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A multi-stakeholder perspective on the use of digital technologies in European organic and agroecological farming systems

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ABSTRACT

In recent years, digital technologies have become increasingly important in the agri-food system. While such technologies have been understood to facilitate precision farming practices, digitalisation also may play a key role in the transition to more sustainable food systems. Given the current knowledge gap in understanding the perceptions of digitalisation by the diverse stakeholders of organic and agroecological production, this research holds particular significance. The aim of this paper is to analyse the perception of farmers, farm advisors and producer organisations, associations and/or cooperatives on the use of digital technologies in organic and agroecological production system in different European countries. A combination of convenience and snowball sampling methods were used to select participants. Analysis of Variance (ANOVA) and chi-square tests were used to discern differences within the collected surveys regarding benefits of using digital technologies, the reason why farmers do not use them, as well as the main barriers, risks and drivers of their use. The results show differences in perceptions according to the type of stakeholder. Surveyed stakeholders agree that digitalisation

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facilitates communication, exchange of knowledge and experiences between actors. The main barriers to the use of digital technologies are related to economic aspects, complexity and unsuitability of equipment. The creation of networks or collaborations between the actors involved to share equipment, costs, exchange knowledge, as well as governmental financial support were considered the main drivers of digital technologies for organic and agroecological systems. The results of this study contribute to theorising on the diffusion of innovations and may be helpful for policy makers and farm advisors as it provides relevant and important information to define and incorporate solid approaches to digital transformation in an agroecology innovation ecosystem.

1. Introduction

Digital technologies (DTs) have become great allies of agricultural systems by providing solutions to increase production through more efficient and sustainable practices [1–4]. DTs are used mainly in precision or large-scale conventional farming [5–8] to optimize inputs and resources, improve product quality, reduce workload and environmental impacts, among others [9–11]. Despite this potential of DTs there are still some questions about the real benefits, as well as the risks, limitations and/or consequences of the digitalisation of agricultural production systems [12–15], especially those with a more sustainable approach [12,16–19].

The European Union recognizes the potential of DTs to contribute to the environmental and socioeconomic sustainability of agricultural systems [20,21], therefore, the *promotion of knowledge, innovation and digitalisation* is one of the actions prioritised in the CAP Strategic Plan (2023–2027). This strategy emphasizes both the need to invest in technologies and the creation of an enabling environment that will help farmers adopt and effectively use digital technologies [21,22]. However, the digitalisation strategies for agriculture and rural areas of the member states include limited considerations on DTs as tools to achieve environmental, climate and rural objectives [21]. While the EU views agroecology and digitalisation as "essential" for achieving the goals of the "Farm to Fork" and "Green Deal" [16], this approach may pose challenges and controversies due to potential misalignments between current DTs and agroecological principles.

Agroecological production systems, as opposed to conventional ones, focuses on socioeconomic sustainability and environmental conservation, by integrating ecological principles in locally adapted farming practices [16,23,24]. Although nowadays many digital tools can be used in organic and agroecological systems (see section 2.1) [25–29], their focus on prioritizing economic efficiency and the few and/or real contributions to addressing social and environmental challenges is still questioned [30–35]. This means that the capacity of DTs to effectively support agroecology is not clearly demonstrated and continues to pose significant challenges [19]. Due to the wide diversity of agroecology criteria (13 agroecological principles) [36], it is suggested that their compatibility with digitalisation depends on multiple factors, including the type of user, the adaptive capacity, the purpose for which digital tools are integrated and/or mobilised in these systems, among others [16,25,27,37].

The use/adoption of DTs in precision and conventional agricultural systems has been extensively studied [34,38–42], however, it seems that the adoption rate is still low and fragmented [4,43]. Osrof et al. [4], provide a comprehensive overview of the main factors (individual, organisational, technological and external) affecting the adoption of DTs. These authors point out that most research has focused on farmers, so there is a gap in the multi-stakeholder understanding of the factors influencing the adoption of DTs. Barriers and drivers for the adoption of DTs may also vary according to country cultures, although a low percentage of existing studies have had a cross-country focus. There is therefore a need to fill this gap with more cross-country studies [4]. In contrast, studies on the digitalisation of agroecological systems are still scarce. Previous literature has mentioned, some factors that might influence farmers' decisions to adopt or reject DTs in organic and/or agroecological systems [16,29,39,44,45]. However, there is no comprehensive study that analyses the differing reasons for non-adoption of DTs and that identifies the main barriers, risks and drivers in such systems. Furthermore, most of the available research has focused on specific contexts, leaving significant gaps in the overall understanding of this topic.

Stakeholders' perception of the direct and indirect benefits of using DTs in farming systems is a key factor influencing the willingness to adopt them [4]. Schnebelin et al. [46], analysed the perception of key representatives of conventional farming, organic farming and digital organisations on digital development in French agriculture. However, to the authors' knowledge, there is no study that analyses this multi-stakeholder perception in agroecological production systems within a broad cross-European context. Schnebelin et al. [46], highlight the need for further research on farmers' uses of technologies and for functional and multi-stakeholder analyses to identify mechanisms to reduce barriers and encourage incentives. Furthermore, Bellon-Maurel et al. [47], suggest that future analyses on key aspects of digitalisation in agroecology should have a multi-stakeholder and participatory approach.

Some research includes reflections on barriers, risks and drivers of digitalisation in organic and/or agroecological systems [16,25,27,46,48]. However, none of these studies analyse these aspects together using primary information and from a multi-stakeholder approach. Organic farming and agroecology have common objectives, principles and drivers. In Europe, most agroecological practices are applied by organic farmers [16]. Despite this, there are no known previous studies that analyse digitalisation jointly in these two types of production systems. Accordingly, the purpose of this study is to analyse the perception of farmers, farm advisors and producer organisations and/or associations and/or cooperatives (collectively, POs/PAs/Coops) on the use of DTs in organic and agroecological production systems in different European countries. In particular this study investigates the research questions (RQ):

> RQ1: What are the perceptions of farmers, farm advisors and POs/PAs/Coops on the benefits of digitalisation of organic and agroecological systems and the differences between the approaches of the three stakeholders?
> RQ2: What are the main reasons for farmers not to use DTs in organic and agroecological production systems?
> RQ3: What perceptions do farmers, farm advisors and POs/PAs/Coops have about the barriers, risks and drivers of using DTs in organic and agroecological production and the differences between the approaches of the three stakeholders?

This study is novel in that it jointly addresses key aspects of digitalisation from the approach of three of the main stakeholders in organic and agroecological production systems in several European countries. The results will provide relevant information for all actors involved in these production systems, technology developers and providers, organisations, research centres and policy makers, who will be able to identify the aspects that need to be strengthened in relation to the strategies, regulatory frameworks and/or polices necessary to guarantee an effective synergy between DTs and organic and/or agroecological systems.

The main objective of the European project in which this study takes place is to ensure that digitalisation functions as an enabler of agroecology and in doing so, respects the characteristics of the EU definitions of organic farming and agroecology. In this study *digital technologies* relate to information technologies and operational technologies. Information technologies refer to the electronic tools, devices, systems and/or resources used for the creation, processing, transmission, and storage of data, while operational technologies facilitate the management, monitoring, supervision, and control of industrial operations, focusing on the physical devices and processes they use. This definition was taken from the classification of digital technologies under the European project, SmartAgriHubs [49].

2. Theoretical background

2.1. Use of digital technologies in organic and/or agroecological production systems

There is a wide variety of DTs that can be applied to facilitate the implementation of the principles of agroecological production systems [25–29]. While Ditzler and Driessen [50] showed the potential of robots in agroecological crop production, they stress that automation in agroecology requires a wide diversity of approaches and actors in order to be in line with the principles of this type of sustainable production system. Paget et al. [48], analysed in a more specific context several existing digital solutions that can contribute to the transition towards agroecology, mainly tools for data collection, decision support, and platforms for knowledge exchange and sharing (drones, satellites, web/social media applications and smartphones). Their main findings highlight the challenges of innovation to adapt to the characteristics of agroecological systems.

Ajena et al. [16], present a case study on how Information and Communication Technologies (ICTs) can support farmer-driven research on agroecological transitions. They point out that it is key to identify technological proposals that promote agroecological and organic principles, support a transformation agenda and are consciously applied according to the conditions and needs of the communities. Tassin [51], shows how digital tools (social media) in China support new young intermediaries who are returning to the land in the promotion of agroecological practice and support the re-emergence of peasant supply chains. At the same time, this author calls attention to the digital inter-knowledge relationships that can shape agroecological circles exclusively for producers who are qualified to belong to them.

Agroecological processes are dynamic and complex, which is reflected by both Gascuel-Odoux et al. [52], and Bellon Maurel et al. [19], studies suggesting that new technologies (high-resolution remote detection, sensors and mapping tools) can contribute to the acquisition and use of data needed to monitor and characterise the trajectories of the main biological processes and create models of complex mechanisms within agroecology. Ewert et al. [27], Ajena et al. [16], and Bellon Maurel and Huyghe [25], emphasise the potential of DTs and their important role as enablers of agroecological transformation. Despite this Ewert et al. [27], stress that there are still critical points and issues that need to be resolved, such as data ownership and the increasing use of non-renewable resources. They also highlight the need for more systematic evaluations to obtain more evidence at different scales and in other farming systems.

2.2. Perceptions and attitudes on the use/adoption of digital technologies in farming systems

Multiple factors (social, economic, cultural, institutional and/or political) may influence farmers' perceptions and attitudes towards DTs [53–56]. According to Smidt and Jokonya [55], farmers' perceptions of technology adoption change over time according to new and emerging technologies. Many studies emphasise that factors such as farmer characteristics, socio-demographics, skills, knowledge, and perceived attributes of the technology, among other aspects, influence farmers' decisions to adopt DTs [4,20,39,42,45,53]. According to Bontsa et al. [56], perceptions of DTs could be a barrier to their adoption, depending on the approach. These authors found that small farmers engaged in cattle raising had a more positive perception of the use of DTs than those dedicated to sheep and goat raising. Among the main factors affecting this perception were age, education level, employment status, income and being part of a cooperative. Cavallo et al. [6,7], identified different opinions and attitudes on tractor technology innovations among Italian farmers. Factors such as age, level of education, farm size, income, suitability and cost of tractors and level of concern for environmental issues make the difference between those willing and those unwilling to adopt tractors with innovative technologies.

Bellon Maurel et al. [19], raises the issue of the divide between large farms that are likely to adopt robots and smaller (non-conventional) farms that are not adopting them or are slow to adopt them. The authors mention that it is important to find innovative solutions that combine a "high-low tech" approach. Earlier studies show that stakeholders in conventional or organic food production systems recognise the potential of new DTs, as well as the opportunities and advantages they can bring them [46,57]. A multi-stakeholder study that assessed the views of Brazilian dairy farmers, advisors and citizens on the characteristics of an ideal farm found that all three stakeholder groups consider that technology plays an important role in dairy farms. However, it highlights that the justifications for this view differ between the groups, possibly because of their individual values and interests [57].

Differences in views can also emerge from a different awareness of existing DTs, their use and benefits between the different stakeholders. Schnebelin et al. [46], through interviews and the use of a multi-stakeholder approach analysed how digitalisation is seen in French organic systems, specifically focusing on perceptions of digitalisation, its impacts and potential. The results show that organic and conventional actors do not perceive the same benefits and risks of using DTs and therefore do not implement the same innovation processes. Ajena et al. [16], analysed the perception and knowledge of Swiss organic farmers on the use of DTs. The results show a division between the opinions of "Artisanal Organic" and "Digital Organic" farmers mainly with regard to the amount and type of tools and/or equipment suitable for use in their organic production systems.

In relation to the aspects mentioned above, Rogers' diffusion of innovations theory states that the perception of certain attributes of innovations by potential adopters is the main influence on adoption decisions [58]. According to this theory, there are 5 attributes that determine people's adoption of innovations: relative advantage, compatibility, complexity, testability and observability [59,60]. This theory also defines five stages of the innovation decision process: awareness, interest, evaluation, trial and adoption [60]. This theory has been widely used to analyse the factors that influence the rate of diffusion and adoption of practices and technologies in agriculture [58,61,62]. The approaches of this theory are relevant for the analysis of certain results of our study, and accordingly in section 5 'discussion' we reflect on some of them in more detail.

2.3. Barriers, risks and drivers for the use/adoption of digital technologies in farming systems

Comprehensive analyses of the factors affecting or limiting the adoption of DTs in precision and conventional large and small-scale production systems are a baseline for analysing these aspects in sustainable production systems. Osrof et al. [4], provides a comprehensive list of barriers and drivers for the adoption of Smart Farming Technologies (SFTs). Ferrari et al. [63], contributes significant insights on the barriers, drivers and impacts of ICTs use in rural areas from the point of view of interdisciplinary experts. The barriers identified mainly in conventional production systems, related to technological, socioeconomic, institutional, behavioral, psychological and other factors, served as references for this study. The high cost of acquisition, operation and maintenance of the DTs, the complexity of their use, the lack of awareness and knowledge of farmers on DTs, among others that are detailed in Table 1, stand out as the main barriers.

Similarly, these barriers have been identified in a more disaggregated manner in studies with organic and/or agroecological systems approaches, some of them under specific contexts. Bellon Maurel and Huyghe [25], Ajena et al. [16] and Paget et al. [48], agree that the main barriers are associated with socio-economic aspects (high investment costs and complexity of using DTs). However, as shown in Tables 1 and in this type of production system, additional barriers associated with the lack of suitability of digital technologies to support the implementation of organic or agroecological practices arise, mainly due to the lack of interaction between the designers of the DTs and the users.

Osrof et al. [4], classified the drivers of SFTs adoption into individual, organisational, technological and external factors. According to experts, the main drivers for the use of ICT in rural areas are economic (cost reduction) and regulatory (strict production monitoring) [63]. As indicated in Table 1, the reduction of the cost of using technology and access to financing programs (subsidies) have been identified also as key aspects to boost the use of DTs in production systems. In general, the main risks associated with the use of DTs in production systems are technology dependence and the exclusion of some actors, with certain limitations to deal with the changes demanded by DTs, for example, small farmers and those with a low level of education and/or limited knowledge.

3. Research methodology

For this study, surveys were conducted among farmers, farm advisors and POs/PAs/Coops of organic and agroecological production systems in 10 European countries.

3.1. Sample and data

Data were collected from three key stakeholders: farmers as users of DTs; farm advisors as informants, trainers and/or facilitators for the implementation of DTs; and POs/APs/Coops with their dual role as users and/or facilitators and intermediaries between technology providers and farmers. The survey was distributed by the partners of the EU project “PATH2DEA” to the targeted groups of stakeholders, between June and September 2023, inclusive. In our study, we employed a combination of convenience sampling and snowball sampling methods to select participants. Convenience sampling is a non-probability method based on criteria of closeness and easy access to the population [66].

We initially recruited participants based on the information available in the databases of the partners involved in the EU project ‘PATH2DEA’. This method was chosen due to the availability of participants. Following initial recruitment, participants were asked to refer others who met the study criteria (i.e., either farmers, farm advisors or POs/PAs/Coops of organic and/or agroecological production systems located in the 10 European countries). This approach was particularly useful for expanding the sample of respondents beyond the databases of the partners of the EU project. The survey link was also distributed via newsletters on the main project website and partner websites, articles in farmers’ magazines, and social media messages. The survey was distributed mainly in the following countries: Austria, Belgium, France, Germany, Greece, Hungary, Italy, Spain, Slovakia, Switzerland. In some of these countries the survey was also distributed on paper to the participants during events that were carried out by the project partners.

While the potential for bias exists with the use of convenience and snowball sampling methods [66,67], some actions were taken to mitigate these biases and ensure a more representative sample. First, we utilized databases from multiple partners involved in the EU project ’PATH2DEA’, each of whom had access to a wide array of participants.

Table 1
Main barriers, risks and drivers for the use of DTs.

Variable	Type of production system	Factors/aspects mentioned	References
Barriers	Conventional	- Complexity and high cost of using DTs. - Perception of risk due to the use of DTs. - DTs are not suitable or are not adapted to local knowledge. - Low capacity to use digital technology. - Lack of digital technology infrastructure or connectivity. - Low level of knowledge and/or skills or technical competencies required for use DTs. - Low levels of education/ literacy. - Low level of information on existing DTs. - Lack of suitable information services. - Low incomes of small-scale farmers. - Regulatory issues on DTs and unclear data governance. - Lack of institutional/ governmental support.	[4,43, 53–56,63, 64]
	Organic and/or agroecological	- Limited research capacity of small and medium-sized farm machinery companies. - Lack of interaction and joint work between designers of DTs and designers of new production systems. - DTs not suitable or adapted for organic or agroecological systems.	[25,44,46, 48]
Risks	Conventional and organic/or agroecological	- Dependence on companies supplying DTs. - Loss of management power of farms. - Hacking or appropriation of data and/or the value created. - Loss of intellectual property, privacy, traceability and freedom. - Exclusion of small farmers due to lack of infrastructure, skills or cost. - Accelerating conventionalization of farming to the detriment of more radical organic farming and smaller farms. - Stress due to increased time investment. - Loss of interactions between stakeholders. - Loss of connection to the land and loss of local knowledge.	[16,28,29, 44,46]
Drivers	Conventional	- Cheaper and more accessible DTs for small farmers. - Collective/organised structures (cooperatives) to facilitate access to technology. - Funding programmes/ financial incentives (subsidies) for cooperation and adoption of DTs. - Training programmes, promotion/awareness-raising campaigns and the creation of digital innovation centres.	[4,43,63, 64]

(*continued on next page*)

Table 1 (*continued*)

Variable	Type of production system	Factors/aspects mentioned	References
	Organic and/or agroecological	- Policies and regulations that contribute to improving access to and use of DTs. - Subcontracting services and sharing equipment among farmers. - Fiscal incentives and a regulatory framework to support the acquisition and use of DTs. - Participatory and combined (bottom-up and top-down) approaches in the design and development of DTs. - DTs co-designed and developed under the organic or agroecological paradigm.	[16,25,44,46,48,65]

Second, we provided initial participants with clear criteria for referring others, specifically encouraging the inclusion of individuals from different backgrounds, roles, and regions. This guidance aimed to broaden the range of participants beyond those who might be most immediately accessible or familiar. A total of 533 surveys were completed by stakeholders.

3.2. Survey design

The questionnaires were designed in LimeSurvey and translated into 9 languages. They were reviewed and validated by native speakers familiar with agroecological and organic agriculture so as to ensure accuracy and understandability. The three questionnaires were structured in sections, as follows: 1. Stakeholder characterisation, with general information on the three types of stakeholders; 2. General aspects of the use of DTs, including questions on perceptions of DTs; and 3. Identification of barriers, drivers and risks in the use of DTs, with specific variables on these three aspects. Each section included different response options: 1. Closed or fixed-response, "yes-no"; 2. Multiple choice response: Range of responses with an open-ended item at the end of the list (other-which?); and 3. Scale responses: alternative responses graded in intensity (5-point Likert-type scale). Most of the studies described in Section 2, especially those listed in Table 1, were used to define the response options and statements included in the scaling questions. The questionnaires were reviewed by multi-actor project partners to ensure optimal user understanding.

3.3. Data analysis

The data obtained from these surveys, using only those completely filled out, were analysed using two statistical techniques with SPSS software (version 29.0): a One-Way Analysis of Variance (ANOVA) and Pearson's Chi-square Test to determine if there are significant differences between the responses of the stakeholder groups. For both tests, significant differences between group responses are considered to exist if p is ≤ 0.05. Other studies have used these techniques to assess preferences and compare the perceptions of different actors' groups [34,68]. To account for the variability of other effects and avoid issues related to non-independence of data in ANOVA, an additional factor (specifically a nested factor) was incorporated into the analysis: country of origin of the surveyed.

4. Results

4.1. General characteristics of the sample and stakeholders' profile

Of the total number of surveys obtained (533), the largest number (308) are from farmers (58 %), followed by advisors with 170 surveys (32 %) and 55 surveys were completed by POs/PAs/Coops (10 %).

Seventy seven percent of the farmers surveyed are natural persons and 21 % are constituted as companies. The main sector in which the farmers are active is vegetables (43 %), followed by arable farming (35 %) and animal production (26 %). The majority of farmers (39 %) have a cultivated area of less than 2 ha and produce under organic (78 % of farmers) and agroecological systems (32 %). Thirty-three percent of the advisors surveyed are natural persons, 31 % are advisors to POs/PAs/Coops, 15 % belong to a private company and 12 % are from a public entity.

More than half of the advisors surveyed provide technical support pre- and post-harvest (55 %). The services provided by the advisors are agronomic analysis and interpretation services (54 %) and advice on integrated farm management (49 %). The vast majority (81 %) of the advisors provide their services to organic production systems and 61 % advise agroecological production systems. Twenty-five of the POs/PAs/Coops surveyed are cooperatives, ten are producer organisations and ten are producer associations. The majority of POs/PAs/Coops work within the arable farming sector. Of the majority of these stakeholders (51 %) work in the fruit sector while 35 % work in the animal production sector. The majority of POs and PAs (80 %) produce under organic production systems. Seventy-six percent of the cooperatives produce under agroecological systems.

4.2. Benefits of the use of digital technologies in organic and/or agroecology farming

Table 2 shows the number of responses according to the degree of agreement of each stakeholder with the statements listed. The analysis of means for each statement (the highest), for the three stakeholder groups, indicates that the three main benefits of the use of DTs in organic and/or agroecological farming are: 1. *Improves and/or facilitates communication, interaction and exchange of knowledge and/or experiences between the actors involved in the production process* (mean value 3.72). 2. *Facilitates and/or enhances strategic farm design, operational management and decision* support (mean value 3.68) and 3. *Offers more opportunities to advance the transition towards more sustainable production systems* (mean value 3.66).

Although these three benefits mentioned above have been prioritised as shown in Table 3, the results of the ANOVA analysis indicate that there are significant differences between stakeholder group perceptions for most of the statements (five out of seven). For example, advisors and POs/PAs/Coops compared to farmers are more likely to agree that DTs facilitate communication, interaction and exchange of knowledge and/or experiences between actors involved in organic and/or agroecological systems BDT2 ($F = 11.200$; $p = < 0.001$).

The same trend of greater agreement between these two groups (advisors and POs/PAs/Coops) is observed for the other two prioritised benefits, BDT01 - *offers more opportunities to advance the transition towards more sustainable production systems* ($F = 4.936$; $p = < 0.008$) and BDT03 - *facilitates and/or enhances strategic farm design, operational management and decision* support ($F = 5.475$; $p = < 0.004$). For the variables BDT5 ($F = 1.178$; $p = 0.309$) and BDT7 ($F = 2.491$; $p = 0.084$) there is greater agreement (no significant differences) between the 3 groups. This means that all three stakeholders agree that the use of DTs supports and/or facilitates the application of organic and/or agroecological farming practices/principles and that it also reduces costs due to the optimisation of inputs and the reduction of the use of natural resources.

4.3. Reasons why farmers do not use digital technologies organic and/or agroecology farming

Of the total number of farmers surveyed, 146 (47 %) do not use any kind of digital technology and the remaining 162 farmers (53 %) do. The

Table 2
Number of responses by stakeholder according to level of agreement on the benefits of DTs in organic/agroecological systems, n = 533.

The use of digital technologies in organic agriculture and/or agroecology	Stakeholder	Strongly disagree	Moderately disagree	Neutral	Moderately agree	Strongly agree
offers more opportunities to advance the transition to more sustainable production systems [BDT01].	Farmers	22	35	79	99	73
	Advisors	3	18	43	57	49
	POs/PAs/Coops	1	3	12	19	20
improves and/or facilitates communication, interaction and exchange of knowledge/experiences between the actors involved in the production process [BDT02].	Farmers	29	27	85	87	80
	Advisors	5	9	33	62	61
	POs/PAs/Coops	0	1	12	25	17
facilitates and/or enhances strategic farm design, operational management and decision support [BDT03].	Farmers	18	39	83	92	76
	Advisors	2	12	42	64	50
	POs/PAs/Coops	2	1	16	21	15
contributes to the efficient management of resources and the reduction of polluting inputs and emissions [BDT04].	Farmers	24	25	105	85	69
	Advisors	6	18	40	59	47
	POs/PAs/Coops	1	2	17	21	14
supports/facilitates the application of organic farming and/or agroecology practices/principles [BDT05].	Farmers	18	31	111	94	54
	Advisors	5	27	54	54	30
	POs/PAs/Coops	2	3	15	26	9
increases income due to quality improvement or traceability and/or certification (which is based on digital technologies) [BDT06].	Farmers	51	51	106	68	32
	Advisors	6	36	60	38	30
	POs/PAs/Coops	2	6	21	22	4
reduces costs due to optimisation of inputs and reduction of natural resources uses [BDT07].	Farmers	40	46	93	84	45
	Advisors	7	30	54	48	31
	POs/PAs/Coops	1	8	21	20	5

Farmers ■ Advisors ■ POs/PAs/Coops ■

three main reasons given by farmers for not using DTs are: 1. *I am not aware of relevant existing DTs* (37 %). 2. *Existing DTs are not adapted to the scale of my production system* (33 %) and 3. *It is too expensive to acquire this type of DTs* (27 %). Lack of sufficient/necessary resources to invest in DTs (25 %) and lack of knowledge/capacity needed for the operation of DTs (22 %) were also other reasons given by farmers. The complete list of reasons and prioritization percentages can be found in fig. 1 (Appendix A). Forty-two percent of the surveyed farmers who do not make use of digital tools are small-scale farmers, i.e. they produce on land of less than 2 ha and 22 % on areas between 2 and 10 ha.

4.4. Main barriers to the use of digital technologies in organic and/or agroecology farming

The three main barriers to digitalisation in organic and/or agroecological production systems are: 1. *High investment costs for the purchase, operation and maintenance of equipment* (58.2 %). 2. *Complexity in the use of equipment/software and in the processing and/or analysis of data, which requires specific knowledge and time-expensive training* (50.1 %) and 3. *Most DTs are designed for industrial-scale production farms and are not suitable for small-scale farmers* (46.5 %). fig. 2 (Appendix A) describes the full list of barriers that were analysed.

In spite of this prioritization, the results of the Chi-square analysis (Table 4) show that there are significant differences in most of the responses from different stakeholders (seven out of nine). For example, for the first prioritised barrier (*High investment costs for the purchase, operation and maintenance of equipment*) ($x^2 = 7.763$; $p = 0.021$), POs/PAs/Coops and farmers are in greater agreement that high investment costs are a barrier to the adoption of DTs. The advisors agree the most with the second prioritised barrier (*Complexity in the use of equipment/software and in the processing and/or analysis of data)* ($x^2 = 20.394$; $p = < 0.001$), followed by the POs/PAs/Coops. There are no significant differences in the responses for the third prioritised barrier ($x^2 = 5.043$; $p = 0.080$), this means that all three stakeholder groups agree that *most DTs are designed for industrial-scale production farms and are not suitable for small-scale farmers*.

4.5. Main risks of the use of digital technologies in organic and/or agroecology farming

All stakeholders agreed that the three main risks of using DTs are: 1. *Dependence on companies for operation/maintenance/repair of equipment and/or data management* (52.9 %), 2. *Exclusion of small farmers due to low investment* (52.9 %) and 3. *Exclusion of farmers due to lack of knowledge and/or skills* (51.6 %). The complete list of risks that were analysed can be found in fig. 3 (Appendix A). There are significant differences in the majority (six out of ten) of answers given by the three groups. However, Table 5 shows that there are no significant differences between the groups' responses for two of the three prioritised risks RI1 ($x^2 = 0.685$; $p = 0.710$) and RI10 ($x^2 = 5.155$; $p = 0.076$). This means, all three stakeholders agree that dependence on companies for the operation and/or maintenance/repair of equipment and the exclusion of farmers due to lack of knowledge and/or skills are risks involved in digitalisation processes. Regarding the exclusion of farmers due to low investment capacity RI8 ($x^2 = 16.193$; $p = < 0.001$), it is the POs/PAs/Coops who perceive this risk the most.

4.6. Main drivers to digitalisation in organic and/or agroecology farming

The primary drivers of digitalisation in organic and/or agroecological farming are: 1. *The creation of networks or collaborations between cooperatives, farming communities and advisors to share equipment, costs, facilitate relationships between stakeholders, exchange knowledge and improve training* (mean value: 3.85), 2. *Participatory design/co-design and implementation (between companies and farmers) of DTs adapted to farm needs and capacities, as well as to organic production and/or agroecology approaches* (mean value: 3.81). and 3. *Improved and/or increased government (financial)* support *for equipment acquisition, installation, operation and education/training in digitalisation processes* (mean value: 3.79) (Table 6).

The results of ANOVA analysis (Table 7) show that there are no significant differences between the responses of the groups with respect to the drivers of DTs in the organic and/or agroecological systems.

Table 3
Results of ANOVA analysis. Stakeholders' perceptions of the benefits of digitalisation, n = 533.

Statement: The use of digital technologies in organic agriculture and/or agroecology	Farmers	Advisors	POs/PAs/Coops	F-value	df	*p* value
	Mean (SD)	Mean (SD)	Mean (SD)			
offers more opportunities to advance the transition to more sustainable production systems [BDT01]	3.54 (1.176)	3.77 (1.038)	3.98 (0.991)	4.936	2	0.008*
improves and/or facilitates communication, interaction and exchange of knowledge/ experiences between the actors involved in the production process [BDT02]	3.53 (1.230)	3.97 (1.017)	4.05 (0.780)	11.200	2	<0.001*
facilitates and/or enhances strategic farm design, operational management and decision support [BDT03]	3.55 (1.162)	3.87 (0.958)	3.84 (0.977)	5.475	2	0.004*
contributes to the efficient management of resources and the reduction of polluting inputs and emissions [BDT04]	3.49 (1.154)	3.72 (1.088)	3.82 (0.925)	3.696	2	0.025[a]
supports/ facilitates the application of organic farming and/or agroecology practices/ principles [BDT05]	3.44 (1.074)	3.45 (1.049)	3.67 (0.944)	1.178	2	0.309
increases income due to quality improvement or traceability and/or certification (which is based on digital technologies) [BDT06]	2.93 (1.210)	3.29 (1.097)	3.36 (0.910)	7.182	2	<0.001[a]
reduces costs due to optimisation of inputs and reduction of natural resources uses [BDT07]	3.16 (1.227)	3.39 (1.100)	3.36 (0.910)	2.491	2	0.084
Country	N/A	N/A	N/A	0.631	2	0.532

[a] Significant difference (≤0.05). SD: Standard deviation.

Significant difference was only evident for one of the seven drivers that were raised- DRI07 *government interventions to ensure the necessary infrastructure for the operation of technologies (rural broadband connectivity)* ($F = 4.197$; $p = 0.016$). In contrast to the previous aspects evaluated (benefits, barriers and risks) the three stakeholders agree that the three prioritised drivers DRI05 (*The creation of networks or collaborations between cooperatives, farming communities and advisors to share equipment, costs, facilitate relationships between stakeholders, exchange knowledge and improve training)* ($F = 0.933$; $p = 0.394$), DRI2 (*Participatory design/co-design and implementation (between companies and farmers) of DTs adapted to farm needs and capacities, as well as to organic production and/or agroecology approaches)* ($F = 0.488$; $p = 0.614$) and DRI1 (*Improved and/or increased government (financial)* support *for equipment acquisition, installation, operation and education/training in digitalisation processes)* ($F = 0.295$; $p = 0.744$) are the most relevant for the digitalisation of organic and/or agroecological systems.

In this survey, representation was heterogeneous between European countries. However, according to the results of the ANOVA (Tables 3 and 7) anal ysis, the country factor did not significantly influence the results.

5. Discussion

5.1. RQ1: What are the perceptions of farmers, farm advisors and POs/PAs/Coops on the benefits of digitalisation of organic and/or agroecological systems and the differences between the approaches of the 3 stakeholders?

Co-creation and sharing of knowledge is one of the principles of agroecology [69]. Ajena et al. [16], stress that the interactive potential of DTs and digital networks can promote and enhance different ways of communication between farmers and experts (bottom-up, top-down, and peer-to-peer). Through the use of technological platforms, processes of knowledge co-creation and interaction among multiple actors can be fostered. The results of our study indicate that the farmers, farm advisors and POs/PAs/Coops surveyed recognise this potential of the DTs to improve and facilitate communication, exchange of knowledge and experiences among the actors that are part of their organic and/or agroecological production systems. Our results are in line with the findings of Schnebelin et al. [46], and Schnebelin [44], regarding the relevance given by French Agricultural Innovation System actors (mainly those related to organic agriculture) to DTs as tools to create and exchange knowledge. This is mainly because these organic stakeholders see digitalisation as a way of developing knowledge. Thus, the results herein seem to reinforce this conclusion [44].

The responses of the POs/PAs/Coops surveyed are an indicator of the relevance of DTs in the processes of interaction and communication among the actors that are part of these organisations. This finding coincides with the observations of Schnebelin et al. [46], and Rijswijk et al. [70], who point out that agricultural organisations and cooperatives are more inclined to use technologies due to the benefits they obtain within their structure. Most of the DTs that are promoted or developed by organic organisations are related to knowledge management and knowledge exchange [46].

Rijswijk et al. [70], also highlight that the technologies that are developed by agricultural cooperatives in collaboration with digital companies are mostly applications to organise and consolidate information so that it is accessible to farmers and supports their farm management operations. This perhaps also explains why there is greater agreement, especially from POs/PAs/Coops that the DTs facilitate and/or improve strategic farm design, operational management and decision support. Schnebelin et al. [46], also found that all stakeholders interviewed (conventional and organic) agreed on the potential of digitalisation in improving working conditions, practices and risks. Similarly, as pointed out by these authors in their study, our results show that these stakeholders, but especially the POs/PAs/Coops, see DTs as opportunities to advance the transition towards more sustainable production systems. This is in line with Bellon Maurel and Huyghe's

Table 4
Chi-square independence test between the type of stakeholder and the barriers, n = 533.

Barrier	Response	Farmers	Advisors	POs/PAs/Coops	Total	Chi-square	p-value
Limited/non-existent supply of technological alternatives suitable or adapted to the needs of organic and/or agroecological farming systems [BA1]	Yes	88	68	17	173	$x^2 =$	0.037*
	No	220	102	38	360	6.593	
Insufficient capacity of digital tools to provide decision support and/or lack of flexibility to be used for simpler tasks [BA2]	Yes	47	52	12	111	$x^2 =$	<0.001*
	No	261	118	43	422	15.646	
Most digital technologies are designed for industrial-scale production farms and are not suitable for small-scale farmers [BA3]	Yes	132	91	25	248	$x^2 =$	0.080
	No	176	79	30	285	5.043	
High investment costs for the purchase, operation and maintenance of equipment [BA4]	Yes	182	88	40	310	$x^2 =$	0.021*
	No	126	82	15	223	7.763	
Complexity in the use of equipment/software and in the processing and/or analysis of data, which requires specific knowledge and time-expensive training [BA5]	Yes	129	107	31	267	$x^2 =$	<0.001*
	No	179	63	24	266	20.394	
Lack of infrastructure and/or connectivity to guarantee the correct functioning of the equipment [BA6]	Yes	57	50	15	122	$x^2 =$	0.018[a]
	No	251	120	40	411	8.048	
Low level of knowledge and/or skills required for the operation of digital technologies [BA7]	Yes	95	103	38	236	$x^2 =$	<0.001*
	No	213	67	17	297	54.583	
Lack of adequate information and/or advisory services on appropriate digital technologies according to needs [BA8]	Yes	63	75	26	164	$x^2 =$	<0.001[a]
	No	245	95	29	369	36.635	
Lack of financial means, absence of funding for the purchase of equipment and implementation of digital technologies [BA9]	Yes	110	55	23	188	$x^2 =$	0,429
	No	198	115	32	345	1693	

[a] Significant difference (≤0.05).

Table 5
Chi-square independence test between the type of stakeholder and the risks, n = 533.

Risk	Response	Farmers	Advisors	POs/PAs/Coops	Total	Chi-square	p-value
Dependence on companies for operation, maintenance/repair of equipment and/or data management [RI1]	Yes	161	89	32	282	$x^2 =$	0.710
	No	147	81	23	251	0.685	
Loss of farm management autonomy/power and focus on the application of traditional/specific practices of organic or agroecological systems [RI2]	Yes	83	53	20	156	$x^2 =$	0.296
	No	225	117	35	377	2.437	
System security (hacking, loss of privacy, cyber security) [RI3]	Yes	63	44	23	130	$x^2 =$	0.003*
	No	245	126	32	403	11.851	
Appropriation of data/information, intellectual property, and/or the value created [RI4]	Yes	66	56	18	140	$x^2 =$	0.012*
	No	242	114	37	393	8.818	
Stress/anxiety due to increased tasks, knowledge, skills and time for the operation of technologies [RI5]	Yes	108	72	29	209	$x^2 =$	0.028[a]
	No	200	98	26	324	7.141	
Loss of local stakeholder interactions and connection to local traditions and knowledge [RI6]	Yes	66	39	20	125	$x^2 =$	0.054[a]
	No	242	131	35	408	5.835	
Increased energy consumption and/or emissions associated with the production and/or use of digital devices [RI7]	Yes	42	31	10	83	$x^2 =$	0.353
	No	266	139	45	450	2.080	
Exclusion of small farmers due to low investment capacity [RI8]	Yes	144	97	41	282	$x^2 =$	<0.001[a]
	No	164	73	14	251	16.193	
Exclusion of farmers due to low/poor infrastructure (rural broadband connectivity) [RI9]	Yes	93	74	29	196	$x^2 =$	<0.001*
	No	215	96	26	337	15.091	
Exclusion of farmers due to lack of knowledge/skills - [RI10]	Yes	146	97	32	275	$x^2 =$	0.076
	No	162	73	23	258	5.155	

[a] Significant difference (≤0.05).

statement. [25], that DTs are a set of resources that, when mobilised together with other resources, allow sustainable agricultural production objectives to be achieved.

Our results confirm the claims of Schnebelin et al. [46], regarding the important role of advisory services and POs/PAs/Coops as intermediaries in the digitalisation process. In addition to supporting the DTs adoption process, POs/PAs/Coops are key in processes where trust is elemental, such as in the implementation of technologies and data management. The findings of our study show that farm advisors and POs/PAs/Coops, compared to farmers, have a better perception and more agreement on the benefits offered by the DTs. This supports the findings of Schnebelin et al. [46], that perceptions of the use of DTs in production systems vary according to the type of actor. In fact, as Ajena et al. [16], and Cavallo et al. [6,7], demonstrated, these perceptions may even differ among farmers themselves. According to Cardoso et al. [57], the differences between these stakeholders perceptions are related to their individual values and interests.

Our results also lead us to reflect on Roger's theory, mainly on the five characteristics that determine how users respond to new innovations (*relative advantage; compatibility; complexity; trialability; and observability*) [60]. According to Montes de Oca Munguia et al. [58], it is key that stakeholders understand the potential benefits of DTs relative to the existing technology or practice that would be replaced, in order to more accurately measure the relative advantage of an alternative. Cavallo et al. [7], identified that one of the characteristics of farmers who were more willing to adopt innovative tractors were those who were culturally developed and well documented about the benefits of tractor innovations. This leads us to suggest that farm advisors and POs/PAs/Coops are more aware or have a greater knowledge of the benefits and/or advantages of using DTs, thus giving them a more positive perception of their use.

Based on the results, we suggest that farm advisors and POs/PAs/Coops recognise the benefits of DTs because they perceive more *relative advantages* of using DTs. In addition, perhaps these two stakeholders, unlike farmers, have had more possibilities to know firsthand positive results of experiments with DTs in organics or agroecology production systems or are possibly linked to farms that use them (*trialability and observability)*. Therefore, as observed by Mbatha's [60], POs/PAs/Coops, farm advisors, governments and other actors involved and/or interested in digitalisation should be aware of how potential

Table 6
Number of responses by stakeholder according to the level of agreement on drivers of digitalisation, n = 533.

Digitalisation in organic and/or agroecological farming should be promoted through	Stakeholder	Strongly disagree	Moderately disagree	Neutral	Moderately agree	Strongly agree
improved/increased government (financial) support for equipment acquisition, installation, operation and education/training in digitalisation processes [DRI01].	Farmers	24	16	69	86	113
	Advisors	6	19	42	50	53
	POs/PAs/Coops	1	6	11	19	18
participatory design/co-design and implementation (between companies and farmers) of digital technologies adapted to farm needs and capacities, as well as to organic production and/or agroecology approaches [DRI02].	Farmers	16	15	78	112	87
	Advisors	6	11	40	60	53
	POs/PAs/Coops	0	4	9	30	12
the development of policies (regulations, standards) that promote the automation of processes, traceability and in general the use and improved access to digital technologies [DRI03].	Farmers	26	29	109	99	45
	Advisors	15	24	49	52	30
	POs/PAs/Coops	5	9	16	17	8
the development of policies regulating data access/use and interoperability to ensure secure/transparent and appropriate use of information [DRI04].	Farmers	15	26	118	94	55
	Advisors	8	24	47	54	37
	POs/PAs/Coops	1	6	16	24	8
the creation of networks or collaborations between cooperatives, farming communities and advisors to share equipment, costs, facilitate relationships between stakeholders, exchange knowledge and improve training [DRI05].	Farmers	20	11	74	107	96
	Advisors	5	9	43	56	57
	POs/PAs/Coops	0	1	15	22	17
cooperation between the public and private sector for the development of user-friendly, secure, open source technology alternatives and data sharing platforms [DRI06].	Farmers	17	19	84	111	77
	Advisors	7	17	35	63	48
	POs/PAs/Coops	0	3	11	26	15
government interventions to ensure the necessary infrastructure for the operation of technologies (rural broadband connectivity) [DRI07].	Farmers	17	33	88	76	94
	Advisors	7	9	41	52	61
	POs/PAs/Coops	0	0	16	23	16

Farmers Advisors POs/PAs/Coops

adopters will be able to observe the benefits of using the DTs in organic and/or agroecological systems (*observability* is key).

Toffolini & Jeuffroy [8] consider that the digitalisation of agriculture is closely linked to the evolution of on-farm experimentation. This form of experimentation facilitates the production of credible, relevant and legitimate data as it adopts a farmer-centred perspective. Perhaps then, experimentation with DTs in organic and/or agroecological production systems can be a good option to ensure feasibility and make the results visible to farmers. POs/PAs/Coops and advisory services, play a key role in showing the benefits of DTs to farmers and encouraging them to use them in their production systems [56].

As Cavallo [7] mentions, this knowledge about farmers' perceptions towards DTs is important for technology providers seeking new business opportunities, for research centres in defining their innovation programs and for governments that are responsible for agricultural policy regulations.

5.2. RQ2: What are the main reasons why farmers do not use DTs in organic and/or agroecological production systems?

The main reason why the farmers surveyed do not use DTs is because *they are not aware of them*, which confirms the view of Qi et al. [53], who argue that farmers' awareness of an emerging technology influences their decision to adopt it in their production systems. In their studies, Smidt and Jokonya [55], and Osrof et al. [4], also acknowledge that one of the factors affecting digital adoption by farmers is the lack of awareness of the potential of using DTs to improve their farming practices. Results from previous studies show similar trends. For example, the findings of Ajena et al. [16], reflect that the little awareness of autonomous machinery among Swiss organic farmers was the reason for low adoption rates.

Zhou et al. [71], found that the percentage of farmers who are aware about technology is very low, i.e. their knowledge/understanding of the technological complexity is weak. They also demonstrated that there is a strong correlation between technology complexity/theoretical background and technology use behaviour. It highlights that only when there is awareness and understanding of these technologies that a positive attitude of farmers towards their use emerges. Our results emphasise the need for awareness raising and training to encourage the use of DTs among smallholder farmers [16,55].

Rogers' diffusion of innovations theory posits a five-step process that people go through when adopting something new: *awareness, interest, evaluation, testing and adoption* [60]. Our results reinforce this theory by showing that *awareness* about DTs is an essential step for their diffusion and subsequent adoption in organic and/or agroecological systems. This low level of awareness of existing DTs explains why farmers have a lower degree of perception of the *relative advantages* of their use. Forty-two percent of the surveyed farmers who do not make use of digital tools are small-scale farmers. To some extent, this explains why farmers consider that *DTs are not adapted to the scale of their production systems*. The above supports Rogers's statement that innovations must meet the values, experiences and needs of the users (*compatibility* is key) [60]. In this case we show that the incompatibility of the DTs has a significant negative impact on the degree of adoption by farmers. This response on the lack of compatibility could also justify the lower degree of agreement among farmers on the benefits of DTs.

Takagi et al. [45], argue that organic farmers are more likely to adopt a new technology if it is compatible with their farm. Likewise, Osrof et al. [4], point out that farmers with small-scale operations are less likely to adopt smart farming technologies because they may not be suitable for their scale. Wittman et al. [65], highlight in their study that although there are some digital farming technologies designed for use by small-scale farmers, most of them have been marketed mainly for industrial and large-scale farms. Cui and Wang [54] and Giua et al. [42], also point out that farmers with larger cultivated areas are more likely to use or try to adopt DTs. Ajena et al. [16], found that poultry and fruit producers are unable to experience far-reaching automation due to their limiting conditions such as their small size. In addition, the findings of Schnebelin [44], show that a large percentage of organic farmers consider that DTs are not or cannot be adapted to their production systems.

Smidt and Jokonya [55], mention that studies conducted several years ago show that farmers did not adopt agricultural technologies due to the high cost of the technologies. The results of our research also

Table 7
Results of ANOVA analysis. Stakeholders' perceptions of the drivers of digitalisation, n = 533.

Statement: Digitalisation in organic and/or agroecological farming should be promoted through	Farmers	Advisors	POs/PAs/Coops	F -value	df	*p* value
	Mean (SD)	Mean (SD)	Mean (SD)			
improved/increased government (financial) support for equipment acquisition, installation, operation and education/training in digitalisation processes [DRI01]	3.81 (1.211)	3.74 (1.123)	3.85 (1.061)	0.295	2	0.744
participatory design/co-design and implementation (between companies and farmers) of digital technologies adapted to farm needs and capacities, as well as to organic production and/or agroecology approaches [DRI02]	3.78 (1.073)	3.84 (1.051)	3.91 (0.823)	0.488	2	0.614
the development of policies (regulations, standards) that promote the automation of processes, traceability and in general the use and improved access to digital technologies [DRI03]	3.35 (1.104)	3.34 (1.182)	3.25 (1.174)	0.168	2	0.845
the development of policies regulating data access/use and interoperability to ensure secure/transparent and appropriate use of information [DRI04]	3.48 (1.035)	3.52 (1.121)	3.58 (0.937)	0.240	2	0.786
the creation of networks or collaborations between cooperatives, farming communities and advisors to share equipment, costs, facilitate relationships between stakeholders, exchange knowledge and improve training [DRI05]	3.81 (1.116)	3.89 (1.029)	4.00 (0.816)	0.933	2	0.394
cooperation between the public and private sector for the development of user-friendly, secure, open source technology alternatives and data sharing platforms [DRI06]	3.69 (1.083)	3.75 (1.098)	3.96 (0.838)	1.585	2	0.206
government interventions to ensure the necessary infrastructure for the operation of technologies (rural broadband connectivity) [DRI07]	3.64 (1.179)	3.89 (1.085)	4.00 (0.770)	4.197	2	0.016[a]
Country	N/A	N/A	N/A	0.631	2	0.532

[a] Significant difference (≤0.05). SD: Standard deviation.

support the statements of Paget et al. [48], Bellon Maurel and Huyghe [25], and Ajena et al. [16], that *the high cost of digital solutions* makes them inaccessible to users of agroecological systems, especially for small farms [72]. To a certain extent, our results also verify the findings of Bontsa et al. [56], that it is mainly socio-economic factors that affect the perception of DTs and their low adoption by farmers.

5.3. RQ3: What perceptions do farmers, farm advisors and POs/PAs/Coops have about the barriers, risks and drivers of using DTs in organic and/or agroecological production and the differences between the approaches of the 3 stakeholders?

- *Main barriers to the use of digital technologies*

Our results reinforce the findings of Barnes et al. [73], Bellon Maurel and Huyghe. [25], and Osrof et al., [4]. In their studies, they identify the *high investment costs* as one of the main barriers to the adoption of DTs in conventional and agroecological production systems. This is perhaps, as mentioned by these authors, the reason why there is a tendency for larger farms to adopt more agricultural technologies in their production processes. Small farmers often have low incomes that do not allow them to make DTs investments on their own [55]. This suggests that access to advisory services and belonging to a group of farmers such as a cooperative or farmers' association, can increase uptake through collective action such as co-purchase, co-use, and co-maintenance of digital tools among neighboring farmers.

Ajena et al. [16], also found that most of the Swiss organic farmers surveyed consider that investment costs increased by the use of DTs, not only because of the cost of the equipment, but also because of the costs of maintenance and updates. The results of Bontsa et al. [56], and Schnebelin et al. [46], show strong agreement among a high percentage of small-scale farmers and organic organisations that DTs are expensive compared to other agricultural technologies and require higher investment. These authors stress the need to offer low-cost DTs to motivate their adoption by small-scale farmers [54].

Regarding this economic barrier, Smidt and Jokonya [55], state that farmers' perception of the cost-related constraints of the technologies has changed. They emphasise that farmers now recognise the need to adopt these technologies for economic and environmental benefits.

However, the above reflections on the results of previous studies and the findings of this research confirm that the *high cost of DTs* remains the main barrier to their adoption. Even interdisciplinary experts on digitalisation and agriculture of rural areas recognise this as one of the main barriers [63].

Complexity in the use of equipment/software and in the processing and/or analysis of data was the second barriers mostly cited by farmers. Bellon Maurel and Huyghe [25], and Schnebelin et al. [46], also agree that the complexity of new technologies can discourage farmers from using them in their organic and/or agroecological production systems. This perception of complexity also explains the low degree of agreement of farmers on the benefits of using DTs.

The third barrier prioritised by all stakeholders is related to one of the reasons for non-use of DTs by farmers, as mentioned above: the *lack of suitability of DTs*. All stakeholders consider that most DTs are designed for industrial-scale production farms and are not suitable for small-scale farmers. These results are also in line with the hypothesis confirmed by Schnebelin [44] on the strong link between DTs for production (mainly precision farming) and industrialisation. The author points out that these types of DTs favour and contribute to the consolidation of dominant industrial agricultural systems.

These three main barriers identified by all stakeholders surveyed (farmers, farm advisor and POs/PAs/Coops) reinforce even more Rogers' statements that *compatibility* and *complexity* are two key attributes that influence the rate of diffusion and adoption of an innovation. Analysing the reasons given by farmers for the non-adoption of DTs (section 5.2) with the barriers described here confirms that the *high cost of use and the lack of suitability of DTs* are the main issues that need to be overcome to advance the digitalisation of organic and/or agroecological systems.

- *Main risks of the use of digital technologies*

Our findings show that on the perception of risks associated with the use of DTs there are also significant differences among stakeholders. This is in line with the statement by Schnebelin et al. [46], that actors involved in organic and/or agroecological innovation systems have heterogeneous perceptions about the risks associated with the use of DTs. However, all stakeholders surveyed agree that *dependency on companies for the operation, maintenance and/or repair of equipment and the exclusion of farmers due to lack of knowledge and/or skills* are the most relevant risks involved in the digitalisation processes of organic and/or agroecological systems.

According to the opinions of farmers and organic organisations, one of the main risks associated with the use of DTs is the possibility of becoming dependent on them, and on repair services, and therefore losing power and control. They also emphasised the risk associated with the exclusion of farmers due to lack of infrastructure, skills and the cost of equipment in the case of farmers who have economic problems. *Exclusion of farmers due to lack of knowledge and/or skills* was also one of the risks prioritised by the stakeholders surveyed. In keeping with this finding, Ciliberti et al., show how the adoption of robots and sensors can contribute to a digital divide among older, less educated and less skilled producers [74]. Regarding the risk of *exclusion of farmers due to their low investment capacity,* Ferrari et al. [63], also identified that one of the negative impacts of digitalisation of rural areas is the exclusion of small farmers who cannot afford to use these DTs.

On this point, the High Level Panel of Experts on Food Security and Nutrition [26] pointed out that larger farmers may have better access to new technologies through government support and subsidies, which can generate disadvantages for small farmers who may even run the risk of having to abandon farming and lose their land. Therefore, from the agroecology approach and following the statement of Bontsa et al. [56], to reduce the digital divide between large and small farmers their characteristics, circumstances and needs should be considered as relevant criteria for the design and implementation of DTs. Gkisakis and Damianakis [29] emphasise that digitalisation in agriculture is not expected to be one of the main drivers for the agroecological transition, nevertheless, it could potentially be compatible when a combination of user innovation processes and a commons-based peer production model is applied.

- *Main drivers for the use of digital technologies*

Schnebelin et al. [46], highlight the importance of the interconnections between knowledge and technologies. This means that digitalisation demands knowledge and in turn creates opportunities for the creation of new knowledge, so that the integration and collaboration of *stakeholder networks* is key to this objective. Similarly, Bellon Maurel and Huyghe [25], conclude that one of the main levers for the adoption of DTs is the creation of farmer networks to foster knowledge transfer, the development of collective actions, the installation of shared equipment and the exchange of data (e.g. on weather, diseases, practices, and so on). In addition, they stress that interaction between farm machinery designers and farmers in agroecological systems is crucial.

Similar drivers were also stressed in the study by Ajena et al., [16]. The authors suggest that among the fundamental aspects for agroecological innovation are cost-sharing between cooperatives and farming communities, or exchange platforms to facilitate relations with others stakeholders. Also, the involvement of farmers in the design and training of DTs and the creation of financial incentives for the purchase of equipment were found important. Our results also ratify Paget et al. [48], claims regarding the importance of *co-design of DTs between key actors in agroecological systems*. In this way, it would be possible to develop suitable digital solutions, in line with the agroecology paradigm that fit the contexts, needs and economic conditions of farmers [50].

As Hilbeck et al. [69], and Cardoso et al. [57], state, the interests, priorities, needs and experiences of the stakeholders involved in farming systems are different and even more so in the case of organic and/or agroecological systems, which perhaps explains the differences in the perceptions of benefits, risks and barriers of the groups we have analysed. It is essential then, as Schnebelin et al. [46], argue, to consider all these perceptions so that digital development also benefits organic and/or agroecological production systems. However, with regard to the drivers herein, there seems to be more unanimity and clarity from all stakeholders surveyed on the aspects that need to be prioritised in order for the DTs to become allies of organic and/or agroecological systems. This makes sense as these drivers seem to be focused on overcoming the constraints, barriers and/or risks that were prioritised earlier by stakeholders, mainly related to aspects of awareness/knowledge, costs and suitability of DTs.

Some studies show positive results from the implementation of some of the actions/measures identified above as 'drivers', mainly the co-design of DTs and financial support. For example, Hilbeck et al. [69], present a case example of a smartphone application designed under the co-creation approach with agroecological smallholder farmers, to assist them in their record-keeping and research tasks. Kihoma et al. [75], illustrated that an evaluation of this tool (smartphone application) helped farmers to identify the most appropriate agroecological practices in their areas and contributed to increasing agroecological knowledge through information sharing. Similarly, with respect to government support, there is greater evidence in the case of conventional production systems that government subsidies can significantly increase farmers' willingness to adopt DTs, especially in the case of smallholder farmers [54,56]. Bellon Maurel and Huyghe [25], also stress the importance of providing specific public subsidies for the purchase of agricultural machinery for agroecology. Furthermore, Lioutas et al. [12], stress that there is a need to provide incentives for the production of low-cost digital tools compatible with small-scale farming and organic and agroecological production.

Bellon-Maurel et al. [47], point out that DTs and agroecology are disruptive innovations that change the practices of actors and agricultural innovation ecosystems. All of the above barriers, risks and drivers identified, provide insights for the definition of key elements to be taken into account in the design and structuring of a solid and integrative agroecology innovation ecosystem that is enhanced through the effective use of the DTs. Some previous studies could serve as a basis for defining the design elements and principles necessary for the creation of this type of digital innovation ecosystems [76–78].

6. Conclusions and implications

This research provides significant insights to better understand key aspects of the digitalisation of organic and/or agroecological systems.

6.1. Theoretical implications

- This study provides new evidence on the differences in stakeholders' perceptions of the use of DTs. Compared to farmers, POs/PAs/Coops and farm advisors are more aware of and/or more familiar with DTs and therefore agree more with the potential benefits of their use in organic and/or agroecological systems. Regarding barriers and risks, perceptions differ significantly among stakeholders, but there is a higher degree of agreement among farmers, farm advisors and POs/PAs/Coops on strategies that would boost the use of DTs in organic and/or agroecological systems.
- The findings confirm the claims of previous studies that the main barriers to the use of DTs are related to socio-economic and technological aspects. Our results also support the assertion that the main risks are associated with dependence on companies and exclusion of farmers due to their socio-economic and/or cultural characteristics/conditions.
- The results support the findings of previous studies on the contribution of DTs in the implementation of the second principle of agroecology 'Co-creation and sharing of knowledge'.
- Evidence is provided to show that: Stakeholder networks, co-design of DTs and governmental financial support are key aspects to take forward the digitalisation of organic and/or agroecological systems. Likewise, POs/PAs/Coops and farm advisors have a vital role in the processes of disseminating and improving knowledge/skills in the use of DTs in organic and/agroecological systems.
- Our results on the adoption of digital technologies in organic and/or agroecological systems reinforce several statements of Rogers' diffusion of innovations theory on the five characteristics that determine users' response to new innovations and on the steps people take when adopting something new technologies.
  - *Relative advantage*: Knowledge and understanding of the potential benefits of DTs improves the perception of the advantages it can offer and this in turn could improve the degree of adoption.
  - *Compatibility and complexity*: The unsuitability of DTs, the complexity of their use and high cost are aspects that negatively affect adoption rates in organic and/or agroecological systems.
  - *Trialability and observability*: Further testing in real-life conditions and disseminating the results is key to providing farmers or other users of DTs in organic and/or agroecology with evidence of the performance of digital tools in this type of production systems.
  - *Awareness as a first step*: Improving the awareness of potential users of DTs is essential for their dissemination and subsequent adoption in organic and/or agroecological systems.

6.2. Implications and recommendations for managers and policy-makers

This research has relevant implications for all stakeholders involved in organic and/or agroecological production systems (public and private) but especially for technology providers, farmers' organisations and/or cooperatives, research centres, and governments and public administrations. Firstly, the findings provide guidance on key issues related to the characteristics and operation of the DTs and on strategies that could improve their functioning. The results also provide important reflections on aspects to consider and/or strengthen in the programmes, regulatory framework and/or public policies on digitalisation and agroecology. In sum, this research represents key inputs to consider for the creation and/or strengthening of an agroecology innovation ecosystem that is enhanced by incorporating strong digital transformation approaches. In this sense, the following should be considered:

- Overcoming the economic barrier is a priority and requires greater attention to smallholder farmers, who seem to be the most affected. Collaboration between technology providers, researchers, advisors, POs/PAs/Coops and farmers is key to the co-design of new DTs that are adapted to the scale of small farms, support agroecological principles and have purchase, operation and maintenance costs that are accessible to all farmers.
- Collaborative networks between farmers, POs/PAs/Coops and farm advisors, for collective action such as co-purchasing, co-use, and co-maintenance of certain DTs and/or the exchange of knowledge can help to take up technologies by reducing investment costs and maintaining the focus on organic and/or agroecological practices.
- Financial support is fundamental, therefore the challenge for governments and public administrations is to foster the integration and joint work of the stakeholders involved in organic and agroecological production systems, mainly through the creation of support networks and/or the financing of advisory services and/or training, with a special focus on small and medium-scale farmers.
- Multi-stakeholder research programmes and incentive strategies and/or financial support for the new design, adaptation and/or acquisition of DTs should be strengthened.
- It is key to understand that, unlike conventional systems, agroecological systems in particular require, in addition to networking, a more localised or context specific approach. In other words, digitalisation will become a great ally of organic and agroecology farming when it offers solutions adapted to the characteristics, contexts and needs of this complex production system.

7. Limitations and future research

This study aims to present an overview of the main aspects associated with the use of DTs by using a sizable general sample of relevant European countries. It is not a complete analysis at the European level nor a cross-country comparative analysis. Accordingly, the results may not be generalisable to all contexts. In order to provide a more holistic view and more specific information on the incidence of contextual issues, future research could consider a broader analysis by including more European countries and larger sets per country. Furthermore, the analysis of the aspects evaluated in non-European countries would allow the comparison of findings and the identification of key aspects relevant at the global level. Similarly, in order to obtain more generalisable results on this topic, future studies could use random sampling methods to reduce the risk of sampling bias.

Methodological limitations due to the use of static data in this study could be overcome with research that uses longitudinal data and includes quantitative variables to better analyse the interrelationship between variables and improve understanding of associations. Future research could also include other types of stakeholders in the analysis, such as technology providers, other supply chain actors, and researchers, who could provide their knowledge and experience and contribute to building a clearer and more complete picture of the digitalisation of organic and agroecological systems.

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CRediT authorship contribution statement

Cynthia Giagnocavo: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis,Funding acquisition, Conceptualization. **Mónica Duque-Acevedo:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eduardo Terán-Yépez:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Joelle Herforth-Rahmé:** Writing – review & editing, Validation, Conceptualization. **Emeline Defossez:** Writing – review & editing, Visualization, Validation, Conceptualization. **Stefano Carlesi:** Writing – review & editing. **Stephanie Delalieux:** Writing – review & editing. **Vasileios Gkisakis:** Writing – review & editing. **Aliz Márton:** Writing – review & editing. **Diana Molina-Delgado:** Writing – review & editing. **José Carlos Moreno:** Writing – review & editing. **Ana G. Ramirez-Santos:** Writing – review & editing. **Evelyn Reinmuth:** Writing – review & editing. **Gladys Sánchez:** Writing – review & editing. **Iria Soto:** Writing – review & editing. **Tom Van Nieuwenhove:** Writing – review & editing. **Iride Volpi:** Writing – review & editing.

Declaration of competing interest

The 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.techsoc.2024.102763.

Data availability

Data will be made available on request.

References

[1] H.J.P. Marvin, Y. Bouzembrak, H.J. van der Fels-Klerx, C. Kempenaar, R. Veerkamp, A. Chauhan, S. Stroosnijder, J. Top, G. Simsek-Senel, H. Vrolijk, W. J. Knibbe, L. Zhang, R. Boom, B. Tekinerdogan, Digitalisation and Artificial Intelligence for sustainable food systems, Trends Food Sci. Technol. 120 (2022) 344–348, https://doi.org/10.1016/j.tifs.2022.01.020.
[2] I.A. Ibrahim, J.M. Truby, FarmTech: regulating the use of digital technologies in the agricultural sector, Food Energy Secur. 12 (2023), https://doi.org/10.1002/fes3.483.
[3] L.T. Ha, An investigation of digital integration's importance on smart and sustainable agriculture in the European region, Resour. Pol. 86 (2023) 104158, https://doi.org/10.1016/j.resourpol.2023.104158.
[4] H.Y. Osrof, C.L. Tan, G. Angappa, S.F. Yeo, K.H. Tan, Adoption of smart farming technologies in field operations: a systematic review and future research agenda, Technol. Soc. 75 (2023) 102400, https://doi.org/10.1016/j.techsoc.2023.102400.
[5] A.-I. García-Agüero, E. Teran-Yepez, A. Batlles-delaFuente, L.J. Belmonte-Ureña, F. Camacho-Ferre, Intellectual and cognitive structures of the agricultural competitiveness research under climate change and structural transformation, Oeconomia Copernicana 14 (2023) 1175–1209, https://doi.org/10.24136/oc.2023.035.
[6] E. Cavallo, E. Ferrari, M. Coccia, Likely technological trajectories in agricultural tractors by analysing innovative attitudes of farmers, Int. J. Technol. Pol. Manag. 15 (2015) 158, https://doi.org/10.1504/IJTPM.2015.069203.
[7] E. Cavallo, E. Ferrari, L. Bollani, M. Coccia, Attitudes and behaviour of adopters of technological innovations in agricultural tractors: a case study in Italian agricultural system, Agric. Syst. 130 (2014) 44–54, https://doi.org/10.1016/j.agsy.2014.05.012.
[8] Q. Toffolini, M.-H. Jeuffroy, On-farm experimentation practices and associated farmer-researcher relationships: a systematic literature review, Agron. Sustain. Dev. 42 (2022) 114, https://doi.org/10.1007/s13593-022-00845-w.
[9] A. Gabriel, M. Gandorfer, Adoption of digital technologies in agriculture—an inventory in a european small-scale farming region, Precis. Agric. 24 (2023) 68–91, https://doi.org/10.1007/s11119-022-09931-1.
[10] M. Bacco, P. Barsocchi, E. Ferro, A. Gotta, M. Ruggeri, The digitisation of agriculture: a survey of research activities on smart farming, Array 3–4 (2019), https://doi.org/10.1016/j.array.2019.100009.
[11] E. Korneeva, C. Alamanova, A. Orozonova, A. Parmanasova, R. Krayneva, Sustainable development of the agricultural sector of the economy, E3S Web of Conferences 431 (2023) 01030, https://doi.org/10.1051/e3sconf/202343101030.
[12] E.D. Lioutas, C. Charatsari, M. De Rosa, Digitalization of agriculture: a way to solve the food problem or a trolley dilemma? Technol. Soc. 67 (2021) 101744 https://doi.org/10.1016/j.techsoc.2021.101744.
[13] E. Jakku, S. Fielke, A. Fleming, C. Stitzlein, Reflecting on opportunities and challenges regarding implementation of responsible digital agri-technology innovation, Sociol Ruralis 62 (2022) 363–388, https://doi.org/10.1111/soru.12366.
[14] J. Mcfadden, Francesca Casalini, Terry Griffin, Jesús Antón, The Digitalisation of Agriculture: A Literature Review and Emerging Policy Issues, OECDpublishing, 2022.
[15] S. Rolandi, G. Brunori, M. Bacco, I. Scotti, The digitalization of agriculture and rural areas: towards a taxonomy of the impacts, Sustainability 13 (2021) 5172, https://doi.org/10.3390/su13095172.
[16] F. Ajena, Nicola Bossard, Chantal Clément, Angelika Hilbeck, Bernadette Oehen, Jim Thomas, Eugenio Tisselli, Agroecology and digitalisation, Traps and opportunities to transform the food system, Brussels, Belgium. https://www.organicseurope.bio/content/uploads/2022/06/IFOAMEU_Agroecology_Digitalization_2020.pdf?dd, 2020.
[17] J. Zscheischler, R. Brunsch, S. Rogga, R.W. Scholz, Perceived risks and vulnerabilities of employing digitalization and digital data in agriculture – socially robust orientations from a transdisciplinary process, J. Clean. Prod. 358 (2022) 132034, https://doi.org/10.1016/j.jclepro.2022.132034.
[18] A. Lajoie-O'Malley, K. Bronson, S. van der Burg, L. Klerkx, The future(s) of digital agriculture and sustainable food systems: an analysis of high-level policy documents, Ecosyst. Serv. 45 (2020) 101183, https://doi.org/10.1016/j.ecoser.2020.101183.
[19] Véronique Bellon Maurel, Pascal Bonnet, Isabelle Piot-Lepetit, Ludovic Brossard, Pierre P. Labarthe, Digital technology and agroecology: opportunities to explore, challenges to overcome, in: Agri- Culture and Digital Technology: Getting the Most Out of Digital Technology to Contribute to the Transition to Sustainable Agriculture and Food Systems, 2022, pp. 76–97.
[20] Barabanova Yulia, Krzysztofowicz Maciej, Digital transition: long-term implications for EU farmers and rural communities, Luxembourg (2023), https://doi.org/10.2760/093463.
[21] European Commission, Approved 28 CAP, Strategic plans (2023-2027). Summary overview for 27 member states, 2023. https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans_en. (Accessed 9 July 2024).
[22] European Commission, Report From the Commission to the European Parliament and the Council, Summary of CAP Strategic Plans for 2023-2027: joint effort and collective ambition, Brussels (2023), 13 pages.
[23] A. Pronti, M. Coccia, Multicriteria analysis of sustainability performance between agroecological and conventional coffee farms in the east region of minas gerais (Brazil), SSRN Electron. J. (2020), https://doi.org/10.2139/ssrn.3783833.
[24] A. Pronti, M. Coccia, Agroecological and conventional agricultural systems: comparative analysis of coffee farms in Brazil for sustainable development, Int. J. Sustain. Dev. 23 (2020) 223, https://doi.org/10.1504/IJSD.2020.10037660.
[25] V. Bellon Maurel, C. Huyghe, Putting agricultural equipment and digital technologies at the cutting edge of agroecology, OCL 24 (2017) D307, https://doi.org/10.1051/ocl/2017028.
[26] HLPE, Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. www.fao.org/cfs/cfs-hlpe, 2019.
[27] F. Ewert, R. Baatz, R. Finger, Agroecology for a sustainable agriculture and food system: from local solutions to large-scale adoption, Annu Rev Resour Economics 15 (2023) 351–381, https://doi.org/10.1146/annurev-resource-102422-090105.
[28] J.-E. Bergez, E. Audouin, O. Therond (Eds.), Agroecological Transitions: from Theory to Practice in Local Participatory Design, Springer International Publishing, Cham, 2019, https://doi.org/10.1007/978-3-030-01953-2.
[29] V.D. Gkisakis, K. Damianakis, Digital innovations for the agroecological transition: a user innovation and commons-based approach, J Sustainable Organic Agric Syst 70 (2020) 1–4, https://doi.org/10.3220/LBF1595407375000.
[30] R.A. Bahn, A.A.K. Yehya, R. Zurayk, Digitalization for sustainable agri-food systems: potential, status, and risks for the MENA region, Sustainability 13 (2021) 3223, https://doi.org/10.3390/su13063223.
[31] J. MacPherson, A. Voglhuber-Slavinsky, M. Olbrisch, P. Schöbel, E. Dönitz, I. Mouratiadou, K. Helming, Future agricultural systems and the role of digitalization for achieving sustainability goals. A review, Agron. Sustain. Dev. 42 (2022) 70, https://doi.org/10.1007/s13593-022-00792-6.
[32] S. Hackfort, Patterns of inequalities in digital agriculture: a systematic literature review, Sustainability 13 (2021) 12345, https://doi.org/10.3390/su132212345.
[33] L. Prause, Digital agriculture and labor: a few challenges for social sustainability, Sustainability 13 (2021) 5980, https://doi.org/10.3390/su13115980.
[34] A.-R. Abdulai, R. Gibson, E.D.G. Fraser, Beyond transformations: zooming in on agricultural digitalization and the changing social practices of rural farming in Northern Ghana, West Africa, J. Rural Stud. 100 (2023) 103019, https://doi.org/10.1016/j.jrurstud.2023.103019.

[35] Y. Li, F. Herzog, C. Levers, F. Mohr, P.H. Verburg, M. Bürgi, R. Dossche, T. G. Williams, Agricultural technology as a driver of sustainable intensification: insights from the diffusion and focus of patents, Agron. Sustain. Dev. 44 (2024) 14, https://doi.org/10.1007/s13593-024-00949-5.

[36] A. Wezel, B.G. Herren, R.B. Kerr, E. Barrios, A.L.R. Gonçalves, F. Sinclair, Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review, Agron. Sustain. Dev. 40 (2020) 40, https://doi.org/10.1007/s13593-020-00646-z.

[37] A. Cooper, A. Burgess, B. Raskin, C. Scott, J. Elliot, J. Gill, J. Hughes, J. Fernandez, K. Burt, L. Halsey, M. Smith, R. Osborn, S. Masero, T. Macmillan, W. Kendall, AgroEcoTech: How Can Technology Accelerate a Transition to Agroecology?, 2021. Gloucestershire, UK,.

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

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

[40] E. Anastasiou, S. Fountas, M. Voulgaraki, V. Psiroukis, M. Koutsiaras, O. Kriezi, E. Lazarou, A. Vatsanidou, L. Fu, F. Di Bartolo, J. Barreiro-Hurle, M. Gómez-Barbero, Precision farming technologies for crop protection: a meta-analysis, Smart Agricultural Technology 5 (2023) 100323, https://doi.org/10.1016/j.atech.2023.100323.

[41] A.P. Barnes, I. Soto, V. Eory, B. Beck, A.T. Balafoutis, B. Sanchez, J. Vangeyte, S. Fountas, T. van der Wal, M. Gómez-Barbero, Influencing incentives for precision agricultural technologies within European arable farming systems, Environ Sci Policy 93 (2019) 66–74, https://doi.org/10.1016/j.envsci.2018.12.014.

[42] C. Giua, V.C. Materia, L. Camanzi, Smart farming technologies adoption: which factors play a role in the digital transition? Technol. Soc. 68 (2022) 101869 https://doi.org/10.1016/j.techsoc.2022.101869.

[43] European Commission, Mapping and analysis of CAP strategic plans assessment of joint efforts for 2023-2027, Brussels, https://doi.org/10.2762/71556, 2023.

[44] É. Schnebelin, Linking the diversity of ecologisation models to farmers' digital use profiles, Ecol. Econ. 196 (2022) 107422, https://doi.org/10.1016/j.ecolecon.2022.107422.

[45] C. Takagi, S.H. Purnomo, M.-K. Kim, Adopting smart agriculture among organic farmers in taiwan, Asian J. Technol. Innovat. 29 (2021) 180–195, https://doi.org/10.1080/19761597.2020.1797514.

[46] É. Schnebelin, P. Labarthe, J.-M. Touzard, How digitalisation interacts with ecologisation? Perspectives from actors of the French Agricultural Innovation System, J. Rural Stud. 86 (2021) 599–610, https://doi.org/10.1016/j.jrurstud.2021.07.023.

[47] V. Bellon-Maurel, E. Lutton, P. Bisquert, L. Brossard, S. Chambaron-Ginhac, P. Labarthe, P. Lagacherie, F. Martignac, J. Molenat, N. Parisey, S. Picault, I. Piot-Lepetit, I. Veissier, Digital revolution for the agroecological transition of food systems: a responsible research and innovation perspective, Agric. Syst. 203 (2022) 103524, https://doi.org/10.1016/j.agsy.2022.103524.

[48] N. Paget, I. Nacambo, S. Fournier, I. Moumouni-Moussa, Traque des innovations numériques au service de la transition agroécologique au Bénin, Cah. Agric. 31 (2022) 13, https://doi.org/10.1051/cagri/2022009.

[49] J.C. Moreno, M. Berenguel, J.G. Donaire, F. Rodríguez, J.A. Sánchez-Molina, J. L. Guzmán, C.L. Giagnocavo, A pending task for the digitalisation of agriculture: a general framework for technologies classification in agriculture, Agric. Syst. 213 (2024) 103794, https://doi.org/10.1016/j.agsy.2023.103794.

[50] L. Ditzler, C. Driessen, Automating agroecology: how to design a farming robot without a monocultural mindset? J. Agric. Environ. Ethics 35 (2022) 2, https://doi.org/10.1007/s10806-021-09876-x.

[51] J. Tassin, Les plateformes paysannes de e-commerce en Chine, Réseaux N° 244 (2024) 151–187, https://doi.org/10.3917/res.244.0151.

[52] C. Gascuel-Odoux, F. Lescourret, B. Dedieu, C. Detang-Dessendre, P. Faverdin, L. Hazard, I. Litrico-Chiarelli, S. Petit, L. Roques, X. Reboud, M. Tixier-Boichard, H. de Vries, T. Caquet, A research agenda for scaling up agroecology in European countries, Agron. Sustain. Dev. 42 (2022) 53, https://doi.org/10.1007/s13593-022-00786-4.

[53] X. Qi, F. Liang, W. Yuan, T. Zhang, J. Li, Factors influencing farmers' adoption of eco-friendly fertilization technology in grain production: an integrated spatial–econometric analysis in China, J. Clean. Prod. 310 (2021) 127536, https://doi.org/10.1016/j.jclepro.2021.127536.

[54] L. Cui, W. Wang, Factors affecting the adoption of digital technology by farmers in China: a systematic literature review, Sustainability 15 (2023) 14824, https://doi.org/10.3390/su152014824.

[55] H.J. Smidt, O. Jokonya, Factors affecting digital technology adoption by small-scale farmers in agriculture value chains (AVCs) in South Africa, Inf. Technol. Dev. 28 (2022) 558–584, https://doi.org/10.1080/02681102.2021.1975256.

[56] N.V. Bontsa, A. Mushunje, S. Ngarava, Factors influencing the perceptions of smallholder farmers towards adoption of digital technologies in eastern cape province, South Africa, Agriculture 13 (2023) 1471, https://doi.org/10.3390/agriculture13081471.

[57] C.S. Cardoso, MarinaA.G. von Keyserlingk, M.J. Hötzel, Views of dairy farmers, agricultural advisors, and lay citizens on the ideal dairy farm, J. Dairy Sci. 102 (2019) 1811–1821, https://doi.org/10.3168/jds.2018-14688.

[58] O. Montes de Oca Munguia, D.J. Pannell, R. Llewellyn, Understanding the adoption of innovations in agriculture: a review of selected conceptual models, Agronomy 11 (2021) 139, https://doi.org/10.3390/agronomy11010139.

[59] V.S. Parmar, Design approach to increase adoption of ICT interventions, in: Proceedings of the 10th International Conference on Theory and Practice of Electronic Governance, ACM, New York, NY, USA, 2017, pp. 272–275, https://doi.org/10.1145/3047273.3047371.

[60] B. Mbatha, Diffusion of innovations: how adoption of new technology spreads in society, in: Dennis Ocholla, Omwoyo Bosire Onyancha, Aderonke Olaitan Adesina (Eds.), Information, Knowledge, and Technology for Teaching and Research in Africa, 2024, pp. 1–18, https://doi.org/10.1007/978-3-031-60267-2_1.

[61] T. Lynch, S. Gregor, D. Midmore, Intelligent support systems in agriculture: how can we do better? Aust. J. Exp. Agric. 40 (2000) 609, https://doi.org/10.1071/EA99082.

[62] D.E. Dewi, P.N.A. Cahyani, L.R. Megawati, Increasing adoption of the internet of things in Indonesian agriculture based on a review of everett Rogers' diffusion theory of innovation, 303–309, https://doi.org/10.2991/978-94-6463-144-9_29, 2023.

[63] A. Ferrari, M. Bacco, K. Gaber, A. Jedlitschka, S. Hess, J. Kaipainen, P. Koltsida, E. Toli, G. Brunori, Drivers, barriers and impacts of digitalisation in rural areas from the viewpoint of experts, Inf Softw Technol 145 (2022) 106816, https://doi.org/10.1016/j.infsof.2021.106816.

[64] M. Sharma, S. Joshi, K. Govindan, Overcoming barriers to implement digital technologies to achieve sustainable production and consumption in the food sector: a circular economy perspective, Sustain. Prod. Consum. 39 (2023) 203–215, https://doi.org/10.1016/j.spc.2023.04.002.

[65] H. Wittman, D. James, Z. Mehrabi, Advancing food sovereignty through farmer-driven digital agroecology, International Journal of Agriculture and Natural Resources 47 (2020) 235–248, https://doi.org/10.7764/ijanr.v47i3.2299.

[66] Y. Shaengchart, T. Kraiwanit, S. Butcharoen, Factors influencing the effects of the Starlink Satellite Project on the internet service provider market in Thailand, Technol. Soc. 74 (2023) 102279, https://doi.org/10.1016/j.techsoc.2023.102279.

[67] D. Askerbekov, J.A. Garza-Reyes, R. Roy Ghatak, R. Joshi, J. Kandasamy, D. Luiz de Mattos Nascimento, Embracing drones and the Internet of drones systems in manufacturing – an exploration of obstacles, Technol. Soc. 78 (2024) 102648, https://doi.org/10.1016/j.techsoc.2024.102648.

[68] M. Duque-Acevedo, L.J. Belmonte-Ureña, E. Terán-Yépez, F. Camacho-Ferre, Sustainability and circularity in fruit and vegetable production. Perceptions and practices of reduction and valorization of agricultural waste biomass in south-eastern Spain, J Environ Manage 316 (2022) 115270, https://doi.org/10.1016/j.jenvman.2022.115270.

[69] A. Hilbeck, H. McCarrick, E. Tisselli, J. Pohl, D. Kleine, Aligning digitalization with agroecological principles to support a transformation agenda. https://doi.org/10.14279/depositonce-16472, 2022.

[70] K. Rijswijk, L. Klerkx, J.A. Turner, Digitalisation in the New Zealand Agricultural Knowledge and Innovation System: initial understandings and emerging organisational responses to digital agriculture, NJAS - Wageningen J. Life Sci. (2019) 90–91, https://doi.org/10.1016/j.njas.2019.100313.

[71] Y. Zhou, H. Guo, Q. Wang, W. Shi, Study on influencing factors of information technology adoption behavior of Grape growers in the digital economy, in: 2022 International Conference on Cloud Computing, Big Data and Internet of Things (3CBIT), IEEE, 2022, pp. 277–280, https://doi.org/10.1109/3CBIT57391.2022.00064.

[72] J.A.J. Mendes, N.G.P. Carvalho, M.N. Mourarias, C.B. Careta, Vânia Gomes Zuin, M.C. Gerolamo, Dimensions of digital transformation in the context of modern agriculture, Sustain. Prod. Consum. 34 (2022) 613–637, https://doi.org/10.1016/j.spc.2022.09.027.

[73] A.P. Barnes, I. Soto, V. Eory, B. Beck, A. Balafoutis, B. Sánchez, J. Vangeyte, S. Fountas, T. van der Wal, M. Gómez-Barbero, Exploring the adoption of precision agricultural technologies: a cross regional study of EU farmers, Land Use Pol. 80 (2019) 163–174, https://doi.org/10.1016/j.landusepol.2018.10.004.

[74] S. Ciliberti, A. Frascarelli, B. Polenzani, G. Brunori, G. Martino, Digitalisation strategies in the agri-food system: the case of PDO Parmigiano Reggiano, Agric. Syst. 218 (2024) 103996, https://doi.org/10.1016/j.agsy.2024.103996.

[75] L.L. Kihoma, A.J. Churi, C.A. Sanga, E. Tisselli, Examining the continued intention of using the Ugunduzi app in farmer-led research of agro-ecological practices among smallholder farmers in selected areas, Tanzania, African Journal of Science, Technology, Innovation and Development 15 (2023) 720–730, https://doi.org/10.1080/20421338.2023.2180176.

[76] Mario Coccia, Digital Pathology ecosystem: basic elements to revolutionize the diagnosis and monitoring of diseases in health sector, in: Nezameddin Faghih (Ed.), Digital Entrepreneurship. Exploring Alertness, Orientation, and Innovation in the Digital Economy, Springer Nature Switzerland, Cham, 2024, https://doi.org/10.1007/978-3-031-58359-9.

[77] S. Wolfert, C. Verdouw, L. van Wassenaer, W. Dolfsma, L. Klerkx, Digital innovation ecosystems in agri-food: design principles and organizational framework, Agric. Syst. 204 (2023) 103558, https://doi.org/10.1016/j.agsy.2022.103558.

[78] M. Coccia, S. Ghazinoori, S. Roshani, Evolutionary pathways of ecosystem literature in organization and management studies. https://doi.org/10.21203/rs.3.rs-2499460/v1, 2023.

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