective learning, institutional integration, and resource endowments as codeterminants of transformation. The second, a strategic innovation-oriented trajectory, links environmental concern and cognitive readiness with innovation orientation and perceived economic returns. Here, sustainability adoption reflects adaptive competitiveness and economically viable strategic positioning.

Conclusions

The results confirm that sustainability transitions in Mediterranean viticulture emerge from interacting behavioural and structural drivers embedded within broader system dynamics. Environmental concern, social influence, and cognitive readiness constitute foundational behavioural conditions, yet no single factor is sufficient in isolation. Instead, adoption materialises through context-dependent, equifinal pathways shaped by governance arrangements, structural characteristics, and social dynamics. While the study does not empirically model AI adoption, it derives conceptual and policy-relevant implications for AI-enabled agricultural systems. First, AI-based decision-support tools may reinforce social influence mechanisms by increasing transparency of peer behaviour through digital benchmarking and collaborative platforms. Second, machine-learning-driven decision systems can reduce cognitive barriers by translating complex agronomic and environmental data into actionable recommendations, thereby interacting with farmers' cognitive adoption capacity. Third, innovation-oriented farmers may represent early adopters of AI-enabled optimisation tools integrating sustainability and competitiveness objectives. From a socioeconomic and innovation-systems perspective, these findings suggest that intelligent agri-food systems should incorporate behavioural segmentation, recognising equifinality and heterogeneity among producers, and therefore avoid one-size-fits-all policies, including digitalization interventions, in favour of inclusive, behaviourally informed sustainability transitions.

Keywords

behavioural drivers, fsQCA, sustainability transitions, viticulture, AI-Sensitive Policy Design

HOW AGRIFOOD RESEARCH CONNECTS DIGITAL TECHNOLOGIES TO SOCIO-PRODUCTIVE CHALLENGES: A GLOBAL EVIDENCE MAP (2015-2025)

José Francisco Díaz Lao^a, Javier Pérez-Barea^a, Zalán Márk Maró^b

^a*Department of Statistics, Econometrics, Operational Research, Business Organization and Applied Economics, University of Córdoba*
g62dilaj@uco.es

^b*Department of Agricultural Economics, Institute of Sustainable Development, Corvinus University of Budapest*

Background

Digital technologies are frequently framed as enablers of sustainability, productivity, and resilience in agrifood systems, yet how research links these technologies to sectoral and social challenges remain fragmented. This study presents a reproducible evidence map that characterizes how the scientific literature conceptualizes intersections between digital technology families and environmental, productive, and social challenges in agrifood systems (2015-2025). Beyond the thematic interest in the impact of AI on the agrifood sector, the study adds methodological value by leveraging a robust semantic representation, grounded in natural language processing, to structure and interrogate the corpus at scale.

Design/methodology/approach

A Scopus-derived corpus of 57,100 records (2015-2025) was curated through a structured query targeting the intersection of agrifood systems, digital technologies, and socioproductive challenges, supported by an auditable Python workflow. Metadata were cleaned and standardized, and texts were prepared to construct a shared semantic representation of the corpus. The design integrates two complementary components. A supervised cross-classification (M1) organizes evidence into a challenge-by-technology family matrix and quantifies non-random associations using chisquare standardized residuals. An unsupervised discovery step (M2) identifies latent thematic domains among records not confidently captured by the curated taxonomy in M1. Both components rely on a semantic representation based on latent semantic analysis (TF-IDF with truncated SVD), ensuring mapping consistency, traceability, and comparability across methods.

Findings

The evidence map reveals a stable tripartite structure in how agrifood challenges are framed, together with an uneven distribution of evidence across technology families. Social challenges rarely

appear in isolation, they co-occur with environmental pressures and are articulated through production-related decisions, indicating that digitalization may mitigate or intensify these challenges depending on implementation pathways and on who can adopt and benefit from solutions. The evidence further points to a gap between the maturity of observation and the capacity for operational response, and to an even larger gap in autonomous execution. In parallel, AI- and machine-learning-based analytics accelerates toward the end of the period, yet remains concentrated in platforms and decision-support settings with human mediation, conditioned by connectivity, interoperability, validation capacity, and training. The unsupervised layer (M2) expands the scope of the map by recovering latent themes that are weakly captured by predefined taxonomies, providing a basis for tracking future thematic evolution and emerging directions in the field.

Conclusions

By clarifying concentrations, gaps, and emerging frontiers at the intersection of technologies and challenges, the evidence map provides a structured basis for research prioritization and for the design of governance and policy frameworks that support responsible digitalization in agrifood systems. The shared semantic representation further shows how text-analytic and semantic modelling techniques can strengthen evidence mapping by improving interpretability, scalability, and auditability when navigating large scientific corpora.

Keywords

agrifood systems, artificial intelligence, evidence mapping, text mining, science mapping

References

- Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, 133, 285-296. <https://doi.org/10.1016/j.jbusres.2021.04.070>
- Fountas, S., Espejo-García, B., Kasimati, A., Mylonas, N., & Darra, N. (2020). The future of digital agriculture: Technologies and opportunities. *IT Professional*, 22(1), 24-28. <https://doi.org/10.1109/MITP.2019.2963412>
- Rethlefsen, M. L., Kirtley, S., Waffenschmidt, S., Ayala, A. P., Moher, D., Page, M. J., Koffel, J. B., & PRISMA-S Group. (2021). PRISMA-S: An extension to the PRISMA Statement for Reporting Literature Searches in Systematic Reviews. *Systematic Reviews*, 10, Article 39. <https://doi.org/10.1186/s13643-02001542-z>
- Tzachor, A., Devare, M., King, B., Avin, S., & Ó hÉigearthaigh, S. (2022). Responsible artificial intelligence in agriculture requires systemic understanding of risks and externalities. *Nature Machine Intelligence*, 4(2), 104-109. <https://doi.org/10.1038/s42256-022-00440-4>

INFLUENCE OF POLICIES ON AGRICULTURAL DIGITALISATION UPTAKE IN THE EUROPEAN UNION

Delgado-Serrano, M.M. & Hurtado, A.R.

Department of Agriculture Economics, Universidad de Córdoba

mmdelgado@uco.es; es2rohuc@uco.es)

Background

The transformation of European agri-food systems in response to climate, environmental, and market pressures requires integrated approaches that bridge technological, institutional, and social domains. Digitalisation is a critical enabler of such systemic change, offering new capacities for resource efficiency, knowledge exchange, monitoring, and adaptive management. However, digitalisation uptake remains uneven among EU countries. This research explored how EU and national policy environments shape agricultural digitalisation in 15 EU and 3 non-EU countries. It examined how institutional settings, governance coherence, AKIS and policy instruments (particularly within the CAP Strategic Plans) enable or constrain digital transitions. The analysis assessed policy mechanisms that support or hinder agricultural digitalisation, identified governance arrangements and institutional capacities that shape the development of conducive digital ecosystems, and examined how AKIS policies and instruments influence farmers' uptake of digital technologies. It has been elaborated as part of the Horizon Europe CODECS project.

Design/methodology/approach

Using a mixed qualitative and comparative approach, it combined policy document analysis, a review of EU-funded projects, and semi-structured interviews with 101 experts from 18 European countries and EU institutions. This approach enabled the mapping of policy environments, the identification of governance patterns, and cross-country comparison of how structural factors, institutional arrangements, and policy frameworks impact digitalisation in agriculture and rural areas.

Findings

Results revealed that digitalisation is not an isolated technological process but a cross-cutting driver in agri-food systems, shaped by policy frameworks, farm structures, advisory networks, and data infrastructures. Persistent gaps in coordination, connectivity, skills, affordability, and data trust hinder its collective benefits. When governance mechanisms promote stability, legal certainty, and collaboration across ministries, sectors, and knowledge and innovation systems, digitalisation more effectively enhances economic viability, ecological performance, and social inclusion. The CAP also offers a significant but under-utilised opportunity to align digital and sustainability transitions. Together, these findings led to a comparative synthesis of national trajectories, grouping EU countries

into four categories based on their levels of agricultural digitalisation: frontrunners, advanced performers, growing performers, and early-stage performers.

Conclusions

This research demonstrates that agricultural digitalisation in Europe is fundamentally shaped by policy coherence, institutional capacity, and governance coordination rather than technology availability alone. The different combinations of these aspects explained the uneven situation across countries and classified countries into different clusters. Strengthening and coordinating policies that affect them will be critical to accelerating inclusive, sustainable, and effective digital transitions across European agri-food systems.

Keywords

Digital adoption; digitalisation policies; governance; digital transition.

References

- Hurtado, A.R. & Delgado-Serrano, M.M. (2025): Report on Policy Environments for Digitalisation in Europe. https://www.horizoncodecs.eu/wp-content/uploads/2025/10/D6-2_Report-on-PolicyEnvironments-for-Digitalisation-in-Europe_30092024-1.pdf

Plenary Session 4: Industry 4.0 and Sustainable Food Systems

Theme: AI in food processing, waste reduction, and circularity.

AI AND BLOCKCHAIN AS ENABLERS OF CIRCULAR ECONOMY IN BRAZILIAN AGRIBUSINESS: MODELS, BARRIERS, ENGAGEMENT STRATEGIES, AND TAX IMPLICATIONS FROM SOLUTION PROVIDERS' PERSPECTIVE

Sehnm, Simone, Dal Magro, Cristian Bau, Mazzioni, Sady

Management Department

simonesehnm_adm@yahoo.com.br, crisbau@unochapeco.edu.br

Background

Industry 4.0 technologies, such as Artificial Intelligence (AI) and Blockchain, offer unique opportunities to automate circular processes (e.g., reverse logistics of agricultural waste); ensure transparency and traceability (e.g., sustainable origin certification) (Silva *et al.*, 2024b); and enable new business models (e.g., carbon credit tokenization) (Sehnm *et al.*, 2023b). However, the adoption of these technologies in agribusiness towards circularity is still incipient and fragmented (Sehnm *et al.*, 2025), especially when considering tax aspects and regional particularities. The objective of this study is to analyze the potential of Artificial Intelligence (AI) and Blockchain to operationalize the circular economy in agribusiness, identifying models, barriers, engagement strategies, and associated tax aspects.

Design/methodology/approach

In-depth interviews were conducted with 15 key stakeholders in agribusiness to further explore the object of analysis of the proposed study: providers of AI and blockchain solutions for agribusiness. The interviews were transcribed in full, and then a preliminary reading was conducted to understand the participants' perceptions. The data analysis was conducted using thematic categorization. Findings: From the perspective of AI and blockchain solution providers for agribusiness, the challenge is not only technological, but also one of ecosystem modeling. The value proposition lies in the ability to transform raw data into circular assets. Despite the potential, there are structural obstacles associated with rural connectivity, resistance to sharing operational data due to fear of loss of competitiveness and scrutiny, the absence of global standards that allow different blockchains and AI to communicate throughout the production chain, and the high initial investment in sensors and digital infrastructure compared to profit margins pressured by commodities. Finally, the complexity of the Brazilian tax system is a critical factor in pricing and enabling solutions. Conclusions: AI and blockchain have high potential to operationalize the circular economy in Brazilian agribusiness,

through traceability, resource optimization, and new tokenized models, benefiting providers with recurring revenues in a market pressured by sustainability. Barriers such as infrastructure and training persist, requiring engagement strategies through partnerships and pilot projects. Tax aspects, anchored in the Lei do Bem (Law of Good) and emerging from the reform, represent levers for innovation, although more geared towards R&D than directly towards circularity. Well-positioned providers can lead this transition, integrating into export chains and capturing value in waste as a new renewable frontier.

Keywords

Circular Economy, Agribusiness, Artificial Intelligence, Blockchain, Sustainability

References

- Bechtsis, D., Tsolakis, N., Iakovou, E., & Vlachos, D. (2022). Data-driven secure, resilient and sustainable supply chains: gaps, opportunities, and a new generalised data sharing and data monetisation framework. *International Journal of Production Research*, 60(14), 4397-4417.
- Beske, P., Land, A., & Seuring, S. (2014). Sustainable supply chain management practices and dynamic capabilities in the food industry: A critical analysis of the literature. *International journal of production economics*, 152, 131-143.
- Cao, Y., Yi, C., Wan, G., Hu, H., Li, Q., & Wang, S. (2022). An analysis on the role of blockchain-based platforms in agricultural supply chains. *Transportation Research Part E: Logistics and Transportation Review*, 163, 102731.
- El Hathat, Z., Venkatesh, V. G., Sreedharan, V. R., Zouadi, T., Manimuthu, A., Shi, Y., & Srinivas, S. S. (2024). Leveraging greenhouse gas emissions traceability in the groundnut supply chain: Blockchain-enabled off-chain machine learning as a driver of sustainability. *Information Systems Frontiers*, 1-18.
- Elliot, T., Goldstein, B., & Charlebois, S. (2025). Over 6 billion liters of Canadian milk wasted since 2012. *Ecological Economics*, 227, 108413.
- Fischer, C., Hartmann, M., Reynolds, N., Leat, P., Revoredo-Giha, C., Henschion, M., ... & Gracia, A. (2009). Factors influencing contractual choice and sustainable relationships in European agri-food supply chains. *European Review of Agricultural Economics*, 36(4), 541-569.
- Flodin, C. L., Liljenfeldt, J., & Boonstra, W. J. (2025). Inclusion and understanding of farmers' perspectives in policies and policymaking for greenhouse gas removal. *Journal of Rural Studies*, 119, 103789.
- Gupta, S., Rikhtehgar Berenji, H., Shukla, M., & Murthy, N. N. (2023). Opportunities in farming research from an operations management perspective. *Production and Operations Management*, 32(6), 1577-1596.
- Madzík, P., Falát, L., & Pakdil, F. (2025). Exploring blockchain technologies in sustainable supply chains: unveiling the latent research topics using an AI approach. *International Journal of Production Research*, 1-27.
- Mangla, S. K., Luthra, S., Rich, N., Kumar, D., Rana, N. P., & Dwivedi, Y. K. (2018). Enablers to implement sustainable initiatives in agri-food supply chains. *International Journal of Production Economics*, 203, 379-393.
- Mangla, S. K., Börühan, G., Ersoy, P., Kazancoglu, Y., & Song, M. (2021). Impact of information hiding on circular food supply chains in business-to-business context. *Journal of Business Research*, 135, 1-18.

TECHNOLOGICAL SOLUTIONS OF AGRO 4.0 AND ITS IMPLICATIONS ON PERFORMANCE IN AGRICULTURAL PRODUCTION UNITS

Bertoglio, Oscar^a; Sehnem, Simone^b; Wegner, Douglas^c

^a *Management Department, Universidade do Oeste de Santa Catarina*

oscar.bertoglio@sertao.ifrs.edu.br

^b *Management Department, Universidade do Sul de Santa Catarina*

simonesehnem_adm@yahoo.com.br

^c *Management Department, Fundação Dom Cabral*

dwegner@fdc.org.br

Background

Despite significant advances in the digitalization of agribusiness across multiple production chains, structured analytical models for assessing the impacts of Industry 4.0 technologies on the performance of Agricultural Production Units (UPAs) remain scarce. UPAs exhibit high structural heterogeneity, connectivity limitations, scale asymmetries, and strong dependence on external infrastructure. This article addresses this gap by proposing and validating a theoretical-analytical model grounded in Production Theory, aiming to interpret the relationships among resources, decision-making processes, and outcomes within the production boundaries of UPAs.

Design/methodology/approach

The research adopted a qualitative design with two complementary validation stages. The first stage comprised 21 semi-structured interviews conducted with experts from academia, research institutions, technology providers, and field professionals who provide technical assistance to agricultural producers. The selection followed an intentional sampling strategy, prioritizing participants with demonstrated adherence to Industry 4.0 themes applied to agribusiness. The second stage comprised empirical research involving 20 Agricultural Production Units (UPAs) in the animal production sector (poultry and swine), combining in-person interviews with farmers, direct observation, and field notes. UPAs were intentionally selected under a post-adoption condition, ensuring that digital technologies were effectively in use, allowing the analysis of adoption processes, integration into production routines, and perceived performance impacts. Data collection was concluded based on theoretical and empirical saturation, as additional interviews no longer produced new analytical elements. The proposed CTP model (Context – Technological Solutions – Performance) was iteratively validated and refined through content analysis of the empirical material.

Findings

Technology adoption in UPAs is partial and selective, primarily involving sensing technologies, Internet of Things, robotics, management systems, and data analytics tools. Adoption is constrained by UPA-specific characteristics, access to technical assistance, recurring operational costs, local connectivity conditions, energy dependency, supply chain organization, and physical infrastructure. Performance improvements are not driven solely by technology deployment; rather, they depend critically on producers' cognitive and managerial maturity and their ability to transform data into informed productive, economic, and strategic decisions. The analysis revealed persistent asymmetries between technical–operational efficiency gains and economic performance outcomes. These findings motivated the incorporation of a cognitive dimension of technical progress into the model, reconceptualizing technology as an input that shifts the production function through enhanced interpretive capacity rather than exclusively through physical gains.

Conclusions

The validated and refined CTP theoretical-analytical model represents a substantive advance in understanding Agro 4.0 dynamics at the level of UPAs. By integrating contextual, technological, cognitive, and performance dimensions, the model provides a robust framework for future empirical research, improved farm management practices, and the formulation of innovation- and sustainability-oriented strategies and public policies in the agricultural sector.

Keywords

Agro 4.0; technology adoption; performance evaluation; agricultural production units; production theory

References

- Benitez, G. B., Ayala, N. F., Frank, A. G., & Romero, D. (2022). Industry 4.0 maturity model: Assessing the digital readiness of manufacturing companies. *International Journal of Production Economics*, 246, 108410. <https://doi.org/10.1016/j.ijpe.2022.108410>
- Bronson, K. (2022). Imagining the digital agricultural future: The role of human labor and social sustainability. *Journal of Rural Studies*, 93, 104–112. <https://doi.org/10.1016/j.jrurstud.2022.06.010>
- De Assis Lage, I., Braga, V., & Marques, C. S. E. (2024). Digital technologies, absorptive capacity and innovation in agribusiness. *Technology in Society*, 76, 102399. <https://doi.org/10.1016/j.techsoc.2023.102399>
- Gazolla, M., & Schneider, S. (2023). Coordination and autonomy in integrated livestock systems: Lessons from Southern Brazil. *Journal of Rural Studies*, 102, 112–123. <https://doi.org/10.1016/j.jrurstud.2023.01.014>
- Hackfort, S. (2023). Unlocking sustainability? The power of corporate lock-ins and how they shape digital agriculture in Germany. *Journal of Rural Studies*, 103, 103065. <https://doi.org/10.1016/j.jrurstud.2023.103065>
- Lioutas, E. D., Charatsari, C., & De Rosa, M. (2021). Digitalization of agriculture: A way to solve the food problem or a trolley dilemma? *Technology in Society*, 67, 101744. <https://doi.org/10.1016/j.techsoc.2021.101744>

- Rijswijk, K., Klerkx, L., Bacco, M., Bartolini, F., Bulten, E., Debruyne, L., Feindt, P. H., ... & Brunori, G. (2021). Digital transformation of agriculture and rural areas: A socio-cyber- physical system framework to support responsabilisation. *Journal of Rural Studies*, 85, 79–90. <https://doi.org/10.1016/j.jrurstud.2021.05.003>
- Uztürk, D., & Büyüközkan, G. (2024). Industry 4.0 technologies in smart agriculture: A review and a technology assessment model proposition. *Technological Forecasting and Social Change*, 208, Article 123640. <https://doi.org/10.1016/j.techfore.2024.123640>

LEVERAGING INDUSTRY 4.0 TECHNOLOGIES IN AUGMENTING CIRCULAR AND SUSTAINABLE AGRO-PROCESSING FOR FOOD LOSS AND WASTE REDUCTION IN AGRI-FOOD SYSTEMS

Othieno Abraham

Economics and Regional Sciences, Hungarian University of Agriculture and Life Sciences

abramieno@gmail.com

Background

Global challenges like climate change, population growth, and resource degradation demand a shift in agro-processing. This shift should prioritize circularity and sustainability, particularly by reducing food loss and waste (FLW).

Design/methodology/approach

This paper employs two methods to examine how new industrial technologies enhance the circularity, sustainability, and efficiency of agro-processing.

Findings

I4.0 technologies—such as Artificial Intelligence (AI), the Internet of Things (IoT), big data analytics, robotics, and blockchain—enable real-time oversight, optimize processes, and valorize waste in the agri-supply chain. But broad adoption is constrained by limited data, technological challenges, and regional differences.

Conclusions

This review points out research gaps. It highlights the need for strong models, combined policy-technology efforts, and partnerships to create a sustainable and circular agri-food sector.

Keywords

circular economy, industry 4.0, agro-processing, Food Loss and Waste, Agri-Food Systems, Sustainability

A COST-INTELLIGENCE DASHBOARD FOR BENCHMARKING OLIVE OIL MILL COOPERATIVES: AN INDUSTRY 4.0 APPROACH FOR STRATEGIC DECISION SUPPORT

Vicario-Modroño, V.^a; González-Bernal, M. J.^a; Caracuel-Sillero, M.^a; López-Domínguez, F.^a; Hidalgo-Fernández, A.^a; López-Nevado, J.^b; Santisteban-Vega, J. M.^b; López-Feria, S.^b; Luque-Del Castillo, A.^c; Ortiz-Arjona, J. L.^d; Sánchez-Zamora, P.^a; Gallardo-Cobos, R.^a

^a *Agricultural Economics Department, ETSIAM, University of Córdoba*

td2vimav@uco.es

^b *R+D+I Department, DCOOP, S.C.A.*

^c *Administration Department, DCOOP, S.C.A.*

^d *Information Technology Department, DCOOP, S.C.A.*

Background

Olive oil mill cooperatives face rising cost volatility and tighter competitiveness constraints, while being expected to strengthen sustainability-oriented performance through better resource use and governance. In practice, however, many cooperatives lack standardised and readily interpretable instruments that translate routine accounting records into operational benchmarks and actionable improvement priorities. To address this gap, this study presents a cooperative-oriented digital tool that operationalises Industry 4.0 principles, that is, data integration, automation, and decision support (Hassoun *et al.*, 2024; Myshko *et al.*, 2024). This tool aims to facilitate systematic cost benchmarking and managerial learning within the olive oil processing stage (Parra-López *et al.*, 2025).

Design/methodology/approach

The study develops and applies an interactive dashboard (Bennett & Loose, 2024) designed for the economic diagnosis of some olive oil mill cooperatives integrated into DCOOP. The tool integrates accounting data from groups 6 and 7 of the Spanish General Accounting Plan, automates classification using rubrics and keywords, and allocates general expenses based on income volume. It examines unit processing costs in €/kg of olive oil across seasons (2017/18-2023/24), as well as expenditure categories and specific cooperatives, enabling user-driven filters to enhance strategic cost management. Benchmarking is executed through two key methods: (i) peer comparison within three production-size strata (small, medium, and large); and (ii) comparison against a “Model Cooperative”, computed as the size-specific mean by season. To ensure privacy, all information is anonymised at the source to prevent reidentification.

Findings

The dashboard provides clear evidence of economies of scale with average unit costs consistently declining as size increases (Vicario *et al.*, 2025). A temporal analysis reveals a significant rise in costs during the 2022/23 and 2023/24 seasons, particularly among smaller cooperatives. In terms of cost composition, raw material purchases emerge as the primary cost driver across all size categories. Conversely, external services and personnel costs carry a comparatively heavier weight in smaller mills. The comparative module, contrasting cooperatives with the Model Cooperative, highlights significant structural overcosts, operational inefficiencies, and deviations arising from purchasing or outsourcing practices.

Conclusions

Overall, the proposed dashboard translates accounting data into a practical benchmarking framework that enhances transparency, comparability, and informed strategic decision-making within olive oil processing cooperatives. By enabling targeted diagnosis by season and cost category, this tool supports evidence-based decisions on investments, process optimisation, and capacity/structure alignment. As a result, it contributes to the development of more resilient and sustainable food systems (Vicario *et al.*, 2023).

Keywords

Benchmarking, Cooperatives, Digitalisation, Costing, Sustainability.

References

- Bennett, A.W.; Loose, S.M. (2024). User-Centered Development of an Online Dashboard Tool for Economic Sustainability for Small and Medium Enterprises. *Sustainability*, 16(2), 557. <https://doi.org/10.3390/su16020557>
- Hassoun, A., Jagtap, S.; Trollman, H.; García-García, G.; Duong, L.N.K.; Saxena, P.; Bouzembrak, Y.; Treiblmaier, H.; Parra-López, C.; Carmona-Torres, C.; Dev, K.; Mhlanga, D.; AïtKaddour, A. (2024). From Food Industry 4.0 to Food Industry 5.0: Identifying technological enablers and potential future applications in the food sector. *Comprehensive Reviews in Food Science and Food Safety*, 23(6), e370040. <https://doi.org/10.1111/1541-4337.70040>
- Myshko, A., Checchinato, F., Colapinto, C., Finotto, V., Mauracher, C. (2024). Towards the twin transition in the agri-food sector? Framing the current debate on sustainability and digitalisation. *Journal of Cleaner Production*, 452, 142063. <https://doi.org/10.1016/j.jclepro.2024.142063>
- Parra-López, C.; Abdallah, S.; Hassoun, A.; Jagtap, S.; García-García, G.; Hassen, B.; Trollman, F.; Carmona-Torres, C. (2025). Digital and Industry 4.0 technologies in olive farming and industry: Recent applications and future outlook. *Smart Agriculture Technology*, Vol 12, December, 101376. <https://doi.org/10.1016/j.atech.2025.101376>
- Vicario-Modroño, V.; Gallardo-Cobos, R.; Sánchez-Zamora, P. (2023). Sustainability evaluation of olive oil mills in Andalusia (Spain): a study based on composite indicators. *Environment, Development and Sustainability*, 25(7), 6363–6392. <https://doi.org/10.1007/s10668-022-02307-5>
- Vicario-Modroño, V.; López-Domínguez, F.; Caracuel-Sillero, M.; Hidalgo-Fernández, A.; López-Nevado, J.; López-Feria, S.; Gallardo-Cobos, R. (2025). Cost efficiency and competitiveness in olive oil cooperatives: a quantitative approach. XXII EXPOLIVA Scientific Technical Symposium

STAKEHOLDER ENGAGEMENT AS A DRIVER OF CIRCULAR ECONOMY ADOPTION IN BRAZILIAN AGTECHS

Tais Provensi^a, Simone Sehnem^{a,b}, Diógenes de Souza Bido^c

^a*Department of Management, Universidade do Oeste de Santa Catarina*
taisprovensi@gmail.com

^b*Department of Management, Universidade do Sul de Santa Catarina*
simonesehnem_adm@yahoo.com.br

^c*Department of Management, Universidade Presbiteriana Mackenzie*
diogenesbido@yahoo.com.br

Background

The transition to the circular economy has been identified as a strategic pathway to promote sustainability in agribusiness, particularly in light of challenges related to food security, the intensive use of natural resources, and increasing global environmental pressures. In this context, agtechs—startups specialised in the development of innovative solutions for the agricultural sector—emerge as central actors in the circular transformation of agribusiness. However, the implementation of circular practices is a complex process that requires coordination among multiple stakeholders and effective forms of engagement. This study aims to analyse the influence of the attributes of power, influence, dependence, and interest of strategic stakeholders on the relationship between stakeholder engagement and the adoption of circular economy practices in Brazilian agtechs.

Design/methodology/approach

Grounded in stakeholder theory, the study assumes that engagement is a key driver of circularity, while salience attributes operate as contextual conditions that may, or may not, strengthen this relationship. A quantitative approach was adopted, based on primary data collected through a survey administered to 155 agtechs operating across different segments of the agribusiness value chain in Brazil. The data were analysed using Partial Least Squares Structural Equation Modelling (PLS-SEM). Through this method, we tested a model in which engagement drives circular economy adoption, while stakeholder attributes act as boundary conditions.

Findings

The results reveal a strong, positive, and statistically significant effect of strategic stakeholder engagement on the adoption of the circular economy in agtechs. Conversely, the attributes of power,

influence, dependence, and interest did not exhibit significant moderating effects in this relationship. These findings suggest that, in technology-based startups at early stages of development, circular economy adoption depends more on the quality and intensity of engagement practices than on the perceived salience of stakeholders. Moreover, the firm's position within the agribusiness value chain proved to be a relevant contextual factor, reinforcing the ecosystem-based nature of the circular transition.

Conclusions

The study contributes theoretically by refining the application of stakeholder theory in the context of startups and emerging economies, demonstrating that salience attributes do not always function as central conditions for engagement effectiveness. From a practical perspective, the results indicate that managers and policymakers should prioritise the strengthening of engagement and collaboration mechanisms, rather than relying exclusively on strategies based on stakeholder hierarchisation, to foster the circular economy in agribusiness.

Keywords

Circular Economy, Stakeholder Management, Agtechs, Sustainable Production, Stakeholder Theory.

References

- Dutia, S. (2014). Agtech: Challenges and opportunities for sustainable growth. Available at SSRN 2431316.
- Ellen Macarthur Foundation. (2015). Rumo à Economia Circular: O Racional de Negócio para Acelerar a Transição. Recovered in 02 de junho, 2024, de https://archive.ellenmacarthurfoundation.org/assets/downloads/Rumo-%C3%A0-economia-circular_SumarioExecutivo.pdf
- Freeman, R. E. (1984). Strategic management: A stakeholder approach. Boston: Pitman/Ballinger.
- Freeman, R. E., Kujala, J., Sachs, S. & Stutz, C. (2017). Stakeholder engagement: practicing the ideas of stakeholder theory, in Freeman, R. E., Kujala, J. & Sachs, S. (Eds), Stakeholder Engagement: Clinical Research Cases, Springer, Zurich, pp. 1-12.
- Hair, J. F., Sarstedt, M., Ringle, C. M. & Mena, J.A. (2012). An assessment of the use of partial least squares structural equation modeling in marketing research. *Journal of the Academy of Marketing Science*, 40(3), 414-433. <https://doi.org/10.1007/s11747-011-0261-6>
- Hair, J. F. (2022). A primer on partial least squares structural equation modeling (PLS-SEM), 3rd ed., Sage, Thousand Oaks, CA.
- Kujala, J., Sachs, S., Leinonen, H., Heikkinen, A., & Laude, D. (2022). Stakeholder engagement: Past, present, and future. *Business & Society*, 61(5), 1136-1196. <https://doi.org/10.1177/00076503211066595>
- Mitchell, R. K., Agle, B. R., & Wood, D. J. (1997). Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts. *Academy of Management Review*, 22(4), 853-886. <https://doi.org/10.5465/amr.1997.9711022105>

AI ADOPTION AND INDUSTRY 4.0 BUNDLES IN THE EUROPEAN AGRI-FOOD BUSINESS ECOSYSTEM

González Polonio Luis^a, López-Cózar Cristina^b, Pindado Tapia Emilio^c

^a *Department of Agricultural Economics, Statistics and Business
Management, Polytechnic University of Madrid*
luis.gonzalez.polonio@upm.es

^b *Department of Agricultural Economics, Statistics and Business
Management, Polytechnic University of Madrid*
cristina.lopezcozar@upm.es

^c *Department of Agricultural Economics, Statistics and Business
Management, Polytechnic University of Madrid*
emilio.pindado@upm.es cristina.lopezcozar@upm.es

Background

We take it for granted that artificial intelligence (AI) is increasingly positioned as a key contributor to productivity, traceability, and sustainability in agri-food systems, including food processing and manufacturing contexts (Hassoun *et al.*, 2023; Semercioz-Oduncuoglu & Luning, 2025). Evidence on how AI spreads among agri-food companies, and whether it is adopted as part of the broader Industry 4.0 technology packages (cloud/data, IoT, cybersecurity) remains to be found. This study profiles the patterns of AI adoption and co-adoption in the European agri-food ecosystem and examines the innovation barriers reported by companies associated with AI adoption.

Design/methodology/approach

We used microdata from the Flash Eurobarometer 559 (European Commission, 2025) and focused on the companies classified in the survey within the agri-food business category, aggregating the observations between countries (N=517). AI adoption is measured as the stated use of artificial intelligence such as machine learning or large language models. Complementary technologies considered include cloud/big data, IoT/sensors, and cybersecurity. We estimate weighted adoption rates using post-stratification weights and calculate co-adoption indicators (AI and cloud, AI and IoT, AI and cybersecurity). To explore the factors associated with adoption, we estimate a survey-weighted logistic regression in which AI adoption is modelled based on firm size, participation in global value chains, and main barriers to innovation (skills, private financial resources, legal/administrative environment), controlling for EU-27 membership; The results are summarized using average marginal effects.

Findings

The survey-weighted adoption of AI in the agri-food category is 17.0% (95% CI: 12.3-21.8). Cloud/big data deployment is 41.4% (35.0-48.0), IoT/sensors 16.2% (11.8-20.6) and cybersecurity 27.8% (22.1-33.5). Co-adoption remains selective: IA&cloud 12.0% (7.9-16.0), AI&cyber 8.1% (4.8-11.5) and AI&IoT 2.7% (1.1-4.4%). The regression results show the lack of private financial resources as an innovation barrier associated with a predicted probability of AI adoption of +12.4 percentage points higher ($p=0.049$), which is consistent with the fact that adopters perceive stricter financing constraints. Other barriers and overall participation in the value chain are not statistically significant, while larger companies show a positive adoption gradient.

Conclusions

The diffusion of AI in the agri-food ecosystem is not negligible, but it remains limited, and integration with sensors/IoT is especially limited, suggesting that database capabilities remain a bottleneck, consistent with Industry 4.0 arguments in the literature on food processing and quality/digitalization (Hassoun *et al.*, 2023; Peres *et al.*, 2025). Policy and industry actions that combine (i) targeted financing instruments for digital investment, (ii) support for data and cloud readiness, and (iii) simplification of regulatory and administrative procedures to facilitate a larger-scale deployment of AI. Country-level inference within this category is limited by small sub-samples within the country; The results should be interpreted as clustered and cross-sectional associations.

Keywords

artificial intelligence; agri-food; Industry 4.0; technology co-adoption; innovation barriers five words maximum, use commas.

References

- European Commission, Brussels (2025). Flash Eurobarometer 559 (Startups, Scaleups and Entrepreneurship) (ZA9016; Version 1.0.0) [Data set]. GESIS, Cologne. <https://doi.org/10.4232/1.14590>
- Hassoun, A., Jagtap, S., Trollman, H., Garcia-Garcia, G., Abdullah, N. A., Goksen, G., ... & Lorenzo, J. M. (2023). Food processing 4.0: Current and future developments spurred by the fourth industrial revolution. *Food Control*, 145, 109507. <https://doi.org/10.1016/j.foodcont.2022.109507>
- Peres, F. A. P., Bondarczuk, B. A., Gomes, L. D. C., Jardim, L. D. C., Corrêa, R. G. D. F., & Baierle, I. C. (2025). Advances in food quality management driven by Industry 4.0: A systematic review-based framework. *Foods*, 14(14), 2429. <https://doi.org/10.3390/foods14142429>
- Semercioz-Oduncuoglu, A. S., & Luning, P. A. (2025). Industry 4.0 technologies in quality and safety control systems in food manufacturing: A systematic techno-managerial analysis on benefits and barriers. *Trends in Food Science & Technology*, 105144. <https://doi.org/10.1016/j.tifs.2025.105144>

DEVELOPMENT AND IMPLEMENTATION OF A DIGITAL TWIN FOR THE OPTIMIZATION OF POSTHARVEST PROCESSES IN THE CITRUS INDUSTRY

Martínez-Ruedas Cristina^a, Santos-Portillo Carolina^b, Jiménez-Jiménez Francisco^c, De la Haba María José^b, Castillejo-González Isabel^d

^aDepartment of Electric Technology, University of Cordoba
z42maruc@uco.es

^bDepartment of Bromatology and Food Technology, University of Cordoba
g52sanpc@uco.es

^cDepartment of Engineering, Universidad Miguel Hernández
francisco.jimenezj@umh.es

^dDepartment of Department Graphic Engineering and Geomatics, University of Córdoba
ilcasti@uco.es

Background

The citrus industry oriented toward fresh consumption faces significant challenges related to operational efficiency, waste reduction, and rising energy costs, within a context of increasing demands for quality, traceability, and sustainability[1]. This work presents the development and implementation of a digital twin applied to an orange handling and packaging facility located in Palma del Río (Córdoba, Spain), with the aim of analyzing and optimizing the postharvest process without interfering with real production operations [2].

Design/methodology/approach

The digital twin has been developed in the MATLAB/Simulink environment, structurally modeling the main stages of the industrial process—reception, selection, washing, grading, packaging, and cold storage—while integrating key variables such as product flows, machinery capacities, waste generation, and energy consumption. Unlike traditional supervision and data acquisition systems, the proposed model enables decoupled simulation of the real process, facilitating the evaluation of alternative operating scenarios, changes in production planning, and energy efficiency improvement strategies without risk to the plant.

Findings

The construction of the digital twin is based on a detailed technical characterization of the facility, a comprehensive machinery inventory, and the historical analysis of production and electricity consumption over several seasons. The results highlight the potential of the digital twin as a decision-support tool, enabling the identification of bottlenecks, the estimation of the energy impact of different operational configurations, and the reduction of waste associated with suboptimal process management.

Conclusions

This work demonstrates the feasibility of digital twins as an enabling technology for advanced digitalization in the agri-food industry, providing a practical and replicable approach to the optimization of postharvest processes in the citrus sector, and contributing to the development of more efficient and sustainable production systems.

Keywords

Digital twin; Agro-industrial systems; Process optimization; MATLAB/Simulink modeling; Citrus supply chain

Acknowledgments

This research is part of CITRIDATA Project: “Federated space for data, models, and services across the citrus value chain in the Autonomous Community of Andalusia”, University of Córdoba (TSI-100121-2024-107), funded by the Secretary of State for Digitalization and Artificial Intelligence and by the European Union - Next Generation EU. Recovery, Transformation and Resilience Plan.

References

- [1] E. E. M. Abdurrahman and G. Ferrari, “Digital Twin applications in the food industry: a review,” *Front. Sustain. Food Syst.*, vol. 9, p. 1538375, Apr. 2025, doi: 10.3389/fsufs.2025.1538375.
- [2] M. Lezoche, H. Panetto, J. Kacprzyk, J. E. Hernandez, and M. M. E. Alemany Díaz, “Agri-food 4.0: A survey of the supply chains and technologies for the future agriculture,” *Comput. Ind.*, vol. 117, p. 103187, May 2020, doi: 10.1016/j.compind.2020.103187.

AI APPLICATION FOR TOMATO-BASED PRODUCT CLASSIFICATION VIA ELECTRONIC NOSE

Víctor Fernández, Félix Meléndez, Yaiza Belacortu^a, Juan Álvaro Fernández^b

^a *Alianza Nanotecnología Diagnóstica*

victorfernandez@antd.eu, felixmelendez@antd.eu, yaizabelacortu@antd.eu

^b *Department of Electrical, Electronic and Automatic Engineering, University of Extremadura*

jalvarof@unex.es

Background

The food processing industry, particularly in tomato derivative production, requires rapid and objective quality control methods to ensure product consistency and safety. Traditional sensory analysis can be subjective and time-consuming. This study explores the application of Artificial Intelligence (AI) to data captured by “electronic noses”—arrays of chemical sensors designed to mimic biological olfaction. The primary objective is to evaluate and compare various machine learning algorithms to identify the most effective models for classifying tomato products and detecting industrial anomalies, such as burnt samples (Maillard reactions) or bacterial growth (fermentations). Similar approaches in recent literature have established E-nose technology as a robust tool for tracking ripeness and volatile organic compounds in fresh produce [1].

Design/methodology/approach

The dataset involved three primary categories: crushed tomato concentrate (14/16 and 28/30) and fried tomato, totaling 109 samples. Measurements included sensory responses from SGP30, SGP40, BME680, CCS811, and PID-A-H2 sensors [2]. Two data representation strategies were tested: using the “full curve” and extracting “characteristic values” (minimum absolute, delta, relative delta, and time-to-minimum). Four supervised learning models were implemented: Logistic Regression, Gaussian Naive Bayes, Support Vector Machines (SVM) with Gaussian kernel, and Multilayer Perceptron (MLP). The use of SVM with Radial Basis Function (RBF) kernels is widely recognized for handling the non-linear odor characteristics inherent in complex food matrices [3, 4].

Findings

Experimental results demonstrated that all tested models achieved 100% classification accuracy on the validation set, with extremely low training times. However, significant performance differences emerged regarding anomaly detection. Logistic Regression and MLP failed to identify unknown samples, incorrectly assigning them to known classes with high confidence. In contrast, Gaussian Naive Bayes and SVM with a Gaussian kernel successfully detected burnt samples and unknown

inputs by providing appropriate probability scores. Recent studies confirm that SVM-based models are particularly effective for odor classification in food safety due to their superior generalization capabilities [5, 6]. Furthermore, training with the full sensor curve offered a slight performance advantage in recognizing atypical patterns compared to using reduced characteristic values.

Conclusions

The study concludes that tomato-based products are easily classifiable using AI models, provided the sensors deliver repeatable signals. SVM and Gaussian Naive Bayes emerged as the superior methods due to their robust ability to handle outliers and unknown samples with minimal computational overhead. These results align with high-impact research suggesting that the primary challenge lies not in algorithmic complexity, but in selecting sensors that maintain long-term stability and minimize signal drift [3, 7]. While characteristic value extraction simplifies data, utilizing the full curve is recommended for industrial environments where anomaly detection is critical for maintaining quality standards. This work is funded by Junta de Extremadura with European funding under Decreto 57/2023 (ref. IDA323-0003-3).

Keywords

Electronic nose, Machine Learning, Food Quality Control, Tomato Derivatives, Anomaly Detection.

References

- [1] A. Müller, J. Schmidt, and L. Fischer, "Integrating Sensor Data, Laboratory Analysis, and Computer Vision in Machine Learning-Driven E-Nose Systems for Predicting Tomato Shelf Life," *Sensors*, vol. 25, no. 13, p. 3936, Jul. 2025.
- [2] F. Meléndez *et al.*, "Design of a Multisensory Device for Tomato Volatile Compound Detection Based on a Mixed Metal Oxide-Electrochemical Sensor Array and Optical Reader" *Micromachines*, vol. 14, no. 9, Sep. 2024.
- [3] C. Sharma and U. Sarma, "Classification of electronic nose data with support vector machines" *Sensors and Actuators B: Chemical*, vol. 107, no. 2, pp. 730-737, Jun. 2005.
- [4] X. Li *et al.*, "Research on non-destructive detection model of tomato fruit quality based on electrical properties and machine learning algorithms," *Scientific Reports*, vol. 15, no. 1, p. 12605, Jan. 2025.
- [5] S. Cervellieri *et al.*, "A Comprehensive Review on Sensor-Based Electronic Nose for Food Quality and Safety," *Foods*, vol. 13, no. 18, p. 12301, Sep. 2024.
- [6] J. Zhang, "Classification of Electronic Nose Data Using the Least Squares Support Vector Machine," *Journal of Physics: Conference Series*, vol. 1894, no. 1, p. 012080, Aug. 2025.
- [7] R. G. Brereton and G. R. Lloyd, "Support Vector Machines for classification and regression," *Analyst*, vol. 135, no. 2, pp. 230-267, 2010.

ARTIFICIAL INTELLIGENCE IN AGRI-FOOD SYSTEMS: TRANSFORMING FOOD SAFETY, QUALITY, AND SUSTAINABILITY ACROSS THE SUPPLY CHAIN

Mohammad Khalid Rashidi^a, Hamid Salari^b, and Mohammad Hasham Rashidi^c

^a *Agronomy, Kabul University*
khalid.rashidi2010@gmail.com

^b *Horticulture, Kabul University*
h.salari@yahoo.com

^c *Management and Business Administration, Ghazni University*
rashidi.hasham2010@gmail.com

Background

Agri-food systems face mounting pressures from climate change, population growth, and resource constraints, rendering conventional management approaches increasingly inadequate. Artificial Intelligence (AI) offers transformative potential through data-driven, predictive, and automated solutions across the value chain; however, integrated systems-level analyses remain limited.

Methodology

This study conducts a structured, systematic literature review combined with a comparative meta-synthesis of peer-reviewed empirical research across agricultural sciences, food engineering, computer science, and data analytics. AI methodologies examined include machine learning (supervised and unsupervised), deep learning (e.g., convolutional neural networks), computer vision, reinforcement learning, predictive modeling, and IoT-enabled monitoring systems. Applications are categorized into four domains: (1) precision agriculture and climate-smart crop management; (2) intelligent post-harvest and food processing systems; (3) AI-driven supply chain optimization and traceability; and (4) data-enabled personalized nutrition. Studies are evaluated based on predictive performance, scalability, sustainability impact, technological readiness, and implementation feasibility.

Findings

AI significantly enhances predictive accuracy in yield forecasting, pest and disease detection, soil health assessment, and irrigation management, improving resource-use efficiency and climate resilience. In post-harvest and processing contexts, deep learning-based computer vision systems enable automated quality assessment, contamination detection, and loss reduction. AI-integrated

supply chain platforms strengthen transparency, demand forecasting, logistics coordination, and risk mitigation. Moreover, data-driven models facilitate personalized nutrition by integrating agricultural production and health analytics. Nevertheless, widespread adoption is constrained by fragmented data ecosystems, limited interoperability, infrastructure disparities, high implementation costs, cybersecurity and ethical concerns, regulatory uncertainty, and insufficient interdisciplinary capacity. Large-scale real-world validation remains limited.

Conclusions

AI holds substantial potential to shift agri-food systems from reactive management toward predictive, adaptive, and autonomous frameworks. Realizing sustainable and equitable transformation requires standardized data governance, interoperable digital infrastructures, transparent and explainable AI models, and enhanced collaboration among academia, industry, and policymakers. This study offers an integrated synthesis of current advancements, identifies critical research and technological gaps, and outlines strategic pathways for accelerating AI-driven innovation in resilient agri-food systems.

Keywords

Agri-Food Systems, Artificial Intelligence (AI), Food Safety and Quality, Machine Learning, Supply Chain Sustainability.

Note

A total of 100 peer-reviewed references published between 2022 and 2026 were systematically reviewed and incorporated into the development of this manuscript. Ten representative references are presented below.

References

- Abass, T., Itua, E. O., Bature, T., & Eruaga, M. A. (2024). Concept paper: Innovative approaches to food quality control: AI and machine learning for predictive analysis. *World Journal of Advanced Research and Reviews*, 21(3), 823-828. <https://doi.org/10.30574/wjarr.2024.21.3.0719>
- Abdulameer, L., Al-Khafaji, M. S., Al-Awadi, A. T., Al Maimuri, N. M., Al-Shammari, M., & Al-Dujaili, A. N. (2025). Artificial Intelligence in Climate-Resilient Water Management: A Systematic Review of Applications, Challenges, and Future Directions. *Water Conservation Science and Engineering*, 10(1), 44. <https://link.springer.com/article/10.1007/s41101-025-00371-2>
- Adil, M., Fan, Y., Xiao, X., Zou, Y., Ren, J., & Faisal Manzoor, M. (2026). Artificial Intelligence and Machine Learning: Shaping the Future of Food Safety, Quality Control, Traceability Systems, and Nutrition. *Food Reviews International*, 1-32. <https://doi.org/10.1080/87559129.2025.2612241>
- Agrawal, K., & Kumar, N. (2023, November). Artificial Intelligence Innovations: Inception of new horizons in food processing sector. In *2023 IEEE Silchar Subsection Conference (SILCON)* (pp. 1-8). IEEE. <https://doi.org/10.1109/SILCON59133.2023.10404183>
- Agrawal, K., Goktas, P., Kumar, N., & Leung, M. F. (2025). Artificial intelligence in personalized nutrition and food manufacturing: a comprehensive review of methods, applications, and future directions. *Frontiers in Nutrition*, 12, 1636980. <https://doi.org/10.3389/fnut.2025.1636980>

- Aijaz, N., Lan, H., Raza, T., Yaqub, M., Iqbal, R., & Pathan, M. S. (2025). Artificial intelligence in agriculture: Advancing crop productivity and sustainability. *Journal of Agriculture and Food Research*, 101762. <https://doi.org/10.1016/j.jafr.2025.101762>
- Ali, M., Anas, M., Umar, U. M., ul Hasnain, M. S., Younas, A., Majeed, A., & Ashraf, S. (2025). Advances and Applications of AI Modeling in Crop Science; A Comprehensive Review. *Haya Saudi J Life Sci*, 10(10), 529-540.
- Akkem, Y., Biswas, S. K., & Varanasi, A. (2024). Streamlit-based enhancing crop recommendation systems with advanced explainable artificial intelligence for smart farming. *Neural Computing and Applications*, 36(32), 20011-20025. <https://link.springer.com/article/10.1007/s00521-024-10208-z>
- Altayeb, J. M., Eleyan, H., Wishah, N. D., Elmahmoum, A. E., Khalil, A. J., Abu-Nasser, B. S., & Abu-Naser, S. S. (2024). AI-driven innovations in agriculture: Transforming farming practices and outcomes. <https://philpapers.org/rec/ALTAII>
- Amudha, S., & Kumar, U. K. (2025). The EXPLAINABLE RECOMMENDATION SYSTEM FOR SMART AGRICULTURE FARMING WITH IMPROVED FOOD PRODUCTIVITY: EXPLAINABLE RECOMMENDATION SYSTEM FOR SMART AGRICULTURE FARMING WITH IMPROVED FOOD PRODUCTIVITY. *SGS-Engineering & Sciences*, 1(3). <https://orcid.org/0000-0002-5859-0352>

THE POTENTIAL OF DIGITAL TECHNOLOGIES FOR CLIMATE CHANGE ADAPTATION AND MITIGATION IN AGRICULTURE

Carlos Parra-López^a, Saker Ben Abdallah^b, Guillermo Garcia-Garcia^c, Abdo Hassoun^d,
Pedro Sánchez-Zamora^e, Hana Trollman^f, Sandeep Jagtap^{g, h}, Carmen Carmona-Torres^{i, a}

^a Department of Agrifood System Economics, Institute of Agricultural and Fisheries Research
and Training (IFAPA), Centre 'Camino de Purchil', s/n, 18004 Granada, Spain

carlos.parra@juntadeandalucia.es

^b Department of Agricultural Engineering, Technical University of
Cartagena, Paseo Alfonso XIII, 48, 30203 Cartagena, Spain

saker.benabdallah@inrat.ucar.tn

^c Department of Chemical Engineering, Faculty of Sciences, University of
Granada, Avda, Fuentenueva, s/n, 18071 Granada, Spain

guillermo.garcia@ugr.es

^d Sustainable AgriFoodtech Innovation & Research (SAFIR), Arras, France

a.hassoun@saf-ir.com

^e Department of Agricultural Economics, Higher Technical School of Agricultural and Forestry
Engineering (ETSIAM), University of Cordoba, Rabanales University Campus, 14071 Cordoba, Spain

pedro.sanchez@uco.es

^f Department of Work, Employment, Management and Organisations, School of Business,
University of Leicester, Brookfield, 266 London Road, Leicester, United Kingdom

ht203@leicester.ac.uk

^g Department of Mechanical Engineering Sciences, Faculty of Engineering, Lund
University, Ole Römers Väg 1, M-Building, 22363 Lund, Sweden

sandeep.jagtap@tlog.lth.se

^h Sustainable Manufacturing Systems Centre, Cranfield University, Cranfield MK 43 0AL, United Kingdom

ⁱ Institute of Regional Development, University of Granada, Rector López Argüeta, s/n, 18071 Granada, Spain

mccarmonat@ugr.es

Background

Agriculture faces the pressing challenge of meeting rising global food demand while operating under increasingly adverse environmental conditions. Climate change intensifies these pressures by exacerbating temperature extremes, altering precipitation patterns, and increasing the frequency of extreme weather events. At the same time, agriculture contributes to climate change through greenhouse gas emissions from soil management, livestock production, and land-use practices. In recent years, digital technologies have emerged as promising tools to enhance both climate change adaptation and mitigation. These technologies offer opportunities to optimise resource use, improve monitoring, aid decision-making, and support more resilient and sustainable production systems. This study provides a comprehensive overview of the current landscape of digital agriculture and examines how digital innovations can support climate-resilient farming.

Design/methodology/approach

We conducted a comprehensive literature review to synthesise existing knowledge on the relationship between climate change and agriculture, with a specific focus on adaptation and mitigation strategies. Academic publications, policy reports, and technological assessments were analysed to identify the range of digital technologies currently deployed in agricultural systems and to evaluate their effectiveness. We also explored barriers to adoption and the enabling conditions necessary for widespread implementation. By integrating insights across technological, environmental, and socio-economic dimensions, our study provides a holistic understanding of the opportunities and constraints shaping the future of digital agriculture.

Findings

We identified a broad portfolio of digital technologies with high potential to enhance agricultural adaptation and mitigation. For instance, remote sensing systems enable real-time crop and soil monitoring, artificial intelligence improve pest detection and tracking, the Internet of Things enables precision fertiliser and irrigation management, nanotechnology can be used for soil enhancement, robots support targeted spraying and field operations, blockchain facilitates greater transparency in soil management and supply chains, and big data supports predictive modelling of water shortages, pest outbreaks, and yield variability. These innovations collectively promote more efficient use of resources like water and fertiliser, reduce greenhouse gas emissions, and support carbon sequestration. However, several constraints limit their adoption, including high initial investment costs, technological complexity, inadequate digital infrastructure, and concerns regarding privacy, data governance, and the environmental footprint of digital systems.

Conclusions

Digital technologies hold significant promise for advancing sustainable and climate-resilient agriculture, but realising this potential requires overcoming substantial barriers. Strategic actions are needed, including investments in digital infrastructure, farmer training, financial incentives, and governance frameworks that promote responsible and equitable technology use. Solutions must be scalable and adapted to local conditions to ensure global applicability. We also underscore the urgency of multi-stakeholder collaboration among farmers, policymakers, researchers, and technology providers to create enabling environments for innovation. By addressing existing challenges,

digital agriculture can play a transformative role in shaping a more sustainable and resilient future for global food systems.

Keywords

climate change, digital technologies, 4.0, agriculture, food.

ARTIFICIAL INTELLIGENCE IN MELISSOPALYNOLOGY VALIDATION OF AN AUTOMATED MICROSCOPY SYSTEM FOR POLLEN QUANTIFICATION IN HONEY

Eduardo Gutiérrez de Ravé Jr., Salud Serrano, Inmaculada Rodríguez

Food Science and Technology, University of Córdoba (Spain)

V52gusee@uco.es; bt2sejis@uco.es; v62rodem@uco.es

Background

Melissopalynological analysis is the reference method for determining the botanical and geographical origin of honey and plays a crucial role in authenticity control, traceability, and quality assessment. However, the classical method based on manual microscopic counting is labour-intensive, time-consuming, and dependent on operator expertise. In the context of increasing demands for standardization, reproducibility, and digital transformation in agrifood laboratories, automated systems based on artificial intelligence (AI) represent a promising alternative. The present study aimed to perform an internal validation of an automated melissopalynological system (Honey AI) by comparing its performance with the classical manual method accepted by the International Honey Commission (IHC), focusing on the determination of pollen percentages for botanical discrimination.

Design/methodology/approach

A paired method-comparison study was conducted using identical physical samples analyzed by both systems. The study included 112 honey samples (103 unifloral and 9 polyfloral) and 63 corbicular pollen samples. All samples were prepared following identical laboratory procedures (sample weight, dissolution volume, centrifugation conditions, sediment volume, and slide mounting technique). The only methodological difference was the addition of safranin staining in the manual method to enhance visualization.

An internal acceptance criterion was established in accordance with the principle of fitness for intended use: a maximum acceptable absolute difference of $\pm 5\%$ in pollen percentage, with at least 95% of samples meeting this threshold. Statistical analysis included descriptive statistics (mean and standard deviation), paired Student's t-test ($\alpha = 0.05$), and Bland–Altman analysis to evaluate agreement, systematic bias, and limits of agreement.

Findings

Across unifloral honey samples, the global mean pollen percentage was 22.55% for Honey AI and 26.29% for the manual method, with an overall mean difference of -2.78% , indicating a slight negative bias within the predefined $\pm 5\%$ acceptance limit. Student's t-test showed no statistically significant

differences between methods ($p > 0.05$), demonstrating the absence of systematic inferential discrepancies.

Bland–Altman analysis confirmed adequate agreement, with a mean bias close to zero and analytically acceptable limits of agreement. No proportional bias or measurement-level dependency was observed. For individual botanical types (e.g., *Citrus*, *Lavandula stoechas*, *Castanea sativa*, *Echium* sp., *Rosmarinus*), mean differences generally remained below 5%, with only isolated cases of larger deviations attributable to sample-specific variability.

In polyfloral samples, both systems consistently identified the absence of a dominant pollen type (>45%), confirming concordant classification. In corbicular pollen samples, the predominant pollen type was consistently identified by both systems, although the manual method reported a higher number of minor pollen types due to its inclusion of taxa below 3% relative frequency, whereas Honey AI applies a reporting threshold. Despite this difference in reporting criteria, the percentages of predominant pollen types showed strong concordance.

Conclusions

The automated Honey AI system demonstrated analytical equivalence to the classical manual melissopalynological method for determining pollen percentages in honey and corbicular pollen samples. Observed differences were minor, within the predefined acceptance criteria, and largely attributable to differences in reporting thresholds rather than analytical inaccuracies.

These results support the internal validation of the AI-based system as a reliable, reproducible, and efficient alternative for routine laboratory use. The implementation of automated microscopy combined with artificial intelligence offers significant advantages in terms of standardization, scalability, and reduction of operator-dependent variability, without compromising analytical accuracy in botanical origin determination.

Keywords

honey, corbicular pollen, melissopalynology, artificial intelligence, validation.

References

- Von der Ohe, W., Persano Oddo, L., Piana, M.L., Morlot, M., & Martin, P. (2004). Harmonized methods of melissopalynology. *Apidologie* 35 (Suppl.), S18–S25.
- Ricciardelli d'Albore, G. (1998). Mediterranean melissopalynology. Università degli Studi, Perugia.
- Zander, E. (1935, 1937, 1941, 1949, 1951). Beiträge zur Herkunftsbestimmung bei Honig (series).
- Feás, X. et al. (2010). Characterization of artisanal honey produced on the Northwest of Portugal by melissopalynological and physico-chemical data. *Food and Chemical Toxicology* 48, 3462–3470.

DESIGN OF A MULTISENSORY AI-POWERED DEVICE FOR RIPENESS MONITORING AND EARLY DETECTION OF BOTRYTIS CINEREA IN TOMATOES

Félix Meléndez^a, Yaiza Belacortu^a, Ramiro Sánchez^b, J. Álvaro Fernández^c, Jesús Lozano^c

^a *Alianza Nanotecnología Diagnóstica, San Sebastián de los Reyes, Madrid, Spain*

felixmelendez@antd.eu, yaizabelacortu@antd.eu

^b *Centro de Investigaciones Científicas y Tecnológicas de Extremadura (CICYTEX), Badajoz, Spain*

ramiro.sanchez@juntaex.es

^c *Departamento de Ingeniería Eléctrica, Electrónica y Automática, Universidad de Extremadura, Badajoz, Spain*

jalvarof@unex.es, jlozano@unex.es

Background

Insufficient control of tomato ripening and infections by fungal pathogens, specifically *Botrytis cinerea*, represent a critical challenge in global agriculture, leading to substantial economic losses during both preharvest and post-harvest stages. Traditional diagnostic methodologies for assessing fruit quality and phytosanitary status are often labor-intensive, expensive, and require specialized centralized laboratories. Aroma has long been recognized as a primary indicator of maturity and health in tomatoes, as volatile profiles shift significantly during physiological changes [1]. To address the need for rapid, in-situ assessment, this study presents “TOMATO-NOSE,” a portable, multi-sensory system that leverages Artificial Intelligence (AI) and electronic nose (E-nose) technology for the real-time, non-destructive monitoring of fruit health. This approach builds upon the foundational principles of biomimetic olfaction, which aim to replicate human sensory perception through sensor arrays and classification algorithms [2].

Design/methodology/approach

The TOMATO-NOSE prototype integrates a sophisticated hybrid sensor array comprising 13 elements, specifically 12 electrochemical (EC) sensors and a metal oxide semiconductor (MOX) sensor. This olfactory core is complemented by an integrated optical reader designed for lateral flow devices (LFD), allowing for the dual-mode verification of biological markers. The system’s architecture includes a custom-developed electronic board for signal conditioning and a smartphone application that facilitates device control, real-time data visualization, and cloud-based storage. For experimental validation, Roma tomatoes were analyzed across different maturity stages (from stage 4 to 6) and subjected to controlled *B. cinerea* inoculations. Data processing was conducted using Principal Component Analysis (PCA), an unsupervised Machine Learning technique employed to reduce the

high dimensionality of the sensor array responses and identify distinctive aromatic volatile organic compound (VOC) patterns, a method previously proven effective for maturity evaluation [3].

Findings

Experimental results demonstrated the system's high sensitivity to physiological changes in the fruit. The device successfully discriminated between different ripeness levels, with the first two principal components of the PCA explaining over 67% of the total data variance. Most significantly, the TOMATO-NOSE achieved early detection of *B. cinerea* infection only 48 hours after inoculation. At this stage, the fungal growth is entirely invisible to the human eye, yet the sensor array captured significant shifts in the VOC profile. In these early detection trials, the PCA models explained a remarkable 98.8% of the total variance, providing a clear and robust separation between healthy, wounded, and infected samples. The integrated LFD optical reader further confirmed these olfactory findings by identifying specific pathogen antigens, providing a definitive molecular cross-check to the AI-driven results.

Conclusions

The results confirm that TOMATO-NOSE is a robust and user-friendly tool for precision agriculture. By combining AI-driven olfactory sensing with visual antigen confirmation, the device empowers farmers and warehouse managers to optimize harvesting schedules and implement targeted disease management strategies. This integrated approach significantly reduces reliance on broad-spectrum chemical pesticides and minimizes post-harvest waste. Future research will focus on field-testing in greenhouse environments and optimizing the sensor response cycles to reduce total acquisition time, further enhancing the tool's portability and immediate decision-making capabilities in industrial settings.

Keywords

Electronic nose, Tomato ripeness, *Botrytis cinerea*, Precision agriculture, Machine learning.

References

- [1] C. Distefano *et al.*, "Aroma Volatiles in Tomato Fruits: The Role of Genetic, Preharvest and Post-harvest Factors," *Agronomy*, vol. 12, no. 376, 2022. DOI: 10.3390/agronomy12020376
- [2] J. W. Gardner and P. N. Bartlett, "A Brief History of Electronic Noses," *Sensors and Actuators B: Chemical*, vol. 18, pp. 210-211, 1994. DOI: 10.1016/0925-4005(94)87085-3
- [3] A. Hernández Gómez *et al.*, "Evaluation of Tomato Maturity by Electronic Nose," *Computers and Electronics in Agriculture*, vol. 54, pp. 44-52, 2006. DOI: 10.1016/j.compag.2006.07.002

COMPACT MULTISENSORY PLATFORM INTEGRATING ELECTRONIC NOSE AND ELECTRONIC EYE FOR TOMATO PASTE ANALYSIS

Víctor González, Juan Álvaro Fernández, Patricia Arroyo, Jesús Lozano

Electrical, electronic, and automatic engineering, University of Extremadura/Industrial Engineering School

victorgb@unex.es, jalvarof@unex.es, parroyoz@unex.es, jesuslozano@unex.es)

Background

In recent years, electronic senses have been developed for sensory evaluation of quality parameters such as odor, taste, and color. By applying data fusion techniques, combining information from these devices can provide more accurate results than using them individually.

Most research focuses on data fusion strategies, typically using commercial or modular hardware, which limits full integration into a single device. Some portable systems have combined two or three technologies, and several patents and companies offer related solutions. However, truly integrated, miniaturized, and portable multisensory hardware remains limited, highlighting the need for compact systems that merge these technologies into one platform.

Design/Methodology/approach

The multisensory system presented in this work is shown in Figure 1. The device includes a USB port for charging a battery and for serial communication with a PC. Communication with peripherals is managed by an STM32WB55 microcontroller, which also integrates a Bluetooth core. The microcontroller communicates with several sensors via I2C. These include five MOX gas sensors and one spectrometer. Four MOX sensors allow hotplate temperature modulation: BME688 and ENS160 through programmable temperature registers, and ZMOD4410 and SGP40 by adjusting the hotplate voltage using a DAC.

Color differences are measured using an AS7341 spectrometer, which detects 11 channels, covering the visible and near-infrared ranges. To ensure consistent illumination, a pair of white LEDs is controlled by PWM using an NMOS transistor circuit, where brightness depends on the applied pulse width.

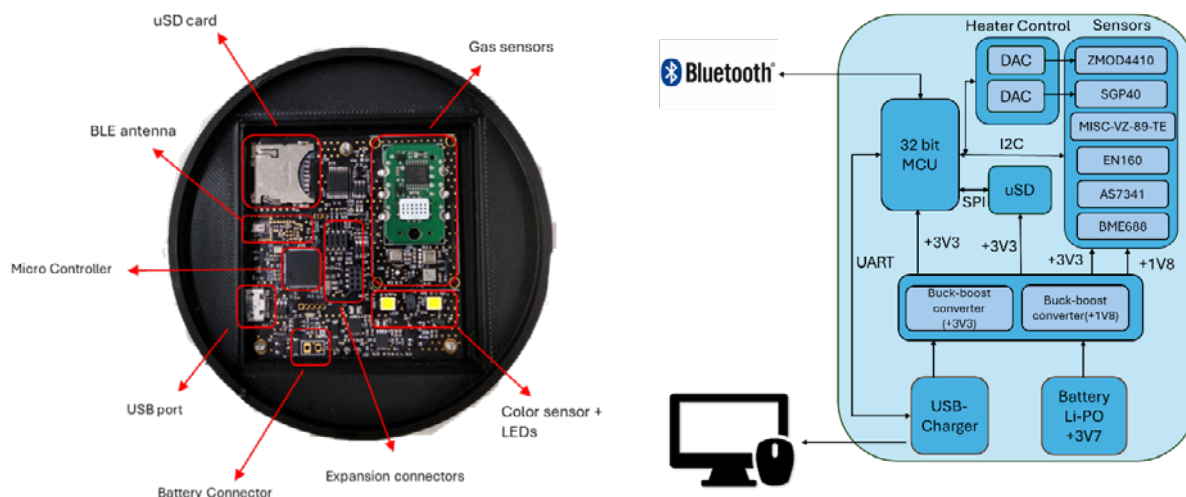


Figure 1. Multisensory device. Multisensory device prototype (a). Multisensory block diagram (b).

Three samples of tomato paste are measured with Maillard reactions. Being the following:

- CB 36/38 (7:46). Increased Maillard reaction.
- CB 36/38 (8:16). Decreased Maillard reaction.
- CB 36/38 (8:24). More decreased Maillard reaction.

Measurements were carried out, allowing 2 minutes of adsorption and 30 minutes of desorption, making four consecutive temperature sweeps from 400 °C to 200 °C in a triangular waveform for the measurements.

Findings

Figure 2 shows results from some sensors used; as can be seen, ENS160 (R1) is capable of differentiating between maillard reaction, changing not only the amplitude of the sensor's response but also the waveform. On the other hand, the spectrometer is also capable of detecting differences between tomato samples. Being the highest Maillard reaction, darker than the decreased ones.

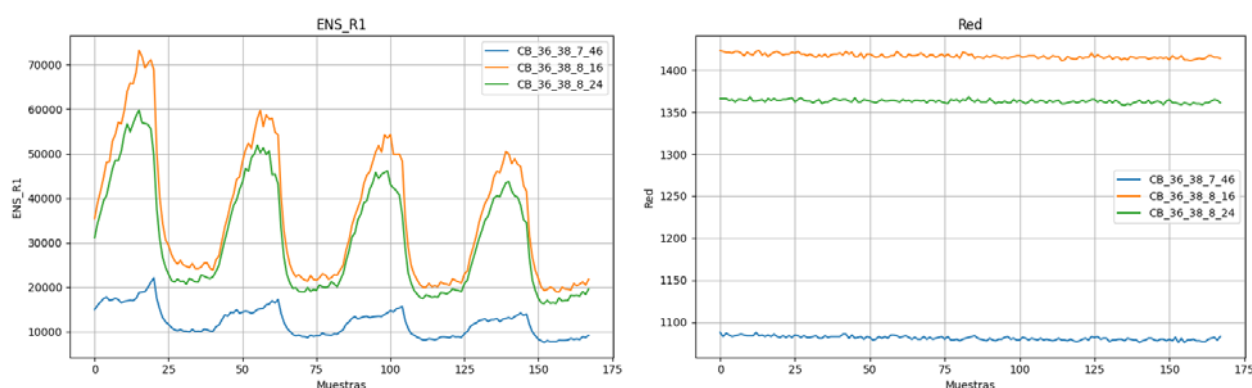


Figure 2. Response of ENS160 (R1) (left), and response of AS7341 (red channel) (Right) to tomato paste samples.

Conclusions

This work introduces an integrated multisensory device combining a temperature-modulated electronic nose with modern digital MOX sensors and also an electronic eye-based spectrometer for color analysis. The system was evaluated using tomato paste samples subjected to different Maillard reaction stages. The electronic nose results revealed clear distinctions among samples, not only in signal amplitude but also in waveform patterns.

Additionally, the spectrometer detected color variations, with the first sample exhibiting a darker tone compared to the later ones. Overall, the device's performance and the integration of advanced MOX sensors with simultaneous color measurement constitute a significant step forward in the development of compact multisensory systems.

Keywords

Portable sensing system, *Multisensor device*, *Electronic nose*, *Electronic eye*, *sensor fusion hardware*.

AI-DRIVEN DROUGHT FORECASTING IN DEHESA GRASSLANDS USING LSTM

Vanwalleghem, Tom

Department of Agronomy, ETSIAM, Universidad de Córdoba

Ag2vavat2uco.es

Background

Drought is one of the major meteorological disasters that impacts on agricultural production (Lazoglou *et al.*, 2024). In Spanish grasslands, agricultural insurance schemes use remote sensing observations of NDVI or vegetation greenness to quantify payments to farmers. Payments for drought damage due to reduced grassland production occur when NDVI is below historical means, with different loss levels depending on the premium paid.

Objectives

The objective of this paper is to predict NDVI time series in Mediterranean dehesa grasslands using long short-term memory (LSTM) neural networks at different lead times, and compare the performance in different zones of Spain.

Approach

We use rainfall and potential evapotranspiration as predictors, derived from Open-meteo. NDVI was obtained from Sentinel-2 through Google Earth Engine at 10m resolution. The training and validation of the NDVI forecast models were performed from 21/07/2015 to 28/2/2025, using a 70-30% data split. We obtained Nash-Sutcliffe efficiency of 0,981 – 0,984 and MSE values of 0,004-0,012. We obtained similar forecast performance in different areas. The LSTM-based predictions significantly improved the conventional random forest model (Milazzo *et al.*, 2024), with NSE between 0,578-0,88 for 7 and 30 days lead time. In the random forest models, predictions at 7 days are more accurate and better forecast the negative effect of drought on vegetation dynamics than 30 days, but in the LSTM-based predictions the difference is minor. This suggests that LSTM is a promising technique for forecasting agricultural drought incidence.

Conclusions

The LSTM-based models achieved very high predictive performance (NSE = 0.981–0.984; MSE = 0.004–0.012) and produced consistent NDVI forecasts across sites along the rainfall gradient. Compared with Random Forest, LSTM substantially improved drought forecasting skill—particularly at

longer lead times—highlighting the potential of AI-based approaches for early detection of agricultural drought impacts on vegetation dynamics.

Keywords

Artificial intelligence, Vegetation dynamics, Sentinel-2, Machine learning, Drought monitoring.

References

- Lazoglou, G., Papadopoulos-Zachos, A., Georgiades, P. *et al.* (2024). Identification of climate change hotspots in the Mediterranean. *Sci Rep* 14, 29817. <https://doi.org/10.1038/s41598-024-80139-1>
- Milazzo, F., Brocca, L., & Vanwalleggem, T. (2024). NDVI Prediction of Mediterranean Permanent Grasslands Using Soil Moisture Products. *Agronomy*, 14(8), 1798. <https://doi.org/10.3390/agronomy14081798>

TWIN OLIVE: A DIGITAL TWIN FRAMEWORK TO IDENTIFY CLIMATIC DRIVERS OF OLIVE YIELD

Ignacio J. Lorite, José M. Cabezas, José O. Alza

IFAPA – Centro Alameda del Obispo

ignacioj.lorite@juntadeandalucia.es, josem.cabezas@juntadeandalucia.es, joseo.alza@juntadeandalucia.es

Background

Mediterranean olive orchards are highly vulnerable to climate change and increasing limitations in water availability. Rising temperatures, more frequent droughts, and growing pressure on water resources threaten the sustainability and productivity of these agroecosystems. Improving water management has therefore become a key challenge for Mediterranean olive cultivation. Advances in sensing technologies, including in situ and remote sensing, together with large datasets and artificial intelligence, are enabling the development of digital twins. These tools offer opportunities to monitor, simulate, and optimize crop management under changing environmental conditions.

Methodology

The digital twin “Twin Olive” is based on three components. First, an open data platform integrates in-field sensing systems, including atmospheric sensors, canopy temperature measurements, and RGB cameras with on-edge image processing connected through a LoRaWAN network. Second, the system incorporates datasets generated by research projects, together with data from public institutions and farmers’ organizations. Third, the platform integrates satellite-derived information, energy balance models, and high-resolution spatial data from the Spanish National Plan for Aerial Orthophotography (PNOA).

Olive reception records from mills covering 2002–2024 were aggregated by agricultural districts and combined with climatic series from reference meteorological stations. From these datasets, more than 430 climatic variables were generated through temporal aggregation. Relationships between climate variables and olive production were analysed using a causal inference framework based on Double Machine Learning (CausalForestDML), estimating production changes associated with climatic variability while controlling for confounding factors. An extreme-season contrast analysis compared the three highest- and three lowest-production campaigns.

Findings

Autumn precipitation acts as an initial conditioning factor by determining soil water recharge during the pre-season. Differences between productive and low-yield seasons are observed, although some interquartile overlap remains, indicating that autumn rainfall establishes initial soil water

reserves but does not determine the final outcome of the season. Indicative thresholds include: risk <100–120 mm, acceptable 120–180 mm, and favourable >180–200 mm.

Winter precipitation emerges as the most determining factor, with virtually no overlap between high- and low-production seasons. Low-yield years are associated with water stress, whereas high-yield seasons coincide with abundant water availability during key stages such as flowering and fruit set. Thresholds include: highly unfavourable <100 mm, transition 100–150 mm, high probability of good production >150–160 mm, and optimal 200–250 mm.

Precipitation from April to August mainly plays a maintenance role, sustaining yield potential but not compensating for early-season deficits. Thresholds include: risk <70 mm, moderate 70–100 mm, and favourable >100–110 mm.

Conclusions

Integrating climatic analysis with digital twin technologies can improve water management in Mediterranean olive orchards under increasing climate variability. Within the “Twin Olive” framework, the combination of in-field sensing, historical datasets, and satellite information enables identification of key climatic drivers of yield variability. Results highlight the dominant role of winter precipitation, the conditioning effect of autumn rainfall on soil water recharge, and the maintenance role of spring–summer precipitation. These thresholds can be incorporated into decision-support systems to support more adaptive and efficient irrigation and crop management strategies.

Keywords

Digital twin, Olive orchards, Climate variability, Causal machine learning, Water management

References

- Cunningham, S. (2021). Causal inference: The mixtape. Yale University Press
- Lorite *et al.* (2022) Enhancing the sustainability of Mediterranean olive groves through adaptation measures to climate change using modelling and response surfaces. *Agricultural and Forest Meteorology* 313: 108742
- Subeesh & Chauhan (2026) Agricultural digital twin for smart farming: A review. *Green Technologies and Sustainability* 4: 100299



This volume is part of the International ENIA Chair on Agriculture - University of Cordoba (TSI-100921-2023-3), funded by the Secretary of State for Digitalisation and Artificial Intelligence and by the European Union - Next Generation EU, within the framework of the Recovery, Transformation and Resilience Plan.

