Addressing needs for the diffusion of digital greenhouse farming. Insights from Living Labs in the Mediterranean basin

Oriana Gava[1*], Sara Sturiale[2], Marisa Gallardo[3], Dolores Buendía Guerrero[4], Dursun Buyuktas[5], Gulcin Ece Aslan[5], Asma Laarif[6], Thameur Bouslama[6], Alejandra Navarro[7], Luca Incrocci[2], Fabio Bartolini[8]

1. Research Centre for Agricultural Policies and Bioeconomy, Council for Agricultural Research and Economics, Viale della Toscana 21, 50127 Firenze, Italy (oriana.gava@crea.gov.it)
2. Department of Agriculture, Food and Environment, University of Pisa, Via del Borghetto 80, 56124 Pisa, Italy (sara.sturiale@phd.unipi.it, luca.incrocci@unipi.it)
3. Department of Agronomy, University of Almería, Carretera de Sacramento s/n, La Cañada de San Urbano, 04120 Almería, Spain (mgallard@ual.es)
4. Research Station of the Cajamar, Paraje Las Palmerillas 25, 04710 El Ejido, Spain (doloresbuendia@fundacioncajamar.com)
5. Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Akdeniz University, Antalya, Turkey (dbuyuktas@akdeniz.edu.tr, ecebacalan@akdeniz.edu.tr)
6. University of Sousse, LR21AGR03, Regional Research Centre on Horticulture and Organic Agriculture (CRRHAB), 57, Chott Mariem, TN-4042 Sousse, Tunisia (laarif.asma@iresa.agrinet.tn, thameurbouslama@gmail.com)
7. Research Centre for Vegetable and Ornamental Crops, Council for Agricultural Research and Economics, Via Cavalleggeri 51, 84098 Pontecagnano – Faiano, Italy (alejandra.navarrogarcia@crea.gov.it)
8. Department of Chemical, Pharmaceutical and Agricultural Sciences, University of Ferrara, Via L. Borsari 46, 44121 Ferrara, Italy (fabio.bartolini@unife.it)

* Corresponding author at: oriana.gava@crea.gov.it

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record.

Please cite this article as:

Gava O., Sturiale S., Gallardo M., Buendía Guerrero D., Buyuktas D., Ece Aslan G., Laarif A., Bouslama t., Navarro A., Incrocci L., Bartolini F. (2025). Addressing needs for the diffusion of digital greenhouse farming. Insights from Living Labs in the Mediterranean basin, Bio-Based and Applied Economics, Just Accepted. DOI:10.36253/bae-17755

Abstract

Agriculture 4.0 represents a huge opportunity for the transformation of agrifood sectors. However, its adoption (and diffusion) in real-world farming contexts faces multiple challenges. This study focuses on greenhouse farming within the Mediterranean basin. It aims to assess the needs of actors involved in the uptake of Agriculture 4.0 and define enabling conditions to support achieving these needs, focusing on the introduction of an innovative decision support system in real-world greenhouses for tomato production. A qualitative and comparative approach is implemented, using participatory data collection methods with cross-disciplinary experts from four case studies across the Mediterranean Basin. Data are collected through one-to-one open discussions, supported using context and SWOT analyses to stimulate reflection and recall. The findings highlight the need to improve digital literacy among farmers and advisors, build trust through tailored education conditions and mentorship, and support young farmers with financial incentives and training. Market dynamics are relevant as well, pinpointing the need for stronger product images and increasing consumer awareness through certification and labelling. Great interest and technology potential emerges from the possibility to enable (partial) remote work thereby benefiting a work-life balance. Simplifying bureaucratic processes and enhancing policy support for cooperation and farmer unions are also essential for encouraging farmers to adopt digital technology.

Keywords: Decision Support System (DSS), agricultural digitalisation, qualitative research, multi-actor engagement, actor needs, enabling

1. Introduction

1.1 Background

Agriculture 4.0, also known as digital agriculture, leverages precision and data-driven technologies such as the Internet of Things, data analytics, artificial intelligence, and machine learning and is viewed as a promising approach to sustainably enhance food production. The use of these technologies is particularly relevant in intensive farming systems like greenhouse production (Maffezzoli et al., 2022; Mondejar et al., 2021). However, while technology-driven solutions can be appealing, resources may be wasted if technologies are not developed responsibly by aligning with the actual needs of actors[1] directly involved in technology adoption and diffusion (Rose et al., 2021). Large literature acknowledge this issue and suggest that a variety of needs exist ranging from developing user-friendly digital applications, reducing access costs and enhancing digital literacy, to improving policy and governance (Klerkx et al., 2019; McFadden et al., 2022; UNESCO, 2018; Wolfert et al., 2017; Yuan and Sun, 2024). These needs often cannot be met, and enabling conditions should be created to facilitate the successful implementation and adoption of specific actions, policies, or technologies (Huber-Stearns et al., 2017). Creating enabling conditions for Agriculture 4.0 requires technical and financial measures and coherent governance frameworks that reconcile productivity, environmental sustainability, and social objectives (Coderoni, 2023). It also requires adopting a responsible research and innovation (RRI) approach through the engagement of a variety of actors (e.g., farmers, researchers, policymakers) directly involved in the technology adoption and its diffusion, prioritising their actual needs and considering the diversity of contextual features at the territorial level (Eastwood et al., 2019; Rose et al., 2021). These actors should be part of the innovation process to ensure that Agriculture 4.0 technologies are implemented in a way is socially

[1] The term "actor" is used consistently throughout this study (instead of “stakeholder”) to ensure homogeneity of wording and to better reflect the actor-centred nature of the presented research.

beneficial, inclusive, and equitable to all the affected actors while minimising negative impacts (Fielke et al., 2022; Klerkx et al., 2019; McGrath et al., 2023; Rose and Chilvers, 2018). This engagement can also lead to improved design of agricultural policies in the frame of Agriculture 4.0 that foster fair and equitable working conditions (da Silveira et al., 2021; Maffezzoli et al., 2022). Living labs (LLs) are increasingly recognised as suitable settings for operationalising RRI, by serving as collaborative platforms for inclusive, reflexive, and context-sensitive innovation and enabling research approach centred on the perspectives of those directly involved in agriculture and innovation (Campos and Marín-González, 2023; Owen et al., 2012).

Research centred on the actors' needs that respond to priority issues at the territorial level requires significant improvement and expansion, especially developed towards LLs (Mgendi, 2024; Ogunyiola et al., 2024). Understanding these needs would yield grounded recommendations to bridge the research-practice gap while supporting the improvement of existing interventions to foster responsible and sustainable agricultural digitalisation (McFadden et al., 2022; Wanner et al., 2018). Also, bridging the research–practice gap is essential for ensuring that digitalisation contributes to sustainability, a challenge long recognised in agricultural policy research (Matthews, 2021). The literature shows that Agriculture 4.0 can help mitigate the strain on limited resources, address climate change, reduce water and agrochemical usage, improve soil health, and boost biodiversity, while maintaining or increasing yields, lowering input costs, and enhancing food safety through better traceability (MacPherson et al., 2022). However, the observed impacts are not without controversy, and there is an ongoing debate regarding the social implications of agricultural digitalisation, with some studies highlighting benefits such as improved working conditions and community well-being, while others point to issues like social inequality, data privacy concerns, and the potential to widen the gap between large and small-scale farmers (Carolan, 2024; Klerkx et al., 2019). To maximize the positive impacts while minimising the negative consequences and fully realize the potential of Agriculture 4.0, it is essential to expand and deepen knowledge about the perspectives and requirements of actors on the ground to understand how to sustain them in addressing the issues they experience (Ingram et al., 2022). The research implications need to be practically useful beyond the case study level by offering a broader perspective on the researched problem (Yin, 2014), although there is a notable lack of research that provides such a varied perspective. Particularly, more studies are needed that incorporate evidence from a wide range of geographical and socio-economic contexts (Fasciolo et al., 2024; Hinson et al., 2019; Klerkx and Rose, 2020; Maffezzoli et al., 2022).

1.2 Aim and contribution of the research

Against this background, the aim of this study is to assess actor needs and propose enabling conditions to foster the diffusion of Agriculture 4.0 in the Mediterranean basin, through qualitative research. The research adopts a qualitative approach framed within a RRI framework, operationalised through LLs established at the project level in each case study. The four RRI dimensions (anticipation, reflexivity, inclusion, and responsiveness) guided research activities and actor engagement from the project's inception through to the generation of findings and policy recommendations. LLs supported innovation implementation and adoption through processes of mutual learning and co-creation across domains of expertise and disciplinary boundaries. Their composition reflects the diversity of actor perspectives in real-world agricultural contexts and constitutes the sample for this study. The research follows a stepwise approach involving: (i) the prioritisation of key socio-economic issues affecting the adoption and diffusion of the DSS (and more broadly, Agriculture 4.0 innovations) in the greenhouse sector; (ii) the identification of priority actor needs, i.e. those directly linked to the identified issues; and (iii) the elaboration of enabling conditions to support the fulfilment of these needs. A real-world situation is examined, i.e. the introduction of an innovative decision support system (DSS) in greenhouses of the Mediterranean basin. Four case studies are considered, i.e. Almería (Spain), Antalya (Turkey), Monastir (Tunisia), and Tuscany (Italy), hosting each of them a real-world pilot farm for testing the DSS in commercial greenhouses (Sturiale et al., 2024a). All case studies are important players in the international greenhouse vegetable market are representatives for the greenhouse sector at the territorial level (Sturiale et al., 2024a). The data were collected from cross-disciplinary experts engaged within LLs.

This research advances knowledge in several ways. First, it centres on actors and their needs, which are essential for identifying priority issues and enabling conditions for digital technology adoption (Soriano et al., 2023). Second, it bridges the science-practice gap by offering grounded yet theoretically sound recommendations, consistent with responsible research and innovation principles (Lajoie-O'Malley et al., 2020; MacPherson et al., 2022). Third, it provides a cross-country perspective across the Mediterranean, a region marked by shared greenhouse technologies and climate concerns but diverse socio-economic contexts, allowing for implications beyond the case study level (Bocean, 2024).

The findings offer a holistic view of Agriculture 4.0 challenges and opportunities, based on diverse Mediterranean case studies (Xu et al., 2024). They clarify actors' prioritised needs and the enabling conditions for digital agriculture uptake. Although focused on Mediterranean greenhouses and a specific DSS, the insights are relevant to broader agricultural sectors globally. The inclusion of varied case studies enriches the analysis and extends its relevance (Bocean, 2024). The operationalisation of RRI through Living Labs (LLs) shaped knowledge co-production and interpretation, revealing socially relevant dynamics and innovation trajectories beyond standard metrics (Stilgoe et al., 2013). LLs facilitated joint reflection, contextual adaptation, and integration of diverse knowledge systems, including those of smallholders, women, and migrant workers (Campos and Marín-González, 2023; Ehlers et al., 2025). This responsiveness aligned innovation with evolving societal needs and values (Kokotovich et al., 2021), positioning LLs as boundary infrastructures where technical, social, and normative dimensions are negotiated. Finally, the research highlights the social implications of agricultural digitalisation, particularly equity and inclusion, which merit greater attention in academic and policy debates (Hundal et al., 2023; Maffezzoli et al., 2022).

2. Theoretical framework

Actor needs are the requirements, expectations, and preferences of those who have an interest or stake in a particular project, process, or system, including a wide range of operational, economic, social, and environmental aspects that are deemed critical for ensuring the successful adoption and implementation of innovations. Identifying and addressing key actor needs is essential for aligning project outcomes with the interests and priorities of all involved parties, thereby enhancing the overall effectiveness and sustainability of the initiative (Feng et al., 2024; Littau et al., 2010). These needs respond to issues experienced not only by farmers but also by other actors, such as e.g., advisors, which are generally context-specific and can negatively affect the uptake and widespread use of digital agriculture in rural areas (Dibbern et al., 2024). Research indicates that real-world issues are barriers to Agriculture 4.0 and can create lock-in situations that hinder the achievement of sustainability goals through digital transformation. Especially, these issues can prevent the full adoption and integration of digital technologies in agriculture, thereby limiting the potential benefits in terms of productivity, profitability, and sustainability (da Silveira et al., 2023a, 2023b).

The literature identifies drivers and barriers of Agriculture 4.0 (da Silveira et al., 2021; Dibbern et al., 2024). Drivers include, e.g., the potential for increased productivity, profitability, and viability of farming through the optimisation of resource use, cost reduction, and enhancement of crop yields (Fragomeli et al., 2024). Other drivers encompass education, age, and farm size; for instance, younger and more educated farmers managing larger, capital-intensive enterprises are more likely to adopt Agriculture 4.0 technologies (Kroupová et al., 2024). Barriers include economic constraints, such as the high initial costs and limited access to capital, which can deter adoption, particularly among small and medium-sized farms (Dibbern et al., 2024). Other examples of barriers are the lack of technical literacy and insufficient information about the benefits and profitability of digital agriculture that hinder farmers' willingness to invest in new technologies (Kroupová et al., 2024). Identifying enabling conditions to support the realisation of actors' needs is of particular relevance to improve the sustainability of farming through digital tools, by removing the barriers and then overcoming lock-in situations (da Silveira et al., 2023b).

Enabling conditions include financial support, technological infrastructure, policy frameworks, and capacity-building initiatives that collectively create a conducive environment to harness the potential of digital tools for enhancing farmers' productivity, resource efficiency, and decision-making capabilities. For instance, financial support through subsidies and incentives can reduce the initial cost burden, making these technologies more accessible to smaller farms (Fragomeli et al., 2024). Public or private support to investment in physical assets in rural areas can address inadequate infrastructure, facilitating the effective and widespread use of Agriculture 4.0 technologies (Derakhti et al., 2023). Implementing training programs to enhance technical expertise among farmers can bridge the knowledge gap and ease the integration of digital tools on farm (Wang et al., 2020). Additionally, creating knowledge-sharing initiatives and fostering a culture of innovation can help overcome resistance to change and build social trust in Agriculture 4.0 (Ganeshkumar et al., 2023).

3. Methodology and data

3.1 The living lab approach in a RRI framework

This study is grounded in a broader project that adopts a RRI approach to balance economic, socio-cultural, and environmental dimensions in addressing complex societal challenges (Owen et al., 2012). RRI offers a normative framework for guiding innovation toward socially desirable outcomes, structured around four interrelated dimensions: anticipation, reflexivity, inclusion, and responsiveness. RRI principles call for early and continuous involvement of diverse actors to ensure that innovation processes align with societal values and needs (Gremmen et al., 2019). LLs have emerged as a promising methodology for operationalising RRI in agricultural digitalisation. They provide collaborative, real-world environments where diverse stakeholders (e.g., farmers, researchers, policymakers, civil society) can co-create, test, and evaluate technologies (Campos and Marín-González, 2023; Ehlers et al., 2025). LLs are particularly suited to addressing the social dimensions of Agriculture 4.0, enabling dialogue, trust-building, and the negotiation of trade-offs between technological promise and lived experience (Cascone et al., 2024; Compagnucci et al., 2021; Gardezi et al., 2022). The LL approach enables the integration of multiple knowledge systems and interests that both shape and are shaped by digital agricultural transitions (Kamilaris et al., 2017; Wolfert et al., 2017). The engagement of locally embedded experts can provide grounded insights into local needs and priorities as and the potential impacts of Agriculture 4.0, supporting knowledge exchange across diverse socio-economic and cultural settings (da Silveira et al., 2021; Regan, 2019; Zhai et al., 2020).

LLs were established in 2021 using a socio-technical systems approach, which recognises that technological innovation is embedded in broader institutional, economic, and cultural contexts (Rijswijk et al., 2021). They are implemented in four Mediterranean regions, i.e. Almería (Spain), Antalya (Turkey), Monastir (Tunisia), and Tuscany (Italy), each hosting a commercial-scale pilot farm for testing a Decision Support System (DSS) for tomato greenhouse production, i.e. the studied innovation. The DSS was specifically developed to optimise input use (water and nutrients), support integrated pest and disease management, and enhance productivity in tomato greenhouses. It uses climate and cultivation data to run simulation models for fertigation and outbreak prediction. Accessible online via Wi-Fi and managed through a mobile app, the DSS is low-cost and compatible with existing farm infrastructure. It provides farmers with tailored guidance on irrigation and fertilisation schedules, along with alerts for pest and disease development to support timely biological control interventions.

The case studies were selected as they meet the criteria of typicality (Mediterranean-type greenhouses, generally low-tech, well-developed greenhouse sector, important market position) and diversity (contextual specificity: socio-economic, cultural, geographical) with respect to a series of relevant sustainability issues related to the low diffusion of Agriculture 4.0 in greenhouse farming (Gong and Tan, 2021; Sovacool, 2011) (Table 1).

Table 1. Implementation of living labs in the case studies and key case study features.

Case studies	Living lab participants			DSS modules	Economic	Social	Environmental	Level of digital technology
	Agribusiness	**Knowledge creation/transfer**	**Policy**					
Almería (Spain)	13	8	7	Water, Fertiliser, Pest Management	High labour costs, decreasing margins, competition from other countries	Predominantly immigrant workforce, labour conditions, specialization, contract stability	Limited adoption of advanced techniques (e.g. closed-loop systems), use of biological control and drip irrigation	Moderate
Antalya (Turkey)	16	4	1	Water, Fertiliser	High production costs, insufficient government support	Predominantly immigrant workforce, labour conditions, specialization, contract stability	Limited adoption of advanced techniques, lack of data on sustainable systems	Low to moderate
Monastir (Tunisia)	4	7	3	Water, Fertiliser, Pest Management	Low financing capacity, misuse of inputs, lack of control over costs and prices	National, predominantly unqualified workforce, reluctance of older farmers, fragmented ownership	High chemical use, limited adoption of sustainable practices and advanced techniques	Low
Tuscany (Italy)	5	28	3	Water, Fertiliser, Pest Management	High labour costs, low market power, poor generational turnover	Predominantly immigrant workforce, low confidence in new technologies	Public concerns about food naturalness, taste, and environmental impact	Low to moderate

The selection rationale informed the LL design and actor engagement strategies, ensuring that the innovation process was locally relevant and socially responsive. For instance, Almería faces high labour costs and market competition; Antalya struggles with limited government support and high input costs; Monastir is affected by low financing capacity and fragmented farm structures; and Tuscany deals with poor generational turnover and low confidence in digital tools. These contextual differences also shaped the implementation decisions made by farmers regarding DSS modules.

Participants were selected through purposive sampling based on their capacity to offer informed insights into the specific challenges and dynamics surrounding digital technology adoption (Patton, 2023; Potters et al., 2022). The sampling strategy aimed to engage individuals knowledgeable about the innovation and committed to sustainability improvements in their local greenhouse sectors. Actor selection was guided by local knowledge and aimed to ensure representation across the agricultural value chain, including producers, advisors, policymakers, technology providers, and civil society. Willingness and capacity to engage across all LL phases, i.e. from problem framing to evaluation, were also considered. Actors participating in each LL constitute the sample for this research (Figure 1).

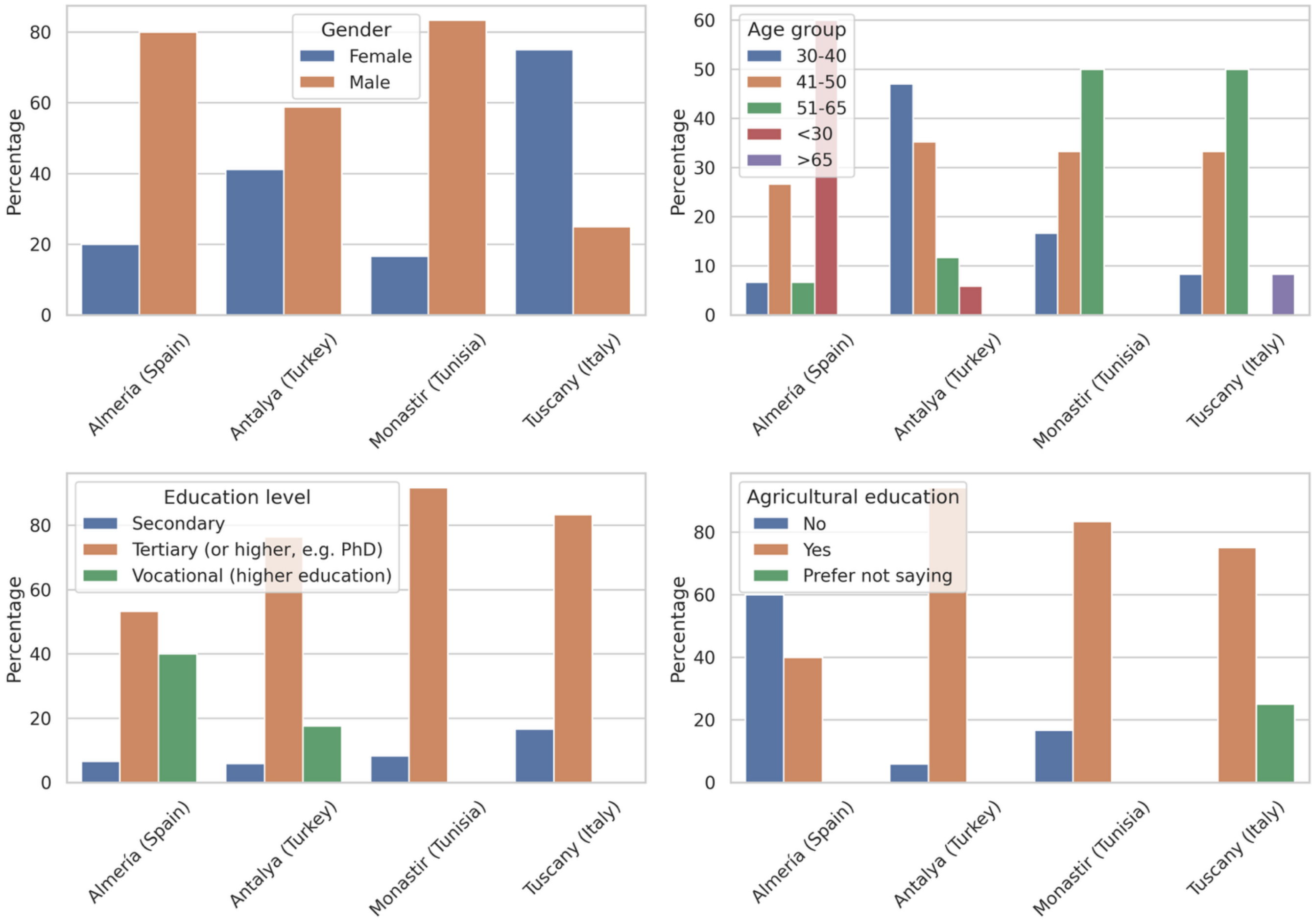

Figure 1. Living lab actor demographics. Software: Python libraries matplotlib (Hunter, 2007), seaborn (Waskom, 2021).

LL actor composition across the case studies shows diversity in terms of gender, age, education level, and agricultural background. However, some cases reveal uneven representation in specific categories, such as a predominance of male participants or limited variation in education levels, reflecting local stakeholder networks, actor availability, and broader socio-institutional dynamics.

LLs were established at the project level as vehicles for embedding RRI principles throughout the innovation process. The established LLs brought together a diverse range of actors operating at both farm and territorial levels. While actor representation differed across case studies, reflecting local technical, social, and cultural contexts, the categorisation of participants aimed to balance inclusivity with operational feasibility, ensuring comparability across cases.

LL structure and activities were explicitly aligned with the four RRI dimensions (anticipation, reflexivity, inclusion, responsiveness), ensuring that the development and diffusion of the DSS were technically sound, ethically grounded, and socially responsive (Ehlers et al., 2025; Stilgoe et al., 2013) (Table 2).

*Table 2. Implementation of living labs (LL) under the dimensions of responsible research and innovation. *Commitment letters are confidential. **Project deliverables report across RRI dimensions.*

Engagement	Anticipation	Reflexivity	Inclusion	Responsiveness
Actors	Practice partners (farmers)	Research team and LL actors	LL actors	Research team and LL actors
Type of involvement	Early engagement	Iterative learning and feedback	Actor mapping and continuous engagement	Adaptation of methods and approaches; identification of impact indicators
Timing	Since project proposal	Throughout project	Throughout project	Throughout project
Activities	Commitment letters*; co-definition of focal questions	Harmonised guidelines; joint interpretation of impact results	Activity protocols; ethical/legal compliance; diverse representation	Context analysis, SWOT, needs assessment (and other sustainability assessment exercises); co-creation and sharing sessions (workshops, training), policy recommendations
Process documentation**	(Bartolini et al., 2021; Incrocci et al., 2024; Laarif et al., 2024a, 2024b; Navarro Garcia and Lupu, 2021; Sturiale et al., 2024c, 2024b)			

Anticipation was embedded from the proposal stage, with early engagement of practice partners to co-define focal questions and explore potential impacts and trade-offs of DSS adoption days (see (Bartolini et al., 2021; Fernández et al., 2024)). Reflexivity was fostered through iterative learning cycles, joint interpretation of impact results, and continuous reflection on the assumptions and values shaping the innovation process experiences (see (Laarif et al., 2024b; Sturiale et al., 2024b)). Inclusion was ensured by mapping and engaging a diverse set of actors across agribusiness, policy, and knowledge domains, with attention to ethical and legal compliance and the representation of marginalised voices (see (Navarro Garcia and Lupu, 2021)). Responsiveness was demonstrated through the adaptation of methods, indicators, and engagement strategies based on contextual feedback, informing both DSS implementation and policy recommendations see (Bartolini et al., 2021; Incrocci et al., 2024; Laarif et al., 2024b, 2024a; Sturiale et al., 2024c)).

3.2 Data collection process and analysis

All data collection and reporting activities were designed and conducted by the research team, with local members operating within their respective LLs. Activities were supported by centrally harmonised guidelines, jointly agreed upon and prepared. These included methodological instructions and templates for data collection and reporting, reflecting best practices in LLs that emphasize structured actor engagement, harmonized protocols, and context-sensitive implementation. Case study-specific findings were initially analysed by the lead author and subsequently reviewed by all co-authors, with the final output discussed and validated collectively. This collaborative and iterative approach aligns with established LL methodologies that promote inclusive and responsible innovation through interdisciplinary co-creation and collective validation (Forbat et al., 2025; Gardezi et al., 2022; Hossain et al., 2019)

Actor engagement was facilitated through one-to-one open discussions aimed at prioritising context-specific issues and identifying corresponding needs and enabling conditions. These interviews were conducted via video call, allowing participants to interact with visual materials and texts as they were developed during the conversation.

The discussions were informed by in-depth context analyses conducted at the case study level as part of related research activities (see (Sturiale et al., 2024c)). These analyses framed the unique circumstances of each agricultural setting and helped identify the factors influencing the adoption and effectiveness of digital technologies (Rijswijk et al., 2021). They included a broad range of information: physical and technological attributes of greenhouse farming (Klerkx et al., 2019); economic aspects such as financial performance, cost structures, and incentives (Metta et al., 2022); social dimensions including workforce demographics, labour conditions, and public perceptions (Eastwood et al., 2019); and environmental considerations related to sustainability practices and impacts (Rose et al., 2021). Before the interviews, respondents received the context analysis along with a clear explanation of the exercise's aims and procedures. The sessions employed SWOT analysis (see Supplementary materials) as a boundary object, leveraging its accessibility and familiarity to facilitate structured dialogue (Spee and Jarzabkowski, 2009). This approach enabled experts with diverse perspectives to collaboratively identify barriers and drivers of digital technology uptake and to prioritise issues relevant to local contexts (Helms and Nixon, 2010; Pagot and Andrighetto, 2024). Respondents were explicitly invited to elaborate through recall and brainstorming with research team members, following a three-step process:

1) Reflect on priority issues that should be addressed in the greenhouse farming sector at the territorial level to foster agricultural digitalisation, based on their experience in the LL and knowledge of the DSS, but not limited to it;

2) Identify barriers and drivers to solving these issues, derived from SWOT items—specifically, barriers from weaknesses and threats, and drivers from strengths and opportunities(Pagot and Andrighetto, 2024);
3) Highlight priority needs that could help overcome barriers or leverage drivers to address the identified issues.

Enabling conditions for these priority needs were defined through discussion during the final project workshop, which included all scientific partners and LL actors. These conditions were informed by the presentation of project outcomes and refined through collective input.

4. Results and discussion

Findings indicate similarities among case studies, particularly regarding needs related to knowledge, farmers' behaviour and bargaining power, and remote work. However, contextual differences highlight specific territorial needs to foster the uptake and diffusion of the DSS and, more broadly, to enable the wider use of digital tools in agriculture (Table 3).

Table 3. Prioritised needs and enabling conditions related to priority issues and SWOT items in the case studies.

Case studies	Priority issues	SWOT items	Priority needs	Enabling conditions
Almería	Knowledge and practical skills	Unskilled labour	Improving technical skills of farmers and advisors	Create and/or improve education and foster knowledge transfer about digital tools
Tuscany		Unskilled labour		
Antalya		Low level of knowledge		
Monastir		Low level of specialisation		
Tuscany	Reluctance to change	Propensity to innovate; Aging farmers	Building acceptability and trust	Create and/or improve education and foster knowledge transfer about digital tools
Almería		Aging farmers		
Antalya		Aging agricultural population		Support for young farmers' entrepreneurship
Monastir		Low profitability		
Monastir	Abandonment of farming activities	Farm exit; Low profitability	Reducing farm exits	Create and/or improve education and knowledge, and foster knowledge transfer about digital tools; Support for young farmers' entrepreneurship
Tuscany		Farm exit; Economic viability		
Almería	High market competition and low consumer awareness	Market competition	Creating product identity	Product branding
Antalya		Market conditions		
Monastir	Too low margin of product sale	Market competitiveness	Increasing farmer margins	Certification and labelling schemes; Policy support for sustainable products
Almería	Unfair distribution of value added along the value chain	Weak bargaining power; Many middlemen	Increasing farmer bargaining	Promote collective approaches (e.g., cooperatives, unions); Organising demand-driven production
Antalya		Many middlemen		
Monastir		Lack of collective organisation		
Tuscany		Low bargaining power; Level of cooperation		
Tuscany	Slow and complex bureaucracy for public incentives	Burdensome bureaucracy	Simplifying bureaucracy	Simplified paperwork for public incentives
Antalya		Low profitability		Production-support policy

Case studies	Priority issues	SWOT items	Priority needs	Enabling conditions
Monastir	Insufficient supply of greenhouse-grown food	Water shortages	Developing land and crop production planning	
Antalya	High production costs	Rising energy costs; High input costs	Increasing liquidity for new technology uptake	Support for investment in digital technology
Monastir		High production costs		
Tuscany	Heavy workload and difficult work-life balance	Work-life balance; Climate change	Facilitating remote farming operations	Education and knowledge transfer; Public/private investment in broadband infrastructure
Almería		Workload; Work-life balance		
Antalya		Many working hours		
Monastir		Difficult management of personal life		

4.1 Improving technical skills of farmers and advisors and knowledge transfer

The widespread deficiency in knowledge and practical skills related to digital tools among agricultural workers presents a significant issue, which can become a barrier to the effective implementation of digital solutions. This was consistently observed across the case studies. Advisors often possess skills in digital technologies, but they lack the time to test or explain them to farmers. This disconnect between research and practice hampers the adoption of Agriculture 4.0 technologies and the DSS under study, potentially leading to suboptimal farm management and productivity.

These findings suggest a pressing need for comprehensive educational reforms and targeted training programs at both national and international levels. Interviewees emphasised the importance of integrating digital skills into agricultural education to ensure that current and future generations of farmers are equipped to use Agriculture 4.0 technologies effectively. They also highlighted the need for robust knowledge transfer mechanisms to bridge the gap between research and practice. This includes fostering partnerships between research institutions and agricultural practitioners to facilitate the dissemination of innovative practices and technologies.

These findings are supported by the literature, which similarly identifies the lack of digital literacy as a systemic issue in agriculture. Studies indicate that enhancing technical skills through targeted educational programs is essential for bridging the gap between research and practical application (Dibbern et al., 2024; Fragomeli et al., 2024). The need for improved knowledge transfer mechanisms is also emphasised, as effective communication of research findings can lead to better farm management practices (Rose et al., 2021). Furthermore, peer-to-peer learning initiatives are recognised as valuable tools for fostering a supportive environment for skill development, enabling farmers to leverage digital tools effectively (da Silveira et al., 2023b).

4.2 Building acceptability and trust

All case studies emphasize the general lack of acceptability and trust in digital technology among farmers. Farmers, particularly older ones, may be reluctant to adopt digital tools due to resistance to change, perceived risks, and a lack of digital literacy. Those who have relied on traditional methods for decades may be sceptical about the benefits of Agriculture 4.0 and prefer to stick with familiar practices. They may see the initial investment and learning curve associated with digital tools as risky. Providing tailored education and training, including mentorship programs that demonstrate the tangible benefits and offer hands-on sessions with digital tools, can help build trust and encourage adoption.

The literature suggests that tailored education and mentorship programs can alleviate farmers' aversion towards new technologies by demonstrating their tangible benefits (da Silveira et al., 2023b; Ganeshkumar et al., 2023). Building trust through hands-on training and engagement is crucial for overcoming scepticism and encouraging adoption (da Silveira et al., 2023a). Additionally, more support for young farmers' entrepreneurship can drive innovation and the adoption of digital tools, as younger farmers may be more open to integrating the DSS and other Agriculture 4.0 technologies into their practices. Younger farmers tend to be more receptive to digital innovations, indicating that fostering entrepreneurship among youth can drive broader acceptance of Agriculture 4.0 technologies (Klerkx and Rose, 2020).

The reluctance of older generations to adopt digital tools highlights the need for tailored educational initiatives that address specific concerns and barriers. Policymakers should consider implementing mentorship programs that pair experienced farmers with younger, tech-savvy individuals to foster trust and facilitate knowledge exchange. The role of young farmers as change agents in the adoption of digital technologies should be recognised and supported through targeted entrepreneurship programs (Bocean, 2024; Shamshiri et al., 2024). Furthermore, cultivating communities of support through collaborative platforms can empower all farmers, including those beyond the greenhouse sector. These platforms encourage peer-to-peer learning, creating a collaborative environment that is also beneficial for enhancing trust and confidence in technology use (Derakhti et al., 2023; Gumbi et al., 2023; Petraki et al., 2025) (Derakhti et al., 2023; Gumbi et al., 2023; Petraki et al., 2025).

4.3 Reducing farm exits

In Monastir and Tuscany, a key issue is the gradual abandonment of farming activities, primarily due to low profitability and very limited generational turnover. This trend poses a significant threat to the agricultural sector, as it may hinder the adoption and diffusion of Agriculture 4.0 technologies, which are essential for modernising farming practices and improving productivity. Therefore, there is a need to reduce farm exits. Supporting young farmers' entrepreneurship through tailored policy initiatives, such as access to training programs, financial incentives, and mentorship opportunities, is vital for revitalising the sector (Derakhti et al., 2023). By making farming more attractive to younger generations, the sector can ensure a continuous influx of new entrants and ideas, which is essential for the adoption of innovative practices (Eastwood et al., 2019).

To reduce farm exits, especially by attracting and retaining young farmers to ensure a continuous influx of new entrants and ideas, several enabling conditions should be established. Providing financial support through subsidies, grants, and low-interest loans can reduce the initial cost burden for young farmers, making farming more attractive and viable (Derakhti et al., 2023). Implementing training programs that focus on new digital tools and how they can support sustainable practices can enhance the technical skills of young farmers, enabling them to adopt and integrate Agriculture 4.0 technologies effectively (Eastwood et al., 2019). Establishing mentorship programs where experienced farmers guide and support young farmers can facilitate knowledge transfer and build confidence.

The trend of farm abandonment due to low profitability and limited generational turnover is a critical issue that requires urgent attention. Attracting and retaining young farmers is essential for the sustainability of the agricultural sector, including its modernisation through digital tools. Incentives, such as access to affordable land, financial support, and training programs focused on digital tools, can create a conducive environment for youth by making farming more appealing to younger generations. In turn, the agricultural sector can benefit from fresh ideas and innovative practices that are needed for the uptake and widespread use of Agriculture 4.0 technologies (MacPherson et al., 2022; Petraki et al., 2025).

4.4 Creating product identity

Meeting market requirements is perceived as a major issue in Almería and Antalya, highlighting the importance of a strong product image to stand out against competitors. The emerging need is for product differentiation in the market and greater consumer awareness, especially by creating a unique identity for greenhouse-grown vegetables, distinguishing them from other horticultural products, e.g. grown elsewhere or using different practices. This involves developing elements that resonate with consumers, such as e.g. product denomination and origin and logo, as well as emphasising the environmental and human health benefits of agricultural products, while ensuring transparency in the production system. This can be achieved by highlighting unique attributes of the products, especially focusing on eco-friendly practices achieved through DSS use, to attract consumers who are increasingly concerned about environmental sustainability and health. Greater consumer awareness is essential to inform and educate the public about sustainability attributes, thus driving specific demand.

Related research highlights the importance of transparency and sustainability in agricultural practices, which can be achieved through digital tools like the DSS examined in this study, enhancing consumer trust and demand (Fragomeli et al., 2024; Maffezzoli et al., 2022). Certification and labelling schemes play a critical role in communicating the value of sustainably produced goods, thereby attracting consumers who prioritise environmental and health benefits (da Silveira et al., 2023b). Certification provides formal recognition of adherence to specific standards, such as organic farming or sustainable practices, which can enhance the credibility and marketability of the products. Labelling schemes offer a clear and accessible way for consumers to identify and trust these certified products. This aligns with the need for greater consumer awareness regarding the attributes of agricultural products (da Silveira et al., 2023a).

The importance of a strong product image in meeting market demands is a key finding that has implications for marketing strategies and consumer education. Farmers should prioritise transparency and sustainability in their practices to enhance consumer trust and demand. This can be achieved through the widespread uptake of effective certification and labelling schemes that communicate the environmental and health benefits of agricultural products. However, initiatives that promote consumer awareness regarding sustainable practices are needed as well to drive or enhance demand for responsibly produced goods (McFadden et al., 2022; Xu et al., 2022).

4.5 Increasing farmer margins

Actors in Monastir highlight the issue of low profit margins in agricultural sales, which discourages investment in new technology. To address this, there is a critical need to allow for a price premium on agricultural products. This can be achieved by differentiating products based on their sustainability and quality attributes, such as environmental and health benefits, appealing to consumers willing to pay more for sustainably produced goods (Derakhti et al., 2023).

Enabling conditions for this need include robust certification processes that ensure transparency and trust in the sustainability claims. Certification and labelling schemes can play a crucial role in communicating the value of sustainable products to consumers, justifying the price premium. Effective marketing campaigns are also essential to educate consumers about the benefits of sustainable food and to increase their willingness to pay for it. Additionally, financial mechanisms like subsidies, grants, or other incentives can support farmers in adopting new technologies by offsetting the costs of DSS uptake and related changes in sustainable agricultural practices and inputs, thereby enhancing their economic viability (Eastwood et al., 2019).

The importance of a strong product image in meeting market demands is a key finding that has implications for marketing strategies and consumer education. Farmers should prioritise transparency and sustainability in their practices to enhance consumer trust and demand. This can be achieved through the widespread uptake of effective certification and labelling schemes that communicate the environmental and health benefits of agricultural products. However, initiatives that promote consumer awareness regarding sustainable practices are needed as well to drive or enhance demand for responsibly produced goods (McFadden et al., 2022; Xu et al., 2022).

4.6 Increasing farmer bargaining

All case studies highlight the issue of unfair value distribution along the food value chain. This imbalance results in farmers receiving a disproportionately small share of the profits compared to other downstream actors, such as distributors and retailers. In some regions, like e.g. Almería and Antalya, this problem is exacerbated by the relatively high number of intermediaries. Inequity in value distribution can lead to financial instability for farmers, discouraging the adoption of innovations such as the DSS and sustainable practices, and may result in low market responsiveness.

Strengthening farmers' bargaining power is then crucial for achieving sustainability objectives through digitalisation.

Key enabling conditions to address this need involve the promotion of collective approaches, such as cooperation initiatives, including second tier-cooperatives, and fostering stronger farmer unions. Additional benefits can be realised by enhancing efficiency through the organisation of demand-driven production. By organising into cooperatives or unions, farmers can pool their resources, share knowledge, and collectively negotiate better prices and terms with downstream actors (Ganeshkumar et al., 2023; Klerkx and Rose, 2020). Example cooperation initiatives include marketing cooperatives that help farmers sell their products collectively or supply cooperatives that enable farmers to purchase inputs at lower costs. For example, second-tier cooperatives, i.e. union of smaller, first-tier cooperatives, proved successful especially in Almeria, working together to provide services, support, and resources (including training) to their cooperative members (Giagnocavo et al., 2014). Also, farmer unions can advocate for policies that support fairer farmer prices, provide legal assistance, and offer entrepreneurial training. These collective actions among farmers can lead to improved market access and enhanced resilience against market fluctuations (Rose et al., 2021). The organisation of demand-driven production can be achieved through the adoption of dedicated digital tools, such as predictive technology and analytics. These tools link supply with demand, helping growers mitigate unexpected risks and challenges by predicting market demand and maximising productivity (Eastwood et al., 2017; Suksa-ngiam and Bechor, 2024). The DSS developed in this research represents a farm-level step towards organising demand-driven production. It equips greenhouses with sensors and IoT devices that provide on-site information useful for predictive models. However, dedicated tools for market predictions are still needed. Cooperation initiatives may help distribute the costs of these additional technologies, enabling their widespread adoption at the territorial level.

Strengthening farmers’ bargaining power is essential for improving their economic viability and enabling the adoption of Agriculture 4.0 technologies. Promoting collective approaches, such as cooperatives and unions, and organising demand-driven production are key strategies. These approaches empower farmers to negotiate better terms, access markets more effectively, and share the costs and benefits of digital innovation.

4.7 Simplifying bureaucracy

In Tuscany, stakeholders emphasise that slow and complex bureaucracy often discourages farmers from applying for public incentives, hindering the sustainable upgrade of farm practices, including the adoption of new digital tools. The complexity and lengthy processes involved in paperwork can be particularly daunting, leading to frustration and disengagement among farmers. Complex bureaucratic processes can deter farmers from applying for public incentives (McFadden et al., 2022). To address these issues, there is a need for simpler bureaucracy.

Enabling conditions for this simplification include implementing streamlined application processes that reduce unnecessary bureaucratic steps and increase assistance to farmers and advisors throughout the application process (Eastwood et al., 2019). Simplified application procedures and targeted support can enhance farmer engagement and participation, making it easier for them to access the support they need for adopting digital tools and sustainable practices.

The complexity of bureaucratic processes can prevent farmers from accessing public incentives. Simplifying these processes is crucial for enhancing farmer engagement and participation in programs aimed at promoting digital agriculture. Policy improvement should prioritise the streamlining of application procedures and the provision of targeted technical support to farmers throughout the bureaucratic process, thereby facilitating access to the resources needed for adopting new technologies (Martens and Zscheischler, 2022; Monda et al., 2023).

4.8 Developing land and crop production planning

Findings from Antalya indicate that the current supply of greenhouse-grown food is insufficient to meet both domestic and foreign market demand. This production gap challenges the region's agricultural sector, potentially leading to missed economic opportunities and reduced competitiveness in both domestic and international markets. Therefore, strategic land and crop production planning is needed to optimise the use of available agricultural land, ensuring that the right crops are grown in the right quantities to meet market demands. This approach can stabilise the market and ensure a steady supply of greenhouse-grown food.

Implementing policies that support effective production strategies is crucial for optimising resource use and enhancing market competitiveness (Derakhti et al., 2023). Actors identify production-support policies as crucial enabling conditions as they can provide the necessary framework and resources to assist farmers in implementing effective land and crop production strategies. These policies can encourage farmers to adopt best practices and invest in DSS or other digital tools that enhance productivity and sustainability (Dibbern et al., 2024).

Addressing production gaps through strategic planning is essential for ensuring food system resilience and competitiveness. Policy frameworks that support land and crop planning can help align production with market needs, reduce inefficiencies, and promote the adoption of digital tools that support data-driven decision-making in agriculture.

4.9 Increasing liquidity for new technology uptake

Farmers in Monastir and Antalya are struggling with rising production costs, making it difficult to sustain their operations. In Tunisia, for instance, this issue arises because equipment like greenhouses and agricultural inputs such as seeds, pesticides, and fertilisers are imported. To overcome this issue, better access to liquidity is needed to invest in new technologies that can enhance efficiency and productivity. Access to liquidity is critical to encourage farmers' uptake of Agriculture 4.0 technologies, such as the DSS, which can help reduce costs and increase yields in greenhouses and other farming systems.

Specific support mechanisms for Agriculture 4.0, including grants and subsidies, can encourage the modernisation of farm production and the adoption of Agriculture 4.0 (Eastwood et al., 2019; Ganeshkumar et al., 2023). Support from public and private institutions is an important enabling condition to help farmers adopt new digital technologies alongside more sustainable practices. This financial backing is essential for enabling farmers to transition to more efficient and sustainable practices (Klerkx and Rose, 2020).

Addressing liquidity constraints is essential for enabling farmers to invest in digital tools and transition toward sustainable agricultural practices. Public and private financial support mechanisms, such as subsidies, grants, and low-interest loans, can reduce the initial cost burden and make digital technologies more accessible, particularly for small and medium-sized farms.

4.10 Facilitating remote farming operations

The heavy workload and difficulty in achieving a work-life balance for the workforce across the case studies underscore the need for technology that facilitates remote farming operations. These issues are particularly sensitive for women and young parents, who often juggle multiple responsibilities. By reducing the need for constant physical presence on the farm, remote farming operations can significantly alleviate the physical and time burdens on farmers, allowing them to manage their greenhouses more efficiently and effectively from a distance (Finger, 2023; Lajoie-O'Malley et al., 2020). The DSS under study is designed to enable remote monitoring of greenhouse conditions, such as climate and soil, and to perform tasks like fertilisation, irrigation, and diseases onset and development. The need to facilitate remote farming operations closely aligns with the overarching objective of the study and is intrinsically linked to other needs, such as improving the technical skills of farmers and advisors, and knowledge transfer and building acceptability and trust. Addressing the need for remote work likely requires most previously mentioned enabling conditions. However, two more specific enabling conditions can be identified that complement those already discussed. First, targeting public and private investments to establish robust digital infrastructure in rural areas to ensure reliable internet connectivity is crucial. While some specialised greenhouse districts in the investigated case studies may already have this infrastructure, a digital divide still exists that must be bridged to enable agricultural digitalisation. (Gumbi et al., 2023; Rose et al., 2021). Second, collaborative efforts are increasingly recognised as vital for digital transformations in agriculture (Martens and Zscheischler, 2022; Wang et al., 2020). Fostering a culture of knowledge sharing and collaboration among farmers can greatly improve their ability and confidence to operate remote farming tasks. Peer-to-peer learning and mentorship programs can play a significant role in enabling farmers to operate remote farming systems confidently. This can be facilitated by developing collaborative platforms that foster a community of support, where farmers can share resources, knowledge, and best practices (Fasciolo et al., 2024; Fragomeli et al., 2024; Jayasiri et al., 2024).

Bridging the gap between urban and rural areas is closely linked to rural improvement: investments in digital infrastructure are expected to offer manifold benefits, by enhancing individual farms and improving the overall quality of life in rural communities. Improved internet connectivity facilitates access to digital tools, which can enrich education, healthcare, and economic opportunities for rural residents (Finger, 2023; Fragomeli et al., 2024). An additional important aspect is the potential to offer partial remote work opportunities through the diffusion of DSS that enable monitoring and operating tasks without the need to be on-site. This aligns the modality of agricultural work with those seen in other economic sectors, making it more appealing. The flexibility enabled by remote farming tasks reduces the physical toll typically experienced by farmers and prioritises the balance between work and personal life, fostering inclusivity for women and young parents in the agricultural workforce (Gabriel and Gandorfer, 2023; Gumbi et al., 2023; Shamshiri et al., 2024; Yuan and Sun, 2024).

4.11 Critical assessment of the research

The limitations of the research should be acknowledged to support informed interpretation and guide future research improvements.

The research is geographically limited to four case studies in the Mediterranean basin. Although these regions represent significant players in the global greenhouse vegetable market, the findings may not be fully generalisable to other regions worldwide.

LL actor selection aimed to ensure representation across the agricultural value chain, however the number of participants per category varied by case study. For instance, in Antalya, only one policy representative was involved, which may have constrained the diversity of policy perspectives relevant to both the local territorial context and Turkey more broadly.

The study relies on qualitative data collected through participatory methods involving a diverse group of actors with interdisciplinary expertise. The sample size and composition of engaged actors may not capture the full diversity of views within each region, and the findings might be influenced by the perspectives and biases of the participants.

Data collection and reporting is based on internally developed procedures and protocols, tailored to the LL approach and the relatively small sample size. In contexts where such internal management is not feasible (e.g., studies involving randomised sampling, large sample sizes, saturation-based sampling) widely recognised tools for reporting qualitative research should be considered. For example, the COREQ checklist (Tong et al., 2007)) offers a structured framework for ensuring transparency and rigour in qualitative research.

Findings emphasise the importance of technical skills, trust, market dynamics, and policy frameworks in fostering the adoption of digital technologies. However, other potential factors that may also play an important role in technology adoption were not extensively explored, e.g., cultural attitudes, social networks, economic incentives.

5. Recommendations for the science-policy-society interface

Findings highlight how technical skills, trust, market dynamics, and policy frameworks interact to shape the adoption of Agriculture 4.0 technologies across Mediterranean regions. Focusing on greenhouse farming, where remote management is relatively more feasible, this study suggests that successful implementations may offer scalable models for broader agricultural applications (Bocean, 2024; Yuan and Sun, 2024). These findings support the generation of recommendations for the science-policy-society interface, emphasising the need for integrated approaches to unlock the full potential of digital tools in agriculture.

There is a critical need for wider and enhanced collaboration among scientists, policymakers, and agricultural practitioners to foster the successful adoption of Agriculture 4.0 technologies (Matthews, 2021). Encouraging interdisciplinary research that integrates insights from agricultural science, social sciences, and technology studies can provide a holistic understanding of the challenges and opportunities associated with digital agriculture (Finger, 2023; Rotz et al., 2019). Developing policy frameworks that are informed by empirical research and stakeholder input can ensure that interventions are relevant and effective. Achieving synergies between digitalisation, sustainability, and food security requires policy coherence and governance models that integrate environmental and economic objectives through participatory, goal-based approaches Coderoni

(2023). Policy enhancement should include the engagement of farmers and agricultural advisors to co-create policies that address their specific needs and concerns (Derakhti et al., 2023; Gabriel and Gandorfer, 2023). Raising public awareness about the benefits of digital agriculture and the importance of sustainable practices is essential for garnering societal support for agricultural innovations. Educational campaigns should target not only farmers but also consumers, fostering a culture of sustainability and responsible consumption (Gouroubera et al., 2025; Rose et al., 2021). Establishing mechanisms for monitoring and evaluating the impact of digital agriculture initiatives can provide valuable insights into their effectiveness and inform future policy decisions. Continuous feedback loops between research, policy, and practice can enhance the adaptability and responsiveness of agricultural interventions towards digitalisation (Fragomeli et al., 2024; Yang et al., 2024).

The successful adoption of digital technologies extends beyond individual farms; it empowers communities and enhances their economic resilience. As these technologies become more widespread, rural areas may experience significant transformations that address longstanding rural-urban disparities (Fragomeli et al., 2024; Yang et al., 2024). As the agricultural landscape evolves, significant potential emerges from the adoption of remote farming technologies. These technologies can improve work-life balance, foster community support, and create new job opportunities, although strategic investment in digital infrastructure is still needed. This appeal can enhance workforce diversity, ensuring that agriculture remains competitive and relevant in the rapidly changing job market. Agricultural digitalisation serves not only ecological sustainability but also uplifts rural communities by fostering a more equitable and diverse agricultural community (Rose et al., 2021; Wolfert et al., 2017).

6. Conclusions

This study identifies key enabling conditions for the effective implementation of Agriculture 4.0 technologies in Mediterranean greenhouse farming. By following a RRI approach, findings from participatory research across LLs case studies suggest that efforts should focus on improving digital literacy, building trust in technology, leveraging market dynamics, and facilitating remote farming operations. These strategies can support the digital transformation of agriculture while promoting social inclusion, equity, and improved workforce conditions, particularly for women and youth.

To support evidence-based decision-making, the following policy recommendations are proposed:

- Invest in digital literacy and training: Tailored educational programs and knowledge transfer mechanisms are essential to bridge the gap between research and farm-level application;
- Support inclusive technology adoption: Initiatives should consider generational and socio-economic differences to avoid inadvertently excluding older or less digitally literate farmers;
- Strengthen market incentives: Certification schemes, consumer awareness campaigns, and simplified bureaucratic processes can enhance product value and encourage investment in digital tools;
- Promote social equity and cooperation: Policies should reinforce farmer unions and collaborative initiatives to improve bargaining power and ensure fair value distribution;
- Enable remote farming solutions: Digital tools that improve work-life balance and operational efficiency can foster sustainability and attract new entrants to the sector.

Key limitations of this study include its context-specific nature and reliance on the socio-institutional dynamics of each territorial LL, which should be carefully considered when interpreting the findings and assessing their broader applicability. Future research should expand the geographical coverage, integrate quantitative methods, and explore additional factors, such as cultural attitudes and social networks, that influence technology adoption. Also, in the context of

LLs, integrating Participatory Action Research principles could offer additional value, particularly in enhancing actor agency and long-term impact, given the strong emphasis placed on collective action and transformation led by participants.

Disclosure of potential conflicts of interest

Authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Data availability statement: Data will be made available upon request

Acknowledgements

This research was funded under the EU Partnership for Research and Innovation in the Mediterranean Area (iGUESS-MED – 'Innovative Greenhouse Support System in the Mediterranean Region efficient fertigation and pest management through IoT based climate control'; Grant Agreement number: 1916; Section 1, Topic 1.2.2: "Sustainability and competitiveness of Mediterranean greenhouse and intensive horticulture"). The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The authors thank all stakeholders in the living lab activities of the iGUESS-MED project for their contributions.

References

Bartolini, F., Incrocci, L., and Buendía Guerrero, D. (2021). Deliverable 4.1 - Conceptual and Analytical Framework. https://www.iguessmed.com/_files/ugd/4b1614_4723ae2439c74e96b1639e3da81ab0e0.pdf.

Benzaghta, M., Elwalda, A., Mousa, M., Erkan, I., and Rahman, M. (2021). SWOT analysis applications: An integrative literature review. Journal of Global Business Insights, 6: 55–73. https://doi.org/10.5038/2640-6489.6.1.1148

Bocean, C.G. (2024). A Cross-Sectional Analysis of the Relationship between Digital Technology

Use and Agricultural Productivity in EU Countries. Agriculture, 14: 519. https://doi.org/10.3390/agriculture14040519

Campos, I., and Marín-González, E. (2023). Renewable energy Living Labs through the lenses of responsible innovation: building an inclusive, reflexive, and sustainable energy transition. Journal of Responsible Innovation, 10 (1): 2213145. https://doi.org/10.1080/23299460.2023.2213145

Carolan, M. (2024). Who and what gets recognized in digital agriculture: agriculture 4.0 at the intersectionality of (Dis)Ableism, labor, and recognition justice. Agriculture and Human Values, 41: 1465–1480. https://doi.org/10.1007/s10460-024-10560-9

Cascone, G., Scuderi, A., Guarnaccia, P., and Timpanaro, G. (2024). Promoting innovations in agriculture: Living labs in the development of rural areas. Journal of Cleaner Production, 443: 141247. https://doi.org/10.1016/j.jclepro.2024.141247

Coderoni, S. (2023). Key policy objectives for European agricultural policies: Some reflections on policy coherence and governance issues. Bio-based and Applied Economics, 12(2), 85–101. https://doi.org/10.36253/bae-13971

Compagnucci, L., Spigarelli, F., Coelho, J., and Duarte, C. (2021). Living Labs and user engagement for innovation and sustainability. Journal of Cleaner Production, 289: 125721. https://doi.org/10.1016/j.jclepro.2020.125721

da Silveira, F., Barbedo, J.G.A., da Silva, S.L.C., and Amaral, F.G. (2023a). Proposal for a framework to manage the barriers that hinder the development of agriculture 4.0 in the agricultural production chain. Computers and Electronics in Agriculture, 214: 108281. https://doi.org/10.1016/j.compag.2023.108281

da Silveira, F., da Silva, S.L.C., Machado, F.M., Barbedo, J.G.A., and Amaral, F.G. (2023b). Farmers' perception of the barriers that hinder the implementation of agriculture 4.0. Agricultural Systems, 208: 103656. https://doi.org/10.1016/j.agsy.2023.103656

da Silveira, F., Lermen, F.H., and Amaral, F.G. (2021). An overview of agriculture 4.0 development: Systematic review of descriptions, technologies, barriers, advantages, and disadvantages. Computers and Electronics in Agriculture, 189: 106405. https://doi.org/10.1016/j.compag.2021.106405

Derakhti, A., Santibanez Gonzalez, E.D.R., and Mardani, A. (2023). Industry 4.0 and Beyond: A Review of the Literature on the Challenges and Barriers Facing the Agri-Food Supply Chain. Sustainability, 15: 5078. https://doi.org/10.3390/su15065078

Dibbern, T., Romani, L.A.S., and Massruhá, S.M.F.S. (2024). Main drivers and barriers to the adoption of Digital Agriculture technologies. Smart Agricultural Technology, 8: 100459. https://doi.org/10.1016/j.atech.2024.100459

Eastwood, C., Klerkx, L., Ayre, M., and Dela Rue, B. (2019). Managing Socio-Ethical Challenges in the Development of Smart Farming: From a Fragmented to a Comprehensive Approach for Responsible Research and Innovation. Journal of Agricultural and Environmental Ethics, 32: 741–768. https://doi.org/10.1007/s10806-017-9704-5

Eastwood, C., Klerkx, L., and Nettle, R. (2017). Dynamics and distribution of public and private research and extension roles for technological innovation and diffusion: Case studies of the implementation and adaptation of precision farming technologies. Journal of Rural Studies, 49: 1–12. https://doi.org/10.1016/j.jrurstud.2016.11.008

Ehlers, M.-H., El Benni, N., and Douziech, M. (2025). Implementing responsible research and innovation and sustainability assessment in research projects: A framework and application.

Research Policy, 54: 105164. https://doi.org/10.1016/j.respol.2024.105164

Fasciolo, B., Panza, L., and Lombardi, F. (2024). Exploring the Integration of Industry 4.0 Technologies in Agriculture: A Comprehensive Bibliometric Review. Sustainability. 16: 8948. https://doi.org/10.3390/su16208948

Feng, Y., Gao, G., Wang, P., and Zhang, Z. (2024). Integrating stakeholder value network with strategic issue management for multi-stakeholder needs and requirements analysis of vertical farming systems. Agricultural Systems, 221: 104133. https://doi.org/10.1016/j.agsy.2024.104133

Fernández, D., Navarro Garcia, A., Laarif, A., Aslan, G.E., Incrocci, L., and Padilla, F. (2024). Deliverable 5.7 - Open field days. https://www.iguessmed.com/_files/ugd/4b1614_fa84b9f5063443ebb2ffcacd2f62bfc6.pdf

Fielke, S., Bronson, K., Carolan, M., Eastwood, C., Higgins, V., Jakku, E., Klerkx, L., Nettle, R., Regan, Á., Rose, D.C., Townsend, L.C., and Wolf, S.A. (2022). A call to expand disciplinary boundaries so that social scientific imagination and practice are central to quests for 'responsible' digital agri-food innovation. Sociol Ruralis, 62: 151–161. https://doi.org/10.1111/soru.12376

Finger, R. (2023). Digital innovations for sustainable and resilient agricultural systems. European Review of Agricultural Economics, 50: 1277–1309. https://doi.org/10.1093/erae/jbad021

Forbat, J., Sahakian, M., Annaheim, J., and Sentic, A. (2025). Assessing processes and results of living labs: toward a general framework. Sustainability: Science, Practice and Policy, 21: 2526892. https://doi.org/10.1080/15487733.2025.2526892

Fragomeli, R., Annunziata, A., and Punzo, G. (2024). Promoting the Transition towards Agriculture 4.0: A Systematic Literature Review on Drivers and Barriers. Sustainability, 16: 2425. https://doi.org/10.3390/su16062425

Gabriel, A., and Gandorfer, M. (2023). Adoption of digital technologies in agriculture—an inventory in a european small-scale farming region. Precision Agriculture, 24: 68–91. https://doi.org/10.1007/s11119-022-09931-1

Ganeshkumar, C., Singh, N.K., Mor, R.S., and Panghal, A. (2023). Investigating the Adoption Barriers to Industry 4.0 Technologies in Farmer Producer Organisations. International Journal of Global Business and Competitiveness (JGBC), 18: 162–174. https://doi.org/10.1007/s42943-023-00083-1

Gardezi, M., Adereti, D.T., Stock, R., and Ogunyiola, A. (2022). In pursuit of responsible innovation for precision agriculture technologies. Journal of Responsible Innovation, 9: 224–247. https://doi.org/10.1080/23299460.2022.2071668

Giagnocavo, C., Gerez, S., and Campos i Climent, V. (2014). Paths to Cooperative Survival: Structure, Strategy and Regeneration of Fruit and Vegetables Cooperatives in Almería and Valencia, Spain. Annals of Public and Cooperative Economics, 85: 617–639. https://doi.org/10.1111/apce.12054

Gong, Y., Tan, R. (2021). Emergence of local collective action for land adjustment in land consolidation in China: An archetype analysis. Landscape and Urban Planning, 214: 104160. https://doi.org/10.1016/j.landurbplan.2021.104160

Gouroubera, M.W., Adechian, S.A., Segnon, A.C., Moumouni-Moussa, I., and Zougmoré, R.B. (2025). Drivers and impacts of mobile phone-mediated scaling of agricultural technologies: a meta-analysis. Frontiers in Sustainable Food Systems, 8: 1514546. https://doi.org/10.3389/fsufs.2024.1514546

Gremmen, B., Blok, V., and Bovenkerk, B. (2019). Responsible Innovation for Life: Five Challenges Agriculture Offers for Responsible Innovation in Agriculture and Food, and the Necessity of an Ethics of Innovation. Journal of Agricultural and Environmental Ethics, 32: 673–679. https://doi.org/10.1007/s10806-019-09808-w

Gumbi, N., Gumbi, L., and Twinomurinzi, H. (2023). Towards Sustainable Digital Agriculture for Smallholder Farmers: A Systematic Literature Review. Sustainability, 15: 12530. https://doi.org/10.3390/su151612530

Helms, M.M., and Nixon, J. (2010). Exploring SWOT analysis – where are we now? Journal of Strategy and Management, 3: 215–251. https://doi.org/10.1108/17554251011064837

Hinson, R., Lensink, R., and Mueller, A. (2019). Transforming agribusiness in developing countries: SDGs and the role of FinTech. Current Opinion in Environmental Sustainability, Sustainability Science: Inclusive business: A multi-Stakeholder issue 41: 1–9. https://doi.org/10.1016/j.cosust.2019.07.002

Hossain, M., Leminen, S., and Westerlund, M. (2019). A systematic review of living lab literature. Journal of Clean Production, 213: 976–988. https://doi.org/10.1016/j.jclepro.2018.12.257

Huber-Stearns, H.R., Bennett, D.E., Posner, S., Richards, R.C., Fair, J.H., Cousins, S.J.M., and Romulo, C.L., (2017). Social-ecological enabling conditions for payments for ecosystem services. Ecology and Society, 22(1): 18. https://doi.org/10.5751/ES-08979-220118

Hundal, G.S., Laux, C.M., Buckmaster, D., Sutton, M.J., and Langemeier, M. (2023). Exploring Barriers to the Adoption of Internet of Things-Based Precision Agriculture Practices. Agriculture, 13: 163. https://doi.org/10.3390/agriculture13010163

Hunter, J.D. (2007). Matplotlib: A 2D Graphics Environment. Computing in Science & Engineering, 9: 90–95. https://doi.org/10.1109/MCSE.2007.55

Incrocci, L., Fernández, D., Navarro Garcia, A., Laarif, A., Aslan, G.E., and Padilla, F. (2024). Deliverable 5.8 - Training courses. https://www.iguessmed.com/_files/ugd/4b1614_dc3ef232a0d7402f8f7907be928d6920.pdf

Ingram, J., Maye, D., Bailye, C., Barnes, A., Bear, C., Bell, M., Cutress, D., Davies, L., de Boon, A., Dinnie, L., Gairdner, J., Hafferty, C., Holloway, L., Kindred, D., Kirby, D., Leake, B., Manning, L., Marchant, B., Morse, A., Oxley, S., Phillips, M., Regan, Á., Rial-Lovera, K., Rose, D.C., Schillings, J., Williams, F., Williams, H., and Wilson, L. (2022). What are the priority research questions for digital agriculture? Land Use Policy, 114: 105962. https://doi.org/10.1016/j.landusepol.2021.105962

Jayasiri, M.M.J.G.C.N., Ingold, K., Weerahewa, J., Dayawansa, N.D.K., and Yadav, S. (2024). Bridging sustainability and effectiveness: assessing pesticide policies and regulation in Sri Lanka. *Environment*, Development and Sustainability. https://doi.org/10.1007/s10668-024-04852-7

Kamilaris, A., Kartakoullis, A., and Prenafeta-Boldú, F.X. (2017). A review on the practice of big data analysis in agriculture. Computers and Electronics in Agriculture, 143: 23–37. https://doi.org/10.1016/j.compag.2017.09.037

Klerkx, L., Jakku, E., and Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS: Wageningen Journal of Life Sciences, 90–91: 100315. https://doi.org/10.1016/j.njas.2019.100315

Klerkx, L., and Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways? Global

Food Security, 24: 100347. https://doi.org/10.1016/j.gfs.2019.100347

Kokotovich, A.E., Kuzma, J., Cummings, C.L., and Grieger, K. (2021). Responsible Innovation Definitions, Practices, and Motivations from Nanotechnology Researchers in Food and Agriculture. Nanoethics, 15: 229–243. https://doi.org/10.1007/s11569-021-00404-9

Kroupová, Z.Ž., Aulová, R., Rumánková, L., Bajan, B., Čechura, L., Šimek, P., and Jarolímek, J. (2024). Drivers and barriers to precision agriculture technology and digitalization adoption: Meta-analysis of decision choice models. Precision Agriculture, 26: 17. https://doi.org/10.1007/s11119-024-10213-1

Laarif, A., Bouslama, T., Mohsen, M., Fernández, D., Navarro Garcia, A., Massa, D., Pane, C., Buyuktas, D., Aslan, G.E., Karaca, C., Incrocci, L., Zeni, V., and Gallardo, M. (2024a). Deliverable 5.6 – WORKSHOPS. https://www.iguessmed.com/_files/ugd/4b1614_56a0b6083c9d44ebb3033876d36780e3.pdf

Laarif, A., Bouslama, T., Sturiale, S., Gava, O., Incrocci, L., and Bartolini, F. (2024b). Deliverable 4.4 - Mutual learning and knowledge exchange. https://www.iguessmed.com/_files/ugd/4b1614_7afc21c581ad4af9a3012dcd445c7014.pdf

Lajoie-O'Malley, A., Bronson, K., van der Burg, S., and Klerkx, L. (2020). The future(s) of digital agriculture and sustainable food systems: An analysis of high-level policy documents. Ecosystem Services, 45: 101183. https://doi.org/10.1016/j.ecoser.2020.101183

Littau, P., Jujagiri, N.J., and Adlbrecht, G. (2010). 25 Years of Stakeholder Theory in Project Management Literature (1984-2009). Project Management Journal, 41: 17–29. https://doi.org/10.1002/pmj.20195

MacPherson, J., Voglhuber-Slavinsky, A., Olbrisch, M., Schöbel, P., Dönitz, E., Mouratiadou, I., and Helming, K. (2022). Future agricultural systems and the role of digitalization for achieving sustainability goals. A review. Agronomy for a Sustainable Development, 42: 70. https://doi.org/10.1007/s13593-022-00792-6

Maffezzoli, F., Ardolino, M., Bacchetti, A., Perona, M., and Renga, F. (2022). Agriculture 4.0: A systematic literature review on the paradigm, technologies and benefits. Futures, 142: 102998. https://doi.org/10.1016/j.futures.2022.102998

Martens, K., and Zscheischler, J. (2022). The Digital Transformation of the Agricultural Value Chain: Discourses on Opportunities, Challenges and Controversial Perspectives on Governance Approaches. Sustainability, 14: 3905. https://doi.org/10.3390/su14073905

Matthews, A. (2021). The contribution of research to agricultural policy in Europe. Bio-based and Applied Economics, 10(3), 185–205. https://doi.org/10.36253/bae-12322

McFadden, J., Casalini, F., Griffin, T., and Antón, J. (2022). The digitalisation of agriculture: A literature review and emerging policy issues. OECD Food, Agriculture and Fisheries Papers, n. 176. Paris. https://doi.org/10.1787/285cc27d-en

McGrath, K., Brown, C., Regan, Á., and Russell, T. (2023). Investigating narratives and trends in digital agriculture: A scoping study of social and behavioural science studies. Agricultural Systems, 207: 103616. https://doi.org/10.1016/j.agsy.2023.103616

Metta, M., Ciliberti, S., Obi, C., Bartolini, F., Klerkx, L., and Brunori, G. (2022). An integrated socio-cyber-physical system framework to assess responsible digitalisation in agriculture: A first application with Living Labs in Europe. Agricultural Systems, 203: 103533. https://doi.org/10.1016/j.agsy.2022.103533

Mgendi, G., (2024). Unlocking the potential of precision agriculture for sustainable farming. Discover Agriculture, 2: 87. https://doi.org/10.1007/s44279-024-00078-3

Monda, A., Feola, R., Parente, R., Vesci, M., and Botti, A. (2023). Rural development and digital technologies: a collaborative framework for policy-making. Transforming Government: People, Process and Policy, 17: 328–343. https://doi.org/10.1108/TG-12-2022-0162

Mondejar, M.E., Avtar, R., Diaz, H.L.B., Dubey, R.K., Esteban, J., Gómez-Morales, A., Hallam, B., Mbungu, N.T., Okolo, C.C., Prasad, K.A., She, Q., and Garcia-Segura, S. (2021). Digitalization to achieve sustainable development goals: Steps towards a Smart Green Planet. Science of The Total Environment, 794: 148539. https://doi.org/10.1016/j.scitotenv.2021.148539

Navarro Garcia, A., and Lupu, A. (2021). Deliverable D1.8 - Ethical and Legal Manual. https://www.iguessmed.com/_files/ugd/4b1614_0ce6f0e84ce0494983808d91aa2ee20f.pdf

Ogunyiola, A., Stock, R., and Gardezi, M. (2024). Precision agriculture and the future of agrarian labor in the US food system. Agriculture and Human Values, 42: 383–403 https://doi.org/10.1007/s10460-024-10615-x

Owen, R., Macnaghten, P., and Stilgoe, J. (2012). Responsible research and innovation: From science in society to science for society, with society. Science and Public Policy, 39, 751–760. https://doi.org/10.1093/scipol/scs093

Pagot, G., and Andrighetto, N. (2024). Fuel for collective action: A SWOT analysis to identify social barriers and drivers for a local woody biomass supply chain in an Italian alpine valley. Heliyon, 10(19): e38170. https://doi.org/10.1016/j.heliyon.2024.e38170

Patton, M.Q. (2023). Qualitative Research & Evaluation Methods: Integrating Theory and Practice. SAGE Publications.

Petraki, D., Gazoulis, I., Kokkini, M., Danaskos, M., Kanatas, P., Rekkas, A., and Travlos, I. (2025). Digital Tools and Decision Support Systems in Agroecology: Benefits, Challenges, and Practical Implementations. Agronomy 15, 236. https://doi.org/10.3390/agronomy15010236

Potters, J., Collins, K., Schoorlemmer, H., Stræte, E.P., Kilis, E., Lane, A., and Leloup, H. (2022). Living Labs as an Approach to Strengthen Agricultural Knowledge and Innovation Systems. EuroChoices, 21: 23–29. https://doi.org/10.1111/1746-692X.12342

Regan, Á., (2019. ‘Smart farming’ in Ireland: A risk perception study with key governance actors. NJAS: Wageningen Journal of Life Sciences, 90–91: 1–10. https://doi.org/10.1016/j.njas.2019.02.003

Rijswijk, K., Klerkx, L., Bacco, M., Bartolini, F., Bulten, E., Debruyne, L., Dessein, J., Scotti, I., and Brunori, G. (2021). Digital transformation of agriculture and rural areas: A socio-cyber-physical system framework to support responsibilisation. Journal of Rural Studies, 85: 79–90. https://doi.org/10.1016/j.jrurstud.2021.05.003

Rose, D.C., and Chilvers, J. (2018). Agriculture 4.0: Broadening Responsible Innovation in an Era of Smart Farming. Frontiers in Sustainable Food Systems, 2: 87. https://doi.org/10.3389/fsufs.2018.00087

Rose, D.C., Wheeler, R., Winter, M., Lobley, M., and Chivers, C.A. (2021). Agriculture 4.0: Making it work for people, production, and the planet. Land Use Policy, 100: 104933. https://doi.org/10.1016/j.landusepol.2020.104933

Rotz, S., Gravely, E., Mosby, I., Duncan, E., Finnis, E., Horgan, M., LeBlanc, J., Martin, R., Neufeld, H.T., Nixon, A., Pant, L., Shalla, V., and Fraser, E. (2019). Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities. Journal of Rural Studies, 68: 112–122. https://doi.org/10.1016/j.jrurstud.2019.01.023

Shamshiri, R.R., Sturm, B., Weltzien, C., Fulton, J., Khosla, R., Schirrmann, M., Raut, S., Basavegowda, D.H., Yamin, M., and Hameed, I.A. (2024). Digitalization of agriculture for sustainable crop production: a use-case review. Frontiers in Environmental Science, 12: 1375193. https://doi.org/10.3389/fenvs.2024.1375193

Soriano, B., Garrido, A., Bertolozzi-Caredio, D., Accatino, F., Antonioli, F., Krupin, V., Meuwissen, M.P.M., Ollendorf, F., Rommel, J., Spiegel, A., Tudor, M., Urquhart, J., Vigani, M., and Bardají, I. (2023). Actors and their roles for improving resilience of farming systems in Europe. Journal of Rural Studies, 98: 134–146. https://doi.org/10.1016/j.jrurstud.2023.02.003

Sovacool, B.K. (2011). An international comparison of four polycentric approaches to climate and energy governance. Energy Policy, 39: 3832–3844. https://doi.org/10.1016/j.enpol.2011.04.014

Spee, A.P., and Jarzabkowski, P. (2009). Strategy tools as boundary objects. Strategic Organization, 7: 223–232. https://doi.org/10.1177/1476127009102674

Stilgoe, J., Owen, R., and Macnaghten, P. (2013). Developing a framework for responsible innovation. Research Policy, 42: 1568–1580. https://doi.org/10.1016/j.respol.2013.05.008

Sturiale, S., Gava, O., Gallardo, M., Buendía Guerrero, D., Buyuktas, D., Aslan, G.E., Laarif, A., Bouslama, T., Navarro, A., Incrocci, L., and Bartolini, F. (2024a). Environmental and Economic Performance of Greenhouse Cropping in the Mediterranean Basin: Lessons Learnt from a Cross-Country Comparison. Sustainability, 16: 4491. https://doi.org/10.3390/su16114491

Sturiale, S., Gava, O., Incrocci, L., and Bartolini, F. (2024b). Deliverable 4.2 - Protocol for living labs creation. https://www.iguessmed.com/_files/ugd/4b1614_995eaa54f104468889e9f48c0a8167de.pdf.

Sturiale, S., Gava, O., Incrocci, L., Buendía Guerrero, D., Gallardo, M., Aslan, G.E., Laarif, A., Bouslama, T., Navarro, A., and Bartolini, F. (2024c). Deliverable 4.3 - Feasibility and sustainability assessment document. https://www.iguessmed.com/_files/ugd/4b1614_a35e59c8b9444e89b8b212f5306b0767.pdf.

Suksa-ngiam, W., and Bechor, T. (2024). The impact of applying digital process innovation to farm management on farmer welfare: A multiple case study. Information Development, 0(0). https://doi.org/10.1177/02666669241258920

Tong, A., Sainsbury, P., and Craig, J. (2007). Consolidated criteria for reporting qualitative research (COREQ): a 32-item checklist for interviews and focus groups. International Journal for Quality in Health Care, 19: 349–357. https://doi.org/10.1093/intqhc/mzm042

UNESCO (201)8. Designing Inclusive Digital Solutions and Developing Digital Skills (Guidelines). United Nations Educational, Scientific and Cultural Organization, Paris, France.

Wang, W., Wang, J., Liu, K., and Wu, Y.J. (2020). Overcoming Barriers to Agriculture Green Technology Diffusion through Stakeholders in China: A Social Network Analysis. International Journal of Environmental Research and Public Health, 17: 6976. https://doi.org/10.3390/ijerph17196976

Wanner, M., Hilger, A., Westerkowski, J., Rose, M., Stelzer, F., and Schäpke, N. (2018). Towards a Cyclical Concept of Real-World Laboratories: A Transdisciplinary Research Practice for Sustainability Transitions. disP - The Planning Review, 54(2): 94–114. https://doi.org/10.1080/02513625.2018.1487651

Waskom, M.L. (2021). seaborn: statistical data visualization. Journal of Open Source Software, 6: 3021. https://doi.org/10.21105/joss.03021

Wolfert, S., Ge, L., Verdouw, C., and Bogaardt, M.J. (2017). Big Data in Smart Farming – A review. Agriculture Systems ,153: 69–80. https://doi.org/10.1016/j.agsy.2017.01.023

Xu, J., Li, Y., Zhang, M., and Zhang, S. (2024). Sustainable agriculture in the digital era: Past, present, and future trends by bibliometric analysis. Heliyon, 10: e34612. https://doi.org/10.1016/j.heliyon.2024.e34612

Xu, J., She, S., and Liu, W. (2022). Role of digitalization in environment, social and governance, and sustainability: Review-based study for implications. Frontiers in Psychology, 13: 961057. https://doi.org/10.3389/fpsyg.2022.961057

Yang, C., Ji, X., Cheng, C., Liao, S., Obuobi, B., and Zhang, Y. (2024). Digital economy empowers sustainable agriculture: Implications for farmers' adoption of ecological agricultural technologies. Ecological Indicators, 159: 111723. https://doi.org/10.1016/j.ecolind.2024.111723

Yin, R.K., (2014. Case study research: design and methods, Fifth edition. ed. SAGE, Los Angeles.

Yuan, Y., and Sun, Y. (2024). Practices, Challenges, and Future of Digital Transformation in Smallholder Agriculture: Insights from a Literature Review. Agriculture, 14: 2193. https://doi.org/10.3390/agriculture14122193

Zhai, Z., Martínez, J.F., Beltran, V., and Martínez, N.L. (2020). Decision support systems for agriculture 4.0: Survey and challenges. Computers and Electronics in Agriculture, 170: 105256. https://doi.org/10.1016/j.compag.2020.105256