CSRF 2025

The Second International Conference on Sustainable and Regenerative Farming

ISBN: 978-1-68558-327-9

October 26th - 30th, 2025

Barcelona, Spain

CSRF 2025 Editors

Lorena Parra, Universidad Politécnica de Madrid, Spain

CSRF 2025

Forward

The Second International Conference on Sustainable and Regenerative Farming (CSRF 2025), held between October 26th, 2025, and October 30th, 2025, in Barcelona, Spain, was an event dedicated to exploring and promoting groundbreaking advancements in agricultural technology. This conference served as a catalyst for collaboration among industry stakeholders, researchers, policymakers, and entrepreneurs, aiming to showcase the latest innovations in Sustainable and Generative Farming, highlighting the transformative potential of technologies such as Artificial Intelligence (AI), Internet of Things (IoT), blockchain, and robotics in revolutionizing agriculture and ensuring sustainable food production for future generations.

We take the opportunity to warmly thank all the members of the CSRF 2025 technical program committee, as well as all the reviewers. The creation of such a high-quality conference program would not have been possible without their involvement. We also kindly thank all the authors who dedicated much of their time and effort to contribute to CSRF 2025. We truly believe that, thanks to all these efforts, the final conference program consisted of top-quality contributions. We also thank the members of the CSRF 2025 organizing committee for their help in handling the logistics of this event.

We hope that CSRF 2025 was a successful international forum for the exchange of ideas and results between academia and industry for the promotion of progress in the field of sustainable and regenerative farming.

CSRF 2025 Chairs

CSRF 2025 General Chairs
Lorena Parra Boronat, Universidad Politécnica de Madrid, Spain
José Miguel Jiménez, Universitat Politecnica de Valencia, Spain
Petre Dini, IARIA, USA/EU

CSRF 2025 Steering Committee
Kuok Ho Daniel Tang, The University of Arizona, USA
Sripada Udupa, International Center for Agricultural Research in the Dry Areas (ICARDA), Morocco
Davie M. Kadyampakeni, Soil, Water, and Ecosystem Sciences, University of Florida, USA
Teresa Delgiudice, Department of Agricultural Sciences, University of Naples Federico II, Italy
Mahmood Ahmad, RIZQ/YUNUS, WEFnex Hub, Thailand
Genhua Niu, Texas A&M University System, USA

CSRF 2025
Committee

CSRF 2025 General Chairs

Lorena Parra Boronat, Universidad Politécnica de Madrid, Spain
José Miguel Jiménez, Universitat Politecnica de Valencia, Spain
Petre Dini, IARIA, USA/EU

CSRF 2025 Steering Committee

Kuok Ho Daniel Tang, The University of Arizona, USA
Sripada Udupa, International Center for Agricultural Research in the Dry Areas (ICARDA), Morocco
Davie M. Kadyampakeni, Soil, Water, and Ecosystem Sciences, University of Florida, USA
Teresa Delgiudice, Department of Agricultural Sciences, University of Naples Federico II, Italy
Mahmood Ahmad, RIZQ/YUNUS, WEFnex Hub, Thailand
Genhua Niu, Texas A&M University System, USA

CSRF 2025 Technical Program Committee

Abdelkader Adla, University of Oran1, Algeria
Ali Ahmad, Universitat Politècnica de València, Spain
Mahmood Ahmad, RIZQ/YUNUS Water, Energy and Food Nexus (WEFnex) Knowledge Hub, Bangkok, Thailand
Adnan Akhter, University of the Punjab, Lahore, Pakistan
Hadi Al-agele, Biological and Ecological Engineering, Oregon State University, USA
Sajid Ali Khan Bangash, vGreens Holding GmbH, Essen, Germany and The University of Agriculture Peshawar, Pakistan
André Carlos Auler, Federal University of Paraná, Brazil
Karina Batista, Instituto de Zootecnia/APTA/SAASP, Brazil
Igor José Boggione Santos, Federal University of São João del-Rei, Brazil
Xuan-Thanh Bui, Ho Chi Minh City University of Technology, Vietnam
Gian Paolo Cesaretti, Simone Cesaretti Foundation, Italy
Fraj Chemak, National Institute for Agricultural Research of Tunisia (INRAT), Tunisia
Pedro Couto, University of Trás-os-Montes e Alto Douro, Portugal
José Victorino Cristiano do Rosário, Universidade de Évora, Portugal
Teresa Delgiudice, Department of Agricultural Sciences - University of Naples Federico II, Italy
Sianan Demir, Isparta University of Applied Sciences, Turkey
Antonella Di Fonzo, Council for Agricultural Research and Economics, Research Centre for Policies and Bioeconomy, Rome, Italy
Francisco Javier Diaz, Universitat Politècnica de València, Spain
Adnane El Yaacoubi, University Sultan Moulay Slimane, Morocco
Barbara Futa, University of Life Sciences in Lublin, Poland
Laura Gálvez, Department of Agricultural Production, Escuela Superior de Ingeniería Agronómica, Alimentaria y de Biosistemas, Universidad Politécnica de Madrid, Spain
Guillermo Garcia-Garcia, University of Granada, Spain

Copyright Information

Table of Contents

An Evaluation of the Use of Sensors for the Detection of Emissions in Slurry Management

Abimbola Y. Ikoyi, Jacqueline Humphries
Technological University of the Shannon (Midwest)
Thurles, Co. Tipperary, Ireland
Email: abimbola.ikoyi@tus.ie; jacqueline.humphries@tus.ie

***Abstract*— The minimization of ammonia and greenhouse gas emissions from slurry management is crucial in meeting emission reduction targets and ensuring the sustainability of the agricultural sector. Whilst there are gains to be made across the wide range of manure management approaches, there is considerable interest in technological advancements, in particular sensors, to add further value. In this paper, an evaluation of existing sensor research in the detection and determination of ammonia and greenhouse gases is conducted. The advantages and disadvantages of the use of sensors are summarized. It is found that while sensors are useful tools in smart agriculture, their use remains largely focused on measurement and descriptive analytics, with limitations still present in their application for predictive analytics for efficient slurry management. This paper emphasizes the need for further research into the application of sensors for minimization of emissions in slurry management for sustainable agriculture.**

Keywords- Sensors; Precision Agriculture; Ammonia; Greenhouse Gas; Emissions; AgriTech.

I. INTRODUCTION

Livestock slurry, while a valuable agricultural resource, poses significant environmental challenges if mismanaged. Slurry contains valuable nutrients like nitrogen and phosphorus, but improper management can lead to significant losses through runoff, leaching, and volatilization. This can cause water pollution (e.g., eutrophication) and air pollution (e.g., ammonia emissions).

There is immense pressure on the agricultural sector in Ireland to minimize Ammonia (NH_3) and Greenhouse Gas (GHG) emissions [1]. This is because the sector accounts for the majority of Irish national NH_3 (99%) and GHG (37.8%) emissions [1]-[3]. Methane (CH_4) emissions from slurry management represent 10.6% of agricultural GHG in Ireland (EPA, 2024). Therefore, minimization of Irish national NH_3 and GHG emissions, especially from agriculture, is crucial in meeting emission reduction targets and ensuring the sustainability of the agricultural sector.

Efforts to reduce emissions occur within the many processes involved in the management of slurry, such as removal and storage management, treatment adjustments, slurry application rates, soil uptake, and so on. However, these are not without challenges. For example, the storage of slurry is accompanied by the release of pollutant gases, such as NH_3 and CH_4 emissions [1][4]. Several manure management approaches have been proposed with the possibility of reducing these dangerous gases associated with slurry management. Ambrose et al. (2023) found that the use of additives, which encourage acidification, reduces CH_4 and NH_3 emissions from slurry storages [5]. Guidance from the United Nations Economic Commission for Europe (UNECE) Task Force on Reactive Nitrogen: Ammonia Guidance Document [6] sets out emission abatement measures in the nitrogen lifecycle from livestock feeding strategies, animal housing techniques, manure storage techniques, through to manure application techniques. Also, research conducted by Buckley et al., (2020) in which the impact, potential, and costs associated with abating national NH_3 emissions up to 2030 also sets out common mitigation strategies [7].

Since the UNECE and Teagasc guidance documents [6][7] were published, there have been exponential advancements in technology. Sensor technology enables the Internet of Things (IoT). Big data is gathered from sensors, hosted on cloud platforms, and analyzed using statistical methods or artificial intelligence to enable real-time predictions - driving the Industrial Revolution known as Industry 4.0 [8]. Agriculture 4.0, using the nomenclature of Industry 4.0, promises the same revolution in smart farming. Indeed, many industry consortia, fora and solution providers propose slurry management solutions which use sensors, and make claims that emissions are reduced. A rigorous journal review process is necessary to substantiate claims and conclusions made in these channels [9]. In this research, the application of advanced sensor technologies for real-time monitoring and control of slurry management processes are investigated. The research questions posed are (1) How can sensors be used in the reduction or mitigation of ammonia or greenhouse gas emissions in slurry management? (2) What are the advantages and disadvantages of the use of advanced sensor technologies when used for this purpose?

The rest of this paper is organized as follows. Section II outlines the research method undertaken. In Section III, the literature is analyzed. In Sections IV and V the findings from the literature are set out, and summarized. The conclusions close the article.

II. RESEARCH METHOD

Narrative literature reviews are a critical tool for theoretical exploration, in that they provide a comprehensive

ISBN: 978-1-68558-327-9

overview of the available knowledge on a particular topic [9], and as such, a narrative literature review is chosen in this research. Journal papers, conference articles and book chapters available on Web of Science, and Scopus databases were chosen as sources for relevant research.

The search query situated the research within the context of modern agriculture which is identified using the terms ("smart farm*" OR "AgriTech" OR "Agriculture 4*" OR “precision agriculture”). The papers were constrained to ammonia and methane emissions using the terms ("ammonia" OR "NH_3" OR “greenhouse gas” OR “GHG”) AND (“slurry” OR “manure”)). The term Agriculture 4.0 has been around for the last ten years, and so for that reason, papers published in the timeline 2015 to 2025 are considered. The inclusion criteria also indicated English as the publication language. 1,037,423 papers were returned.

The first round of elimination included reading the title, abstract, and conclusions leaving 11,584 papers.

The second round of elimination involved reading the full text of all articles and retaining articles that focus on the research objective, and classifying the papers. 101 papers were retained. In addition to the initial database search, backward citation tracking was employed by screening the reference lists of the included studies to identify further potentially relevant publications.

III. LITERATURE REVIEW

As previously mentioned, the emergence of smart farming and precision agriculture is due to advancements in technology. There has been an increase in the applications of such technologies for sustainable agriculture, and an emerging area is the mitigation of emissions in agriculture. An example is the use of IoT technology for the improvement of slurry management on farms. These field-based IoT sensors record and monitor soil and weather-related conditions targeted at helping farmers make better decisions on best timing for slurry application to minimize losses and maximize nutrient use. However, these sensors were unable to measure key slurry parameters (such as pH, dry matter, temperature, and nutrient content), perform in situ and online monitoring, or provide data for comprehensive slurry management [28].

Several authors [12][14][21][23][26][27] have reported on the application of sensors for determination of nutrient components of slurry. However, few reports have been published on the use of sensors for the quantification of gas emissions, such as ammonia and greenhouse gases (methane, nitrous oxide and CO_2). This review covers the three major stages in the traditional management of slurry: slurry production in animal houses, slurry storage and field application.

A. *Slurry Production*

Livestock production results in the generation of animal waste. Housing of animals comes with the challenge of handling and management of slurry. Efficient manure management reduces environmental impact, thus maintaining animal health. Environmental sensors measuring factors like air quality and humidity, generate vast amounts of data providing crucial insights into the well-being of the herd and the optimization of the farm environment [19].

Air quality in farmhouses is linked with ammonia, CO_2, Particulate Matter (PM) and Hydrogen Sulphide (H_2S) concentrations. These gases have negative effects on animals and human health in the environment. The quality of air is affected by some other factors, such as frequency of slurry removal and floor type [17]. A 21-day study which utilized an IoT gas and environmental sensors for continuous detection of NH_3, CO_2, H_2S and PM concentrations in two piggeries revealed that housing structures and slurry management systems had a huge impact on the gas emissions in the piggeries. Specifically, slurry management resulted in increased H_2S up to 1.9 ppm and increased NH_3 concentration of 63%. In addition, the structure of housings resulted in accumulation of gases, CO_2 and NH_3 increasing up to 52% and 34% than daily average value respectively [17]. The use of sensors at different times of the day, further confirms the need for advanced technology for the mitigation of environmental impacts of agriculture.

Optimum environmental conditions (temperature, moisture, air quality, etc.) must be maintained in livestock houses. The maintenance of these conditions results in huge electrical energy consumption particularly in poultry houses (broiler house - 75.5%, laying hen house - 58.9%) due to the use of various equipment [29]. This is predicted to increase in the future due to technological advancement which indirectly leads to increased GHG emissions. Consequently, for improved efficiency and sustainability, the prediction of the energy consumption of the indoor environmental condition for intensive poultry farming is expedient [13].

In order to minimize reliance on additional equipment, [13] developed a customized hourly model for the interpretation and analysis of electronically collected data. In this study, gas sensors were utilised for the measurement of CO_2 (Model 336, Huakong Xingye Technology, Beijing, China) and ammonia gas concentration (Model 458, Zhize, Jinan, China) emitted in a poultry house. The average CO_2 and ammonia concentration detected by the sensors were similar to the average predicted data using the developed model [13]. On the other hand, there is need for improvement in the sensitivity levels for the gas sensors to enable accurate detection at extremely low concentrations.

As indicated previously, NH_3 is typically an odorous compound produced from the decomposition of organic nitrogen and is a precursor of secondary inorganic aerosols. Similarly, H_2S, a strong odorous and toxic compound that affects animal and human health, is mainly produced from anaerobic digestion of organic sulphur [15]. These gases are usually at high concentrations in animal houses. A study evaluated the use of Electrochemical (EC) gas sensors for the quantification of odours from ammonia (Model #SO1198 Senko LTD. Korea) and hydrogen sulphide (Model #SO1N8 Senko LTD Korea) in a piggeries’ manure treatment facility. Acceptable values were obtained for linearity, accuracy, repeatability, lowest detection limit and response time for the sensors, thus confirming their suitability for on-field testing. However, a longer sampling time of at least 15 minutes might be necessary for ammonia monitoring to reach target concentration point [15].

B. Slurry Storage

Upon generation of faeces from animals in the animal houses, the slurry (manure) is usually stored for a specific amount of time. Sensor networks that monitor real-time changes in ammonia concentrations assist in minimizing losses of plant-available nitrogen during manure storage [25]. The duration of storage varies and is affected by several factors, such as time of the year, regulation governing spreading as organic fertilizer, farm slurry storage capacity and so on. Sensors were used in a study for the development of a prediction model for methane and ammonia gas emissions in piggeries with two different types of manure management systems: Long Storage (LS) in deep pits and Short Storage (SS) by daily flushing of a shallow pit with sloped walls and partial manure dilution [20]. The study revealed a positive correlation between calculated and measured CH_4 and NH_3 emissions on an annual basis. This confirms the reduction potential of the studied measures for CH_4 and NH_3 emissions from pig houses. In addition, the developed model provides a possibility for the assessment of mitigation measures on CH_4 and NH_3 emissions. This provides a robust basis for assessing the impact of management and housing strategies on CH_4 and NH_3 emissions from pig houses, which in turn, helps support more sustainable practices in pig farming [20].

In a similar study, manure management and sensor location played a huge role in the determination of gas concentration [10]. Higher ammonia concentration was recorded for open slurry pit compared to the slurry management system with daily removal of slurry. Meanwhile, electro-chemical DOL53 ammonia sensors (DOL Sensors, Aarhus, Denmark) located at 1.0m above floor level recorded approximated ammonia concentrations and were more vulnerable to local fluctuations in comparison to those located at 1.8 m above floor level [10].

In contrast to the previous studies where electro-chemical sensors were used for gas concentration determination, a Fourier-Transform Infrared (FTIR) spectroscopy monitor was used to measure gas transport and concentrations of greenhouses gases (methane, carbon dioxide, and nitrous oxide) and ammonia inside manure piles at various depths. Results showed that carbon dioxide dominated the greenhouse gas emissions. An interesting observation in this study was the reduction of gas emissions with increased moisture content in manure with high water holding capacity [11]. Results obtained using FTIR Spectroscopy monitor provided insights into management strategies for emission reduction from solid dairy manure [11] .

Drones are used as platforms to carry and deploy sensors**,** such as RGB cameras, multispectral, hyperspectral, and thermal sensors for aerial imaging and mapping, multispectral or LiDAR sensors for soil and field analysis, and gas sensors (e.g., methane, ammonia), infrared or laser-based detectors sensors to detect and map emission. Drones are effective in counting animal populations and detecting methane leaks in natural gas infrastructure. These techniques have been applied on a small scale to assess and determine livestock-related methane emissions on farms [16].

Electrochemical sensors were found to have several advantages, such as multi-gas non-specific detection, high sensitivity and precision, making them the preferred alternative for emission detection, albeit they have a long response time and short service life. Similarly, FTIR spectroscopy have the advantage of multi-gas non-specific detection but have higher operating cost in comparison with electrochemical sensors [16].

A UAV-based active AirCore system for the estimation of CH_4 emissions from dairy cow farms is outlined in [25]. The inclusion of local wind speed and direction measurement would result in increased accuracy of methane estimation [25]. In addition, there is need for further research in the use of aerial technology for the assessment of emissions from livestock farming.

C. Field Application of Slurry

The application of fertilizers and manure on fields is the largest source of NH_3 in the atmosphere. Ammonia emission from agriculture has negative environmental consequences and is largely controlled by the chemical microenvironment and the respective biological activity of the soil [18]. While gas phase and bulk measurements can describe the emission on a large scale, those measurements fail to unravel the local processes and spatial heterogeneity at the soil air interface [18].

For better understanding of some of these processes, a two-dimensional (2D) imaging approach which visualized three of the most important chemical parameters associated with NH_3 emission from soil was developed by [8]. Ammonia, O_2 and pH microenvironments were imaged using reversible optodes in real-time with a spatial resolution of $<100\mu m$. This NH_3 optode enhanced the understanding of microscale factors influencing NH_3 emissions, allowing for visualization of the soil's chemical microenvironment following manure application [18].

Though there is a surge in the incorporation of precision agriculture tools, these systems often operate in isolation, focusing on specific parameters without providing a holistic view of the agricultural environment [22]. There is a need to bridge this gap by integrating multiple sensors and data sources into a unified monitoring system. In [22] a comprehensive monitoring system using sensors was developed for the measurement of gases, such as CO_2, methane, and ammonia. This system known as Agri-Guard consists of two sets of devices: the IoT based Agri-cones and a centralized camera stand. The Agri-cones consisted of an array of sensors including temperature, humidity, moisture, CO_2 and methane gas sensors. Upon manure application to the soil, substantial increase in sensor readings were observed in the CO_2 and methane gas sensor (MQ9), due to the organic matter decomposition in the manure. Similarly, as microbial decay progressed, the ammonia sensor (MQ135), showed a slight increase, signifying the breakdown of organic nitrogen compounds in the manure [22].

TABLE 1. SUMMARY OF APPLICATION OF SENSORS FOR THE MITIGATION OF EMISSIONS IN SLURRY MANAGEMENT

	Summary of application of sensors for the mitigation of emissions from slurry		
	Purpose of Study	***Sensor***	***Monitored animal/slurry source***
1	Evaluation of slurry management in two different housing structures	Environmental Sensor	Pigs
2	Development of energy consumption model for animal houses	Gas Sensors	Pigs
3	Emission monitoring and odour intensity estimation	Electrochemical Sensor	Pigs
4	Development of prediction models for emissions from various slurry storage systems	Gas Sensors	Pigs
5	Effect of manure management and sensor location on emission concentration	Electrochemical	Piggeries
6	Evaluation of compaction effects on emissions from dairy manure	FTIR	Cattle
7	Estimation of emissions from dairy cows manure	UAV	Cattle
8	Visualization of emissions from soil upon manure application	Optical sensors	Livestock (unspecified)
9	Monitoring of gaseous emissions from manure in farms	Gas sensors	Livestock(Unspecified)

TABLE 2. ADVANTAGES AND DISAVANTAGES OF SENSORS TECHNOLOGY FOR EMISSION REDUCTION IN SLURRY MANAGEMENT

	Advantages and disadvantages associated with use of sensors in slurry management	
	Advantages	**Disadvantages**
1	Real time monitoring and decision support [17] [22]	Limited capabilities for slurry characterization [28]
2	Enhanced detection capabilities [11] [13]	Variation in sensor sensitivity and accuracy [13] [15]
3	Improved emision quantification [20]	Operational constraint [10] [16]
4	Spatial temporal precisions [18] [24]	High cost and maintenance [11]
5	Support and sustainable practices [19]	Fragmented system design [22]

IV. RESULTS

The applications of sensors in slurry management are outlined in Table 1, covering housing, storage, and field use. Their advantages and disadvantages are summarized in Table 2, showing benefits for monitoring and quantification alongside limitations in sensitivity, cost, and integration.

V. DISCUSSION

In this section, the findings are discussed in relation to the two central research questions: firstly, how sensors can be employed to reduce or mitigate ammonia and greenhouse gas emissions in slurry management, and secondly, to summarize the advantages and disadvantages associated with the use of advanced sensor technologies for this purpose.

A. How can sensors be employed to reduce or mitigate ammonia and greenhouse gas emissions in slurry management?

The aim of employing sensors is to minimize negative environmental impacts while optimizing nutrient recovery and beneficial use. Data-driven management facilitated by sensors enables more efficient and environmentally friendly slurry handling. Observations reported in this review present the various types of sensors utilized for monitoring and quantification of hazardous gases (H_2S and NH_3), and GHG, such as CO_2 and methane. There seemed to be few experiments conducted on the use of sensors for the quantification of NO_2. This could be due to the presence of NO_2 in lower concentrations in the various stages of slurry management in comparison to all the other gases. This would require the development of highly sensitive equipment with increased lower detection limit for measurement. Similarly, the use of FTIR was reported once in this review for the monitoring of ammonia, CO_2, NO_2 and CH_4. This contrasts with most of the other experiments where electrochemical sensors were used for emission detection and quantification.

The majority of studies primarily use descriptive analytics on the data captured from sensors. In these studies, focus is on reporting sensor measurements, conditions, or observed effects [11][15]-[18][22][25]. However, a few studies incorporate predictive elements, particularly those that develop or validate models for estimating gas emissions, use data to build or validate models, or attempt forecasting or scenario analysis [13][20].

B. Advantages and Disadvantages Associated with the Use of Sensor Technologies in slurry management

1) Advantages

a) Real-Time Monitoring and Decision Support: IoT-based sensors allow real-time measurement of environmental parameters, such as temperature, humidity, and gas concentrations (e.g., NH_3, CO_2, H_2S), which support better decision-making regarding optimal slurry application timing to reduce emissions [17][22].

b) Enhanced Detection Capabilities: EC sensors and FTIR spectroscopy can detect multiple gases, including ammonia and greenhouse gases, such as methane and CO_2, providing valuable insights across different stages of slurry management—from housing to field application [11][13].

c) Improved Emission Quantification: Sensors facilitate accurate quantification of gaseous emissions, which is critical for developing predictive models and validating mitigation strategies [20].

d) Spatial and Temporal Precision: Technologies, such as optode-based imaging and UAV-mounted sensors, provide high-resolution spatial and temporal data, enabling precise mapping of emission hotspots and variability [18][24].

e) Support for Sustainable Practices: Sensor integration into farm management systems contributes to more efficient nutrient use and helps meet regulatory and sustainability goals through emission reduction [19].

2) *Disadvantages*

a) Limited Capability for Slurry Characterization: Despite their usefulness, many current sensors do not measure key slurry properties, such as pH, dry matter content, and nutrient composition in-situ, thus limiting their utility for comprehensive slurry management [28].

b) Sensor Sensitivity and Accuracy: Certain sensors, especially for gas detection, require improvements in sensitivity to accurately detect low-concentration gases, such as nitrous oxide, which was underrepresented in the literature [13][15].

c) Operational Constraints: Some sensors, particularly electrochemical types, have drawbacks including long response times, vulnerability to environmental fluctuations, had implementation constraints, such as the specific distances they had to be placed in relation to the slurry source, and relatively short operational life [10][16].

d) High Cost and Maintenance: Advanced technologies, such as FTIR, are costly to operate and maintain, which may limit their adoption on smaller farms or in developing regions [11].

e) Fragmented System Design: Many precision agriculture tools, including gas sensors, are not integrated into unified platforms, which limits their ability to provide a holistic understanding of the slurry management system [22].

VI. CONCLUSION

Traditional slurry management practices often lead to pollution and greenhouse gas emissions. There is potential within slurry management to reduce these emissions and have a positive impact on national emissions targets. Significant efforts to reduce emissions occur within the lifecycle of slurry, from livestock feed selection through manure spreading or the alternative pathway of biomethane production. In the past ten years there have been exponential developments in technology that have fuelled Smart Agriculture.

At the core of these developments are the use of sensors which capture and, in some instances, analyze data at source. In this narrative review an overview of the various applications of sensors for the monitoring of emissions in slurry management is provided, and as such provides an insight to the reduction of emissions in the slurry life cycle in livestock farming.

This review found that sensors add value in smart agriculture. Currently they are used largely for the purpose of measurement and descriptive analysis which provide benefits in slurry management around real-time monitoring and decision support, enhanced detection capabilities, improved emission quantification, spatial and temporal precision, and support for sustainable practices. There are currently limitations in their application, such as limited capability for slurry characterization, sensor sensitivity and accuracy, operational constraints, high cost and maintenance, and fragmented system design.

A. *Further Research*

This review has shown that there is limited research conducted on the use of sensors for the quantification of greenhouse gases emissions from slurry particularly at the field application stage. Therefore, there is a need for further research to develop, calibrate, and validate robust and reliable sensor systems for measurement of greenhouse gases during all stages of the slurry life cycle. This includes addressing challenges related to sensor fouling, durability, and data accuracy in harsh, slurry environments.

Furthermore, the majority of studies use descriptive analytics on sensor data, which although they provide valuable insights into current and past conditions, help identify emission patterns, hotspots, and the effectiveness of management practices in real time, they are not useful for proactive decision-making. Future studies should incorporate predictive and prescriptive analytics, which allow forecasting future emissions or simulated scenarios, such as extreme weather events. Predictive and prescriptive analytics are more useful for proactive decision-making and long-term mitigation planning, helping to avoid emissions before they happen.

B. *Limitations*

This narrative review is conducted on a search of two databases, in English, and on the last ten years. This will have limited the results. It is therefore probable that some relevant research has not been included. The results could be repeated on other databases, other languages, different timeframes, and through the use of alternative synonyms.

There is the saying that 'research follows industry', and that the period for rigorous research to be conducted, and published, is slower than that which may be occurring in the field and industry. Thus, there may be many advances in technology that haven't yet been reported in research databases.

REFERENCES

[1] Environmental Protection Agency (EPA), "Ireland's National Inventory Report" available at: https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/Ireland's-NIR-2024_cov.pdf, 2024a. [retrieved: February 2025].

[2] Environmental Protection Agency (EPA), "Latest emissions data", available at: https://www.epa.ie/our-services/monitoring–assessment/climate-change/ghg/latest-emissions-data/, 2024c. [retrieved: February 2025]

[3] Teagasc, "Alternative slurry amendments for cattle slurry storage" available at: https://www.teagasc.ie/news--events/daily/dairy/alternative-slurry-amendments-for cattleslurrystorage.php, 2023.

[4] Environmental Protection Agency (EPA) "Ireland's Informative Inventory Report 2023", available at: https://www.epa.ie/publications/ monitoring--assessment/climate-change/air-emissions/IIR_Ireland_2024v1.pdf, 2024b. [retrieved: February 2025].

[5] H. W. Ambrose, F. R. Dalby, A. Feilberg, and M. Kofoed, "Additives and methods for the mitigation of methane emission from stored liquid manure", Biosystems Engineering 229: 209–245, 2023.

[6] S. Bittman, M. Dedina, C. M. Howard, O. Oenema, and M. A. Sutton, "Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen", NERC/Centre for Ecology & Hydrology, 2014.

[7] C. Buckley et al., "An Analysis of the Cost of the Abatement of Ammonia Emissions in Irish Agriculture to 2030", Teagasc, 2020

[8] J. Humphries, A. Ryan, and P. Van de Ven, "A New Model for Quality 4.0" in: J. Reis et al. "Driving Quality Management and Sustainability in VUCA Environments", ICQUIS, Springer Proceedings in Business and Economics. Springer, Cham doi.org/10.1007/978-3-031-52723-4_15, 2024.

[9] M. N. Ahmad, "Narrative Literature Reviews in Scientific Research: Pros and Cons", Jordan Journal of Agricultural Sciences, 21(1), pp. 1–4, doi.org/10.35516/jjas.v21i1.4143, 2025.

[10] J. Bus et al., "Short-term associations between ambient ammonia concentrations and growing-finishing pig performance and health", Preventive Veterinary Medicine, 242, doi.org/10.1016/j.prevetmed.2025.106555, 2025.

[11] F. Chang, E. Fabian-Wheeler, T. L. Richard, and M. Hile, "Compaction effects on greenhouse gas and ammonia emissions from solid dairy manure", Journal of Environmental Management, 332. doi.org/10.1016/j.jenvman.2023. 117399, 2023

[12] B. Chugh et al., "Electrochemical sensors for agricultural application", Nanosensors for Smart Agriculture, pp. 147–164. doi.org/10.1016/B978-0-12-824554-5.00018-5, 2022.

[13] L. Du et al., "Development and Validation of an Energy Consumption Model for Animal Houses Achieving Precision Livestock Farming", Animals, 12(19). doi.org/10.3390/ani12192580, 2022.

[14] X. Feng, R. A. Larson, and M. F. Digman, "Evaluation of Near-Infrared Reflectance and Transflectance Sensing System for Predicting Manure Nutrients", Remote Sensing, 14(4), doi.org/10.3390/rs14040963, 2022.

[15] H. Joo et al., "Field application of cost-effective sensors for the monitoring of NH3, H2S, and TVOC in environmental treatment facilities and the estimation of odor intensity", Journal of the Air and Waste Management Assoc., 73(1), pp. 50–64, doi.org/10.1080/10962247.2022.2131652, 2023

[16] W. Ma et al., "Automatic Monitoring Methods for Greenhouse and Hazardous Gases Emitted from Ruminant Production Systems: A Review", Sensors (Vol. 24, Issue 13), Multidisciplinary Digital Publishing Institute (MDPI), doi.org/10.3390/s24134423, 2024.

[17] A. Mautone and A. Finzi, "Air quality monitoring in piggeries through an IoT gas and environmental sensors device", 11th European Conference on Precision Livestock Farming, pp. 1728–1736, 2024.

[18] T. Merl and K. Koren, "Visualizing NH3 emission and the local O2 and pH microenvironment of soil upon manure application using optical sensors", Environment International, 144. doi.org/10.1016/j.envint.2020.106080, 2020.

[19] S. Neethirajan, "Net Zero Dairy Farming—Advancing Climate Goals with Big Data and Artificial Intelligence", Climate (Vol. 12, Issue 2). Multidisciplinary Digital Publishing Institute (MDPI), doi.org/10.3390/cli12020015, 2024.

[20] P. Sefeedpari, S. H. Pishgar-Komleh, and A. J. A. Aarnink "Model Adaptation and Validation for Estimating Methane and Ammonia Emissions from Fattening Pig Houses: Effect of Manure Management System", Animals, 14(6), doi.org/10.3390/ani14060964, 2024

[21] F. M. Silva et al., "Precision Fertilization: A critical review analysis on sensing technologies for nitrogen, phosphorous and potassium quantification", Computers and Electronics in Agriculture, 224. doi.org/10.1016/j.compag.2024/109220, 2024.

[22] K. Singh, K. A. Momin, M. Nishal, C. Sultania, and M. Rao, "Agri-Guard: IoT-Based Network for Agricultural Health Monitoring with Fault Detection", International Conference on Internet of Things, Big Data and Security, IoTBDS - Proceedings, pp. 223–230. doi.org/10.5220/ 0013209500003944, 2025.

[23] M. K. Sørensen, O. Jensen, O. N. Bakharev, T. Nyord, and N. C. Nielsen, "NPK NMR Sensor: Online Monitoring of Nitrogen, Phosphorus, and Potassium in Animal Slurry", Analytical Chemistry, 87(13), pp. 6446–6450. doi.org/10.1021/acs.analchem.5b01924, 2015.

[24] K. Vinković et al., "Evaluating the use of an Unmanned Aerial Vehicle-based active AirCore system to quantify methane emissions from dairy cows", Science of the Total Environment, 831. doi.org/10.1016/j.scitotenv.2022.154898, 2022.

[25] J. K. Whalen, B. W. Thomas, and M. Sharifi, "Novel Practices and Smart Technologies to Maximize the Nitrogen Fertilizer Value of Manure for Crop Production in Cold Humid Temperate Regions" pp. 1–85, doi.org/10.1016/bs.agron. 2018.09.002, 2019.

[26] A. Y. Ikoyi and B. A. Younge, "Impact of Sample Volume and Wavelength Region on the Near Infrared Spectroscopy (NIRS) Prediction of Inorganic Nutrient in Equine Faeces", National Symposium on NIR Spectroscopy - Proceedings, 2021.

[27] A. Y. Ikoyi and B. A. Younge, "Faecal near-infrared reflectance spectroscopy profiling for the prediction of dietary nutritional characteristics for equines", Animal Feed Science and Technology, 290. doi.org/10.1016/j.anifeedsci. 2022.115363, 2022.

[28] J. Hughes, "European Innovation Partnership Using Internet of Things technology to improve slurry management on farms - Year 2 Report", buisnesswales.gov.wales/farmingconnect/ sites/farmingconnect/files/documents/EIP%20Wales_IoT%20 Management_Final%20Report.pdf, 2023.

[29] A. Costantino, E. Fabrizio, A. Biglia, P. Cornale, and L. Battaglini, "Energy Use for Climate Control of Animal Houses: The State of the Art in Europe", Energy Procedia, 101, pp. 184–191. doi.org/10.1016/j.egypro.2016.11.024, 2016.

Cereals Supply-Chain Traceability Using Blockchain and IoT Technology

Marianthi Giannakopoulou
Agricultural Research Institute
Rural Development department
Nicosia, Cyprus
email: mgiannakopoulou@ari.moa.gov.cy

George Adamides
Agricultural Research Institute
Rural Development department
Nicosia, Cyprus
email: gadamides@ari.moa.gov.cy

Andreas Pallides
Agricultural Research Institute
Plant Improvement department
Nicosia, Cyprus
email: apallides@ari.moa.gov.cy

Nikos Nikoloudakis
Cyprus University of Technology
Department of Agricultural Sciences, Biotechnology and Food Science,
Limassol, Cyprus
email: n.nikoloudakis@cut.ac.cy

***Abstract*—The TraCEREAL project explores the integration of Blockchain and Internet of Things (IoT) technologies to enhance traceability, transparency, and efficiency in Cyprus' cereal supply chain. By identifying the farm-to-fork key actors, their needs and priorities, the project develops a prototype system across the critical points of production and distribution by combining intelligent algorithms and real-time data for improved decision-making.**

Keywords - blockchain; cereal; Internet of Things; traceability.

I. INTRODUCTION

The world faces a multitude of challenges related to food security, health, nutrition, and sustainability [1]. These issues stem from a combination of factors, such as the growing global population, the escalating impacts of the climatic crisis, water scarcity, and limited local food production (often caused by ongoing conflicts around the globe), which result in a fragile cereal supply chain that is highly reliant on imports [2]. The cereal supply chain is vital for food security, but also for ensuring food quality, as pests and toxins can contaminate cereals.

Blockchain technology is emerging as a promising solution to the many challenges facing food supply chains, as it promotes transparency and efficiency by creating secure, immutable records of transactions, thereby enhancing traceability [3]. In addition to traceability, there is also the need for accurate and real-time information on the factors that affect both qualitative and quantitative yield traits. When applied in agriculture, the IoT, a network of interconnected devices that collect, analyze, and enhance data in real-time, enables precision agriculture, automation, and data-driven decision making [4] [5].

The TraCEREAL project [6], is dedicated to investigating how blockchain technology, in conjunction with advanced IoT capabilities, can contribute to the establishment of resilient supply-chain operations within Cyprus. The project's objective is to develop and demonstrate a functional prototype system consisting of an intelligent algorithmic framework, seamlessly integrated with IoT technology. To this end, cultivation practices for recording sensory data were implemented as part of the demonstration activities, including a set of pilot experimental fields established across Cyprus. Telemetric stations equipped with IoT sensors were installed in mid-January at each plot to comprehensively track and report crucial environmental and soil conditions. The sensors can collect real-time data on various critical soil parameters, such as moisture levels, temperature, salinity, PH, and nitrogen/phosphorus/potassium content.

For the development of the TraCEREAL system, the first step was to map the key actors across the cereal supply chain: (a) breeders, can document and track the genetic characteristics of new crop varieties, ensuring their adaptation to environmental conditions and market needs, (b) seed producers, receive insights on seed quality, germination rates, and resistance to environmental factors, facilitating better production planning, (c) farmers, can utilize IoT sensor data and platform recommendations to optimize agricultural inputs, irrigation, fertilization and yield, ensuring sustainable and high-quality production, (d) flour mills, gain access to detailed grain quality analyses, enabling them to maintain consistency and improve processing efficiency, and (e) end consumers, i.e., bakeries and consumers benefit from full traceability, with access to information on the origin, nutritional properties, and processing history of food products (e.g., flour, pasta). The main objective of this paper was to identify and document the priorities and needs of the key actors across the cereal supply chain.

The structure of this paper is organized as follows: Section 1 introduces the background and objective of the study. Section 2 describes the materials and methods used in the study. In Section 3, we present the results of our empirical investigation. Finally, Section 4 concludes the paper with a summary and main findings.

II. METHODOLOGY

Three different structured questionnaires (grouped as either producer, milling industry, and end-users) were co-created to determine which traits should be included in the blockchain, recognizing that each stakeholder has unique priorities and needs. The first questionnaire was addressed to

 ISBN: 978-1-68558-327-9

seed producers and cereal farmers, the second questionnaire was directed towards flour mills, and the third questionnaire was interested in the views of end consumers (e.g., local bakeries and consumers).

Personal interviews were conducted, between November 2024 and January 2025, with seed producers, cereal farmers, mills' executives, and bakers. Consumers answered an online-version of the questionnaire. Representatives of two mills provided input to the relevant questionnaire. Two out of the four of the seed producers and thirty-three cereal farmers answered the second questionnaire. Eleven bakery owners and 101 consumers answered the third questionnaire.

III. RESULTS

A. *Seed producers and cereal farmers*

Among the most desirable wheat traits that seed producers and cereal farmers wish to be informed about through the blockchain system are drought resistance, disease resistance, as well as the adaptation to diverse edaphoclimatic conditions. Surprisingly, the breeding method, i.e., conventional breeding or the use of New Genomic Techniques, is not a primary concern (Figure 1). In addition, seed producers (cereal farmers) are particularly interested in accessing data on yield, soil temperature, soil moisture, and fertilization needs. Conversely, important traits, such as starch composition and dough traits are of limited interest to seed producers and cereal farmers.

Figure 1. Seed producers (cereal farmers) data traceability requirements.

B. *Milling industry*

The milling industry has a distinct set of priorities regarding the data of interest within the blockchain system. The most important traits that emerged are the type of cultivation (conventional or organic), protein and starch content, as well as dough elasticity, since these features affect both the price and quality of the produced flour.

C. *Bakeries and consumers*

For the end-consumers, the most important aspects of traceability information are the country of origin for the raw material, the origin of the final product (e.g., flour, pasta), and the type of the cultivation (Figure 2).

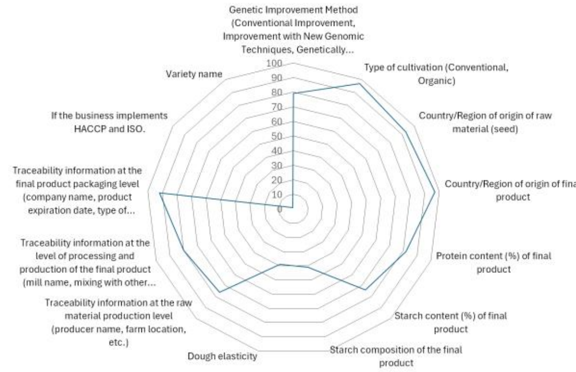

Figure 2. End consumers traceability data requirements.

Interestingly, consumers do not prioritize the implementation of Hazard Analysis and Critical Control Points (HACCP) and International Organization for Standardization (ISO) certificates, nor the specific crop varieties used.

IV. CONCLUSION

TraCEREAL is an ongoing project focused on leveraging blockchain and IoT to ensure secure, immutable data storage, fostering trust among all stakeholders across the cereal value chain. The initial phase involved mapping and documenting the priorities and requirements of the main stakeholders throughout the cereal supply chain. Survey results revealed that each key actor has distinct priorities and needs. The feedback from these stakeholders will contribute to building the TraCEREAL blockchain framework and database. This system aims to assist policymakers and industry players in creating more resilient cereal supply chains, specifically adapted to the unique needs of Cyprus.

ACKNOWLEDGMENT

This research was partially funded by the European Union Recovery and Resilience Facility of the NextGenerationEU instrument, through the Research and Innovation Foundation CODEVELOP-AG-SH-HE/0823/0133.

REFERENCES

[1] Unicef, "In Brief to The State of Food Security and Nutrition in the World 2024," 2024.
[2] A. Molotoks, P. Smith, and T. P. Dawson, "Impacts of land use, population, and climate change on global food security," *Food and energy security,* vol. 10, no. 1, p. e261, 2021.
[3] Z. Zheng, S. Xie, H. Dai, X. Chen, and H. Wang, "An overview of blockchain technology: Architecture, consensus, and future trends," in *2017 IEEE international congress on big data (BigData congress)*, 2017: Ieee, pp. 557-564.
[4] A. Sharma *et al.*, "Artificial intelligence and internet of things oriented sustainable precision farming: Towards modern agriculture," *Open Life Sciences,* vol. 18, no. 1, p. 20220713, 2023.
[5] G. Adamides, "A Review of Climate-Smart Agriculture Applications in Cyprus," *Atmosphere,* vol. 11, no. 9, p. 898, 2020.
[6] TraCEREAL. "A Comprehensive Cereal Supply Chain Quality Control and Decision-Making Framework." https://tracereal.weebly.com/ (accessed 2025).

Predictive Modeling of Soil Moisture: A Review of Benchmark Datasets, Their Strengths, and Limitations

Kamrul Hasan, Arnold Muiruri
College of Computing
Grand Valley State University
Allendale, MI, USA
e-mail: {hasanka | muiruria}@mail.gvsu.edu

***Abstract*—Groundwater depletion, primarily driven by unsustainable irrigation practices in agriculture, has become a pressing global issue. Accurate soil moisture monitoring and prediction are essential for supporting sustainable water resource management. This review contributes to an ongoing research effort aimed at developing a predictive soil moisture modeling framework by integrating signals from sparsely distributed ground-based sensors with satellite-derived datasets, including NASA's Soil Moisture Active Passive (SMAP) products. As a part of this study, a case analysis involving several International Soil Moisture Network (ISMN) stations in the United States is conducted to evaluate the agreement between in-situ and satellite-derived measurements. While both data sources reveal consistent seasonal trends, significant discrepancies in magnitude highlight concerns regarding the reliability of these data as a universal benchmark. The paper provides a comprehensive review of recent advances and persistent challenges in soil moisture prediction, emphasizing the role of ISMN data. The overarching goal is to guide the development of robust, high-resolution tools for precision agriculture and sustainable groundwater management.**

Keywords-soil moisture prediction; remote sensing; international soil moisture network; data fusion; machine learning.

I. INTRODUCTION

Groundwater levels are declining at an alarming rate across the globe due to various factors, with excessive irrigation practices being one of the primary ones [1][2]. According to the 2018 U.S. Census of Agriculture, approximately 50% of the irrigated land in the United States depends exclusively on groundwater, while an additional 16% relies on a combination of groundwater and surface water. Alarmingly, nearly half of the monitoring sites across 28 U.S. states have reported significant groundwater depletion since 1980, indicating unsustainable usage patterns [3].

To address this growing crisis, it is imperative to optimize agricultural water consumption. An ongoing research project at Grand Valley State University (GVSU), Michigan, conducted under the Precision Agriculture Research Lab, aims to address this challenge. The focus of the project is on predicting soil moisture by integrating data from sparsely distributed in-situ moisture sensors with satellite-based observations, such as NASA's Soil Moisture Active Passive (SMAP) mission [4] and the European Space Agency's Climate Change Initiative (ESA CCI) [5].

Soil moisture monitoring and predictions can play a pivotal role not only in minimizing water waste but also in enabling informed decision-making for farmers and policy makers.

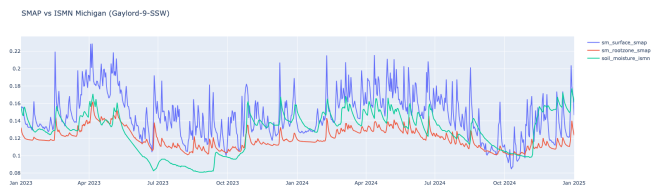

Figure 1. Average daily soil moisture by SMAP (surface-level and rootzone) vs ISMN at Gaylord-9-SSW (Michigan, U.S.). Null values were imputed through forward-fill (rolling average with window-size=3).

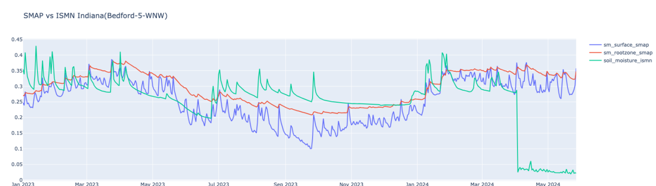

Figure 2. Average daily soil moisture by SMAP (surface-level and rootzone) vs ISMN at Bedford-5-WNW (Indiana, U.S.). Null values were imputed through forward-fill (rolling average with window-size=3).

Effective soil moisture management supports long-term soil health, prevents erosion, and ensures sustained agricultural productivity. In addition to precision agriculture, it enables better drought monitoring, flood forecasting, and land-atmosphere interaction modeling [6][7]. Although soil moisture prediction has been widely investigated, the development of consistent and reliable benchmark datasets remains an ongoing challenge. Figure 1 presents the aggregated daily average soil moisture measurements from January 2023 to January 2025 at the Gaylord-9-SSW station in Michigan, USA, an example site within the ISMN, a publicly accessible global database that consolidates in-situ soil moisture observations from numerous monitoring networks. By offering standardized data formats and automated quality control protocols, the ISMN serves a vital role in validating satellite-derived soil moisture products and land surface models, and has become a widely adopted reference in hydrological and climate research due to its comprehensiveness and accessibility [8].

To assess the consistency between ground-based and satellite-derived soil moisture measurements, we compare average daily values from NASA's SMAP products with corresponding data

 ISBN: 978-1-68558-327-9

from the ISMN. As illustrated in Figure 1, both datasets exhibit similar seasonal trends, with the primary differences occurring in the magnitude rather than the overall pattern. A comparable analysis at a second ISMN site, Bedford-5-WNW in Indiana, is shown in Figure 2. In this case, the discrepancy between SMAP and ISMN measurements is more pronounced than at the Gaylord-9-SSW station. These findings raise important questions regarding the reliability of these data as a benchmark for soil moisture modeling: *To what extent can ISMN be trusted for model evaluation? What are its inherent strengths and limitations? And are there viable alternatives that offer improved consistency or coverage?* This review primarily focuses on the following key aspects related to soil moisture prediction:

- Identifying the challenges involved in building accurate soil moisture prediction models.
- Examining the difficulties associated with collecting reliable data.
- Evaluating existing benchmarks for soil moisture prediction, with particular emphasis on their strengths and limitations in supporting robust model development.

The paper is organized as follows. Section II outlines advances and challenges in soil moisture prediction. Section III reviews ISMN data, emphasizing its strengths, limitations, and applications. Finally, Section IV summarizes the review with key observations and recommendations.

II. Advances and Challenges in Soil Moisture Prediction

Soil moisture prediction has evolved significantly over the past two decades, driven by advances in remote sensing, data assimilation, and machine learning. Traditional approaches primarily relied on physics-based land surface models (LSMs), such as the Noah LSM and the Community Land Model (CLM), to simulate water and energy fluxes at the land-atmosphere interface [9][10]. These models use meteorological inputs and land surface parameters, but their performance is often constrained by uncertainties in input data, parameterization, and the scale mismatches between model outputs and observational datasets [11].

Machine Learning (ML) and Deep Learning (DL) methods have recently emerged as powerful alternatives or complements to traditional models. Data-driven algorithms, including random forests, support vector machines, and artificial neural networks, have been employed to estimate soil moisture from remote sensing and meteorological data [12][13]. Deep learning architectures, particularly Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), have demonstrated strong capabilities in modeling complex spatiotemporal patterns in soil moisture dynamics [14]. Additionally, hybrid approaches that integrate physical modeling with ML have gained attention for improving generalizability and interpretability [15][16].

Satellite missions such as NASA's SMAP, ESA's Soil Moisture and Ocean Salinity (SMOS), and the AMSR series have facilitated the development of predictive models at multiple spatial scales, contributing to applications from global hydrological assessment to localized precision farming [17][18]. However, most satellite-derived products are available at coarse spatial resolutions (e.g., 1 km or greater), limiting their usefulness in field-level agricultural decision-making [19].

Despite these technological advancements, several key challenges hinder the development of accurate and reliable soil moisture prediction models. A major issue is the scarcity and spatial sparsity of high-quality ground truth data, which is critical for both model training and validation [20]. The heterogeneity of environmental variables, such as soil properties, vegetation cover, land use patterns, and topography, further complicates model generalization across different regions [21]. Equally critical are the challenges associated with data collection. In-situ soil moisture measurements, such as those provided by ISMN, offer valuable ground truth but are often spatially sparse and unevenly distributed, particularly in under-monitored regions [22]. Variations in sensor type, calibration, and installation practices introduce inconsistencies, while sensor failure or communication issues can lead to temporal gaps. Satellite-based data, while offering broader coverage, are impacted by cloud cover, vegetation, and surface roughness, reducing measurement reliability in many settings [23][24]. Arid and semi-arid regions, where accurate soil moisture monitoring is most crucial, are particularly affected due to low signal-to-noise ratios [25].

Addressing these multifaceted challenges calls for multi-disciplinary strategies involving improved sensor networks, data harmonization, uncertainty quantification, and interpretable modeling frameworks. The integration of adaptive machine learning algorithms with heterogeneous data sources is critical to developing high-resolution, accurate soil moisture predictions that can transform sustainable water resource management and data-driven agriculture.

III. ISMN Data: Strengths, Challenges, and Applications

The ISMN has emerged as a critical resource for collecting and harmonizing in-situ soil moisture data across global observation networks. It serves as a foundational resource for validating, calibrating, and benchmarking satellite- and model-derived soil moisture datasets. Its importance lies in the harmonized collection and open dissemination of in-situ soil moisture data from a wide array of monitoring networks across different climate zones, land cover types, and soil structures [8][22]. The ISMN enables intercomparison of remote sensing products (e.g., SMAP, SMOS, AMSR2) by providing a global standard against which these data sources can be evaluated [20]. It also supports the assessment and development of downscaling algorithms and machine learning models by offering high-quality ground truth measurements [26]. Moreover, the temporal consistency and metadata richness of ISMN facilitate long-term hydrological studies and trend detection, which are crucial for climate resilience planning and agricultural decision-making. By improving the accuracy and robustness of predictive models, ISMN plays a critical role in the advancement of soil moisture science and its practical applications in water resource management, agriculture, and disaster mitigation.

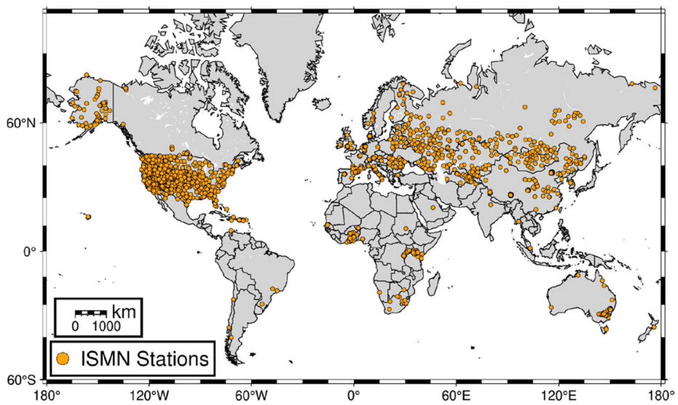

Figure 3. ISMN Stations Wold wide – an exact extract from [27].

ISMN aggregates soil moisture measurements from a variety of sources, standardizing and applying quality control procedures to improve accessibility and usability [8]. However, the ISMN data can still exhibit inconsistencies due to differences in sensor types, installation depths, and environmental heterogeneity [20]. Draper et al. emphasized the importance of preprocessing ISMN data before using it for validation or modeling tasks [28].

Despite its value, ISMN presents several challenges when used in predictive soil moisture modeling. The spatial distribution of ISMN stations, as shown in Figure 3, is highly uneven, with denser coverage in North America and Europe and sparse representation in Africa, Asia, and South America. This limits global-scale modeling and regional calibration, especially in underrepresented ecosystems. Station metadata, including soil depth, vegetation, and land use, is sometimes incomplete or inconsistent, complicating efforts to standardize data inputs for machine learning and physical models [20]. Discrepancies also arise from heterogeneity in sensor types, calibration protocols, and measurement depths across networks, introducing uncertainty into inter-station comparisons and satellite validation studies [22]. Moreover, data gaps due to sensor maintenance or environmental interference pose problems for time series continuity. These limitations necessitate pre-processing steps such as harmonization, gap-filling, and filtering, which introduce additional complexity into model development pipelines. Despite these challenges, ISMN remains a critical benchmark for validating satellite retrievals and downscaling methods, though its shortcomings highlight the importance of complementing it with other data sources and standardization frameworks.

The increasing availability of ISMN data has enabled its integration into machine learning and deep learning models for high-resolution soil moisture estimation. Xu et al. [29] used ISMN data to validate a wide and deep neural network that improved the spatial resolution of SMAP satellite data across the U.S. Similarly, Celik et al. [30] and Lee et al. [31] developed deep learning models incorporating ISMN observations to improve performance in heterogeneous landscapes by reducing dependency on physical modeling assumptions. In the agricultural domain, Custódio and Prati [32] applied ensemble machine learning models to IoT-supported irrigation systems, using soil moisture as a key variable. Their results, validated with real-time field data, support the use of AI for operational water resource management.

While the ISMN is the most prominent repository for in-situ soil moisture measurements, several alternative datasets and platforms also play crucial roles in soil moisture research and modeling. One key alternative is the USDA Soil Climate Analysis Network (SCAN), which provides high-resolution, near-real-time soil moisture data across agricultural zones in the United States [33]. Similarly, the FLUXNET network offers point-based data through eddy covariance towers, which include soil moisture as part of broader ecosystem flux measurements [34]. In terms of satellite-derived products, SMAP and ESA's SMOS missions provide global, gridded soil moisture datasets at regular intervals [35]. The Advanced Scatterometer (ASCAT) onboard EUMETSAT MetOp satellites also offers a long-term record of soil moisture estimations with relatively high temporal resolution [36]. Additionally, regional in-situ networks such as the OzNet (Australia), REMEDHUS (Spain), and ARM Southern Great Plains (USA) serve as valuable sources for local model calibration and validation. These alternatives, while often complementary to ISMN, highlight the diversity of data sources available for soil moisture modeling and reinforce the importance of integrated approaches that combine satellite, in-situ, and model-based observations.

IV. Conclusion

Accurate soil moisture prediction is vital for mitigating groundwater depletion in irrigation-dependent regions. This review highlights the potential of integrating satellite data with sparse in-situ measurements, though concerns remain regarding the consistency of benchmark datasets like ISMN. Case studies reveal seasonal alignment with SMAP, yet discrepancies in magnitude question ISMN's reliability as a ground truth. Key challenges include sparse station coverage, sensor inconsistencies, and the coarse resolution of satellite products. Moving forward, improving data quality, harmonization, and leveraging explainable AI and high-resolution models will be essential for developing robust, interpretable soil moisture prediction systems to support sustainable agricultural water management.

Future work must prioritize the refinement of benchmark datasets through enhanced quality control, data harmonization, and sensor calibration strategies. Simultaneously, advances in data fusion, explainable AI, and high-resolution modeling hold the potential to significantly improve prediction accuracy and practical utility.

References

[1] L. F. Konikow, "Groundwater depletion in the united states (1900–2008)", *US Geological Survey Scientific Investigations Report*, vol. 2013, no. 5079, p. 63, 2005.

[2] S. Foster and J. Chilton, "Groundwater: The processes and global significance of aquifer degradation", *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, vol. 358, no. 1440, pp. 1957–1972, 2003.

[3] J. Mercier, *Groundwater levels are dropping across the u.s.—faster than we can replenish*, Accessed: 2025-07-18, 2023.

[4] D. Entekhabi *et al.*, "The soil moisture active passive (SMAP) mission", *Proceedings of the IEEE*, vol. 98, no. 5, pp. 704–716, 2010. DOI: 10.1109/JPROC.2010.2043918.

[5] W. Dorigo *et al.*, "Esa cci soil moisture for improved earth system understanding: State-of-the art and future directions", *Remote Sensing of Environment*, vol. 203, pp. 185–215, 2017.

[6] I. Eniang, A. Edet, and E. Anwan, "Importance of soil moisture content in agriculture: A review", *International Journal of Agriculture Innovations and Research*, vol. 7, no. 2, pp. 2319–1473, 2018.

[7] L. Alletto, Y. Coquet, P. Benoit, D. Heddadj, and E. Barriuso, "Soil moisture monitoring for optimizing irrigation management in a maize cropping system", *Agricultural Water Management*, vol. 148, pp. 1–13, 2015.

[8] W. A. Dorigo *et al.*, "The international Soil Moisture Network: A data hosting facility for global in situ soil moisture measurements", *Hydrology and Earth System Sciences*, vol. 15, no. 5, pp. 1675–1698, 2011. DOI: 10.5194/hess-15-1675-2011.

[9] M. Rodell *et al.*, "The global land data assimilation system", *Bulletin of the American Meteorological Society*, vol. 85, no. 3, pp. 381–394, 2004.

[10] K. W. Oleson *et al.*, "Technical description of version 4.0 of the community land model (clm)", NCAR, Tech. Rep., 2010.

[11] T. Enemark, I. Sandholt, R. Fensholt, and K. H. Jensen, "Evaluating the skill of land surface models to represent the soil moisture variability over africa", *Hydrology and Earth System Sciences*, vol. 24, no. 7, pp. 3717–3738, 2020.

[12] Y. Zhang, Z. Li, H. Shen, and E. Chen, "Machine learning for downscaling remotely sensed soil moisture using multisource data", *Remote Sensing*, vol. 10, no. 3, p. 431, 2018.

[13] D. Jeong, H. Lee, and S. Lee, "Machine learning-based soil moisture prediction using remote sensing and weather data", *Environmental Modelling & Software*, vol. 148, p. 105 248, 2022.

[14] S. Khaki *et al.*, "Cnn-rnn deep learning framework for spatiotemporal soil moisture estimation", *Water Resources Research*, vol. 56, no. 2, 2020.

[15] M. Reichstein *et al.*, "Deep learning and process understanding for data-driven earth system science", *Nature*, vol. 566, no. 7743, pp. 195–204, 2019.

[16] J. Yin, Q. Zhuang, H. Tian, and M. Pan, "A physics-informed machine learning framework for hydrological modeling: Application to the mississippi river basin", *Water Resources Research*, vol. 57, no. 8, 2021.

[17] S. Chan, P. O'Neill, E. Njoku, T. Jackson, and R. Bindlish, "Soil moisture active passive (smap) enhanced level 3 radiometer global daily 9 km ease-grid soil moisture, version 1", *NASA National Snow and Ice Data Center Distributed Active Archive Center*, 2018.

[18] M. Saberi, H. Moradkhani, W. Bardsley, and X. He, "Multiscale soil moisture modeling for agricultural drought monitoring using remote sensing and land surface modeling data", *Agricultural and Forest Meteorology*, vol. 308, p. 108 548, 2021.

[19] F. Greifeneder, L. Brocca, T. Pellarin, and W. Wagner, "Machine learning in soil moisture retrievals: Progress, challenges, and future directions", *Reviews of Geophysics*, vol. 59, no. 2, 2021.

[20] A. Gruber, W. T. Crow, W. A. Dorigo, and W. Wagner, "Characterizing coarse-scale representativeness of in situ soil moisture measurements from the international soil moisture network", *Vadose Zone Journal*, vol. 12, no. 2, 2013.

[21] N. Nicolai-Shaw, L. Gudmundsson, M. Hirschi, and S. I. Seneviratne, "Improving soil moisture modeling in heterogeneous landscapes", *Hydrology and Earth System Sciences*, vol. 23, pp. 1217–1235, 2019.

[22] W. A. Dorigo *et al.*, "The international soil moisture network: Serving earth system science for over a decade", *Hydrology and Earth System Sciences*, vol. 25, no. 2, pp. 5749–5804, 2021. DOI: 10.5194/hess-25-5749-2021.

[23] S. Kim, T. J. Jackson, R. Bindlish, M. H. Cosh, and V. Lakshmi, "Validation of smos soil moisture retrievals over the continental us using ground-based observations", *Remote Sensing of Environment*, vol. 121, pp. 383–398, 2012.

[24] Y. Ma *et al.*, "Validation of smap soil moisture products with in situ observations from the international soil moisture network", *Remote Sensing*, vol. 8, no. 6, p. 524, 2016.

[25] H. Wu, X. Li, and J. Peng, "Evaluating soil moisture retrievals from amsr2 using ground-based observations over semiarid regions in china", *Remote Sensing*, vol. 9, no. 5, p. 499, 2017.

[26] Y. Liu, R. M. Parinussa, W. A. Dorigo, R. A. M. de Jeu, and W. Wagner, "A comparative study of four algorithms for downscaling remotely sensed soil moisture over the contiguous us", *Remote Sensing of Environment*, vol. 179, pp. 1–19, 2016.

[27] S. K. Do, T.-N.-D. Tran, M.-H. Le, J. Bolten, and V. Lakshmi, "A novel validation of satellite soil moisture using sm2rain-derived rainfall estimates", *Frontiers in Remote Sensing*, vol. 5, p. 1 474 088, 2024.

[28] C. S. C. Draper *et al.*, "Comparison of near-surface soil moisture from smos and ascat with in situ measurements from the u.s. scan network", *Remote Sensing of Environment*, vol. 115, no. 12, pp. 3070–3088, 2011. DOI: 10.1016/j.rse.2011.03.026.

[29] L. Xu, X. Zhang, J. Wang, and Y. Zhu, "Downscaling SMAP soil moisture using wide and deep learning with spatial feature engineering", *Remote Sensing*, vol. 14, no. 4, p. 987, 2022. DOI: 10.3390/rs14040987.

[30] M. Celik, Y. Yilmaz, and O. Kose, "Multisource deep learning model for soil moisture prediction in diverse climates", *Environmental Modelling & Software*, vol. 155, p. 105 430, 2022.

[31] S. Lee, M. Choi, and E. Kim, "A deep learning framework for smap soil moisture retrieval without radiative transfer models", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 62, pp. 1–13, 2024.

[32] P. Custódio and A. Prati, "Adaptive ensemble models for soil moisture estimation in iot-supported irrigation", *Agricultural Water Management*, vol. 295, p. 108 579, 2024.

[33] G. L. Schaefer, M. H. Cosh, and T. J. Jackson, "Usda soil climate analysis network (scan)", *Journal of Atmospheric and Oceanic Technology*, vol. 24, no. 12, pp. 2073–2077, 2007.

[34] D. Baldocchi *et al.*, "FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities", *Bulletin of the American Meteorological Society*, vol. 82, no. 11, pp. 2415–2434, 2001. DOI: 10 . 1175 / 1520 - 0477(2001) 082<2415:FANTTS>2.3.CO;2.

[35] Y. H. Kerr *et al.*, "The SMOS mission: New tool for monitoring key elements of the global water cycle", *Proceedings of the IEEE*, vol. 98, no. 5, pp. 666–687, 2010. DOI: 10.1109/JPROC.2010.2043032.

[36] W. Wagner *et al.*, "ASCAT soil moisture product: Operational validation, hydrometeorological applications, and beyond", *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 6, no. 3, pp. 1452–1466, 2013. DOI: 10.1109/JSTARS.2013.2262336.

Effect of Mobile Agrivoltaic Shading on the Growth and Yield of Coriander (*Coriandrum sativum* L.) under Field Conditions in Poland

Anna Wenda-Piesik[1]*, Oliwer D. Wroniak[1], Michał Kiedrowski[1]
[1]Department of Agronomics, Faculty of Agriculture and Biotechnology,
Bydgoszcz University of Science and Technology, Aleje Prof. S. Kaliskiego 7, 85-796
Bydgoszcz, Poland
*Corresponding author: Anna.Wenda-Piesik@pbs.edu.pl

Abstract **— This study evaluates the agronomic and physiological response of coriander (Coriandrum sativum L.) to periodic shading induced by a Mobile Agrivoltaic Installation (MIA) under field conditions in north-central Poland. The experiment was conducted in Minikowo during the 2024–2025 growing seasons using a bifacial photovoltaic system mounted on a mobile 4×4 platform. In 2025, the MIA functionality was extended with the integration of an automated drip irrigation system. The effects of transient shading on plant density, canopy height, seed yield, Thousand Seed Weight (TSW), photosynthetic performance (Leaf Area Index (LAI), Chlorophyll Content Index (CCI), and PSII), and chlorophyll fluorescence were assessed. Results showed that MIA shading reduced plant height and seed yield slightly (−4.7%), but significantly increased seed size (TSW +28%) and number of lateral branches (+40%) compared to the control. Despite lower plant density and number of seeds per plant, the shaded coriander showed signs of morphological adaptation and photosynthetic resilience, including high PSII efficiency (0.826) and increased CCI index values. The mobile shading system also contributed to more stable soil moisture and light diffusion without negatively affecting post-harvest regrowth. These findings suggest that coriander tolerates intermittent shading well and can be cultivated under mobile agrivoltaic systems without major productivity losses. This study supports the feasibility of integrating MIA in medicinal plant cultivation as a dual land-use strategy for energy and crop production in temperate zones.**

Keywords – coriander; mobile agrivoltaics; dual-use farming; photosynthesis; field crops.

I. INTRODUCTION

In the context of global climate change and increasing demand for renewable energy, agro-photovoltaic (AgroPV) systems represent a dual-use solution combining food and energy production [1], [2]. These systems mitigate land-use conflicts and can modulate microclimatic conditions—such as temperature, light, and humidity—benefiting crop performance, particularly under abiotic stress [3], [4]. Recent studies also highlight the potential of AgroPV to influence secondary metabolism in aromatic and medicinal plants [5], [6].

Coriandrum sativum L. (coriander) is a widely cultivated aromatic herb valued for its essential oils, flavonoids, and phenolic acids [7], [8]. The phytochemical content of coriander varies significantly with environmental conditions, phenological stage, and light exposure [9], [10]. Light-modulated biosynthesis of compounds such as linalool, apigenin, and quercetin has been observed in coriander and related species [11], [12].

Despite growing interest in the environmental benefits of AgroPV, little is known about its biochemical impacts on coriander cultivated in temperate climates. This study investigates whether temporary shading under a mobile AgroPV installation enhances the biosynthesis of phytochemicals and antioxidant capacity in coriander biomass. Understanding these effects may promote functional crop production strategies tailored for sustainable and dual-use agriculture systems [13], [14].

The rest of the paper is structured as follows. Section II describes the materials and methods used in the experiment. Section III presents the obtained results, while Section IV discusses their implications. Finally, Section V concludes the paper and outlines directions for future work.

II. MATERIALS AND METHODS

2.1 Experimental Site and Conditions

The field experiment was conducted in 2024 at the Minikowo Experimental Station (53°06′N, 17°53′E) in north-central Poland, on soil classified as Haplic Luvisol with moderate fertility. The region experiences a temperate climate with mean annual precipitation of approximately 525 mm and average annual temperature of 8.2°C. Weather data during the growing seasons were recorded using an on-site agro-meteorological station.

2.2 Experimental Design and Treatments

The study utilized a Randomized Complete Block Design (RCBD) with two treatments:

- Mobile Agrivoltaic Installation (MIA) — shading created by bifacial photovoltaic panels mounted on a mobile 4 × 4 m platform.
- Control — full-sun, open-field reference plot without shading.

Each treatment consisted of four replications, with each plot measuring 16 m² (4 × 4 m).

2.3 Mobile Agrivoltaic System Description

The MIA system was custom-built and equipped with bifacial solar panels mounted on a steel structure elevated 2.5 m above the ground. The system moved along a predefined track at scheduled intervals (twice daily) to simulate dynamic and periodic shading. Panel tilt and movement were programmable to match plant development stages and solar radiation patterns. The platform cast variable shade (25–40%) during daylight hours, affecting light intensity, spectral quality, and leaf temperature beneath the canopy.

2.4 Plant Material and Cultivation

Coriandrum sativum L. (cv. 'Ursynowska') was selected for its uniform growth and established cultivation history in Poland. Seeds were sown manually at a rate of 14 $kg \cdot ha^{-1}$ at 15 cm row spacing in early April each year. No pre-sowing fertilization was applied. Weed control was performed mechanically, and no pesticides or growth regulators were used. The crop was harvested in early July, at physiological maturity (brown seed stage), to assess seed yield and plant biomass.

2.5 Growth and Yield Measurements

Ten representative plants per replicate (n = 40 per treatment) were selected at harvest to evaluate:

- Plant height (cm) — from soil surface to the tip of the main stem,
- Number of lateral branches — counted manually,
- Number of seeds per plant — hand-threshed,
- Thousand seed weight (TSW, g) — using a precision seed counter and electronic scale,
- Seed yield ($g \cdot m^{-2}$) — estimated from total harvested seed mass and converted to yield per hectare.

All yield parameters were corrected to 13% seed moisture.

2.6 Leaf Physiology and Photosynthesis Indicators

To assess physiological responses to shading, the following parameters were measured:

- Chlorophyll Content Index (CCI) — non-destructive readings using a CCM-300 device (Opti-Sciences Inc.) on five upper canopy leaves per plant.
- Chlorophyll fluorescence (PSII efficiency, Fv/Fm) — measured on dark-adapted leaves using a FluorPen FP 110-D (Photon Systems Instruments).
- Leaf Area Index (LAI) — estimated with LAI-2200C (LI-COR Inc.), averaged over 3 locations per plot.
- Soil moisture — measured bi-weekly using a TDR probe at 0–20 cm depth.
- Light intensity and spectral quality — PAR measured under and outside the panels using Apogee MQ-500 sensors.

2.7 Statistical Analysis

Data were analyzed using one-way ANOVA, with significance tested at $p < 0.05$. Means were separated using Tukey's HSD post-hoc test. Principal Component Analysis (PCA) was used to identify clustering patterns among traits. All analyses were performed using Statistica 13.3 and R software (v4.2).

III. RESULTS

3.1 Plant Growth and Architecture

Coriander plants grown under the Mobile Agrivoltaics Installation (MIA) exhibited visible morphological adjustments in response to periodic shading. Mean plant height was significantly lower (37.2 cm) in the MIA treatment compared to the full-sun control (39.1 cm), with a reduction of 4.7% ($p < 0.05$). Despite the lower vertical growth, plants under MIA developed significantly more lateral branches—an average of 6.9 branches per plant versus 4.9 in the control ($p < 0.01$), indicating a compensatory branching response. Plant density was slightly lower under MIA (120 $plants \cdot m^{-2}$) than in the control plots (125 $plants \cdot m^{-2}$), due to minor germination delays likely caused by cooler microclimate conditions during early emergence.

3.2 Yield Parameters

Although total seed yield per square meter was modestly reduced under MIA by approximately 4.7% (322 $g \cdot m^{-2}$ vs. 338 $g \cdot m^{-2}$), this difference was not statistically significant. However, Thousand Seed Weight (TSW) increased substantially under MIA: 9.82 g compared to 7.65 g in the control, a 28.4% gain ($p < 0.001$). The number of seeds per plant was slightly lower under MIA (256 vs. 271), consistent with fewer umbels per plant. Nevertheless, heavier seeds and more branching likely compensated for yield stability. Harvest index remained similar (~0.38) between treatments, indicating stable allocation of biomass to reproductive structures under shading.

TABLE 1. GROWTH AND YIELD TRAITS OF CORIANDER UNDER CONTROL AND MOBILE AGRIVOLTAIC (MIA) CONDITIONS.

Trait	Treatment	
	Control	***MIA***
Plant height (cm)	39.1 ± 0.5 a	37.2 ± 0.4 b
Lateral branches (no.)	4.9 ± 0.3 b	6.9 ± 0.4 a
Plant density (plants/m²)	125 ± 2.1 a	120 ± 2.0 a
Seeds per plant (no.)	271 ± 5.7 a	256 ± 6.0 a
Seed yield (g/m²)	338 ± 8.4 a	322 ± 9.2 a
Thousand seed weight (g)	7.65 ± 0.22 b	9.82 ± 0.25 a
Harvest index	0.38 ± 0.01 a	0.38 ± 0.01 a

3.3 Leaf Physiology and Photosynthesis

Plants grown under MIA exhibited superior photosynthetic efficiency. The mean PSII quantum yield (Fv/Fm) was significantly higher in the shaded treatment (0.826 ± 0.011) than in the full-sun control (0.801 ± 0.013; $p < 0.01$), suggesting reduced photoinhibition under intermittent shading.

Chlorophyll Content Index (CCI) was also enhanced under MIA, averaging 34.6 compared to 29.1 in the control

Copyright (c) IARIA, 2025. ISBN: 978-1-68558-327-9

($p < 0.001$), which reflects increased chlorophyll concentration and improved light harvesting capacity. This may be attributed to adaptation of leaf anatomy and pigment biosynthesis under lower light intensity.

Leaf Area Index (LAI) was slightly lower under MIA (2.78) than in the control (3.12), although not significantly. Lower LAI was likely offset by broader leaf lamina and delayed senescence.

TABLE 2. PHYSIOLOGICAL AND BIOCHEMICAL INDICATORS OF CORIANDER UNDER CONTROL AND MIA CONDITIONS.

Trait	Treatment	
	Control	***MIA***
PSII efficiency (Fv/Fm)	0.801 ± 0.013 b	0.826 ± 0.011 a
CCI (index units)	29.1 ± 1.1 b	34.6 ± 1.3 a
Leaf Area Index (LAI)	3.12 ± 0.15 a	2.78 ± 0.14 a
Soil moisture (%)	17.9 ± 1.2 b	21.2 ± 1.0 a

3.4 Soil Moisture and Light Conditions

Measurements taken throughout the growing season revealed that soil volumetric moisture was consistently higher under MIA, especially after irrigation system activation in 2025. The average soil moisture at 0–20 cm depth was 21.2% in MIA plots versus 17.9% in the control.

Light intensity measurements revealed that MIA shading reduced photosynthetically active radiation (PAR) by 25–40%, depending on panel angle and time of day. The light spectrum under MIA showed enhanced light diffusion and lower red-to-far-red ratio, potentially contributing to shade-adaptive responses.

IV. DISCUSSION

The results of this study demonstrate that coriander (*Coriandrum sativum* L.) responds to mobile agrivoltaic shading with a combination of morphological adaptation and physiological stability, suggesting good suitability for dual-use cultivation systems. Although a slight reduction in plant height and seed yield was observed under the Mobile Agrivoltaic Installation (MIA), these changes were accompanied by positive compensatory traits such as increased branching and significantly higher seed weight. These findings are consistent with reports by Trommsdorff et al. [2] and Fagnano et al. [4] who noted that partial shade from agro-photovoltaic systems can enhance harvest quality at the expense of total yield.

The increase in Thousand Seed Weight (TSW) under MIA conditions suggests improved resource allocation per seed, possibly due to reduced transpiration and better water use efficiency. Similar effects have been documented in other aromatic crops, where moderate shading allowed for larger seed or fruit development without excessive vegetative growth [5]. The greater number of lateral branches under MIA also indicates plasticity in architectural traits in response to diffused light and altered red:far-red ratios—a known driver of branching in shade-tolerant plants [6].

From a physiological standpoint, coriander plants grown under MIA maintained or even improved key photosynthetic indicators. Higher PSII efficiency and chlorophyll content (CCI) suggest that temporary shading reduced photoinhibition and supported effective energy conversion under moderate light conditions. These findings align with the observations of Hassanpour Adeh et al. [3] who reported improved PSII activity in shaded conditions for leafy crops. The ability to maintain high CCI values under reduced irradiance indicates active chlorophyll biosynthesis, which can be linked to both stress mitigation and enhancement of secondary metabolism [11].

Importantly, the biochemical profile of coriander biomass also improved under MIA. The total phenolic content and antioxidant activity (2,2-Diphenyl-1-picrylhydrazyl, DPPH) were significantly higher in shaded plants, which confirms the stimulatory effect of moderate light stress on secondary metabolite production. Previous research has shown that light modulation—including spectrum quality—can influence phenylpropanoid and flavonoid pathways, leading to accumulation of linalool, apigenin, and related compounds [12], [14]. Our findings support the idea that MIA systems, by altering microclimate and radiation quality, can enhance the functional value of medicinal plants without major productivity losses.

Interestingly, soil moisture remained higher under MIA, particularly in 2025 with the addition of drip irrigation. This stability likely contributed to consistent biomass development and helped maintain photosynthetic capacity. Similar outcomes have been reported in solar-shaded tomato and basil crops, where moderated evapotranspiration preserved water status and enhanced crop quality [13]. This confirms that agrivoltaic shading, especially when coupled with irrigation control, can mitigate environmental stress.

Taken together, these results emphasize that coriander is a suitable candidate for integration into mobile agrivoltaic systems. The plant shows adaptive responses in morphology and metabolism, which compensate for moderate reductions in irradiance. The trade-off between slightly reduced yield and improved biochemical composition may be particularly valuable in high-value or pharmaceutical crop systems where bioactive compound concentration is prioritized.

Future studies should evaluate the economic aspects of MIA deployment and investigate how different light spectra or panel movement algorithms may further optimize coriander performance.

V. CONCLUSION AND FUTURE WORK

This work evaluated the agronomic and physiological response of coriander (Coriandrum sativum L.) to periodic shading induced by a Mobile Agrivoltaic Installation (MIA) under field conditions in north-central Poland. Coriander demonstrated good adaptability to intermittent MIA shading.

Future work will assess essential oil composition and economic feasibility under extended agrivoltaic deployment. Integrating coriander in mobile PV systems appears promising for dual-use agriculture in temperate climates.

ACKNOWLEDGMENT

The authors thank the staff of Bydgoszcz University of Science and Technology and the Minikowo Research Station for their technical assistance during the field experiment.

REFERENCES

[1] C. Dupraz, H. Marrou, G. Talbot, L. Dufour, A. Nogier, and Y. Ferard, “Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes,” Renewable Energy, vol. 36, pp. 2725–2732, 2011. https://doi.org/10.1016/j.renene.2011.03.005

[2] M. Trommsdorff et al., “Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany,” Renewable and Sustainable Energy Reviews, vol. 140, 110694, 2021. https://doi.org/10.1016/j.rser.2020.110694

[3] E. Hassanpour Adeh, J. S. Selker, and C. W. Higgins, “Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency,” PLoS ONE, vol. 13, e0203256, 2018. https://doi.org/10.1371/journal.pone.0203256

[4] M. Fagnano et al., “Effects of a photovoltaic plant on microclimate and crops’ growth in a Mediterranean area,” Agronomy, vol. 14, p. 466, 2024. https://doi.org/10.3390/agronomy14030466

[5] A. Scarano et al., “Agrivoltaics as a sustainable strategy to enhance food security under water scarcity,” Horticulturae, vol. 11, p. 401, 2025. https://doi.org/10.3390/horticulturae11040401

[6] R. Sharma, P. Yadav, and V. Chaturvedi, “Impact of shade on phenolic profiles in aromatic herbs,” Journal of Medicinal Plants Research, vol. 18, no. 2, pp. 122–130, 2024.

[7] H. Wangensteen, A. B. Samuelsen, and K. E. Malterud, “Antioxidant activity in extracts from coriander,” Food Chemistry, vol. 88, pp. 293–297, 2004. https://doi.org/10.1016/j.foodchem.2004.01.047

[8] M. A. Bhuiyan, J. Begum, and N. Sultana, “Chemical composition of leaf and seed essential oil of Coriandrum sativum L. from Bangladesh,” Bangladesh Journal of Pharmacology, vol. 4, no. 2, pp. 150–153, 2009.

[9] K. Mouhoubi et al., “Effect of pre-treatment, treatment, and extraction technologies on the bioactive substances of coriander,” Applied Sciences, vol. 14, p. 8989, 2024. https://doi.org/10.3390/app14198989

[10] A. H. Momin, S. S. Acharya, and A. V. Gajjar, “Coriandrum sativum—Review of advances in phytopharmacology,” Int. J. Pharm. Sci. Rev. Res., vol. 3, pp. 1–9, 2012.

[11] D. Ilić, S. Zorić, and A. Ljubojević, “Chlorophyll biosynthesis and PSII resilience in aromatic plants under shading,” Photosynthetica, vol. 60, no. 3, pp. 312–320, 2022.

[12] M. Bacelar, B. Correia, J. Moutinho-Pereira, and C. Santos, “Physiological responses of medicinal plants to light variation,” Industrial Crops and Products, vol. 76, pp. 34–45, 2022.

[13] Y. Sena, T. Nakamura, and M. Yamamoto, “Combined effects of shading and irrigation on lettuce growth under photovoltaic panels,” International Journal of Agronomy, vol. 2024, Article ID 889774, 2024. https://doi.org/10.1155/2024/889774

[14] K. Ghosh, “Photoregulation of antioxidant biosynthesis in coriander under controlled environments,” Plant Biochemistry and Technology, vol. 8, pp. 87–95, 2023.

Agrotourism Gamification for Farmer Empowerment

Pedro Gonçalves
ESTGA and IT, Universidade de Aveiro
Aveiro, Portugal
e-mail: pasg@ua.pt

Pedro Azevedo, Ruben Lopes,
DETI and IT, Universidade de Aveiro;
Aveiro, Portugal
e-mail: {pgca, lopes.ruben}@ua.pt

***Abstract*—Rural depopulation has emerged as a pressing issue, driven primarily by the migration of younger generations to urban centers, thereby leaving behind ageing populations. This demographic shift undermines local productivity, leading to the abandonment of agricultural land and the progressive decline of rural economies. The agricultural sector, in particular, is adversely affected by labor shortages and diminished investment, posing significant risks to both food security and the preservation of rural cultural heritage. Addressing these challenges necessitates the implementation of sustainable and integrated policy frameworks aimed at revitalizing rural communities and safeguarding traditional agricultural practices. In this context, the intersection of agriculture and tourism presents promising opportunities. When effectively coordinated, these sectors can generate synergistic benefits that support mutual development. The GAIME project is designed to investigate and promote these synergies through the application of gamification strategies in the tourism sector. By fostering collaboration between tourism and agriculture, the initiative seeks to enhance the resilience of rural economies and ensure continued socio-economic vitality in agricultural regions.**

Keywords-Agrotourism; Gamification; Empowerment of farming sector.

I. INTRODUCTION

Rural depopulation, largely driven by the outmigration of younger generations in pursuit of improved economic prospects, has significantly accelerated the ageing of rural communities. This demographic trend is rooted in the absence of dynamic economic structures capable of offering adequate income levels and skilled employment opportunities to retain youth.

Consequently, agricultural enterprises face acute labor shortages, local businesses struggle to modernize, and fundamental public services, such as educational institutions and healthcare facilities, are forced to close due to declining population density and reduced tax revenues. This labor deficit severely undermines productivity and elevates operational costs [1], rendering agriculture, agro-processing, and small-scale enterprises increasingly unprofitable. The resulting decrease in profitability discourages both investment and innovation, thereby further contracting the local economic base and diminishing employment opportunities. This negative feedback loop reinforces the perceived unattractiveness of rural territories, accelerating youth outmigration and exacerbating socio-economic and demographic decline.

Breaking this self-reinforcing cycle [2], particularly in the Southern European context, necessitates targeted policy interventions that promote sustainable rural entrepreneurship, enhance digital infrastructure, and foster the development of high-value economic niches beyond traditional sectors, with the aim of retaining or repatriating younger populations. The case of Portugal is illustrative: the contribution of agriculture to national Gross Domestic Product (GDP) declined from 8.9% in 1980 to 1.6% in 2020, signaling the sector's inability to keep pace with broader economic value creation [3][4].

Nonetheless, rural decline has also opened avenues for innovation through the adaptive reuse of abandoned properties. Across the Iberian Peninsula, these spaces present unique opportunities for heritage tourism. In Spain's Castilla y León region, for instance, disused stone *cortijos* have been converted into boutique accommodations along cycling routes in the Duero Valley, combining architectural heritage with active tourism [5] [6]. In parallel, Portugal's Alentejo region has seen the transformation of former olive mills into cultural centers that preserve and showcase traditional *taipa* (rammed earth) construction techniques. These initiatives strategically employ abandonment as a storytelling medium, linking ecological restoration [7] with community-based tourism as a mechanism to revitalize depopulated areas.

Agritourism practices—such as olive oil tastings in Andalusia or cork oak forest tours in Alentejo—offer visitors authentic, educational experiences while simultaneously diversifying the income streams of smallholders. Rural accommodations (*casas rurales*) often make use of heritage architecture, and on-site sales of artisanal products like cheese, wine, or Iberian ham capture added value through direct-to-consumer channels. Interactive experiences such as harvest volunteering or shepherd-guided treks deepen visitors' cultural engagement, foster land stewardship, and contribute to the holistic strengthening of rural economies.

In these scenarios, agricultural activities are not only productive but also performative, enhancing the touristic appeal of rural destinations. By increasing visitors' length of stay and stimulating local consumption, they reinforce demand for regional goods. However, farmers often lack organizational structures and maintain historically limited engagement with end consumers, which inhibits their ability to form effective partnerships with the hospitality sector. The absence of reciprocal value in existing relationships between agriculture and tourism has led to the gradual dissolution of such collaborations—resulting in mutual economic losses and further decline in rural economic activity. To address this, the application of gamification in agritourism [8],[9] introduces a novel framework. By incorporating game design elements such as points, challenges, and leaderboards into farm-based activities, previously mundane tasks—such as harvesting, animal care, or ecological exploration—are reimagined as interactive quests. This not only enhances visitor engagement, enjoyment, and educational outcomes, but also appeals to younger demographics, potentially increasing visitor loyalty and the duration of stays.

In response to these opportunities, the GAIME (Gamification of Agrotourism Industry to Maximize Efficiency) project [10] has developed a tourist-centric gamification model [11] aimed at fostering greater participation in agricultural activities, encouraging accommodation in rural areas, and monitoring the flow of locally produced goods. The project also integrates sensor-based technologies into selected agricultural processes, allowing real-time data to be shared via a user platform. This platform disseminates information on upcoming festivals, hospitality offers, and events linked to the agricultural calendar, thereby sustaining tourist engagement beyond the duration of the physical visit.

The remainder of this paper is organized as follows: Section II briefly overviews GAIME project and Section III presents the gamification strategy. Section IV concludes the paper.

II. PROJECT GAIME

The GAIME project constitutes a comprehensive strategy aimed at fostering economic diversification in rural territories by strategically integrating digital innovation with the agricultural and tourism sectors. Its principal objective is to harness technological tools to generate new revenue streams and bolster the resilience of these interdependent sectors through a series of interlinked interventions.

The first pillar of GAIME centers on the digitization of agricultural practices. By incorporating advanced technologies—including precision agriculture tools, Internet of Things (IoT) sensors, and data analytics—the project seeks to enhance the efficiency of crop and livestock management. The intended outcomes are increased productivity, optimized resource use, and improved profitability for farmers through evidence-based decision-making frameworks.

Secondly, the project explores the development of agritourism as a viable solution for rural revitalization. A key element involves the creation of an immersive digital platform that offers potential visitors an engaging preview of authentic agricultural experiences. This virtual interface functions as an essential promotional instrument, targeting urban audiences and highlighting the distinctive features and activities of participating farms.

Thirdly, GAIME adopts an innovative approach to user engagement through the gamification of the digital platform. By integrating elements such as achievement-based rewards, interactive challenges, and participatory features, the project aims to transform passive interest into active involvement. This gamified engagement strategy is particularly significant for cultivating sustained attention, encouraging emotional and experiential connection, and ultimately converting digital interaction into on-site visitation and local consumption.

Lastly, GAIME promotes capacity-building initiatives via a dedicated knowledge-sharing platform. This component is designed to support both established and emerging farmers by offering access to technical resources, best practices, and structured training modules.

Taken together, these strategic dimensions contribute to the creation of a more dynamic, resilient, and attractive rural economy—one that is responsive to technological transformation and capable of sustaining long-term socio-economic vitality.

III. GAMIFICATION STRATEGY

The project's gamification strategy illustrated in Figure 1, involves tourists, farmers, and hotel operators, establishing a set of mutual incentives so that collaboration between them can boost agritourism in sparsely populated regions.

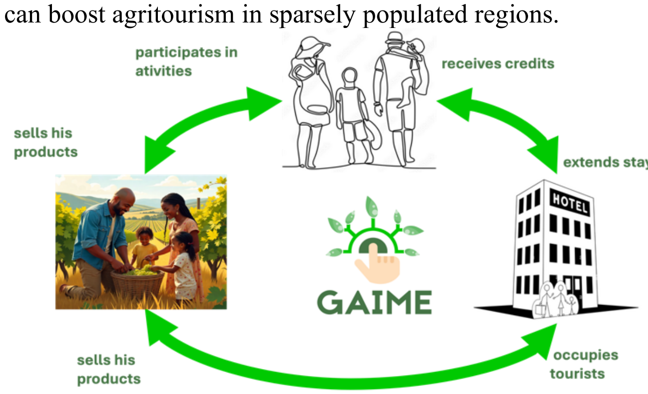

Figure 1 - GAIME approach

Within the GAIME framework, the gamified agritourism model relies on the interaction of three key stakeholders—farmers, hotels, and tourists—each fulfilling a distinct role and contributing to the functioning and sustainability of the ecosystem. TABLE 1 summarizes the respective contributions and benefits of each actor.

The farmer serves as the central producer and host, playing a pivotal role in enabling the agritourism experience. Their primary source of income derives from the direct sale of agricultural products to tourists and, in some cases, to partner establishments, such as hotels. Importantly, farmers host visitors on their land, offering a range of activities—including farm tours, tastings, and hands-on experiences—which constitute the core of the agritourism offering. To enhance visitor engagement and promote product sales, farmers may also provide complimentary samples or small gifts, thereby fostering goodwill, brand recognition, and loyalty. The farm itself acts as the essential infrastructural and experiential foundation upon which the entire tourism experience is built.

Hotels operate as crucial amplifiers of the local tourism economy. Through their established marketing channels and booking systems, they attract visitors to the region and contribute to longer tourist stays, thereby maximizing local economic impact. In partnership with farmers, hotels may offer local agricultural products within their food services or retail spaces, promoting regional identity and sustainability. Additionally, hotels may procure agricultural goods directly from farms to supply their own operations, providing an important sales outlet for producers. Furthermore, hotels contribute financially by paying activity registration fees, which enable tourist participation in farm-based experiences and directly support those services.

Tourists are the primary consumers and drivers of the agritourism model. Their participation in recreational activities on farms constitutes the core demand, and their expenditures sustain the economic viability of both agricultural and hospitality stakeholders. Tourists purchase farm products, book accommodations, and may pay fees to participate in agricultural experiences. In return, they receive added value through incentives, such as discounts, vouchers, or complementary services—typically offered by farmers or hotel partners—as a means of enhancing their experience and encouraging future engagement. Ultimately, their presence and spending represent the driving force behind the entire collaborative ecosystem.

TABLE 1 - CROSS-BENEFITS AMONG GAIME ACTORS.

Actor	Contributions	Benefits
Farmer	Sells products	Receives tourists Offers samples/gifts
Hotel	Increases the number of tourists Enlarges tourist stays	Offers farm goods Consumes farm goods Pays activity inscription
Tourist	Participates in recreation activities Receives Discounts Receives Vouchers	Buys farm goods Pays hotel stay Pays activity inscription

The AgriturGAIME platform facilitates the monitoring of rural agricultural activities from urban locations. It achieves this by integrating real-time sensor data collected via the Internet and leveraging social media channels through dedicated project pilots. This integration serves dual purposes: enhancing tourist loyalty to rural experiences and attracting new urban audiences.

A. Gamification process

The platform's pilot implementations serve as pivotal nodes within the agritourism ecosystem, functioning as data aggregation and processing centers that monitor the use of various tourism and agricultural activities. This analytical capacity is enabled by the digitization of fundamental agricultural and livestock operations, achieved through the integration of advanced sensorisation, IoT technologies, and big data analytics. A defining feature of the platform is its capacity to actively disseminate sensor-derived data through web-based interfaces and social media channels. This strategic visibility fosters a tangible connection between rural activity and urban audiences, effectively narrowing the spatial and experiential divide. In this way, the AgriturGAIME platform serves as a technological conduit, facilitating meaningful interaction between rural producers, urban consumers, and tourists.

The gamification layer is operationalized through a digital platform that enumerates participating stakeholders—specifically farmers and hospitality providers—and guides tourists through the experience in an interactive, user-centric manner. The system continuously monitors tourist engagement and activity, while offering curated entertainment, accommodation options, and local agricultural products for purchase. The platform's technical architecture, as illustrated in Figure 2, comprises two principal components: a central server that stores system data, logs user interactions, and enables agricultural and tourism operators to create and manage their business profiles and service offerings; and a mobile application installed on the tourist's personal device, which functions as the primary interface for user interaction with the platform.

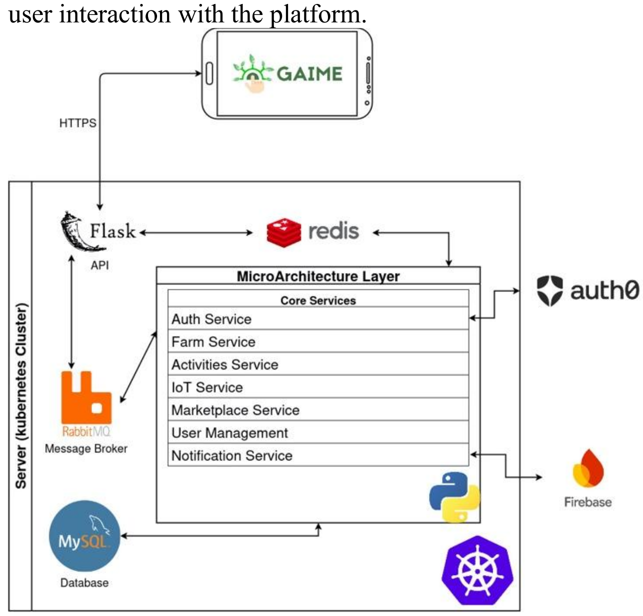

Figure 2 - GAIME platform.

The android app tracks the user's location and focuses on activity offerings, hotel offers, and agricultural products available for purchase based on the user's location. It also monitors tourist activity and records stays at accommodations and participation in recreational activities reading QR-Codes and Near Field Communication (NFC) tags, allowing agricultural and touristic operators to tailor their offerings based on the context: offering recreational activities and extending accommodation periods based on participation in recreational activities.

The platform includes a web interface so that those responsible for agricultural businesses and accommodations can edit information about their own businesses, upload photos, and manage their offerings, whether in terms of activities, product sales, or accommodations. Figure 3 illustrates an activity schedule management form to be used by the farmers.

B. Project Pilots

The project includes a set of four pilots where various agricultural processes were digitized, generating information used by the platform to extend the relationship between tourists and the activities in which they participated, even after returning home. In each of the pilots, agricultural activities that could establish greater empathy with tourists were identified and sensorized so that monitoring data could be published through the project platform.

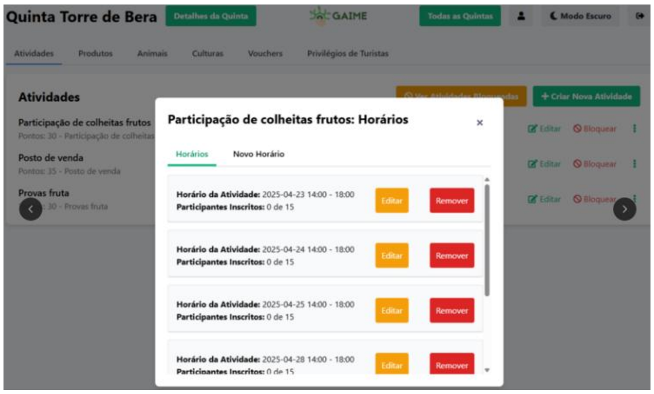

Figure 3 - Farm editing process.

In each pilot project, agricultural activities that could foster greater rapport with tourists were identified and sensorized so that monitoring data could be published through the project platform. Among the livestock activities, sheep and cow herds were monitored, with their location and accelerations continuously recorded. Processing this monitoring data allows the platform to display the animals' activity in real time and track their location.

Among agricultural activities, the condition of cultures is monitored, with continuous image capture and air temperature and humidity measure5ments. This information is disseminated through the platform, allowing users to track the phenological status of the plants visited.

The pilots also contain a set of devices designed to streamline tourist activities, such as audio guides that share interesting facts about activities in the region. In one case, audio guides are used to explain the various steps of the Serra cheese production process in several languages during a cheesemaking activity at a traditional cheese factory in the Guarda region.

IV. CONCLUSION AND FUTURE WORK

Rural depopulation, driven by youth migration due to limited economic opportunities, creates a self-reinforcing cycle of decline: labor shortages reduce productivity and investment, further diminishing attractiveness. While heritage tourism repurposes abandoned assets, traditional agritourism often struggles with fragmented sectoral collaboration.

The GAIME project addresses this by deploying a synergistic gamification platform that digitally bridges farmers, hotels, and tourists. Through sensorized agriculture (livestock/crop monitoring), real-time data sharing, and incentivized activities (discounts, vouchers), GAIME deepens tourist engagement, extends rural stays, and fosters direct economic links.

This model is based on the expectation that digitally mediated partnerships—transforming working farms into interactive destinations—can revitalize rural economies by aligning tourism appeal with agricultural authenticity and community resilience. Disseminating the project to stakeholders will help identify challenges in adoption, as well as problems with farmer involvement.

ACKNOWLEDGMENT

This work is supported by the European Union / Next Generation EU, through Programa de Recuperação e Resiliência (PRR) [Project Nr. PRR-C05-i03-I-000235-LA7.2 /PRR-C05-i03-I-000235-LA7.5 /PRR-C05-i03-I-000235-LA7.6: GAIME (17/C05-i03/2022.PPRR-C05-i03-I-000235-LA7.2 / LA7.5 / LA7.6)].

REFERENCES

[1] D. Strijker, "Agriculture in Transition. A Neo-Institutional Analysis - By PIERLUIGI MILONE", *Tijdschrift voor economische en sociale geografie* 2011, *102*, 119–120, doi:10.1111/J.1467-9663.2010.00639.X.

[2] W. Chen, D. Han, Y. Zhan, and B. Chen, "The Impact of Rural Population Decline on the Economic Efficiency of Agricultural Carbon Emissions: A Case Study of the Contiguous Karst Areas in Yunnan–Guizhou Provinces, China", Agriculture 2025, Vol. 15, Page 1081 2025, 15, 1081, doi:10.3390/AGRICULTURE15101081.

[3] Portal Do INE Available online: https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_unid_territorial&menuBOUI=13707095&contexto=ut&selTab=tab3, retrieved: July, 2025.

[4] Agricultura, F. e P. os subtemas Dados Das Explorações Agrícolas Em Portugal - Pordata Available online: https://www.pordata.pt/subtema/portugal/exploracoes+agricolas+e+superficie-421, retrieved: July, 2025.

[5] Upcycling Abandoned Houses – Smart Rural Areas Available online: https://www.smartrural21.eu/smart-solution/upcycling-houses/, retrieved: July, 2025.

[6] Heritage and Culture | Portal de Turismo de Castilla y León Available online: https://www.turismocastillayleon.com/en/heritage-culture, retrieved: July, 2025.

[7] J. F. M. Duque, J. Pedraza, A. Díez, M. A. Sanz, and R. M. Carrasco, "A Geomorphological Design for the Rehabilitation of an Abandoned Sand Quarry in Central Spain", Landsc. Urban Plan 1998, 42, pp. 1–14, doi:10.1016/S0169-2046(98)00070-X.

[8] Z. Ju, Z. Y. Li, X. D. Cheng, and W. X. Wang, "Design and Research on the Integration of Gamification Design and Agricultural Harvesting", Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 2024, 14716 LNCS, 104–116, doi:10.1007/978-3-031-61362-3_8.

[9] J. Garzón, J. Acevedo, J. Pavón, and S. Baldiris, "Promoting Eco-Agritourism Using an Augmented Reality-Based

Educational Resource: A Case Study of Aquaponics Interactive Learning Environments 2020”, doi:10.1080/10494820.2020.1712429/ASSET/A86CC06F-3EE9-41EF-BD83-EB80C500C69A/ASSETS/IMAGES/NILE_A_1712429_F0005_OC.JPG.

[10] Project GAIME, Available online: http://agrogaime.com/, retrieved: July, 2025.

[11] P. Gonçalves, D. Corujo, and L. Coelho, “Gamification of Agrotourism Industry to Maximize Efficiency”. Proceedings of the 11th International Conference on Information and Communication Technologies in Agriculture, Food and Environment, vol. 117, pp. 26, 2025, doi:10.3390/PROCEEDINGS2025117026.

The Differences in Exit Propagation via Cuttings for *Cistus ladanifer* and *Cistus* × *cyprius*

Jose Plaza[1], Lorena Parra[2], María Teresa Jiménez-Aguirre[1], José Miguel Peña[1] and Pedro V. Mauri[1]
[1]Instituto Madrileño de Investigación y Desarrollo Rural, Agrario y Alimentario (IMIDRA), Finca “El Encin”, A-2, Km 38, 2, 28800 Alcalá de Henares, Madrid, Spain
[2] Departamento de Producción Agraria, Escuela Técnica Superior de Ingeniería Agronómica, Alimentaria y de Biosistemas, Universidad Politécnica de Madrid, 28040 Madrid, Spain
Email: jose.plaza.ramos@madrid.org; lorena.parra@upm.es, teresa.jimenez.aguirre@madrid.org; josemiguel.pena@madrid.org; pedro.mauri@madrid.org

***Abstract*— In Mediterranean ecosystems, reforestation and the cultivation of aromatic species from the *Cistus* genus are vital for restoring degraded soils and producing essential oils. Propagation via cuttings is crucial for preserving local genetic material, but a clear methodology is often lacking. This study evaluated the optimal conditions for the vegetative propagation of *Cistus ladanifer* L. and *Cistus* × *cyprius* Lam. from cuttings, with the goal of maximizing both the rooting rate and root length. Cuttings from both species were collected across four seasons (winter, spring, summer, and autumn) and were subjected to four different doses of IndoleButyric Acid (IBA) in four distinct greenhouse temperatures. The results from statistical analyses (ANOVA) demonstrated that the time of year is the most significant factor. The highest rooting percentages and longest roots were obtained from cuttings collected in winter and autumn, while summer proved to be the worst period. A dose of 750 mg/l of IBA was found to be most effective for promoting root growth. Additionally, higher cultivation table temperatures, up to 32 °C, favored greater root length. In conclusion, this study provides a clear methodology: for successful propagation, it is recommended to take cuttings in autumn or winter, treat them with 750 mg/l of IBA, and cultivate them at 32 °C.**

Keywords-Cistus; rooting; cutting propagation; cultivation conditions; aromatic shrubs.

I. INTRODUCTION

In Mediterranean areas, reforestation and forest cultivation have become more important given the impact of climate change and wildfires on soil loss and habitat degradation [1]. Efforts to restore degraded ecosystems by means of forest cultivation and restoration are vital to maintaining rural and natural ecosystems and ensuring the profitability of primary activity in rural areas. Thus, trees and shrubs are being grown for restoration and forest cultivation. Nonetheless, while the origin of specimens for agricultural production might not be crucial, the biodiversity and ensuring the local origin of implanted specimens are essential in forest cultivation.

The use of local genetic material in both reforestation and forest cultivation is essential to ensure that planted individuals are well adapted to the specific edaphoclimatic conditions of the area [2]. This impacts both the survival rate of reforested specimens and the productivity of forest cultivation. Moreover, using local individuals helps prevent the genetic contamination of native populations, thereby safeguarding their evolutionary potential and the species' genetic integrity.

Besides the use of forestry species for restoration, some of them can potentially be exploited for commercial purposes. In the case of aromatic shrubs, the extraction of essential oils has become a valuable resource. Some Mediterranean species currently exploited for their essential oil and other subproducts, are from the *Salvia, Cistus*, and *Thymus* genera. The propagation of some species can become challenging, since this propagation in natural conditions is linked to the occurrence of wildfires. These are known as pyrophytic species; examples are *Cistus ladanifer* L. and *Cistus laurifolius* L, among others [3]. *C. ladanifer* is an important species for its essential oil production [4]. The most effective way of artificially propagating the local specimens is the use of cuttings. Moreover, propagating the exploited individuals by seeds does not ensure that new individuals share the same traits as the original one.

Even though there are multiple benefits of using cuttings as a strategy for propagation, the success of the cutting depends on multiple factors. Some authors indicated that cutting propagation moment, the planting moment, might even interfere in the production of essential oil [5]. Propagation success is commonly evaluated based on the rooting rate, expressed as the proportion of cuttings that formed roots under controlled conditions. Some of these factors can be extrinsic, such as environmental temperature, photoperiod, or the inclusion of growth regulator hormones. In contrast, other factors are intrinsic and directly related to the plant physiology when the cutting collection occurs. In fact, differences among species' ecology can generate the fact that the best conditions for a given species' propagation differ from those for other species.

The aim of this paper is to evaluate the best conditions for propagating specimens of *C. ladanifer* and *C.* × *cyprius* for production purposes. To do so, cuttings were propagated at four different times of the year. Individuals of both species are included in this study to assess if there are differences between them. To homogenise the environmental conditions, propagation was conducted under stable temperatures.

The main challenge for this research is the limited natural distribution of *C.* × *cyprius*. Besides, the lack of previous studies of cutting propagation success in *C. ladanifer* and *C.*

× cyprius populations in Spain, jointly with diverse results in other populations, poses a scenario with multiple factors to be studied.

The rest of the paper has been structured as follows; Section 2 outlines the related work. The materials and methods are described in Section 3. Then, Section 4 discusses the obtained results, indicating the best conditions to propagate individuals of both species. Finally, the conclusions are summarised in Section 5.

II. Related Work

In this section, we summarise current efforts comparing the best conditions for propagating Mediterranean species through different methods.

A recent study conducted by Kostas et al. [6] in Greece with *Rosmarinus officinalis* L. indicates rooting success across all seasons (April, July, October and January) from 7 different locations. Currings were grown in controlled conditions, and potassium salt Indole-3-butyric acid (K-IBA) was used. The results indicate that when no K-IBA was used, success is strongly conditioned by the season, reaching the best success in October with a success rate of about 40 %. When K-IBA was used, success reached 80 % in October. There is a high variability in rooting success among locations and seasons.

A similar study was performed by Scaltrito et al. [7] in Italy with *Salvia* 'Farina Silver Blue' and 'La Siesta'. They evaluated the success rate of cuttings under an aeroponics system. Spraying interval and the IBA dose were the evaluated factors, while the root length and root diameters were the evaluated parameters. Their results indicated that propagation by cuttings in an aeroponic system is possible and has a high success rate with a spraing interval of 10 minutes and with 1g/L of IBA. Results are similar for both cultivars in terms of root length but strongly differ in root diameter.

A recent study, conducted on specimens of the genus *Cistus,* was presented by K. Ioannidis and Koropouli [8] with *Cistus creticus* L. (rockrose). In this case, in vitro culturing was evaluated. They determined that the origin of plant material does not impact the success of propagation. The maximum success in routing reached 98.61 % using an enriched medium. Other authors have assessed the in vitro propagation of *C. ladanifer* to culture tissues from leaf and stem explants [9]. Finally, Boukili et al. [10] in Morocco have assessed the in vitro propagation of a given ornamental variety of *C. ladanifer*. They have used explants from seed germination and from wild plants in the field. Their results indicate a low caulogenic response for explants from wild plants. High success was achieved using microcuttings derived from shoots regenerated through micropropagation.

Some authors pointed out that the best moment for *C. ladanifer* propagation is during autumn [11], but no data is provided to support this affirmation, and no information on the percentage of routing success has been reached. In addition, no details of an effective method for cutting propagation have been provided.

As far as we are concerned, no clear methodology was found for cutting propagation of *C. ladanifer* or *C. × cyprius*. Using in vitro cultivation has also been challenging and relies on seeds, which do not ensure maintaining the genetic traits of parental plants. Therefore, the obtention of a method to effectively propagate individuals for both production and reforestation purposes is needed.

III. Materials and Methods

This section describes the origin of plant material and the methods and materials for plant propagation by cuttings.

A. Sampled Area Description

The plant material was sampled at the Sierra Norte of the Community of Madrid (Spain), where specimens of *C. ladanifer* were collected at Berzosa del Lozoya and *C. × cyprius* at Bustarviejo.

Both sites are characterized by an altitude over 1200 meters above sea level, the climate is continental (average temperature of 10.4 ºC and annual precipitation of 520 mm, typically distributed along spring and autumn). The area has very stony soil, which is classified as Inceptisols/Entisols [12]. Dominant vegetation includes forests of oaks and pine, alongside a rich understory of Mediterranean scrub, mainly the *Cistus* genus.

B. Sample Collection

Throughout the hydrological year (winter, spring, summer and autumn), fifty plants from both specimens were collected in order to cover their entire phenological spectrum. This corresponded to the months of December, March, June and September.

The collection was carried out manually by selecting cuttings that had sprouted during the year. The cuttings were 15–20 cm long, with 2–3 whorls kept and the leaves removed to prevent further water loss. The sampling locations of the individuals were geolocated so that they could be reproduced in future. On the same day, the cuttings were transferred to IMIDRA and stored at 4–6 °C until the following day.

C. Treatmeants

Heated tables were prepared at 20, 24, 28 and 32 °C in a greenhouse with a perlite substrate prior to the cuttings being placed on them (Figure 1). Four treatments of IndoleButyric Acid (IBA), a synthetic hormone used as a rooting promoter, were also applied at concentrations of 0, 750, 1500 and 3000 mg/l. The day after collection, the cuttings were immersed in the solution for two minutes and immediately placed on the substrate.

D. Cultivation and Measures

The greenhouse tables were covered with plastic (Figure 1d) and irrigated every two hours for two minutes to maintain a saturated atmosphere. Fungicide treatments were applied as needed.

Four months after planting, the success of the rooting process was evaluated. The number of cuttings that had rooted was determined by measuring the length of the root. Those that had not rooted were differentiated according to

 ISBN: 978-1-68558-327-9

whether they had continued to grow after planting or had died since being cut.

Other measures were made, but not included in this work.

E. Statistical Analysis

The differences in rooting and root length success among the various treatments were assessed using variance analysis (ANOVA). The Least Significant Difference was used to obtain a multiple-range group test. Statgraphics Centurion XVIII was employed.

The factors studied are: species (*C. ladanifer* and *C.* × *cyprius*), season (autumn, winter, spring, summer), IBA dosses (0, 750, 1500, and 3000 mg/L), and temperature (20, 24, 28, and 32 ºC).

IV. Results

This study analyses the influence of the cutting season, growth temperature and rooting hormone dose applied, both quantitatively and qualitatively, in the *C. ladanifer* variety and its hybrid, *C.* × *cyprius*. The quantitative analysis is based on measuring the success rate of rooting for the total number of cuttings planted (6,385), while the qualitative analysis is based on measuring the root length obtained for the 2,119 cuttings that showed roots.

A. Successful rooting

The analysis considered three scenarios: the presence of roots, the absence of roots, and the death of the cutting. The species with the lowest mortality rate and the highest number of individuals with developed roots is considered to be the best for cuttings. Figure 2a shows that there are no graphical differences in mortality between species with similar rates: 9 % for *C. ladanifer* and 8 % for *C.* × *cyprius*. However, there is greater success in rooting (19 %) for *C.* × *cyprius* compared to 15 % for *C. ladanifer*.

Regarding the season for cutting, there is a clear difference, with winter and autumn being the best periods for cutting (see Figure 2b), since *Cistus* plants are dormant at these times and do not produce any vegetative growth. Both periods show low mortality rates among the cuttings, with the winter period standing out with zero mortality and a higher number of individuals with roots. In contrast, during spring and summer, mortality rates reach 8 % of individuals. Furthermore, summer is clearly the worst time to carry out these grafting tasks, as only 1 % of individuals had roots.

Figure 1. Greenhouse tables: (a) setting up; (b and c) heating system for 20, 24, 28 and 32 °C; (d) winter cuttings on perlite substrate.

 ISBN: 978-1-68558-327-9

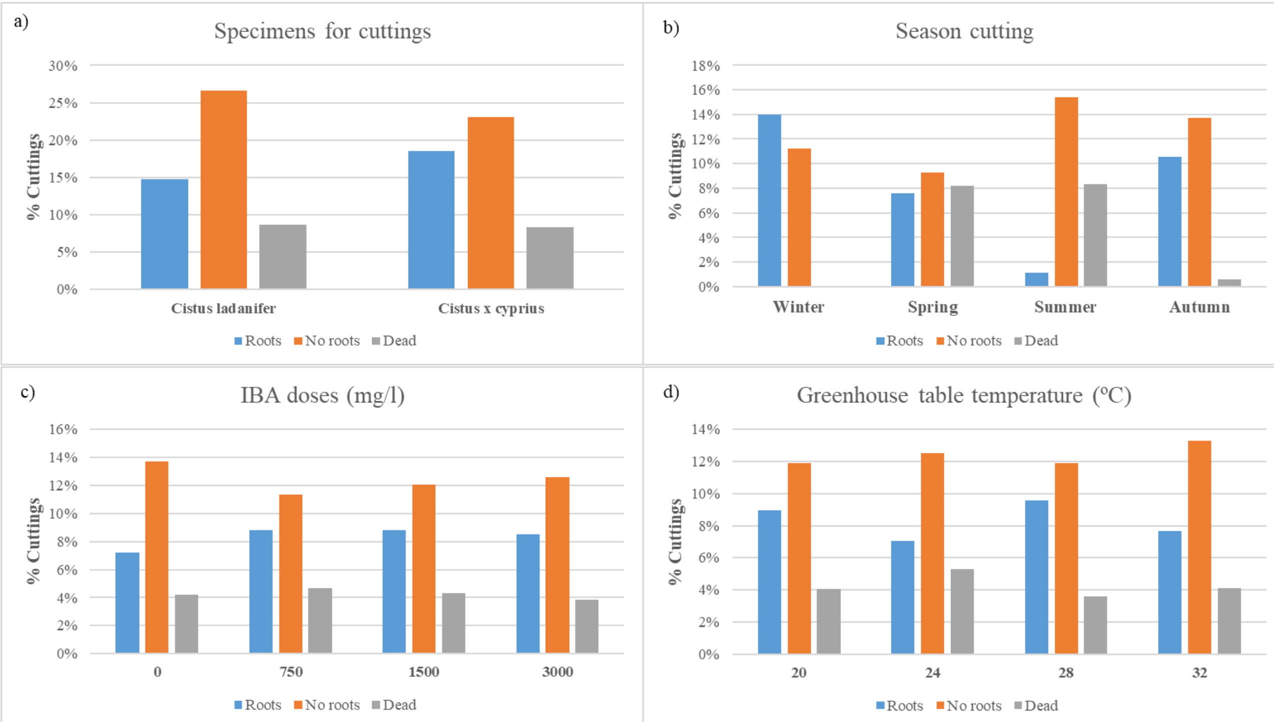

Figure 2. Rooting Success by (a) specimens of *C. ladanifer* and *C. x cyprius*, (b) season cutting, (c) IBA doses and (d) greenhouse table temperature.

Regarding the effect of applying IBA (Figure 2c) or varying the temperature conditions of the table (Figure 2d), neither seems to significantly affect rooting success. However, a slight increase in root presence is observed when IBA is applied compared to when it is not.

B. Root length

Following, the differences in root length are analysed. First of all, the effects of different factors are presented. Then, some images are provided to evidence the encountered differences.

Root lengths ranged from 0.5 to 45 cm, with an average of 11.6 cm ± 6.4 and a median of 11.0 cm for the 2,119 individuals with roots (see Table I and Figure 3). ANOVA was performed on these to determine the most effective treatment combinations for taking cuttings from *C. ladanifer* and *C. x cyprius*. The analysis confirmed that there were significant differences in root length depending on the time of year that cuttings were taken. Winter resulted in the longest roots, with average length of 13.9 cm, followed by autumn with an average length of 11.2 cm (Figure 3b). However, there were no differences in root length between species (Figure 3a).

TABLE I. ROOT LENGTH BY ALL ROOTED INDIVIDUALS AND BY THE FACTORS CONSIDERED. THE LETTERS SYMBOLIZE GROUPS OF SIGNIFICANCE.

		N	**Avg ± SD**	**Median**
Total Rooted		2119	11.6 ± 6.4	11.0
Specimens	*C. ladanifer*	935	$11.4^{a} \pm 6.4$	10.5
	C. × cyprius	1184	$11.7^{a} \pm 6.4$	11.5
Season	Winter	887	$13.9^{a} \pm 6.3$	14.0
	Spring	483	$8.7^{b} \pm 5.7$	8.0
	Summer	73	$6.4^{c} \pm 5.6$	5.0
	Autumn	676	$11.2^{d} \pm 5.8$	10.5
IBA (mg/l)	0	454	$11^{a} \pm 6.1$	10.5
	750	562	$12.5^{b} \pm 6.7$	12.0
	1500	561	$11.1^{a} \pm 6$	10.0
	3000	542	$11.7^{a} \pm 6.6$	11.0
Temp. (ºC)	20	566	$10.9^{a} \pm 5.2$	11.0
	24	451	$11.2^{ab} \pm 6$	11.0
	28	612	$11.9^{bc} \pm 6.9$	10.5
	32	490	$12.3^{c} \pm 7.2$	12.0

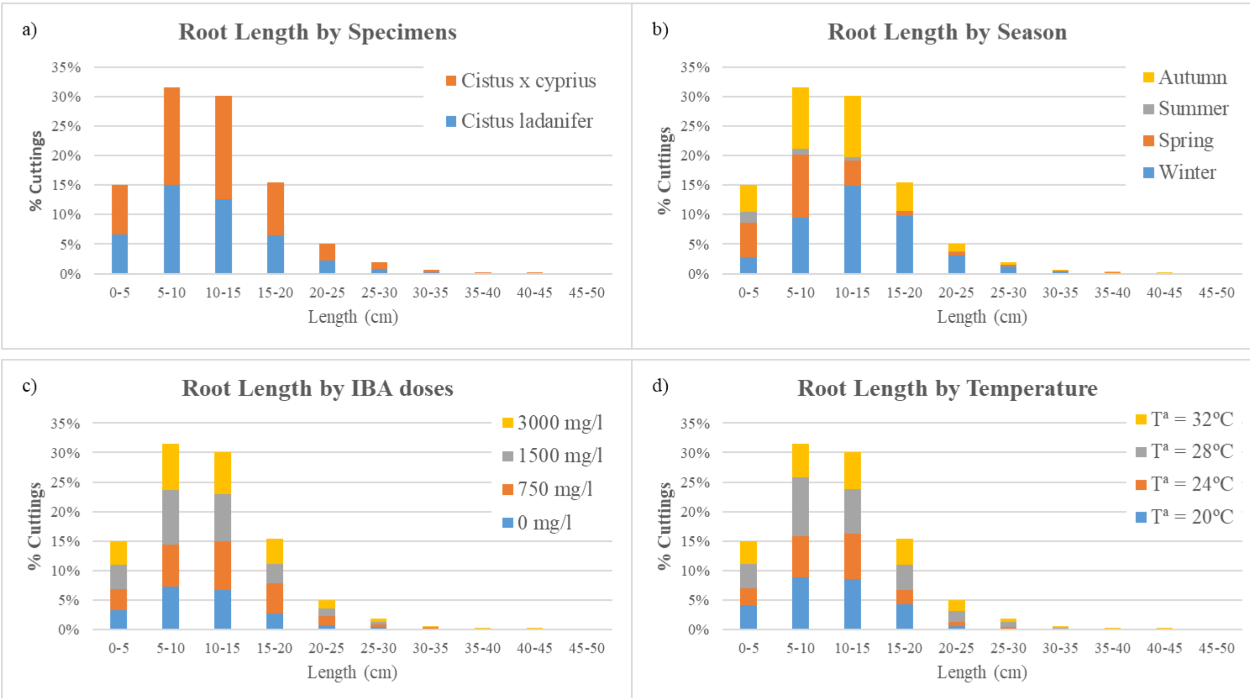

Figure 3. Rooting Length by (a) specimens of *Cistus ladanifer* and *Cistus* x *cyprius*, (b) season cutting, (c) IBA doses and (d) greenhouse table temperature.

The IBA dose applied (Table I, Figure. 3c) only shows differences for the 750 mg/l dose with a root length of ~1.5 cm greater than the other doses considered (Figure 4). This suggests that the crop's capacity to absorb the hormone is exceeded at higher doses, resulting in waste.

The temperature of the greenhouse table (Table I, Figure 3d) shows an upward trend in root length as the temperature increases, with differences appearing when the distance between them exceeds 4°C. Thus, the 32°C table stands out with a greater root length (12.3 ±7.2 cm).

Multifactorial ANOVA analysis shows that the only significant factor affecting root length is the season in which the cuttings are taken. However, several significant interactions were identified, indicating that the combined effect of IBA treatment and temperature on root growth varies substantially depending on the season. Furthermore, when cuttings are taken in spring, it is observed that the C. ladanifer variety has longer roots, and the interaction between temperature and IBA dose is maintained. In this case, however, the recommended temperature would be 24 °C, with the dose remaining at 750 mg/l.

Figure 4. *Cistus ladanifer* spring cuttings roots on 24 ºC table with (a) no, (b) 750 mg/l, (c) 1500 mg/l and (d) 3000 mg/l of IBA doses.

V. Discussion

Finally, a discussion comparing the obtained results with existing literature is provided.

Compared with existing studies, the obtained root success was considerably lower [6][8]. In [6], the success rates range from 40 to 80 % for *Rosmarinus officinalis* and in [8] the success rate exceeds 98 % for *Cistus criticus*. Other authors have also reported variable success rate with *Myrtus communis L*. ranging from maximum rates of 43% for white myrtle to 76 % for black myrtle [13] or *Juniperus sabina L.* with maximum rates of 60 % [14] or Salvia fruticosa Mill. with maximum rooting success of 80 % [15]. For *C. ladanifer* and *C.* × *cyprius*, the success rate never reached 40 %. Nonetheless, the used species are different from those in the aforementioned papers. Thus, differences in routing success might be due to the different growing conditions and physiology of different species. There is no data about routing success in previous work conducted with the used species (*C. ladanifer* and *C.* × *cyprius*).

Concerning the best conditions for cutting, our results indicate that the best moment for propagation of *C. ladanifer* is in both winter and autumn, which is partially aligned with [6] and [11]. The highest success and longest roots were achieved with 0.75 g/l of IBA, which is similar to the conclusions of [7]. The maximum rate was reached with 1 g/l [14] and with 0.5 g/L in [13]. Thus, our results in terms of the effects of the analysed factors are aligned with existing literature.

VI. Conclusion and Future Work

In this paper, the success of cutting propagation, in terms of rooting, of two Mediterranean species has been evaluated. Research has shown that the rooting capacity of both species remains consistent, with the exception of spring rooting. In this season, *C. ladanifer* exhibits a marginally enhanced response, as indicated by an increase in root length.

The best season for cutting is autumn and winter, preferably winter, applying a hormonal treatment of 750 mg/l IBA and maintaining the greenhouse table temperature at 32 ºC. If cutting is carried out in spring, the table temperature can be reduced to 24 ºC. Cuttings should be avoided during the summer months.

In future work, the evaluation of other aspects, such as flower development of the cuttings and their adaptation and survival in field conditions, will be conducted. Moreover, intermediate doses of IBA will be studied. Finally, efforts to conduct in vitro propagation to reach higher success will be considered.

Acknowledgment

This research was funded by project FP24-ESSENZIALI+D, by Comunidad de Madrid regional government through the Instituto Madrileño de Investigación y Desarrollo Rural, Agrario y Alimentario (IMIDRA).

References

[1] J. Peñuelas and J. Sardans, “Global Change and Forest Disturbances in the Mediterranean Basin: Breakthroughs, Knowledge Gaps, and Recommendations,” Forests, vol 12, no 5, p 603, 2021.

[2] T. Sampaio, E. Gonçalves, M. S. Patrício, T. M. Cota, and M. H. Almeida, “Seed origin drives differences in survival and growth traits of cork oak (Quercus suber L.) populations,” For. Ecol. Manage., vol. 448, pp. 267–277, Sep. 2019.

[3] R. M. Ugarte, M. M. R. García, and D. Sánchez-Mata, “Evaluating the post-fire natural regeneration of Mediterranean-type scrublands in Central Spain,” Mediterr. Bot., vol. 42, no. 0 SE-Special issue: Vegetation Diversity and Global Change, p. e67331, Jun. 2021.

[4] S. Viciano-Tudela, S. Sendra, L. Parra, J. M. Jimenez, and J. Lloret, “Proposal of a Gas Sensor-Based Device for Detecting Adulteration in Essential Oil of Cistus ladanifer,” Sustain. 2023, Vol. 15, Page 3357, vol. 15, no. 4, p. 3357, Feb. 2023.

[5] A. Soltanbeigi, M. Özgüven, and M. B. Hassanpouraghdam, “Planting-date and cutting-time affect the growth and essential oil composition of Mentha × piperita and Mentha arvensis,” Ind. Crops Prod., vol. 170, p. 113790, Oct. 2021.

[6] S. Kostas et al., “Sustainable Exploitation of Greek Rosmarinus officinalis L. Populations for Ornamental Use through Propagation by Shoot Cuttings and In Vitro Cultures,” Sustain., vol. 14, no. 7, p. 4059, Mar. 2022.

[7] E. Scaltrito, G. Cristiano, A. E. Sdao, N. S. Gruda, D. Loconsole, and B. De Lucia, “Influence of water spraying intervals and indole-3-butyric acid concentrations on Salvia rooted cuttings quality in a closed aeroponics system,” Sci. Hortic. (Amsterdam)., vol. 337, p. 113452, Nov. 2024.

[8] K. Ioannidis and P. Koropouli, “Effects of Different Media and Their Strengths in In Vitro Culture of Three Different Cistus creticus L. Populations and Their Genetic Assessment Using Simple Sequence Repeat Molecular Markers,” Horticulturae, vol. 10, no. 1, p. 104, Jan. 2024.

[9] D. Frazão, C. Barroca, A. Silva, F. Delgado, and J. Gonçalves, “Cistus ladanifer L. Tissue Culture from Leaf and Stem Explants,” J. Biotechnol. Bioresearch, vol. 4, Nov. 2022.

[10] M. Boukili, S. Chakir, Z. Haloui, and G. Echchgadda, “Rapid in vitro multiplication of Cistus ladanifer L. var. maculates Dun,” J. Mater. Environ. Sci., vol. 9 (5), pp. 1489–1494, 2018.

[11] J. R. Raimundo et al., “Neglected Mediterranean plant species are valuable resources: the example of Cistus ladanifer,” Planta, vol. 248, no. 6, pp. 1351–1364, 2018.

[12] C. Cano-Shaw, J. Plaza Ramos, B. Stefanuti, L. Parra, and P. V. Mauri Ablanque, “Variación de la cantidad y calidad del aceite esencial de Cistus ladanifer con distintos tiempos de destilación.,” 26th Int. Congr. Proj. Manag. Eng., pp. 525–544, 2022, Accessed: Sep. 12, 2025. [Online]. Available: http://dspace.aeipro.com/xmlui/handle/123456789/3235

[13] E. Alım and A. S. Kaya, “Effect of Different Concentrations of IBA and Time of Taking Cutting on Propagation of Black and White Myrtle (Myrtus communis L.) Cuttings,” Hortic. Stud., vol. 40, no. 1, pp. 8–15, 2023.

[14] M. Abshahi, F. A. García-Morote, H. Zarei, B. Zahedi, and A. R. Nejad, “Improvement of Rooting Performance in Stem Cuttings of Savin Juniper (Juniperus sabina L.) as a Function of IBA Pretreatment, Substrate, and Season,” For. 2022, Vol. 13, Page 1705, vol. 13, no. 10, p. 1705, Oct. 2022.

[15] K. F. Bertsouklis, A. N. Martini, and M. Papafotiou, “Effect of cutting type and indole butyric acid on propagation of Salvia fruticosa with cuttings,” in Acta Horticulturae, International Society for Horticultural Science (ISHS), Leuven, Belgium, Sep. 2022, pp. 389–394.

 ISBN: 978-1-68558-327-9

Efficiency of Rainfed Wheat Production: A Global Assessment Using Data Envelopment Analysis

Amir Dadrasi*, Davina Vačkářová, Fatemeh Salmani, Jan Weinzettel*
Charles University, Environment Centre, Prague, Czech Republic
Emails: Amir.dadrasi@czp.cuni.cz, davina.vackarova@czp.cuni.cz, fatemeh.salmani@czp.cuni.cz, and Jan.Weinzettel@czp.cuni.cz

***Abstract*—Rainfed wheat, covering 160 million hectares globally, is critical to food security but faces significant yield gaps due to inefficient resource use and variable climatic conditions. This study evaluates the efficiency of nitrogen (N) and phosphorus (P) fertilizer use in rainfed wheat production worldwide, aiming to identify optimal application rates for achieving 50%, 70%, and 80% of water-limited potential yield (Yw) while minimizing environmental impacts. Building on an expanded Global Yield Gap Atlas (GYGA) dataset previously extended from 49 countries to global coverage using stepwise regression, we applied Data Envelopment Analysis (DEA) to assess production efficiency across 122 countries and their climate zones. Inputs included annual precipitation and N and P applications, with outputs comprising crop yield, production, water productivity, and nutrient use efficiencies under the Constant Returns to Scale (CCR) model. Results reveal stark efficiency disparities: Sweden, Ukraine, Ireland, Finland, and Belgium achieved maximum efficiency (1.0), while India, Iran, and others scored as low as 0.18-0.37 under current conditions. Efficiency improved with higher yield targets, with optimal N and P rates significantly lower than current applications in many regions e.g., Montenegro's N use dropped from 427 kg/ha to 132 kg/ha for actual yield optimization. Climate zone analysis further identified efficient production hotspots, guiding targeted interventions. These findings underscore the potential to enhance global rainfed wheat productivity through optimized fertilizer strategies, offering a pathway to close yield gaps, boost food security, and reduce ecological footprints.**

Keywords-Rainfed wheat; Yield gap; Fertilizer efficiency; Data envelopment analysis; Sustainable agriculture.

I. INTRODUCTION

The global population continues to expand rapidly, driving an escalating demand for food and intensifying pressure on agricultural systems worldwide. Rainfed wheat, cultivated across approximately 160 million hectares, stands as a cornerstone of global food security, particularly for regions reliant on this staple crop to meet nutritional needs [1]. However, its production faces significant challenges due to its dependence on unpredictable rainfall patterns, which exacerbate yield gaps defined as the disparity between actual yields (Ya) and water-limited potential yields (Yw) and threaten sustainable food supply chains. Addressing these challenges requires identifying regions with high production potential and optimizing resource use, particularly for critical inputs like nitrogen (N) and phosphorus (P) fertilizers, to close yield gaps while minimizing environmental impacts [2][3]. Fertilizers, especially N and P, are indispensable for enhancing crop productivity and achieving higher yields. Their use has surged dramatically to support growing food demands, with synthetic fertilizer consumption exceeding safe planetary boundaries [4][5]. This overuse has triggered severe environmental consequences, including air pollution from particulate matter and aerosols [6], climate change and ozone depletion [7][8][10], eutrophication of aquatic ecosystems [9], biodiversity loss [10], and soil acidification [11]. Such inefficiencies not only strain economic returns for farmers but also undermine food security by limiting sustainable productivity [3]. Consequently, optimizing fertilizer application is imperative to balance productivity gains with ecological sustainability, a goal that hinges on determining region-specific, efficient input levels to achieve target yields, such as 50%, 70%, or 80% of Yw. Previous research has laid critical groundwork for understanding fertilizer use and yield relationships. For instance, Smerald et al. [12] demonstrated that redistributing N globally could maintain cereal production with a 32% reduction in fertilizer use or boost output by 15% without increasing N levels, thereby reducing environmental N losses. Similarly, Anderson et al. [2] underscored the need to enhance P Use Efficiency (PUE) to mitigate pollution and conserve finite P reserves. Historical analyses of global N and P fertilizer trends further highlight shifting hotspots and nutrient imbalances, emphasizing the need for spatially explicit strategies [5]. Building on these insights, our prior work expanded the GYGA dataset originally covering 49 countries for rainfed wheat by employing stepwise regression models to extrapolate climate, soil, and management relationships to a global scale [13]. This globally extended dataset provides a robust foundation for assessing production potential and yield gaps worldwide.

Despite these advances, a critical research gap persists: no study has comprehensively evaluated the efficiency of N and P use in rainfed wheat production on a global scale while identifying optimal fertilizer levels to achieve specific yield targets. Access to detailed, spatially variable data is essential for such analyses. While datasets from the International Fertilizer Association (IFA) and Food and Agriculture Organization (FAO) have offered country-level fertilizer use since 1961, they assume uniform application rates, overlooking within-country variations [14]. Efforts to refine these data, such as those by Potter et al. [15] and Mueller et al. [16], incorporated crop-specific patterns but remain temporally limited (circa 2000), restricting their utility for contemporary optimization studies. In contrast, our current study leverages the globally extended GYGA dataset to apply DEA, a nonparametric method, to assess the efficiency of rainfed wheat production across countries and climate zones. By integrating actual and potential yield data with N and P inputs, we aim to identify efficient and inefficient production regions and determine optimal fertilizer application rates for achieving 50%, 70%, and 80% of Yw. This approach not only advances our understanding of resource use efficiency but also offers actionable insights for sustainable agricultural intensification, aligning productivity goals with environmental stewardship. The rest of this paper is organized as follows. Section II outlines the data sources and methodology used. Section III presents the results of the efficiency analysis. Section IV discusses the implications of optimal nitrogen and phosphorus application. Section V provides conclusions and future research directions. The acknowledgments and references conclude the article.

II. MATERIALS AND METHODS

A. Data Sources and Conceptual Framework

This study builds on the GYGA database, which aggregates crop modeling outputs for rainfed wheat across 49 countries, providing actual yield (Ya), water-limited potential yield (Yw), yield gaps (Yg), nitrogen (N) and phosphorus (P) application rates, and target nutrient requirements (N50, N70, N80; P50, P70, P80) for 50%, 70%, and 80% of Yw. Water productivity data (for actual yield (WPA), and potential yield (WPP)) are also included, derived from 15-year simulations using validated models (e.g., Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production Systems sIMulator (APSIM)) per GYGA protocols [1]. These targets align with realistic yield potentials under rainfed conditions, informed by nutrient uptake dynamics. The dataset was globally extended by mapping GYGA data to climate zones, using rainfed wheat acreage from the Spatial Production Allocation Model (SPAM2020), soil data from the FAO Harmonized World Soil Database (e.g., organic carbon, pH), and climate variables from GYGA Environmental Data (e.g., growing degree days, aridity index). The extension methodology, including data integration and predictor selection, is fully described in Dadrasi et al. [13].

B. Stepwise Regression Extension and Uncertainty Considerations

The GYGA dataset extension to 122 countries relied on stepwise regression modelling, as outlined in Dadrasi et al. [13], where environmental and management variables were used to predict GYGA parameters (Ya, Yw, N, P needs) across climate zones. This involved analysing approximately 180,000 data points per parameter, averaged by region, with model performance validated (R^2 = 0.78–0.85) using the cited study's approach. For this study, the extended dataset supports DEA analysis. Uncertainties include: (1) aggregation of sub-national fertilizer use variability, potentially masking local differences; (2) coarse spatial resolution of global soil and climate data; and (3) assumptions of consistent crop responses across agroecological zones, which may affect DEA accuracy. These were partially mitigated in the original extension through cross-validation with regional data (China, India, USA) and are further addressed here by using relative efficiency scores in DEA, which reduce sensitivity to absolute input errors. Additional details on the regression equations and validation metrics are available in Dadrasi et al. [13].

The GYGA dataset was extrapolated from its original 49-country scope to 122 countries using stepwise regression to extend climate, soil, and management relationships. The validity of this extrapolation was supported by previous studies [13][17], which reported a strong correlation ($r = 0.80$, $p < 0.01$) between modeled and observed yields across 122 countries, thereby confirming the robustness of the approach.

C. Data Envelopment Analysis (DEA)

DEA, introduced by Charnes et al. [18], is a nonparametric linear programming technique employed to estimate production functions and assess the efficiency of multiple Decision-Making Unit (DMUs) [19]. Its primary objective is to optimize efficiency by achieving maximum output with minimum input, either by enhancing output while maintaining input constant or obtaining a specific output with minimal input. The choice between these options depends on the DMUs under consideration. This study adopts an input-oriented approach with multiple inputs and outputs. DEA is utilized to evaluate DMUs' efficiency [20][21].

The DEA was conducted using the deaR package [22] in R (version 4.3.2). To perform DEA, the primary focus was on the countries that account for 98.9% of the rainfed wheat crop area globally. The analysis was based on the annual precipitation, and the application of N and P fertilizers in each climate zone of each country, to achieve the actual yield, as well as 50%, 70%, and 80% of the water-limited potential yield as input and crop yield, crop production, water productivity, N use efficiency, P use efficiency were as output in the CCR model. A specific equation was used in the DEA to estimate the efficiency value in each country and climate zone. The CCR model is a specific variant of DEA used to evaluate the relative efficiency of DMUs in converting inputs into outputs. In the CCR model, the efficiency of each DMU is assessed under the assumption of Variable Returns to Scale (VRS), allowing for scale efficiency to be considered.

Considering j = 1, 2, 3, m DMUs using Xi| i = 1, 2, 3, ., n inputs to produce Yr | r = 1, 2, 3, ., outputs and Ya or Yw (multipliers) Vi and Ur associated with those inputs and outputs, we can also formalize the efficiency expression in (1) as the ratio of weighted outputs to weighted inputs:

$$Efficiency = \frac{\sum_{r=1}^{\delta} \mu r y j r}{\sum_{i=1}^{n} \gamma i x j i} \quad (1)$$

Following the analysis, we obtained efficiency scores ranging from 0 to 1, which reflect the relative efficiency of each DMUs, such as countries or specific climate zones within countries. Using the multiplier (input-oriented) model, we also derived the marginal contributions of each input and output, identified efficiency peers, and calculated their corresponding weights within the envelopment framework. Additionally, the model allowed us to pinpoint areas for

 ISBN: 978-1-68558-327-9

improvement, including input excesses and output shortfalls, often referred to as slacks.

An efficiency scores close to 1 indicates that a DMU is performing efficiently, while scores below 1 suggest varying levels of inefficiency. The CCR model further enables us to assess scale efficiency, helping to determine whether a DMU is operating at an optimal scale based on its input-output configuration. These DEA equations are essential tools for evaluating and benchmarking efficiency across different sectors, including agricultural systems. Based on the DEA results, we extracted both the efficiency scores and the target values for each input and output variable included in the model.

III. RESULTS

A. Efficiency

DEA was performed using N and P application rates as input variables under different yield target scenarios. The analysis showed that six countries including Sweden, Ukraine, Ireland, Finland and Belgium, achieved an efficiency score of 1, indicating optimal input use, while all other countries scored below 1 (Figure 1A). The lowest efficiency scores under current conditions were observed in India (0.18), Iran (0.25), Dominican Republic (0.34), Guyana (0.35), Brazil (0.37) and Burundi. These results highlight sub-optimal fertilizer use relative to yield performance. Results from the GYGA were used to determine the optimal level of fertilizer application required to achieve 50% of Yw. As shown in Figure 1B, only seven countries including Ireland, Sweden, Botswana, Cameroon, Guyana, Guernsey and the Netherlands achieved full efficiency (score = 1), while all other rainfed wheat producing countries (out of 122 evaluated) scored lower. The lowest efficiency scores in this scenario were recorded in Mongolia (0.65), the Canary Islands (0.66), South Africa (0.67), Iraq (0.68), Ecuador and Syria. As the yield target increased to 70% and 80% of Yw, efficiencies improved in all countries (Figure 1C, D). The highest efficiencies were observed in Ireland, China, Sweden, Eritrea, Ukraine and the Netherlands, probably due to their high Yw values. Conversely, the lowest efficiencies in these scenarios - ranging from 0.71 to 0.77 - were associated with Portugal, Greece, Afghanistan, Kazakhstan and Syria.

B. Optimal N application

The findings from Figure 2 illustrate nitrogen (N) application rates across various countries, comparing actual or estimated values with optimal values derived from DEA under different scenarios. Under current conditions (Figure 2A), N application reaches its highest levels, averaging 427 kg/ha in Montenegro, 337 kg/ha in Belgium, 314 kg/ha in Ireland, 312 kg/ha in the Netherlands, and 274 kg/ha in China. In contrast, the lowest N fertilizer application rates—averaging 17, 26, 38, 39, 40, 45, and 52 kg/ha—are observed in Tanzania, Tunisia, Ethiopia, Morocco, Kenya, Australia, and Moldova, respectively. These figures, calculated using actual yield (Ya) as the DEA output, have been optimized and reduced, reflecting adjustments in N input based on output. For example, in Montenegro, where the actual yield is 3.09 t/ha with an N application of 427 kg/ha, optimization lowers this to 132.00 kg/ha. In Belgium and Ireland, however, with actual yields of 8.52 t/ha and 8.73 t/ha, respectively, the optimized N application aligns with the actual rates. For the 50%Yw target, the estimated N application is 85 kg/ha, while the optimal value for achieving this target is slightly lower at 81.11 kg/ha. In countries with the lowest N application under current conditions, as depicted in Figures 2B and B1, the estimated N value based on GYGA results is 46.4 kg/ha, with an optimal value of 36.17 kg/ha for 50%Yw. Comparable patterns emerge for the 70%Yw and 80%Yw targets (Figures 2C, C1, D, and D1).

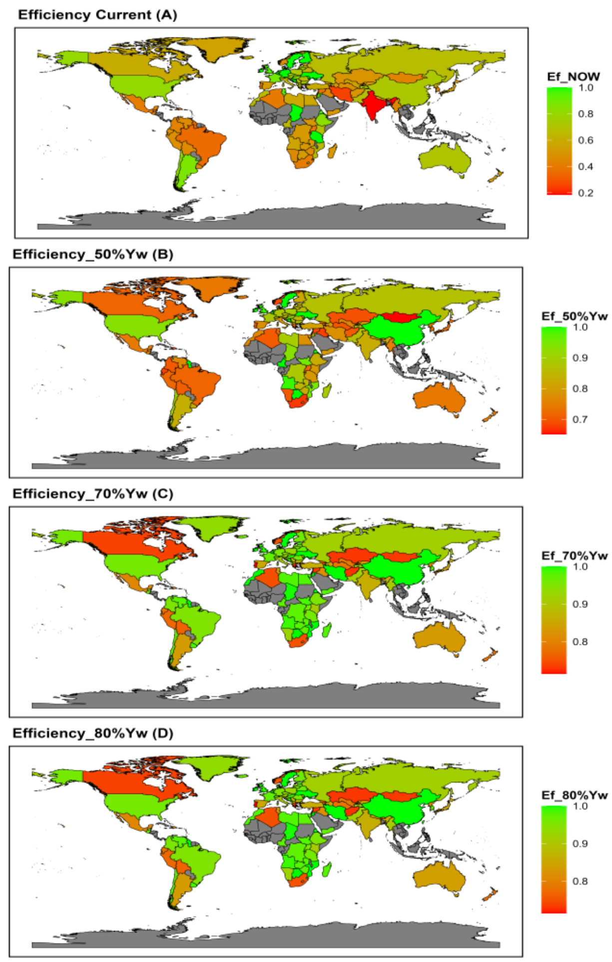

Figure 1. Results of DEA for efficiency values in current conditions (A), Minimum N and P input requirements for achieving target yields of 50% (B), 70% (C), and 80% (D) of Yw based on map and number of efficient and inefficient countries.

Detailed values and further data are provided in the supplementary Excel file across various conditions and scenarios. A key insight from these results is the significant gap between the highest N application under current conditions (427 kg/ha) and the amount required to achieve 80%Yw, which is only 250 kg/ha. This indicates that current N application rates for rainfed wheat production often exceed what is necessary to reach 80%Yw.

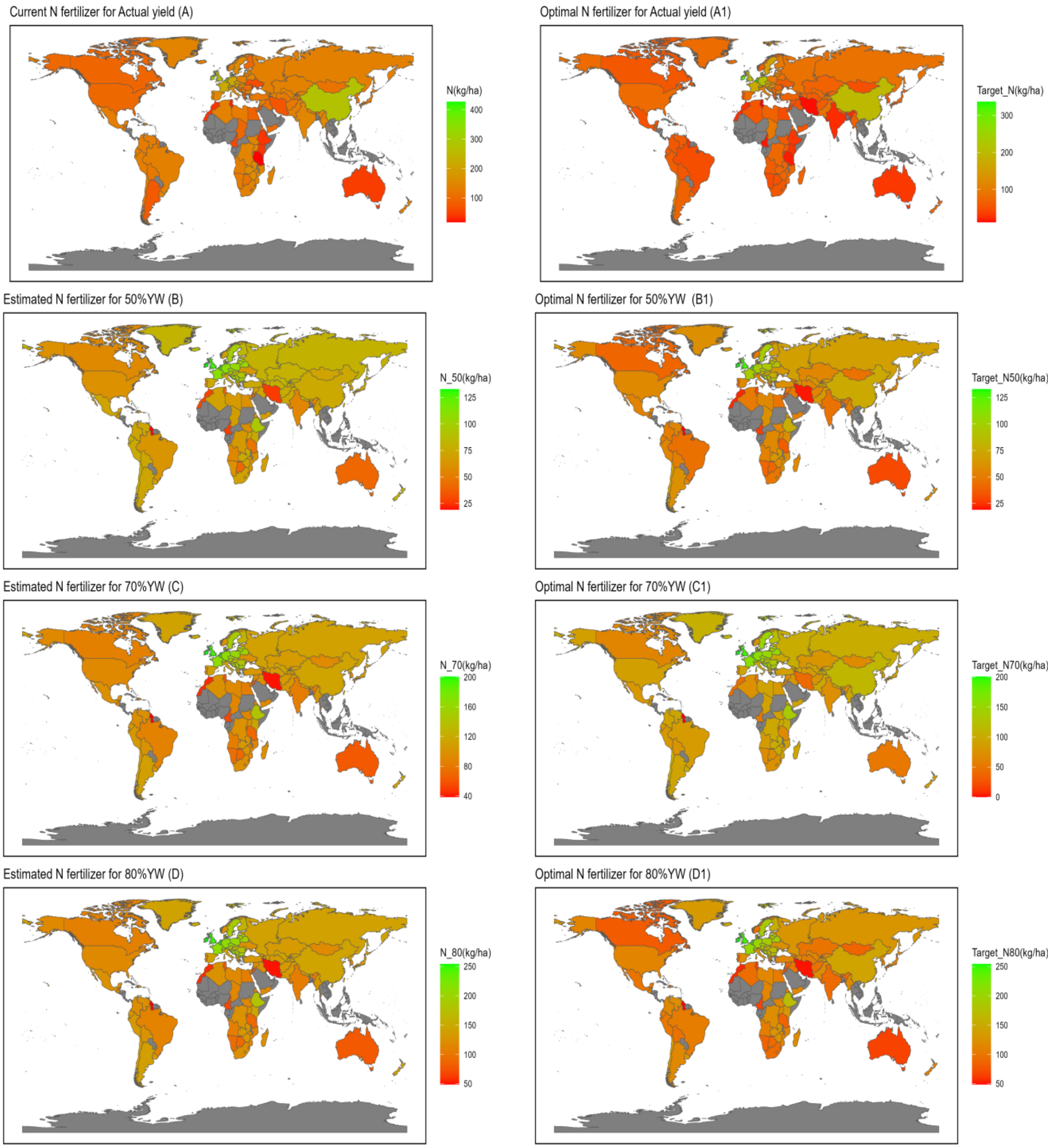

Figure 2. The results of N application levels in both actual and optimal values, derived from DEA analysis across various scenarios. These scenarios encompass current conditions (A and A1), minimum N input requirements, and the optimal necessary to attain target yields of 50%Yw (B and B1), 70%Yw (C and C1), and 80%Yw (D and D1) in rainfed wheat.

C. Optimal P application

The extended GYGA results and DEA for actual or estimated and optimal P fertilizer application in rainfed wheat production are detailed in Figure 3, covering current conditions and scenarios targeting 50%, 70%, and 80% yield water-limited potential (Yw). These findings reveal that P application under current conditions often exceeds the levels needed to achieve 70% and 80%Yw. In the current scenario, the highest P application rates are observed in China at 58 kg/ha, Ireland at 45 kg/ha, Montenegro at 41 kg/ha, and the Netherlands at 31 kg/ha. However, DEA-optimized target values for these countries, identified as having the highest P applications, decrease to 16.8 kg/ha, 45 kg/ha, 15.71 kg/ha, and 30 kg/ha, respectively (Figures 3A and A1). Ireland and the Netherlands show no change in their optimal P values due to their high Ya. Meanwhile, the lowest P inputs averaging 1, 2, 3, 3, and 3 kg/ha are recorded in Tanzania, Tunisia, Ethiopia, Ukraine, and Cameroon, respectively.

In the 50%Yw scenario (Figures 3B and B1), estimated P requirements based on GYGA and DEA range from 3.3 to 25 kg/ha. The highest values averaging 25.5, 25, 24.8, 24.4, and 21.3 kg/ha are linked to Ireland, the Netherlands, the United Kingdom, Belgium, and Liechtenstein, respectively, with optimal P requirements matching these estimates due to their higher Yw compared to other countries. Conversely, the lowest P requirements averaging 3.4, 4.84, 5.1, 5.7, and 7.4 kg/ha are observed in Guyana, Cameroon, Iran, Morocco, and Jordan, respectively. Notably, in China, P application decreases under both estimated and DEA predictions, reflecting its relatively lower Yw. For the 70%Yw scenario (Figures 3C and C1), the highest P requirements averaging 35.7, 34.9, 34.7, 34.1, and 29.19 kg/ha are associated with Ireland, the Netherlands, the United Kingdom, Belgium, and Liechtenstein, respectively, with optimal P values aligning with these estimates due to their superior Yw. The lowest P requirements averaging 7.1, 7.10, 8, 9.53, and 10.4 kg/ha are found in Iran, Guyana, Morocco, Cameroon, and Jordan, respectively, with optimal values remaining unchanged due to their lower Yw. In the 80%Yw scenario (Figures 3D and D1), the highest P requirements averaging 40.8, 39.9, 39.7, 39.1, and 33.40 kg/ha are again linked to Ireland, the Netherlands, the United Kingdom, Belgium, and Liechtenstein, with optimal P values consistent with these estimates due to their high Yw. The lowest P requirements averaging 7.8, 8.2, 9.1, 12.3, 12.5, 10.80, and 11.8 kg/ha are recorded in Guyana, Iran, Morocco, Tunisia, Australia, Cameroon, and Jordan, respectively, with optimal P values unchanged due to their lower Yw. A brief review of the maps highlights that, under current conditions, P fertilizer application frequently surpasses the amounts needed to achieve 70% and 80%Yw, underscoring potential inefficiencies in current practices.

IV. DISCUSSION

A. *Optimum* N and P *application* and efficiency

DEA serves as a methodology for evaluating the efficiency of DMUs undertaking similar tasks within a production framework that utilizes multiple inputs to generate multiple outputs [23]. Over time, several DEA models have emerged, including the Charnes, Cooper, and Rhodes (CCR) model, the Banker, Charnes, and Cooper (BCC) model, and the Free Disposal Hull (FDH) model, which are recognized as fundamental DEA models for evaluating the efficiency of decision-making units [24].

In this study, the CCR model was utilized. The findings from Figures 2 and 3 provide insights into the use of N and P fertilizers in rainfed wheat farming across various countries. It highlights the current (estimated for target Yw) and optimized values obtained from DEA under different scenarios. Optimizing N and P fertilizers based on DEA output (Ya) suggests the adjustment of input levels to achieve target yields more efficiently. As a result, countries like Montenegro, which have excessively high N fertilizer application rates in the current condition, show significant reductions in optimized values to align with yield targets more effectively. Conversely, countries like Belgium and Ireland, with already high actual yields, show optimized N application values that match current practices. As indicated in Figures 2A and 2B, there is a positive and direct correlation between N and P application, which is reported by GYGA and extended for other areas, and Yw at different levels. Also, there are several reports about direct and positive relationships between N and P fertilizer applications with maize yield [25], groundnut [26], barley [27], and wheat [28][29]. The results also highlight the importance of optimizing fertilizer application strategies to maximize crop yield while minimizing input costs and environmental impact. Another output because of DEA is the efficiency value in different DMUs (countries and climate zones in each country). DEA analysis revealed disparities in fertilizer efficiency among different nations. Countries such as Sweden, Ukraine, Ireland, Finland, and Belgium exhibited the highest efficiency, with a value of 1, indicating optimal use of N and P fertilizers to achieve target yields. Conversely, countries like India, Iran, the Dominican Republic, Guyana, Brazil, and Burundi showed lower efficiency, suggesting suboptimal utilization of fertilizers relative to their yield potential. This comparison helps to delineate the optimal N and P fertilizer application rates based on yield values, thereby assisting in refining fertilizer management practices for rainfed wheat production systems.

Furthermore, the evaluation of N and P requirements to achieve target yields of 50%, 70%, and 80% of Yw (actual yield) using GYGA results sheds light on the efficiency of fertilizer utilization across different countries. The analysis revealed varying levels of efficiency, with only a few countries achieving an efficiency of 1, indicating optimal fertilizer use, while others exhibited lower efficiency scores. Moreover, as the target yield percentage increased from 50% to 80% of Yw, the efficiency of fertilizer application generally improved across all countries. Countries with higher actual yields tended to demonstrate higher efficiency in fertilizer utilization compared to those with lower yields. This underscores the importance of considering yield potential when determining optimal fertilizer application rates.

It is possible to increase yield or reduce fertilizer usage by cultivating rainfed wheat in suitable climate zones and limiting cultivation in unsuitable areas [30]. In addition, inside of our results, which defined the suitable climate zone based on efficiency in each country in Figure 1, several fertilizer management techniques have been reported by other studies that can help reduce the amount of fertilizer used while increasing its efficiency. It was reported that optimal nitrogen and phosphorus use efficiency is influenced by a range of management factors beyond fertilizer rates [31]. For example, optimal irrigation scheduling (two irriga-

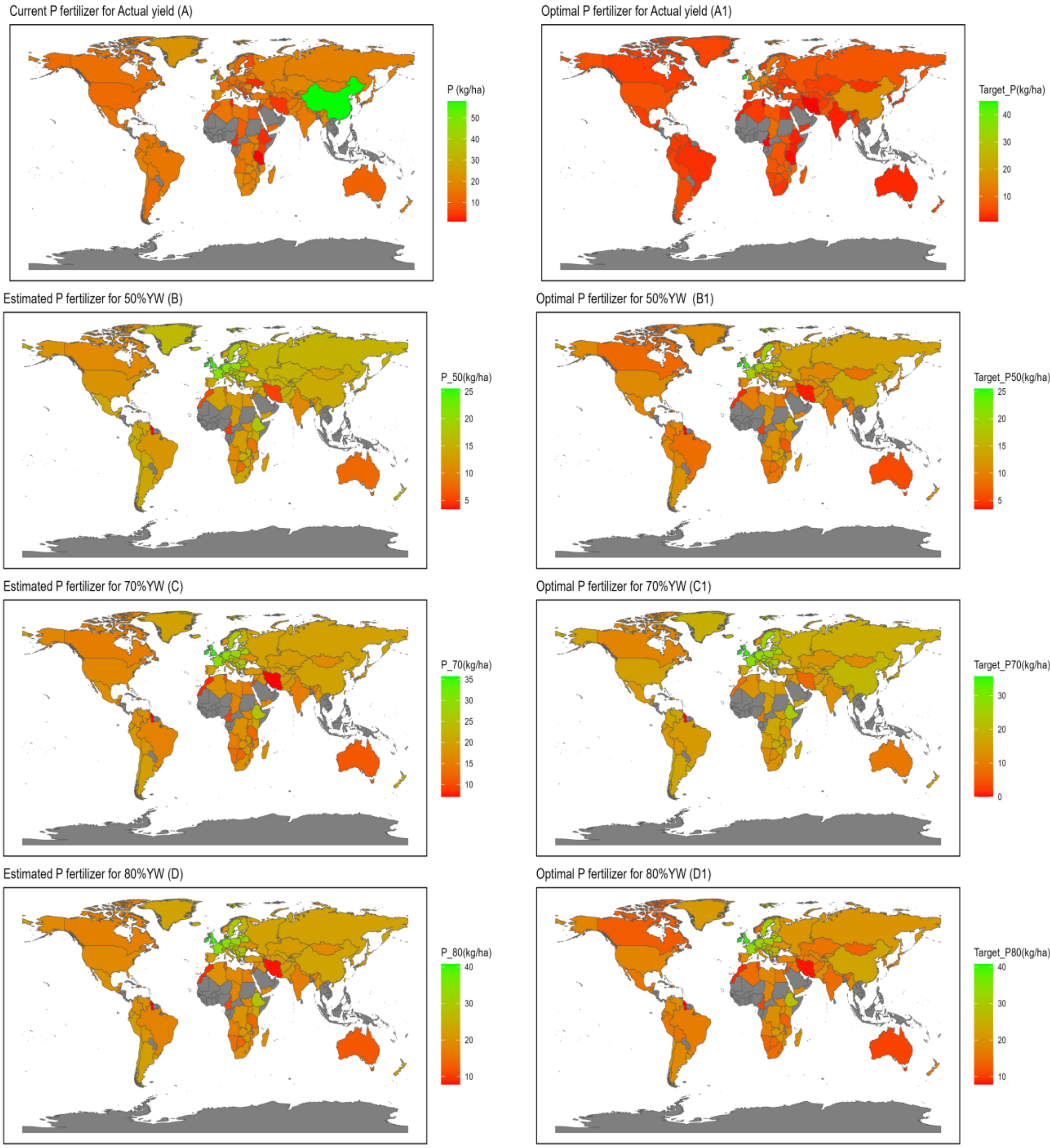

Figure 3. The results of P application levels in both actual and optimal values, derived from DEA analysis across various scenarios. These scenarios encompass current conditions (A and A1), minimum P input requirements, and the optimal necessary to attain target yields of 50% Yw (B and B1), 70% Yw (C and C1), and 80% Yw (D and D1) in rainfed wheat.

tions of 60 mm at stem elongation and flowering) combined with moderate nitrogen rates significantly improves Nitrogen Use Efficiency (NUE) and yield while reducing nitrate accumulation [32]. Long-term manure application, especially when combined with chemical fertilizers, increases soil organic matter and enhances both NUE and crop yields [33]. Retaining crop residues in the field can increase phosphorus use efficiency by over 35%, with additional benefits from factors such as fertilizer type, application method, duration, and climate [34]. Reduced tillage and residue retention further increase soil organic carbon, available phosphorus, and biological activity, supporting better nutrient use [35].

 ISBN: 978-1-68558-327-9

Partial substitution of chemical phosphorus fertilizer with organic manure also significantly increases phosphorus fertilizer efficiency and crop yield [36]. Overall, practices such as optimizing planting date, irrigation, residue retention, increasing soil organic matter, and integrating organic amendments with mineral fertilizers, along with adapting to local climate and soil conditions, are all crucial for improving nitrogen and phosphorus use efficiency. In addition, various fertilizer management approaches, including Enhanced Efficient Fertilizers (EEFs), Integrated Nutrient Management (INM), and split N application, offer potential solutions to enhance NUE and reduce losses [31][37]. It seems that for P fertilizer, the issue lies not in excessive application but rather in the timing of its application, particularly during seed planting. Implementing strategies that involve drawing application during seed planting time appears to be the most effective approach for increasing Phosphorus Use Efficiency (PUE) while minimizing surplus application [38]. By focusing on the timing of P fertilizer application, agricultural practices can optimize the utilization of this essential nutrient, ensuring that it is available to the crop when needed most, particularly during critical growth stages like germination and early seedling establishment [39]. This targeted approach helps enhance PUE by maximizing the uptake and utilization of phosphorus by the crops while minimizing wastage or excess application that may contribute to environmental concerns. Implementing precise application techniques, such as placing P fertilizer directly in the seed zone during planting, allows for more efficient utilization of the nutrient by the emerging seedlings [40].

V. CONCLUSION AND FUTURE WORK

This study aimed to assess the efficiency of N and P fertilizer use in rainfed wheat production across 122 countries, targeting optimal application rates for 50%, 70%, and 80% of Yw while minimizing environmental impacts. We used an expanded GYGA dataset, extended globally via stepwise regression, and applied DEA with the CCR model. Inputs included annual precipitation and N and P applications, with outputs covering crop yield, production, water productivity, and nutrient use efficiencies. Results showed significant efficiency differences, with countries like Sweden, Ukraine, Ireland, Finland, and Belgium achieving full efficiency (1.0), while others, such as India and Iran, scored 0.18–0.37 under current conditions. Optimized N and P rates were often lower, e.g., Montenegro's N use dropped from 427 kg/ha to 132 kg/ha for actual yield optimization. Efficiency improved with higher yield targets, and climate zone analysis identified efficient production regions, providing insights for enhancing global rainfed wheat productivity and sustainability.

ACKNOWLEDGEMENTS

The research was supported by Czech Science Foundation grant no. 23-07984X.

REFERENCES

[1] A. Dadrasi, M. Chaichi, A. Nehbandani, A. Sheikhi, F. Salmani, and A. Nemati, "Addressing food insecurity: An exploration of wheat production expansion," *Plos one*, vol. 18, no. 12, p. e0290684, 2023.

[2] W. Anderson, C. Johansen, and K. H. Siddique, "Addressing the yield gap in rainfed crops: a review," *Agronomy for Sustainable Development*, vol. 36, pp. 1-13, 2016.

[3] J. P. Aryal, N. Manchanda, and T. Sonobe, "Expectations for household food security in the coming decades: A global scenario," in *Future Foods*, Academic Press, pp. 107-131, 2022.

[4] J. W. Erisman, M. A. Sutton, J. Galloway, Z. Klimont, and W. Winiwarter, "How a century of ammonia synthesis changed the world," *Nature Geoscience*, vol. 1, no. 10, pp. 636-639, 2008.

[5] C. Lu and H. Tian, "Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance," *Earth System Science Data*, vol. 9, no. 1, pp. 181-192, 2017.

[6] X. Wu et al., "ORCHIDEE-CROP (v0), a new process-based agro-land surface model: model description and evaluation over Europe," *Geoscientific Model Development*, vol. 9, no. 2, pp. 857-873, 2016.

[7] M. A. Clark et al., "Global food system emissions could preclude achieving the 1.5 and 2 C climate change targets," *Science*, vol. 370, no. 6517, pp. 705-708, 2020.

[8] A. Hauglustaine, Y. Balkanski, M. Schulz, "A global model simulation of present and future nitrate aerosols and their direct radiative forcing of climate," *Atmospheric Chemistry and Physics*, vol. 14, no. 20, pp. 11031-11063, 2014.

[9] M. Fowler et al., "The global nitrogen cycle in the twenty-first century," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 368, no. 1621, p. 20130164, 2013.

[10] Eskelinen, W. S. Harpole, M. T. Jessen, R. Virtanen, and Y. Hautier, "Light competition drives herbivore and nutrient effects on plant diversity," *Nature*, vol. 611, no. 7935, pp. 301-305, 2022.

[11] B. Gu et al., "Cost-effective mitigation of nitrogen pollution from global croplands," *Nature*, vol. 613, no. 7942, pp. 77-84, 2023.

[12] A. Smerald, D. Kraus, J. Rahimi, K. Fuchs, R. Kiese, K. Butterbach-Bahl, and C. Scheer, "A redistribution of nitrogen fertiliser across global croplands can help achieve food security within environmental boundaries," *Communications Earth & Environment*, vol. 4, no. 1, p. 315, 2023.

[13] A. Dadrasi, J. Weinzettel, G. Wei, D. Vačkářová, and J. Frouz, "Closing global yield gap of rainfed wheat by optimizing nitrogen and phosphorus inputs," *Zenodo*, 2025, doi:10.5281/zenodo.14887610.

[14] I. Ludemann, A. Gruere, P. Heffer, and A. Dobermann, "Global data on fertilizer use by crop and by country," *Scientific Data*, vol. 9, no. 1, pp. 1-8, 2022.

[15] P. Potter, N. Ramankutty, E. M. Bennett, and S. D. Donner, "Characterizing the spatial patterns of global fertilizer application and manure production," *Earth Interactions*, vol. 14, no. 2, pp. 1-22, 2010.

[16] N. D. Mueller, J. S. Gerber, M. Johnston, D. K. Ray, N. Ramankutty, and J. A. Foley, "Closing yield gaps through nutrient and water management," *Nature*, vol. 490, no. 7419, pp. 254-257, 2012.

[17] F. Aramburu-Merlos, M. P. van Loon, M. K. van Ittersum, and P. Grassini, "High-resolution global maps of yield potential with local relevance for targeted crop production improvement," *Nature Food*, vol. 5, no. 8, pp. 667-672, 2024.

[18] A. Charnes, W. W. Cooper, and E. Rhodes, "Measuring the efficiency of decision making units," *European Journal of Operational Research*, vol. 2, no. 6, pp. 429-444, 1978, doi:10.1016/0377-2217(78)90138-8.

[19] R. Färe, C. A. K. Lovell, and K. Zieschang, "Measuring the technical efficiency of multiple output production technologies," in *Quantitative Studies on Production and Prices*, pp. 159-171, 1983.

[20] M. Mohsin, I. Hanif, F. Taghizadeh-Hesary, Q. Abbas, and W. Iqbal, "Nexus between energy efficiency and electricity reforms: A DEA-based way forward for clean power development," *Energy Policy*, vol. 149, p. 112052, 2021, doi:10.1016/j.enpol.2020.112052.

[21] S. A. A. Shah, P. Zhou, G. D. Walasai, and M. Mohsin, "Energy security and environmental sustainability index of South Asian countries: a composite index approach," *Ecological Indicators*, vol. 106, p. 105507, 2019, doi:10.1016/j.ecolind.2019.105507.

[22] V. Coll-Serrano, V. J. Bolón-Canedo, and M. C. Miranda, "deaR: Conventional and fuzzy data envelopment analysis," *R package version 4.3.2*, 2023.

[23] W. Huang, H. Li, K. Chen, X. Teng, Y. Cui, H. Yu, C. Bi, M. Huang, and Y. Tang, "Improved evaluation of cultivation performance for maize based on group decision method of data envelopment analysis model," *Applied Sciences*, vol. 13, no. 1, p. 521, 2022.

[24] M. Pokushko, A. Stupina, I. Medina-Bulo, S. Ezhemanskaya, R. Kuzmich, and R. Pokushko, "Algorithm for application of a basic model for the data envelopment analysis method in technical systems," *Algorithms*, vol. 16, no. 10, p. 460, 2023.

[25] Z. Wen, J. Shen, M. Blackwell, H. Li, B. Zhao, and H. Yuan, "Combined applications of nitrogen and phosphorus fertilizers with manure increase maize yield and nutrient uptake via stimulating root growth in a long-term experiment," *Pedosphere*, vol. 26, pp. 62-73, 2016, doi:10.1016/S1002-0160(15)60023-6.

[26] K. Tekulu, G. Taye, and D. Assefa, "Effect of starter nitrogen and phosphorus fertilizer rates on yield and yield components, grain protein content of groundnut (Arachis Hypogaea L.) and residual soil nitrogen content in a semiarid north Ethiopia," *Heliyon*, vol. 6, 2020, doi:10.1016/j.heliyon.2020.e05101.

[27] M. Kassa and Z. Sorsa, "Effect of nitrogen and phosphorus fertilizer rates on yield and yield components of barley (Hordeum Vulgare L.) varieties at Damot Gale District, Wolaita Zone, Ethiopia," *American Journal of Agriculture and Forestry*, vol. 3, p. 271, 2015, doi:10.11648/j.ajaf.20150306.15.

[28] X. Yan et al., "Exploring phosphorus fertiliser management in wheat production," *European Journal of Agronomy*, vol. 153, p. 127063, 2024.

[29] L. Liu et al., "Thresholds of nitrogen and phosphorus input substantially alter arbuscular mycorrhizal fungal communities and wheat yield in dryland farmland," *Journal of Agricultural and Food Chemistry*, vol. 72, no. 33, pp. 18287-18299, 2024.

[30] R. Allende-Montalbán et al., "Nitrogen fertilization and sowing date as wheat climate change adaptation tools under Mediterranean conditions," *European Journal of Agronomy*, vol. 153, 127346, 2024, doi:10.1016/j.eja.2024.127346.

[31] S. Zhang, X. Hou, C. Wu, and C. Zhang, "Impacts of climate and planting structure changes on watershed runoff and nitrogen and phosphorus loss," *The Science of the Total Environment*, vol. 706, 134489, 2019, doi:10.1016/j.scitotenv.2019.134489.

[32] H. Li, H. Wang, Q. Fang, B. Jia, D. Li, J. He, and R. Li, "Effects of irrigation and nitrogen application on NO3–N distribution in soil, nitrogen absorption, utilization and translocation by winter wheat," *Agricultural Water Management*, vol. 276, 108058, 2023, doi:10.1016/j.agwat.2022.108058.

[33] Y. Liu et al., "Enhancing soybean and maize yields through improved nitrogen and soil water use efficiencies: A 40-year study on the impact of farmyard manure amendment in Northeast China," *Plants*, vol. 13, 500, 2024, doi:10.3390/plants13040500.

[34] X. Liu, C. Wu, Z. Wang, M. Zhang, Y. Zhang, and Z. Chen, "A global synthesis on the rational management practices for enhancing phosphorus use efficiency in agricultural systems," *Agriculture, Ecosystems & Environment*, vol. 375, 109408, 2025, doi:10.1016/j.agee.2024.109408.

[35] S. Sharma and P. Singh, "Tillage intensity and straw retention impacts on soil organic carbon, phosphorus and biological pools in soil aggregates under rice-wheat cropping system in Punjab, north-western India," *European Journal of Agronomy*, 2023, doi:10.1016/j.eja.2023.126913.

[36] Jin, Z. Teng, Y. Shu, K. Li, X. Lin, and X. Liu, "Partial substitution of inorganic fertilizer with organic manure and reduced phosphorus inputs enhance rice yields and phosphorus fertilizer efficiency," *Sustainability*, vol. 17, no. 9, 2025, doi:10.3390/su17093878.

[37] L. Xia, S. K. Lam, D. Chen, J. Wang, Q. Tang, and X. Yan, "Can knowledge-based N management produce more staple grain with lower greenhouse gas emission and reactive nitrogen pollution? A meta-analysis," *Global Change Biology*, vol. 23, pp. 1917-1925, 2017, doi:10.1111/gcb.13455.

[38] M. Qaswar et al., "Interaction of liming and long-term fertilization increased crop yield and phosphorus use efficiency (PUE) through mediating exchangeable cations in acidic soil under wheat–maize cropping system," *Scientific Reports*, vol. 10, 2020, doi:10.1038/s41598-020-76892-8.

[39] L. Liang, H. Qi, P. Xu, X. Zhao, X. Dong, and R. Shen, "High phosphorus at seedling stage decreases the post-transplanting fertiliser requirement of cucumber (Cucumis sativus L.)," *Scientia Horticulturae*, vol. 190, pp. 98-103, 2015, doi:10.1016/j.scienta.2015.04.025.

[40] Xing, S. Li, B. Xia, and H. Wen, "Effects of phosphorus fertilization on yield of winter wheat and utilization of soil nitrogen," *Ying yong sheng tai xue bao [English: The Journal of Applied Ecology]*, vol. 26, no. 2, pp. 437-442, 2015.