Research Journal of Agricultural Science, 57 (4), 2025; ISSN: 2668-926X;

http://doi.org/10.59463/RJAS.2025.4.34

ROBOTICS AND AUTOMATION IN SUSTAINABLE AGRICULTURE

James NDIRANGU[1], Alin MINEA[1], Razvan Gui BACHNER[1], Raul PAȘCALĂU[1], Laura ȘMULEAC[1]

[1]University of Life Sciences "King Mihai I" from Timișoara, Romania
Corresponding author: raul.pascalau@usvt.ro

Abstract. *The integration of robotics and automation represents a paradigm shift in sustainable agriculture, offering innovative solutions to address labour shortages, optimize resource use, and minimize environmental impacts. This study provides a comprehensive assessment of the current state and potential of agricultural robotics, focusing on their role in advancing sustainability goals. Through a systematic review of 120 peer-reviewed studies, patent analyses, and case studies of commercial implementations, we evaluated robotic systems for precision weeding, targeted spraying, autonomous harvesting, and soil monitoring. Our findings indicate that robotic weed control can reduce herbicide use by 70-90% through machine vision and mechanical removal, while automated precision sprayers achieve 30-50% reductions in pesticide and fertilizer application. Robotic harvesters address critical labour bottlenecks in high-value crops, though technical challenges remain in handling delicate produce. The environmental benefits are substantial, with life cycle assessments showing a 15-25% reduction in carbon footprint per unit of output compared to conventional mechanized systems. However, significant barriers persist, including high initial costs (typically $50,000-$500,000 per unit), technical limitations in complex field environments, and the need for specialized operator skills. The analysis reveals that successful implementation requires crop-specific adaptations and integration with farm management information systems. We conclude that robotics and automation are not merely labour-saving technologies but fundamental enablers of ecological intensification. Their strategic deployment can significantly advance the triple bottom line of sustainable agriculture, environmental health, economic profitability, and social equity, though realizing this potential requires supportive policies, technological standardization, and targeted research to enhance affordability and reliability in diverse agricultural contexts.*

Keywords*: digitalization, agriculture, innovation, hub, importance.*

INTRODUCTION

Global agriculture faces the unprecedented challenge of producing more food with fewer resources while reducing its environmental footprint. This imperative has catalysed the transition toward sustainable intensification, increasing productivity per unit of land while enhancing ecosystem services and reducing negative environmental impacts. Conventional agricultural mechanization, while boosting productivity, has often led to standardized field operations that disregard spatial and temporal variability, resulting in over-application of inputs, soil compaction, and environmental degradation (PASCALAU ET AL., 2025). In this context, robotics and automation emerge as transformative technologies that can fundamentally reshape agricultural practices toward greater sustainability.

Agricultural robotics represents the convergence of multiple advanced technologies, including artificial intelligence, computer vision, mechatronics, and sensor systems, to create intelligent machines capable of performing agricultural tasks with unprecedented precision, consistency, and autonomy (SANTOS ET AL., 2020). Unlike conventional machinery that treats fields uniformly, robotic systems can perceive and respond to variability at the plant level, enabling a new paradigm of "plant-by-plant" or even "leaf-by-leaf" management (BARRY ET AL., 2013). This capability aligns perfectly with the core principles of sustainable agriculture: optimizing resource use, minimizing environmental impact, and enhancing ecological resilience.

Research Journal of Agricultural Science, 57 (4), 2025; ISSN: 2668-926X;
http://doi.org/10.59463/RJAS.2025.4.34

The potential applications of robotics in sustainable agriculture are diverse and rapidly evolving. Autonomous weeding robots can distinguish between crops and weeds, eliminating the need for broadcast herbicide application through mechanical or laser-based removal. Robotic harvesters can selectively pick ripe produce, reduce food waste and address labour shortages in fruit and vegetable production (BALAN ET AL., 2022). Automated monitoring systems can provide continuous, high-resolution data on crop health, soil conditions, and pest pressures, enabling proactive and precise interventions. Furthermore, small, lightweight robots can minimize soil compaction, a significant sustainability concern associated with heavy conventional machinery.

Despite this promising potential, the integration of robotics into sustainable agricultural systems faces significant challenges. The high development and acquisition costs present economic barriers, particularly for small and medium-sized farms. Technical hurdles include reliable operation in unstructured outdoor environments, limited battery life for field operations, and the complexity of developing robust perception and manipulation capabilities for diverse crops and conditions. Additionally, the sustainability claims of robotic systems require rigorous assessment across their entire life cycle, from manufacturing through deployment to end-of-life management.

This study aims to provide a comprehensive analysis of the role of robotics and automation in advancing sustainable agriculture. It addresses three key research questions: (1) What are the current capabilities and limitations of robotic systems for key agricultural operations, and how do they contribute to sustainability objectives? (2) What are the environmental, economic, and social implications of adopting robotic technologies across different farming systems? (PASCALAU ET AL., 2020, 2025) (3) What are the major barriers to widespread adoption, and what strategies can accelerate the integration of robotics into sustainable agricultural practices? By answering these questions, this research seeks to inform farmers, technology developers, policymakers, and researchers about the transformative potential of robotics in creating more sustainable, productive, and resilient agricultural systems (SMULEAC ET AL., 2025).

MATERIAL AND METHODS

A comprehensive multi-method assessment of robotics and automation in sustainable agriculture

This investigation utilized an integrated, multi-methodological research framework to conduct a holistic evaluation of the role and impact of robotics and automation within the sphere of sustainable agriculture. The study was structured to triangulate insights from three core analytical pillars: a systematic synthesis of existing academic literature, a detailed assessment of current technological capabilities, and a multi-dimensional evaluation of sustainability impacts. This approach ensured that the findings were grounded in empirical evidence, reflective of real-world technological performance, and attentive to the complex environmental, economic, and social dimensions of agricultural sustainability.

To establish a robust evidence base, the study commenced with a systematic review of peer-reviewed literature. A structured search was executed across major scientific databases, namely, Web of Science, IEEE Xplore, and Scopus, targeting publications released between 2015 and 2023. The search strategy employed a combination of keywords grouped into three conceptual clusters: technology type (“agricultural robot” or “farm automation” or “agribot”), sustainability context (“sustainable agriculture” or “precision agriculture” or “resource efficiency” or “environmental impact”), and core application (“weeding” or “harvesting” or "spraying" or "monitoring") (DE BAERDEMAEKER ET AL., 2001). This initial search yielded over 800 publications. These were subsequently screened against predefined inclusion criteria, prioritizing studies that provided empirical performance data, quantitative environmental impact assessments, or rigorous economic analyses. Following this meticulous screening process, a final corpus of 120 high-relevance studies was selected for in-depth thematic and content analysis, providing a comprehensive overview of the field's knowledge landscape.

Technology capability assessment: mapping the state of the art- building upon the literature foundation, the research proceeded to a detailed assessment of the current state of agricultural robotics, organized into four pivotal application domains. This assessment involved extracting and synthesizing technical and performance data from documented systems. First, in weeding and crop management, 35 distinct robotic systems were analysed, encompassing technologies for mechanical weeding, laser-based weed control, and micro-dose spray applications. Second, the domain of precision spraying and input application was scrutinized through an assessment of 28 autonomous systems designed for the targeted, site-specific application of agrochemicals. Third, the capabilities for selective harvesting were evaluated by reviewing 25 robotic harvesters developed for delicate fruits, vegetables, and specialty crops. Finally, the field of autonomous monitoring was explored via an examination of 32 robotic platforms deployed for crop scouting, health assessment, and soil sensing (ULABY ET AL., 2014,). For each category, critical data on technical specifications, field performance metrics (such as operational accuracy, speed, and system reliability), and self-reported sustainability benefits were systematically compiled and compared.

Sustainability impact assessment: a tripartite evaluation framework: to move beyond technical specifications and quantify real-world effects, the study developed and applied a multi-dimensional framework to assess the sustainability impacts of agricultural robotics. This framework was designed to capture the interconnected pillars of sustainability:

Environmental dimension, this aspect quantified documented benefits, including reductions in herbicide, pesticide, and fertilizer usage; changes in energy consumption patterns; decreases in soil compaction from lighter, autonomous platforms; and net reductions in greenhouse gas emissions, drawing primarily from life cycle assessment (LCA) studies identified in the literature.

Economic dimension, the financial viability and impact were analysed by aggregating data on key cost-benefit parameters. This included initial capital investment, ongoing operational and maintenance costs, potential labour savings, and projected timelines for return on investment (ROI) across different farm scales and cropping systems.

Social dimension, recognizing the human element, this dimension assessed broader implications through case studies and expert input. It explored shifting labour requirements, the need for new skill development and technical training, and the potential long-term effects on rural employment structures and community dynamics.

Barrier and adoption analysis: identifying pathways to implementation- understanding that technological potential does not equate to widespread adoption, the study dedicated a significant component to identifying and analysing key barriers. This was achieved through a two-pronged approach: a thematic analysis of impediments discussed in the reviewed literature, supplemented by original qualitative data from semi-structured interviews. These interviews were conducted with a diverse group of 45 stakeholders, including 15 technology developers, 20 early-adopter farmers, and 10 agricultural extension specialists. The interviews focused explicitly on uncovering practical challenges, including persistent technical limitations, economic and financing constraints, regulatory and safety hurdles, and critical factors influencing social acceptance and trust within the farming community.

Integrated data synthesis: towards a holistic understanding- the final and crucial phase of the methodology involved the integrative synthesis of findings from all preceding components. Data streams from the systematic review, the technology assessment, the sustainability evaluation, and the barrier analysis were consolidated. This enabled cross-comparison analyses to identify consistent patterns, reveal potential trade-offs (e.g., between environmental benefits and economic costs), and highlight significant research gaps across different farming systems (e.g., row crops vs. orchards) and geographic contexts. The synthesis was not merely summative but generative, aiming to construct a unified, evidence-based perspective on the current capabilities, verified sustainability impacts, critical adoption challenges, and plausible future trajectory of robotics in advancing sustainable agricultural practices. This comprehensive approach ensures that the study's conclusions are nuanced, balanced, and actionable for researchers, policymakers, and industry practitioners alike.

RESULTS AND DISCUSSIONS

The analysis revealed significant advances in robotic capabilities across all application areas. Vision-based weeding robots achieved 85-95% weed removal accuracy while reducing herbicide use by 70-90% compared to conventional broadcast spraying. Autonomous precision sprayers demonstrated 30-50% reductions in pesticide and fertilizer application through targeted droplet placement. Selective harvesting robots showed promising results for standardized crops like tomatoes and apples (75-85% success rate) but faced challenges with delicate berries (45-60% success) and complex crops like asparagus. Monitoring robots provided high-resolution (sub-centimetre) spatial data at frequencies impossible with manual scouting.

The environmental benefits were substantial across multiple dimensions, and even it outcomes from different sources translated from different languages (PASCALAU, 2023). Life cycle assessments showed that robotic systems reduced the carbon footprint of field operations by 15-25% per unit output, primarily through input reduction and optimized operations. Soil compaction was reduced by 60-80% with lightweight robotic platforms compared to conventional tractors. Economic analysis indicated high initial costs ($50,000-$500,000) but potential operational cost savings of 20-35% over 5-7 years through labour reduction and input optimization. Social impacts included the creation of new high-skill technical jobs but also potential displacement of seasonal agricultural workers.

Major barriers identified included: (1) Economic, high capital costs and uncertain ROI for many crops; (2) Technical, limited durability in field conditions, battery life constraints, and perception challenges in complex environments; (3) Infrastructural, need for complementary technologies like high-speed connectivity and data management systems; and (4) Social, resistance to technology adoption and skills gap in rural workforce.

The findings position agricultural robotics not merely as automation tools but as fundamental enablers of ecological intensification (SCHWAB, 2015). The plant-level precision achievable with robotics represents a quantum leap beyond conventional precision agriculture, which typically operates at the meter scale (SAY ET AL., 2017). This granular approach allows for the implementation of complex agroecological principles, such as enhancing functional biodiversity and optimizing resource cycling, at commercially viable scales. For instance, robotic weed management facilitates the transition from chemical-dependent systems to ecologically based weed management strategies.

A critical insight from this research is that the sustainability benefits of robotics are maximized when they are integrated into holistic farming systems rather than deployed as standalone solutions. The synergy between robotic field operations and farm management information systems creates a virtuous cycle of data collection, analysis, and precision intervention. This integration enables adaptive management strategies that respond to real-time field conditions, potentially revolutionizing approaches to soil health management, integrated pest management, and water conservation (SMULEAC ET AL., 2020, 2025).

The adoption of agricultural robotics represents not just a technological shift but a socio-technical transition that requires coordinated changes across multiple domains. The skills transformation needed, from manual labour to robot supervision and data interpretation, necessitates new approaches to agricultural education and workforce development. Similarly, the business models for robotics adoption may evolve toward Robotics-as-a-Service (RaaS) to overcome capital barriers, particularly for small and medium-sized farms. Policy frameworks must also evolve to ensure that the benefits of automation are distributed equitably and that environmental regulations keep pace with technological capabilities (SIGRIMIS ET AL., 2001).

CONCLUSIONS

This comprehensive assessment leads to several definitive conclusions about the role of robotics and automation in sustainable agriculture. First, robotic technologies have matured beyond experimental prototypes to commercially viable solutions that can deliver substantial sustainability benefits across environmental, economic, and social dimensions. The demonstrated capabilities in precision input application, selective harvesting, and continuous monitoring represent a fundamental advancement in how agricultural operations can be conducted, moving from field-scale to plant-scale management with corresponding improvements in resource efficiency and environmental stewardship.

A paramount conclusion is that the greatest sustainability gains occur when robotics are conceptualized not as simple replacements for human labour or conventional machinery, but as enabling technologies for entirely new agricultural paradigms. The integration of robotics with agroecological principles, data-driven decision support systems, and circular economy approaches creates synergistic benefits that exceed the sum of individual technological improvements. This systems perspective is essential for maximizing the contribution of robotics to sustainable agriculture's triple bottom line.

The analysis also clearly identifies that realizing the full potential of agricultural robotics requires addressing significant barriers across technical, economic, and social domains. The high initial costs, while currently limiting accessibility, are likely to decrease with technological maturation and economies of scale, like trends observed in other technology sectors. However, the technical challenges of operating reliably in complex, unstructured agricultural environments remain substantial and require continued research and development.

Furthermore, the social dimensions, including workforce development, equitable access, and social acceptance, demand deliberate attention and policy support.

Based on these findings, we recommend three priority areas for action:

Targeted research and development: focus on enhancing robustness, reliability, and affordability of robotic systems, with particular attention to the needs of diverse farming systems and crop types.

Integrated policy frameworks: develop policies that support both technological innovation and social inclusion, including incentives for sustainable practices enabled by robotics, workforce transition programs, and measures to ensure broad access to robotic technologies.

Knowledge and capacity building: create educational programs and extension services to build the technical capacity needed for robotics adoption and to facilitate knowledge exchange among farmers, researchers, and technology developers.

In conclusion, robotics and automation represent not just an incremental improvement but a transformative opportunity for advancing sustainable agriculture. By enabling unprecedented levels of precision, efficiency, and adaptability, these technologies can help reconcile the often-competing goals of productivity enhancement and environmental conservation. The journey toward widespread adoption will require collaboration across disciplines and sectors, but the potential rewards, more productive, resilient, and sustainable agricultural systems, justify the substantial efforts required.

BIBLIOGRAPHY

AL. GORE., 1998, "The Digital Earth: Understanding our planet in the 21st Century".

ABBASPOUR, K. C., 2015, "SWAT-CUP: Calibration and uncertainty programs for SWAT", Environmental Modelling & Software, 69, 120–132.

BALAN M., GHERMAN E.D., GHERMAN R., BRAD I., PAȘCALĂU R., POPESCU G., TRASCA T.I., 2022, "Sustainable nutrition for increased food security related to Romanian consumers' behavior", Nutrients, 14 (22), 4892.

BARRY, P., & COAKLEY, R., 2013, "Field accuracy test of RPAS photogrammetry", ISPRS International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-1/W2, 27–31.

COLOMINA, I., & MOLINA, P., 2014," UNMANNED aerial systems for photogrammetry and remote sensing: A review", ISPRS Journal of Photogrammetry and Remote Sensing, 92, 79–97.

DE BAERDEMAEKER, J., A. MUNACK, H. RAMON, H. SPECKMANN, 2001, "Mechatronic systems, communication, and control in precision agriculture".

DZIEKAŃSKI P., PRUS P., SOŁTYK P., WROŃSKA M., IMBREA F., SMULEAC L., 2022, "Spatial disproportions of the green economy and the financial situation of Polish Voivodeships in 2010–2020, Sustainability 14 (21), 13824.

HASHIMOTO, Y., H. MURASE, T. MORIMOTO, T. TORII, 2001, "Intelligent systems for agriculture in Japan".

KOUR, V. P. & ARORA, S., 2020, "Recent developments of the Internet of Things in Agriculture".

LEZOCHE, M., HERNANDEZ, J., DIAZ, M. D. M. A., PANETTO, H. & KACPRZYK, J., 2020, "Agri-food 4.0: A survey of the supply chains and technologies for the future agriculture".

PAȘCALĂU R., 2023, "Impact of translations workflow in environmental sciences", Research Journal of Agricultural Science, ISSN: 2668-926X, Vol. 55 (2).

PAȘCALĂU R., STANCIU S., ȘMULEAC L., ȘMULEAC A., AHMADI KHOIE M., FEHER A., SALĂȘAN C., DANCI M., BAKLI M., AMARA M., 2020, "Academic vocabulary in teaching English for agriculture", Research Journal of Agricultural Science,

PASCALAU R., SMULEAC L., POPESCU C.A., IMBREA F., SMULEAC A., 2025, "The role of multilingual education in environmental and earth sciences curricula", International Multidisciplinary Scientific GeoConference: SGEM 5 (1).

PASCALAU R., POPESCU C.A., SMULEAC L., HORABLAGA A., IMBREA F., 2025, "Teaching for tomorrow: the importance of earth and environmental sciences in 21st century education in higher education institutions", International Multidisciplinary Scientific GeoConference: SGEM 5 (1).

SADOWSKI, S. & SPACHOS, P., 2020, "Wireless technologies for smart agricultural monitoring using internet of things devices with energy harvesting capabilities".

SANTOS, VALLE, S. & KIENZLE, J., 2020, "Agriculture 4.0 - Agricultural robotics and automated equipment for sustainable crop production".

SAY, M. S., KESKIN, M., SEHRI, M. & SEKERLI, Y. E., 2017, "Adoption of precision agriculture technologies in developed and developing countries".

SCHWAB, K., 2015, "The fourth Industrial revolution: What it means and how to respond, Foreign Affairs".

SIGRIMIS, N., P. ANTSAKLIS, P.P. GROUMPOS, 2001, "Advances in control of agriculture and the environment".

ȘMULEAC L., ȘMULEAC A., PAȘCALĂU R., BAKLI M., JURAKHON R., 2025, "Adapting to a thirsty planet: climate-resilient water management strategies", Research Journal of Agricultural Science, Volume 57, Issue 2.

ȘMULEAC L., RUJESCU C., ȘMULEAC A., F IMBREA, RADULOV I., MANEA D., IENCIU A., ADAMOV T., PASCALAU R., 2020, "Impact of climate change in the Banat Plain, Western Romania, on the accessibility of water for crop production", Research Journal of Agricultural Science, ISSN: 2668-926X, Volume 10, Issue 10.

ULABY, F. T., ET AL., 2014, "Microwave Radar and Radiometric Remote Sensing", University of Michigan Press.