Discover Sustainability

RESEARCH Open Access

Exploring the impact of digitalization on sustainability challenges in German fruit production from the perspectives of stakeholders

Kirsten Gaber[1,2*], Christine Rösch[1] and Claudia Bieling[2]

*Correspondence:
Kirsten Gaber
Kirsten.gaber@kit.edu
[1]Institute for Technology Assessment and Systems Analysis, Karlsruhe Institute of Technology, P.O. Box 3640, 76021 Karlsruhe, Germany
[2]Institute of Social Sciences in Agriculture, Societal Transition and Agriculture (430B), University of Hohenheim, Stuttgart, Germany

Abstract
Unique challenges exist in the fruit cultivation sector and, if not considered in the development and application of technologies, this sector is at risk of being left behind in the ongoing digital transformation of agriculture. While understanding perspectives of stakeholders is critical for technology acceptance, their knowledge and views are underrepresented in analyses on the impact of digitalization on fruit production. This research works to fill this knowledge gap by qualitatively analyzing semi-structured interviews on the impact of digitalization on sustainability challenges in fruit production with 34 stakeholders along the fruit value chain in the case study region of Lake Constance, Germany. Societal acceptance and understanding of fruit cultivation practices, restricted plant protection product use, labour availability, and biodiversity support were the main reported environmental and socio-economic challenges. Nearly all stakeholders (94%) were hopeful that digital technologies could effectively address environmental challenges in fruit production, particularly through increased efficiency, while greater uncertainties were reported for the socio-economic challenges. Perceptions of digitalization's chances and challenges varied among individuals, fruit production systems, and farm sizes. Authors provide recommendations, including targeted support for small-scale fruit farmers and suggestions for future research activities, and emphasize the importance of factual knowledge dissemination on digitalization in fruit farming to support informed adoption choices for intended users. The results of this study offer critical viewpoints on the current challenges in fruit production and the potential for digitalization to increase sustainability in this sector.

Keywords Digital technologies, Biodiversity, Agricultural inputs, Labour availability, Societal acceptance, Lake Constance

1 Introduction

Climate change and weather extremes pose substantial challenges for fruit farmers, disrupting horticultural processes, altering growing conditions, and amplifying pest and disease pressures [1–3]. Early blossoming exposes crops to frost, while dry spring and summer periods reduce water availability, leading to potential yield losses. Societal demands and consumer expectations, emphasizing nature protection and specific concerns, e.g. about bee survival, further complicate the fruit farming landscape. Simultaneously, consumers expect consistently high quality and affordably priced fruits, creating a dual pressure on fruit farming. In response to environmental concerns, the use of pesticides in fruit production is under scrutiny, with the European Commission aiming for a 50% reduction in chemical pesticide use by 2030 [4, 5]. Of all crops grown in Germany, apple cultivation is the most pesticide-intensive, due to the low genetic diversity and susceptibility to fungal infections, as well as the societal demands for visually flawless products [6]. The potential for technologies in digitalized agriculture (and its sub-forms, including precision farming and smart farming) to contribute to increased sustainability in agriculture has been demonstrated [7–12]. Digitalized agriculture is inspired by the paradigm of Industry 4.0 and includes a wide range of technologies and technological advances, from artificial intelligence (AI) and the Internet of Things (IoT) to robots and drones [13]. These technologies hold promises such as a 90% reduction in pesticide use, but simultaneously pose the risk of a rebound-effect, such as increased energy usage through new technologies or the expansion of intensive agricultural production [6]. The history of technology has shown that next to the intended positive effects, unintended negative side-effects, so-called "unseens", occur [14–16]. Digital technologies' social sustainability impacts receive less attention than their environmental counterparts [17, 18]. A number of ethical issues regarding digital agriculture exist, including invasion of farmers' privacy and lack of accountability for problems resulting from AI tool use [19–21] and potential rural unemployment and amplified inequalities through the use of agricultural robotics (e.g. [22]). The cooperation of humans and robots for the execution of agri-food tasks may be the best strategy to realizing societal goals and responding to modern challenges [23]. Public acceptance of agricultural sustainability may be improved if the positive impact of using digital technologies in food production, such as the reduction of inputs during weed control measures through precise herbicide spraying techniques, is communicated to the public [24].

As digitalization progresses within agricultural sectors, and as urgent environmental and social issues threaten the sustainability of agricultural production, it is critical to understand which positive and negative effects are anticipated. Qualitative research involving stakeholders provides valuable insights on the interests, needs, expectations, and adoption tendencies of the intended users for digital technologies to influence the sustainability of agricultural systems, which can enable a user-oriented digital transformation. Existing studies indicate varying interest levels among farmers towards digitalization, with larger farms showing a greater inclination to adopt these technologies due to their capital-intensive nature [25]. Typically, farmers embrace most agricultural innovations [26]. Reviews on farmer adoption tendencies for agricultural innovations, precision agriculture technologies (e.g. [26–28]) and field robotics and Unmanned Aerial Vehicles (UAVs) (e.g. [29]) highlight commonalities across agricultural sectors and regions, such as the factors of age, farm size, and education level.

In the case of fruit production, development of digital innovations is progressing. Autonomous robots have been developed for fruit harvesting (e.g. [30, 31]) and farm management tasks can be conducted by UAVs and robots (e.g. [32–35]). Efficiency in apple production can be enhanced through smart sensors and modelling (e.g. [36–38]). Artificial intelligence models are additionally altering the fruit production landscape. Deep learning approaches for fruit sizing (e.g. [39]), detection and segmentation (e.g. [40]) have been developed to aid the particularly labour-intensive activity of harvesting fruit, as well as for early recognition of fruit disease like pear and apple scab [41]. Machine learning as a digital assistant for farmers has been developed to achieve a sustainable and competitive fruit and wine production through, for instance, disease prognosis, early pest detection, and suggestions of optimal dates for harvest [42]. Smart traceability systems along the value chain using Industry 4.0 technologies such as blockchain and AI, a concept referred to as Food Traceability 4.0, offer the potential for enhanced traceability, improved safety and product quality, and decreased food waste in the fruit and vegetable sector [43].

Despite the rapid progression of digital technology development, adoption rates in fruit farming lag behind those of arable farming [44]. The reasoning behind this lag is currently unclear, although research specific to the German fruit sector suggests that misguided marketing and inadequate information on digitalization may be the cause [45]. Studies on stakeholder perceptions of digital tools in other agricultural sectors in Germany offer largely positive results with some exceptions. For instance, a representative sample of the German public were positively inclined towards autonomous crop robots, particularly for the goal of reduced agrochemical use in plant production [46]. While Pfeiffer et al. [17] also found overall positive attitudes among the German population towards digitalisation in agriculture, great differentiations in attitudes among German citizens were found in the study by Langer and Kühl [47] on robots in dairy farming. German farmers as critical stakeholders in the digital transformation tend to have a neutral to positive view on field robots (e.g. [48, 49]). Another representative survey of German citizens by Wilmes et al. [50] determined digital technologies to have a negative effect on willingness to buy food products produced by farms in Germany; however, this effect turned positive when environmental arguments in favour of digital technologies were introduced. Still, stakeholder perspectives on the benefits and drawbacks of digital technologies, particularly regarding sustainability, remain largely unexplored. Within the limited research on stakeholder perspectives on digitalization in relation to environmental and social sustainability, for instance towards agroforestry [51], water resources in mediteranean agriculture [52], or large scale German arable farming [53], studies representing stakeholder perspectives and sustainability in fruit cultivation do not yet exist.

The research conducted for this study contributes to filling this literature gap and was completed within the same research framework as articles [45, 54]. The results of this study build on the previous findings, providing a comprehensive understanding of stakeholder perspectives on how digital technologies might contribute towards sustainability in German fruit production. Specifically, this study adds to the existing scientific discourse on stakeholder perceptions of digital tools in German agriculture by first examining the socio-economic and environmental challenges in the sector of fruit production, considering factors such as farm size and production systems. The research then investigates whether digital technologies can effectively address these challenges and contribute to enhanced sustainability and acceptability from the perspectives of farmers and other fruit value chain stakeholders. The study encompasses both small and large-scale farms[1] and includes organic and Integrated Production (IP) systems[2] in its analysis.

2 Methods and materials

This study employs a case-study methodology, concentrating on the Lake Constance region in Baden-Württemberg, which is recognized as the second-largest apple-growing region in Germany. Using a qualitative, open, and empirical approach, the research delves into stakeholders' expectations, concerns, and beliefs regarding digitalized fruit production and sustainability. The methodological framework included stakeholder identification, a semi-structured questionnaire, and 34 stakeholder interviews. Following data collection, the information was transcribed, translated, and comprehensively analysed using MAXQDA 2020 software. This meticulous process aimed to ensure a nuanced understanding of the diverse perspectives within the fruit farming community of the Lake Constance region, offering insights into the intricate dynamics of adopting digital technologies in fruit cultivation.

2.1 Description of the case study region

The Lake Constance region, encompassing the counties of Konstanz, Bodensee-Kreis, Ravensburg, and Lindau, stands as a vital hub for fruit farming, boasting over 1,000 fruit farms [59]. Benefiting from mild temperatures and an annual precipitation of 900 mm, the region holds particular significance as the primary fruit-growing zone in Baden-Württemberg, covering more than half of the cultivated tree fruit area at over 9,000 hectares out of a total of 17,640 hectares [60]. Fruit farms in the Lake Constance region are traditionally small-scale and have an average size of 8,8 hectares [61]. Small-scale farms are widely acknowledged for their pivotal role in promoting greater landscape diversity and making significant contributions to biodiversity conservation, as well as environmental and socio-economic benefits (e.g. [62, 63]). Within Baden-Württemberg, the approximately 3,560 orchards have an average size of five hectares. Nearly 400 of these orchards adhere to organic cultivation practices, collectively managing an area of 3,260 hectares. A particularly noteworthy trend is the substantial 14% increase in the number of organic fruit growers from 2017 to 2022, standing out amidst the overall decrease in fruit farms by 11% over this same time period [60].

2.1.1 Environmental context

One of the key challenges facing fruit production in the study region is the impact of climate change and weather extremes, which include wet periods leading to heightened mildew pressures, adversely affecting fruit production [64]. The study region's proximity to the nation's largest drinking water reservoir, the Lake of Constance, necessitates stringent regulations governing the application of agricultural inputs, such as plant

[1] In Germany, where large farms are considered to be over 100 ha, the average farm size is about 65 ha [55]. Nearly half of all German fruit farms are categorized as small, each covering less than 20 hectares [56].

[2] German horticulture is comprised of two production systems: integrated production (IP) and organic. Current "conventional" fruit production is carried out according to IP guidelines. Therefore, IP and organic fruit farming encompass the conventional/organic binary. The choice of PPP and the holistic nature of the production system differentiate the two systems [57, 58]

protection products and fertilizers, to mitigate the risks of polluting the drinking water through runoff or leaching into the reservoir [65]. This underscores the need to explore different options for reducing chemical inputs as a proactive response to these challenges, including technological changes in farm management.

2.1.2 Socio-economic context

Fruit production in the Lake Constance region is deeply rooted in tradition and is characterized by small- to medium-sized family farms, who take pride in their family farm structures and long tradition of fruit growing. Recent political strategies and societal pressures have increased tensions in the area. Regional actors in the fruit value chain, including farmers, are particularly active in the community regarding current political pressures and social movements related to agriculture. Recent examples include their reactions to the "Save the Bees" referendum by the state of Baden-Württemberg in 2019 and 2020 [66] and silent protests as part of the continued European farmer protests at the internationally-recognized fruit production expo "Fruchtwelt Bodensee" [67]. On a national scale, civil activism to disrupt systems in Germany is well-established, and conflicting interests in current themes has led to protests that gain international attention, a current example being the ongoing farmers protests that began at the end of 2023 (see [68]). Criticism towards agriculture in Germany is a well-known phenomenon (e.g. [17, 69]). At the same time, German citizens place high value on regional products and tend to choose these for environmental purposes [70].

2.2 Stakeholder selection and qualitative interviews

This study employed a qualitative and explorative research design based on interviews. Stakeholders were strategically selected following a purposive sampling approach [71], guided by two key criteria:

1. Stakeholders identified as either intended users or developers of digital technologies.
2. Stakeholders engaged in the fruit value chain, spanning farm-level participants, marketing and wholesale representatives, and those viewing the industry from a broader technology or research perspective.

Authors generated a list of stakeholders who met these criteria with the use of an internet search engine, which included websites of technology companies, research groups, and farmer associations. Additionally, initial interviews were conducted with experts in regional farming and digital farming technologies, serving as a foundation to refine stakeholder groups and identify additional relevant stakeholders. This iterative process mirrored elements of snowball sampling [72]. These experts also played a crucial role in shaping the interview guideline, as outlined in the Appendix. The finalized list of stakeholders was categorized into six distinct groups (Table 1), forming the basis for in-depth qualitative exploration in this study.

Utilizing the power-interest matrix developed by Johnson et al. [73] and adapted from Mendelow [74], stakeholder groups were evaluated according to their level of interest and power in influencing the sustainability of digitalization in fruit production (Fig. 1). Initially, a target of five to six interviews was set for each stakeholder group. However, recognizing farmers as the primary audience for digital technologies and acknowledging

Table 1 Stakeholder group categories and their descriptions, adapted from [45, 54]

Fruit farmers	Farmers, predominantly engaged in fruit production on their agricultural land, employing either IP or organic principles
Technology developers	Individuals working as employees or leaders in agricultural machinery or technology companies, ranging from start-ups to international corporations
Cultivation consultants	Individuals, whether privately or publicly employed, advise farmers on on-farm activities and/or the purchase and application of agricultural inputs, such as Plant Protection Products (PPPs) and fertilisers
Researchers	Local or national-based researchers affiliated with public or private institutions possessing knowledge of fruit cultivation, fruit value chain conditions, and/or agricultural technologies
Nature, agriculture and consumer associations (NAC associations)	Individuals who are members, employees, or leaders of public or private organisations dedicated to nature preservation, agriculture, or consumer interests. These individuals play a role in representing the interests of groups or communities related to these sectors
Fruit wholesalers or marketers	Individuals serving as employees or leaders within fruit wholesale organisations or companies or individuals in similar roles within farm shops that offer local delivery services

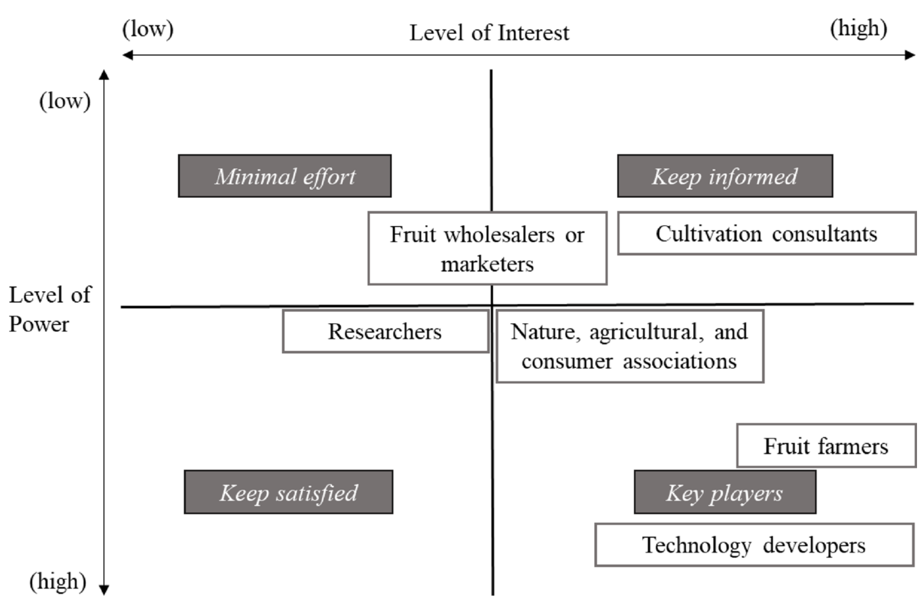

Fig. 1 In the Power-Interest matrix, as found in [54] and based on Johnson et al. [73] and adapted from Mendelow [74], stakeholder groups are assessed according to their level of interest and power concerning digitalization in fruit production. This matrix helps identify the importance and influence of each stakeholder group in shaping the outcomes and sustainability of digitalization initiatives in the context of fruit farming

their pivotal role, this group was given a higher target of eight interviews evenly distributed between organic and IP farmers.

Among the six identified stakeholder groups, two were found to be underrepresented in the region and challenging to engage: (1) technology developers and (2) nature, agricultural, and consumer groups. Recognizing the importance of these groups, proactive efforts were made to actively pursue and include them by expanding the geographical search area to ensure their participation. This approach successfully met the targeted number of interviews for each stakeholder group. While proximity to the Lake Constance region was prioritized, it was not a strict requirement for all stakeholders, especially considering the national and international scales at which digital technologies are developed. Certain groups, such as farmers and consultants, were expected to have regional expertise, allowing for an expanded stakeholder radius.

Between October 2020 and April 2021, 34 stakeholders from six stakeholder groups participated in interviews. 15 interviews were conducted digitally using Zoom-online software, while 19 were conducted in-person. Each interview had an approximate duration of one hour and were one-on-one interviews between the stakeholder and the corresponding author of this article. Characteristics of the interviewed stakeholders (Fig. 2) reveal commonalities. Most stakeholders were male, falling within the age range of 41 to 60. Their professional affiliations were primarily in the private sector and they resided in predominantly rural or mixed regions. All stakeholders had completed post-secondary training or education, contributing to a diverse and knowledgeable participant pool.

A number of limitations should be considered during the interpretation of the results. The sample size of 34 stakeholders is small and cannot be considered representative of the fruit growing sector; however, the stakeholder selection methodology exhausted the limited number of relevant and interested stakeholders in the case study region. Due to financing project constraints, it was not possible to increase the sample size to reflect a more diverse sample. In the same way, it was additionally not possible to have enabled a more balanced gender representation among the stakeholders, as the German agricultural sector is largely male-dominated [75]. Although the authors made equal efforts to interview both IP and organic farmers, ultimately, more organic farmers were interested in participating than IP farmers, resulting in five organic and three IP farmers. Finally, the authors recognize that while the data could be considered outdated, the stakeholder interviews in this study provided a valuable snapshot into the perspectives in the region and sector at a critical moment in the ongoing digital transformation. These findings can be used as a basis for comparison with future studies that utilise similar methods to observe changes over time.

The interview guideline (Appendix) was formulated as part of an interview series for the DESIRA project (Digitization: Economic and Social Impacts in Rural Areas [76]) and therefore covers more topics than are relevant for the present study. Only responses from questions 18, 19, 21, and 22 were considered relevant for this study. The guideline

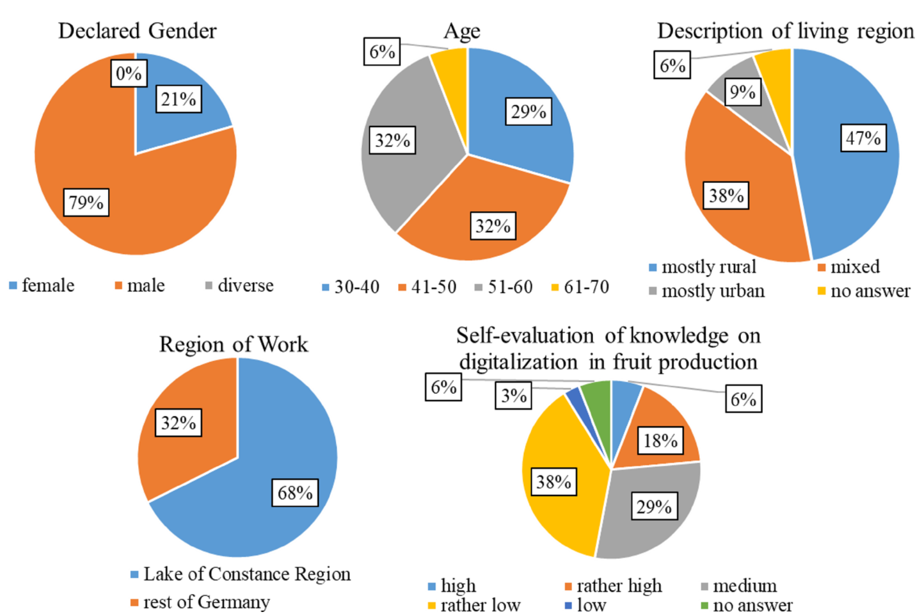

Fig. 2 The characteristics of the six stakeholder groups (n = 34 participants) engaged in the interviews within the study region or online, adapted from [54]

consisted of 20 questions, with an expanded set of 27 questions tailored for farmers. Questions 1–17 were demographic-related for analysis purposes and thus formulated to be closed in order to simplify this straightforward phase of the interview. Questions 18–26 were the content-focused questions intended to answer the research questions. These were formulated as open-ended questions to encourage discussion by the participant. Question 27 was a closed question and was included for the purposes of the DESIRA project. The additional seven questions for farmers focused on eliciting information about farm characteristics, encompassing details such as farm size and the types of crops cultivated. The interview guideline underwent a refinement process and finalization, benefiting from feedback obtained through two expert interviews conducted in early 2020. These experts, both of whom are established researchers on digitalisation in German agriculture, were selected based on their prominence in the relevant scientific literature and involvement in research projects on digitalisation in German agricultural contexts. This iterative approach ensured that the questions were comprehensive and effectively aligned with the study's objectives.

Interview questions were not provided to participants in advance, ensuring a consistent and spontaneous response pattern. The participants viewed the questions during the interview- either via the shared screen during the online interview format or with a provided question set during the in-person interviews- to support comprehension of the interview questions. The interviewer intentionally omitted a definition of the term „digitalization ". As the goal of these interview questions was to gather perspectives and inductively code and categorize the responses ex-post, this omission allowed interviewees to respond from the basis of their own understanding of digitalisation in fruit cultivation without strictly framing the discussion around the researcher's perspective. Consequently, the interview questions in this study reflect the interviewees' interpretations of digitalization. Further information on these stakeholders' perspectives on the meaning of digitalization in fruit cultivation can be found in previously published work through the same interview series in the DESIRA project by Gaber et al. [45]. The interview process adhered to the principle of free, prior and informed consent from all participants. The interviews were initiated by exploring the primary environmental and socio-economic challenges faced by fruit growers in the Lake Constance region, focusing on potential distinctions between IP and organic fruit growing, as well as variations based on farm size. Subsequently, stakeholders' perspectives on the digitalization of fruit production were examined, exploring the potential of digitalization to address environmental, socio-economic, and social challenges.

2.3 Interview result analysis

The recorded interview audio files underwent a thorough anonymization process and were transcribed by a third-party transcription company. The ensuing analysis employed Qualitative Content Analysis [77] with MaxQDA 2020 software. Transcripts were systematically organized according to stakeholder groups. In the analytical phase, interview responses were coded using a two-phase inductive coding method proposed by Saldaña [78]. In the first coding phase, one-word or short statement codes that derived directly from the participants' own spoken language (in-vivo) were identified, preserving the authenticity of the original responses. In the second phase, pattern coding was used to identify major themes from the data: the in-vivo codes were re-coded using descriptive

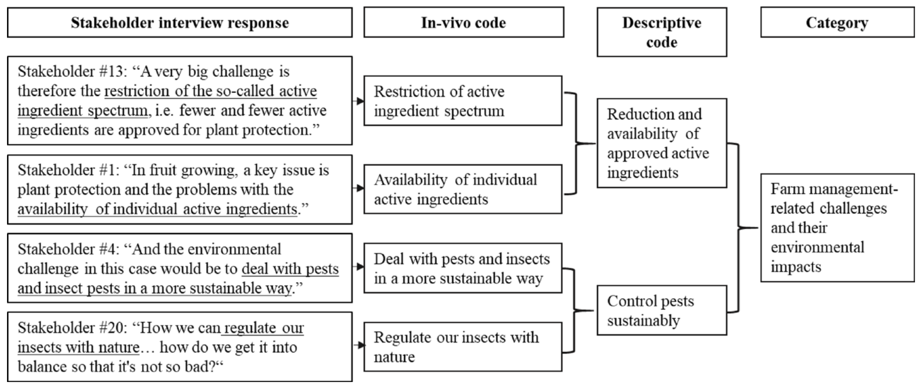

Fig. 3 Example of coding process of interview excerpts (translated) regarding environmental challenges in fruit production

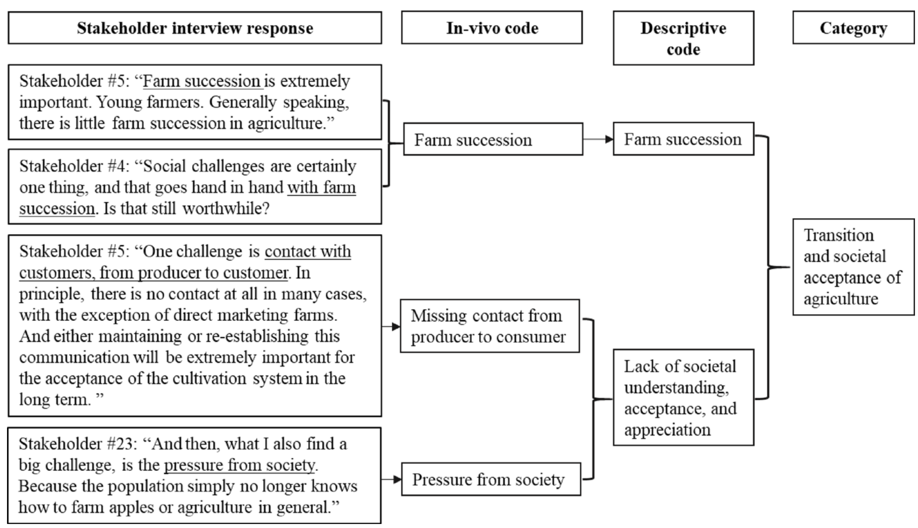

Fig. 4 Example of coding process of interview excerpts (translated) regarding socio-economic challenges in fruit production

codes to group similar codes together, facilitating the emergence of themes. Category titles were then assigned to groups of similar descriptive codes to summarize and structure the analysis (Figs. 3 and 4; Table 2; descriptions in Tables 3 and 4 in the Appendix). The corresponding author conducted the coding. The co-authors worked collaboratively during the iterative coding process to ensure reliability and feasibility of the coding framework. This rigorous analysis ensures a comprehensive exploration of stakeholder perspectives, providing valuable insights into the challenges and opportunities associated with digitalization in fruit production. The excerpts, example coding, and categories presented in this article have been translated to English.

3 Findings

This results section is structured as follows: first, Sect. 3.1 illustrates common themes within the reported environmental challenges, then perceived differences in production system and farm size. This is followed by an elaboration of the described potential for digitalization to mitigate the reported challenges. The same structure for the socio-economic challenges follows in Sect. 3.2. Some challenges naturally relate, cause, or even

Table 2 Environmental and socio-economic categories and coded challenges

Environmental challenges		Socio-economic challenges	
Category	**Descriptive code of challenge**	**Category**	**Descriptive code of challenge**
Farm management- related challenges and their environmental impacts	Reduction and availability of approved active ingredients	Challenges related to farm labour and management	Wages and housing standards for farm labourers
	Reduction of use of PPPs		Integration of foreign seasonal workers into the community
	Untrustworthy active ingredients		Reliability, work ethic, training of the labourers
	PPP drift and nitrate leaching		Labour availability
	Minimize residues		Dependency on seasonal workers due to shortage of local labourers
	Control pests sustainably		Bureaucracy
	Need-based fertilization	Transition and societal acceptance of agriculture	Structural change of farming
	Maintain high yield and quality with changing regulations		Disturbance to tourism industry by certain agricultural practices
	Support of biodiversity, avoidance of species loss		Creation of valuable, attractive jobs/ retention of employees
	Increase resilience		Farm succession
	Soil compaction		Lack of societal understanding, acceptance, and appreciation
	Avoiding resistance	Markets and marketing	Power of monopolies
	High fuel consumption		Price competition and pressure
Climate and energy	Climate change		Inadequate marketing methods/ channels
	Weather extremes		Global competition
	Access to water	Socio-economic-environmental nexus	Crop losses due to weather extremes
	Frost		Land use competition
	Hail and precipitation		Food security
Insects, pests, and diseases	Disease		
	Intensive permaculture increases pest challenges		
	Scab pressure		
	Damage from insects		
	Pollination		
Regional environment	Humidity from lake proximity causes increased apple scab		
	Problematic, weak young sites		
	Lake largest water reservoir, protected area		
	High local precipitation		

exacerbate other challenges. Stakeholders also frequently provided multiple responses to interview questions; unless clarified, the responses were considered to have equal value. For these reasons and because of the added value that the nuances found within qualitative analyses can offer over quantitative, the focus of this results section is on the qualitative analysis. Descriptive statistics and graphs are used to emphasize the general frequencies of which categories of responses were reported by stakeholders, but should be understood with reservations, also with consideration of the small sample sizes of stakeholders.

3.1 Environmental challenges and digitalization in fruit production

3.1.1 Reduction of PPP use and supporting biodiversity

Stakeholder descriptions of environmental challenges in fruit production were grouped into the following categories: farm management- related challenges and their environmental impacts; climate and energy; insects, pests, and diseases; and regional environment (Table 3 and Fig. 7, located in the Appendix). Environmental challenges within the category “farm management- related challenges and their environmental impacts” were most commonly reported by stakeholders. This category related to the interactions between farm-management practices and the environmental impact these interactions created on the surrounding ecosystem. The reduction of PPP use was a critical theme among the reported current environmental challenges for fruit production in the Lake Constance region. This challenge was described to stem from societal, political, economic, and environmental pressures. For instance, a developer: “How can I reduce or minimize spraying agents? It is always interesting from a cost point of view, of course, economically… but also extremely interesting from an ecological point of view”, and an advisor: “Over the next few years, it will be a legal requirement to reduce the proportion of chemical-synthetic products by 40 to 50 percent. In other words, what we have already been doing for years, decades, in integrated production: reducing the proportion of chemical-synthetic products has now been enshrined in law as a task”. Many of the response elaborations linked the reduction of PPP use to other challenges, demonstrating the natural interrelation between environmental issues. Representatives from NAC associations named this challenge more than any other group. One representative described this challenge in relation to another, namely sustainably controlling pests: “I believe that, on the one hand, we could simply reduce the use of critical pesticides even further. And the ecological challenge in this case would be to deal with pests and insect pests in a more sustainable way”.

Neither organic nor IP fruit farmers named this challenge of PPP reduction. Instead, farmers were more concerned by challenges related to precipitation and crop management. “The classic challenge, and also here in the region, is disease because we have a lot of precipitation, there is probably [more] scab pressure compared to other regions” reported an organic farmer. Another organic farmer linked precipitation to high fuel consumption and PPP application: “High fuel consumption, I would definitely put it there. Because of the weather. I would not even say climate, but weather. Because quite honestly, yes, when the weather is, let us say, bad for us, we have to make a lot of passes with the crop protection sprayer”.

Biodiversity support and avoidance of species loss was a second critical category of responses. Similar to the challenge of PPP reduction, biodiversity support was often described in relation to political and societal pressures. “And the challenges [of biodiversity support] will be considerable over the next few years, especially as political and public pressure is increasing in this direction, especially now with the Bee Protection Ordinance and so on” reported an organic farmer. One wholesaler described biodiversity itself to not be the issue, but rather the myth surrounding biodiversity issues in farming: “Of course, we have biodiversity, this insect extinction as a keyword. Where I say that this is not really a challenge. We have studies that show that [biodiversity] in fruit production, both conventional and organic, is actually quite good. But in the public perception, it is somehow always bad. And so, yes, we are always challenged to justify ourselves about something that is actually not a problem at all, from my point of view”. This implies that the narrative on fruit cultivation and sustainability in the public is currently inadequate and is allowing misinformation to be spread, leading to both negative public perception of fruit cultivation and increased frustrations of the farmers towards the public.

The majority of stakeholders (over 70%) believed a difference in environmental challenges exists based on production system. Stakeholders who responded with "yes" often elaborated upon their answers, whereas "no" responses did not elicit further elaboration. All organic fruit farmers and nature, agricultural, and consumer group stakeholders believed a difference exists, whereas other groups, such as fruit cultivation consultants, were more critical. Most challenges described to differ based on production systems belonged to the response category "farm management- related challenges and their environmental impacts". In particular, stakeholders described the PPPs allowed in IP to be more efficient than those in organic farming, and that fewer PPPs are approved for use in organic farming. Stakeholders mentioned that the challenge of biodiversity support and avoidance of species loss differs by production system. IP farming was reported to be more threatened by this challenge, as the organic farming system incorporates the positive potential of insects, for instance through flowering strips, more often than in IP farming. However, this depends largely on the interests of the farmer rather than the certified production system of the fruit farm: "in organic farming, we try to have biodiversity over the entire area. And we try to get the incredible insect potential into the entire area. In IP or conventional cultivation, we try to keep the insects out of the plants due to approvals of plant protection products… then it is again up to the head of the farmer whether they use the free space sensibly", reported an organic fruit farmer. Still, other stakeholders said there are no significant differences between production systems because in the end, the regional characteristics and challenges are the same regardless of production method: "For me, this has nothing to do with ecology or anything else. But almost rather with bureaucracy… So these problems in plant protection are pretty much the same between [IP] and organic production", described a fruit wholesaler.

When asked if a difference in environmental challenges exists based on the size of the fruit farm, a wider variety of stakeholder opinions was observed than for differences based on the production system. Less than half of all stakeholders believed a difference exists, and a few chose not to respond to this question for undisclosed reasons. As with the previous question, some stakeholders provided two answers. For instance, most interview partners who believed differences exist based on farm size referred to ecosystem challenges in relation to cost efficiency. A fruit wholesaler described biodiversity mitigation strategies to be easier for larger farms to conduct, depending on the strategy: "depending on how [a farmer manages] biodiversity, larger farms can take part of their land out of production and, yes, perhaps do some hedge planting or extensification measures there. If a small farm does that, it is often a high proportion of its farmland and it cannot afford to give up that area". In contrast, a consultant described smaller farms to be less challenged by issues related to biodiversity, as they have a greater positive impact on species diversity through their small structures, which offer more possibilities for diversification. Still, many respondents saw differences in how farms face environmental challenges to depend on the farmer or organization of the farm, not the farm size: "there are no differences. It is up to what the farmer does", described an organic farmer; "the people who work there are the decisive factor… What knowledge and expertise do they have? What are their goals? What kind of ethical background do they have?" reported a researcher.

3.1.2 Digitalization to mitigate environmental challenges through increased efficiency and productivity

Nearly all stakeholders (32 of 34; 94%) believed that digitalization could mitigate the environmental challenges (Fig. 5); all interviewed researchers, consultants, representatives from NAC associations and developers were convinced of this. Increased efficiency and productivity were strong themes among stakeholder responses. One developer mentioned the endurance of digitalized machinery: "people simply do get tired… [the digitalized machinery] can just deliver the same performance over a whole day". Other stakeholders in these groups described digitalization to improve the quality of the products and the productivity of on-farm tasks through automation, leading to overall improved environmental efficiency. A consultant was optimistic that digitalization could address two challenges at once: earlier, more precise application with PPPs that are less effective. "In order to be able to consciously use ecological products in advance that do not have such a high degree of efficiency, but can still regulate an initial population well, these are possibilities, perhaps, that we will be able to master the ecological challenges in the future through digitalization". Another developer provided an example in the case of fungicide application: "A concrete example would be when I can draw conclusions about fungal infestation on the basis of image data information. I can then take much more selective and time-limited measures, i.e., at the optimal time, and no longer have to apply pesticides over large areas as a preventive measure". The precision aspect of digitalization was an additional benefit mentioned by many stakeholders: precise measurements of the soil and plants could reduce the amount of applied PPPs and therefore alleviate the related environmental challenges. Similarly, stakeholders discussed how optimized weather prognoses could allow for more efficient management of the farm and PPP applications.

Over 80% of the stakeholders in the farmer group and the fruit wholesaler group (seven out of eight farmers, four out of five wholesalers) believed digitalization could mitigate reported environmental challenges, but these groups also included more sceptical opinions than the others. One fruit wholesaler and one IP fruit farmer did not believe that digitalization could mitigate current environmental challenges. Six stakeholders responded with "no" when asked if digitalization could mitigate the described environmental challenges. However, four of these stakeholders also provided "yes" responses in their open-ended interview answers. As previously described, unless otherwise clarified, both responses were considered to have equal value. An organic farmer mentioned

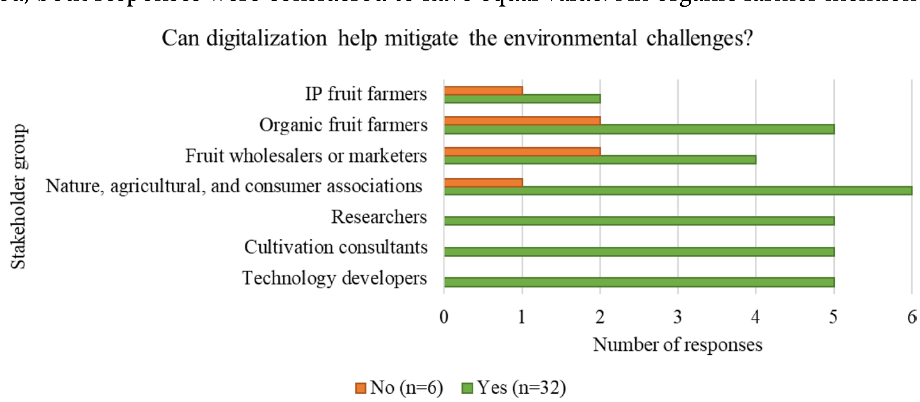

Fig. 5 Stakeholder group responses to the influence of digitalization on the environmental challenges in fruit production. Stakeholders could provide multiple answers

that existing digital tools in fruit production do not offer mitigation strategies for the challenge of biodiversity: "there are solutions for the work around it, for biodiversity, for maintenance work in certain areas. But to get more biodiversity, I do not see any digitalization options yet". Either this signifies a lack of digital tools for this issue, or if they do exist, the communication about these tools may be insufficient.

3.2 Socio-economic challenges and digitalization in fruit production

3.2.1 Societal acceptance and labour availability

Stakeholders were asked to name the most important socio-economic challenges in fruit production in the Lake of Constance region (Table 4 and Fig. 8, located in the Appendix). Socio-economic challenges can be understood as societal and/or economic issues that threaten the activities within and/or the overall existence of fruit production. In-vivo coding of the interview responses and inductive categorization resulted in the following categories: challenges related to farm labour and management; transition and societal acceptance of agriculture; markets and marketing; and socio-economic-environmental nexus. The majority of named challenges were grouped into the category "transition and societal acceptance of agriculture". Overwhelmingly, stakeholders were concerned about societal values around agricultural production: the challenge "lack of societal understanding, acceptance, and appreciation" was reported by over 90% of stakeholders. Increased quality expectations among consumers, demands for low prices, and societal pressures regarding agricultural practices, such as PPP reduction, were described to stem from deficient competencies about farming. "What I also find to be a big challenge is the pressure from the population. Because the population simply no longer knows how to farm apples or agriculture in general", reported a representative from an NAC association. Consultants, researchers, NAC association representatives, and fruit wholesalers/marketers were particularly concerned that, despite the perceived lack of care or understanding from consumers about how fruit is produced, consumers are quick to criticize the need for pesticides or higher prices for organic products.

To combat this disconnect, stakeholders frequently reported that consumers must learn to recognize added value in products, from higher quality standards to regional products. A consultant suggested, "Maintaining or re-establishing communication [between farmers and consumers] will be extremely important for the acceptance of the cultivation system in the long term. That consumers understand why a product looks the way it does in the supermarket. And why it costs what it costs. And, on the other hand, that farmers understand why consumers make the choices they do. And there are now so many intermediate storage, processing and marketing steps in between, all of which want to make a profit". While farmers did not express this concern as frequently as other groups, one IP farmer also hoped for greater appreciation for regional products and less partiality for organic labels by consumers. He also connected the socio-economic challenge of societal acceptance and appreciation to environmental concerns: "I would simply like to see a little more appreciation for our local agriculture and for what we do here. Because the apple that comes from Italy or from somewhere else has seen completely different pesticides than the one here in the Lake Constance region. And then organic is not necessarily better. And we still do not get that across to our customers. So we cannot go on consuming everything just because it says organic on it. We can no longer afford that, I am deeply convinced… I do not think it is the way we can go for the next few years and for the next few generations… Because all this organic stuff that has been carted around the globe does not have a great environmental footprint either".

As with the environmental challenges, socio-economic issues are interrelated. For instance, stakeholders linked labour challenges to societal competence. The lack of appealing, well-paid positions with career prospects, which attract and retain employees, creates a strain on the regional fruit production. "Again, this aspect of appreciation comes into play, how attractive the profession is, who actually wants to do it?" reported a developer. All stakeholder groups except researchers and farmers reported concerns over farm succession. Instead, stakeholders from these groups focused more on the direct challenges related to farm labour and management.

Labour availability was the second-most important challenge according to stakeholders. The concern about attaining domestic and foreign labour is related to a multitude of reported factors, including unappealing physical labour, rising minimum wage, and the lack of regional farm labourers. A researcher mentioned that in fruit production, "you really aim for the cheapest possible labour for unpleasant routine work. And that's a huge challenge. That is not going to work anymore. It already does not work today". In German fruit farming, when imported fruit can be purchased at much lower prices, it is a challenge for German farmers to offer the minimum wage to employees while pricing their products competitively. "You always have to make sure that you are competitive in order to be able to sell the fruit in the country in the end. And that does present challenges", described a developer. The increasing costs required by farmers to employ labourers threaten the economic feasibility of the occupation. While other stakeholder groups reported farmers to deal with intensive bureaucracy, especially when employing foreign seasonal labourers, this challenge was not described by farmers themselves.

Most interviewed stakeholders (62%) believe that differences exist between production systems regarding socio-economic challenges. A common theme among descriptions was that organic agriculture has a better image and therefore is more accepted by society than IP or conventional production methods. An IP farmer reported, "I lost customers [at the farmer's market] because I said very clearly, I am not an organic farmer", implying a disadvantage for non-organic farmers regarding social acceptance and stigma of non-organic production methods. Still, interviewed organic farmers mentioned that consumers have higher expectations for the quality of organic fruit than for non-organic fruit, but simultaneously expect low prices, creating greater social acceptance challenges and market pressures for organic farmers. Some stakeholders reported the requirements for labourer conditions to be higher in organic than in IP fruit farming. An organic farmer conveyed, "The amount of work, manual labour on the organic farm is definitely higher than on an IP farm". Therefore, organic farmers may be more confronted by the described challenges related to domestic and foreign labourers. Stakeholders within the technology developers group described organic farming as having both a price advantage over IP farming, yet they must tackle the challenge of reaching the same yield potential and therefore economic margins as an IP farm.

Similar to the socio-economic challenges for different production systems, most interviewed stakeholders (82%) agreed that there are also differences in these challenges based on farm size. The stakeholders who provided responses in the groups fruit wholesalers or marketers, fruit cultivation consultants, and technology developers all agreed that farm size does imply a difference in challenges. Specifically, developers mentioned that farm organization and management is easier for larger farms, as well as the benefit of the economy of scale. One developer said, “We know that the large companies in particular also benefit from certain economies of scale. Of course, this cannot be generalized, but they also demonstrate a certain professionalism, have lower costs and are simply organized in a completely different way”. Similarly, larger farms benefit from synergy effects, such as the better economic utilization of machinery. However, these stakeholders also mentioned that smaller farms are less challenged in hiring labourers and more often received familial help than large farms with more land area. An organic farmer described small farms to offer better working conditions for their hired workers and that the farm manager has a better overview of their team than a manager of a large farm. Still, other farmers reported that workers on larger farms tend to earn higher salaries. Smaller farms may have more issues finding farm successors and face greater challenges to enter the market with their products, according to a NAC association stakeholder. Regarding societal acceptance, smaller fruit farms may have an advantage. A developer reported that “small farms in particular are somewhat glorified in public, because there is a bit of a prejudice that as soon as a farm is small, it is good, it is what we imagine idyllic about agriculture and everything is good. And as soon as the farm is large, it can no longer be good, because if it is mass production, it cannot be good”. Stakeholders who believed that differences in these challenges do not exist based on farm size did not elaborate on their answers.

3.2.2 Digitalization to mitigate socio-economic challenges through increased efficiency and transparency

When asked if digitalization can help mitigate the socio-economic challenges (Fig. 6), perspectives varied within each stakeholder group. Of the stakeholders who believed digitalization could mitigate said challenges (16 of 34 stakeholders; 47%), responses centred largely around two themes: increased efficiency through automation and increased transparency along the value chain for increased acceptance and market advantage. Specifically, the challenge of labour availability and the dependency that farmers were reported to have on labourers- domestic and foreign, permanent and seasonal- could be eased through automated technologies. An IP farmer mentioned that the use of automated machinery could make work more accessible for a wider scope of potential labourers, for instance people with intellectual or physical disabilities, and therefore

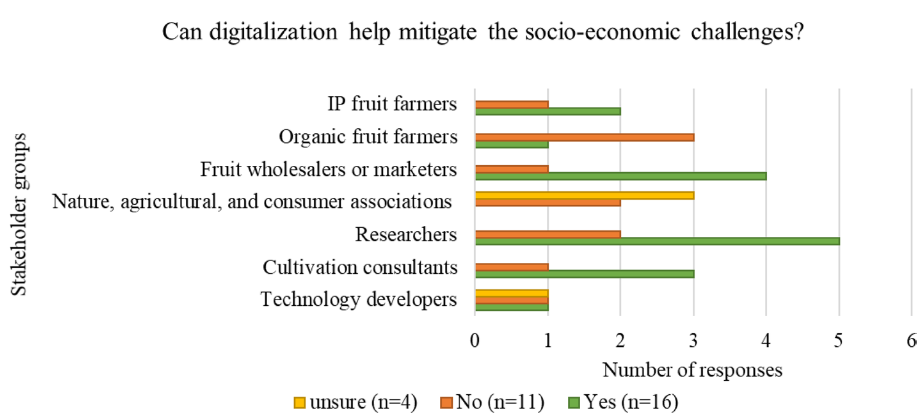

Fig. 6 Stakeholder group responses to the influence of digitalization on the socio-economic challenges in fruit production. Stakeholders could provide multiple answers

increase local job opportunities. When discussing what digitalization could replace, a researcher listed “tasks that you no longer want to do, that are unpleasant, exhausting, boring, not challenging, are no longer necessary. And higher, more interesting fields of activity are created, which make the workplace more interesting”. However, the same researcher described the risk of higher wages for labourers and job discrimination associated with this positive aspect of digitalization: “with the higher added value that can then be realized, appropriate payment is also really necessary… whoever cannot fulfil [the higher paying jobs] gets kicked out”.

The second theme of increased transparency for consumers into the production of agricultural products through technologies was described to potentially allow for more public knowledge and social acceptance of fruit cultivation methods, which could in turn lead to a price advantage for local farmers. Consultants and researchers most frequently mentioned this potential. The traceability of products and production conditions may additionally lead to easier, more reliable quality control by wholesalers and certification bodies. Stakeholders also mentioned the marketing advantage: more customers can be reached through online platforms or social media than through non-digitalized forms of marketing.

Of the respondents who were uncertain, stakeholders reported not seeing a direct connection from digital technologies to socio-economic challenges. Additionally, some stakeholders reported that the customer base is already developed and loyal, and because people tend to exhibit habitual behaviours and therefore are not likely to change their buying patterns due to increased transparency of products or different marketing via digitalization. A researcher mentioned that while he has observed new technologies like robotics to improve societal acceptance of arable farming, this may not be the case in all agricultural sectors. He used animal husbandry as an example: “But if we then look into the stalls and look at the topic of ‘animal welfare’, we actually find that these arguments that we put forward, that digitalization in the barn probably leads to animal welfare. In principle, yes, it is seen as positive, but overall we have found that it does not really move us forward in terms of acceptance, because the situation is that if the entire husbandry system is rejected, then, and it seems to be the case in some cases, then yes, minor changes in the system [through digitalization] do not move you forward [towards acceptance]”.

4 Discussion

Stakeholder perceptions and interests determine the role they play in the digital transformation of agriculture. The willingness of stakeholders to take part in this transformation depends partially on the extent to which they believe digitalization can influence sustainability. The results of this study indicate that the majority of interviewed stakeholders believe digitalization can positively influence current sustainability challenges in fruit production in the Lake Constance region, particularly through increased efficiency, productivity, and transparency.

This research delves into real-world problems by exploring participants' experiences, perceptions and behaviours, answering “how” and “why” questions rather than “how many” or “how much” in order to understand themes and patterns that are difficult to quantify. Although it presents some numerical data, it is important to keep in mind the limited sample size and to emphasise the importance of context and narrative.

This discussion section is separated into two parts: the first section explores support measures for digitalization to mitigate environmental and socio-economic sustainability challenges based on the findings of this study. Second, the discussion is concluded with a section that examines the role that digitalization could play specifically with the socio-economic sustainability of fruit farming in the Lake Constance region.

4.1 Support for digitalization to mitigate environmental and socio-economic sustainability challenges

While the majority of stakeholders believed that digitalization could mitigate both environmental and socio-economic challenges, responses were higher for the former category. Digitalization was believed to be able to mitigate environmental challenges in fruit production through greater endurance of machinery over human labourers, improved environmental efficiency and precision and optimized prognoses. These expectations may not be attainable with the complexities surrounding digitalized fruit cultivation today, including unsuitable tool development and an uneven distribution of digital knowledge in the fruit cultivation industry [45]. Arguably, these themes of efficiency and productivity belong to the growth paradigm that has led to a number of sustainability problems existing today. Digital technologies developed by large agro-food companies are not radically changing how agriculture is conducted, but rather optimising the current production model, and may lock farmers into the current and unsustainable system that uses large-scale machinery and chemical inputs [79–81]. Considering that digitalization of the fruit sector is already underway, the responsible way forward is to ensure that it is focused on mitigating current and future sustainability challenges, with consideration of the unique challenges and regional contexts found within this sector. The digitalization of fruit production requires support in order to continue to function in this same paradigm and not contribute to further degradation of the environment, but rather contribute positively to sustainability.

The environmental challenges described by stakeholders were numerous and primarily concerned reduction and use of PPPs, support of biodiversity and avoidance of species loss, weather extremes, climate change, and sustainable pest control. These reported, perceived challenges match those found in the literature on fruit cultivation (e.g. [82, 83]) and those of concern by political frameworks and current goals around environmental sustainability. These include the EU Commission's proposal to cut greenhouse gas emissions by at least 55% by 2030 [5], the Climate Law to be climate neutral by 2050 [84], and the Green Deal's Farm to Fork strategy [85]. Communication on- and support for digitalization at the national government level has typically focused on environmental aspects, such as the strategy to support biodiversity by the federal ministry of food and agriculture [86], and the Rentenbank Investment Program for Agriculture which supports investments in particularly environment- and climate-friendly management practices [87]. The environmental impact of digitalization is more researched and more awareness has been brought to this aspect than potential socio-economic impacts, despite the fundamental changes digitalization could impose across all aspects related to agriculture [18]. This may be the reason why stakeholders were more confident that digitalization could mitigate environmental challenges in comparison to socio-economic. However, as some stakeholders reported not seeing a direct connection from digital technologies to socio-economic challenges, the root of this difference may instead be a lack of digital tools to solve these complex issues, or if they do exist, communication to the intended users about available tools and their functions may be insufficient, as previously found by [45].

Martens and Zscheischler argue that digitalization's contribution to solving sustainability challenges is dependent upon the design of political, legal, and economic frameworks [88]. Numerous socio-economic challenges were described by stakeholders; within the ubiquitous 3-pillar concept of sustainability (e.g. [89]), the pillars are inherently interdependent and thus require equal political attention and support. Yet, challenges listed by stakeholders such as those related to farm management, societal competence, and agricultural transition are seldom described by policy makers in Germany. To the authors' knowledge, national funding programs for digitalization with a focus on the named socio-economic challenges do not exist and research initiatives that employ qualitative, empirical, and/or transdisciplinary methods in fruit production are lacking. As such, the current political framework lacks adequate strategies to support sustainability challenges facing fruit cultivation in the digital agricultural transformation. Considering the accelerated pace of digitalization in agriculture, it is critical that support structures exist for all agricultural sectors, otherwise the risk of sectoral digital divide, or the gap between those able to benefit from the digital age and those who are not [90], may become reality.

4.2 Highlight: socio-economic sustainability challenges and digitalization in fruit production

In light of the previously described structural deficits, as well as the frequency and calibre of the socio-economic challenges expressed by stakeholders, the following section highlights the challenges and opportunities for digitalization in the context of socio-economic sustainability and fruit cultivation in the Lake Constance region.

Stakeholders were primarily concerned by the low societal acceptance of fruit cultivation and products, and listed numerous challenges related to labour availability. Increased efficiency through automation and increased transparency along the value chain for increased acceptance and market advantage were the main themes that emerged regarding digitalization's potential to mitigate the socio-economic challenges. The results of this study both confirm and contest findings from the limited existing literature on digitalization as a potential mitigation strategy for socio-economic challenges in agriculture, such as the opportunities that agriculture may gain through the digital transformation (see e.g. [11, 91]) including becoming a more attractive activity, offering new jobs, and improving the economic sustainability of agricultural businesses. In particular, stakeholders reported digitalization to potentially ease the frequently named challenges related to dependency on domestic and foreign, permanent and seasonal labourers, while also expressing concerns that digitalized jobs may become discriminatory, exclusive, and require higher wages than farmers can afford. The interviews for the present study began in the fall of 2020, following a particularly challenging harvest season. Due to the COVID-19 pandemic, seasonal labourers, particularly from outside countries, were harder to hire than usual. This timing should be considered when looking at the frequency of manual labour challenges mentioned by stakeholders in the results of this paper. While digital farming technologies may replace manpower as labour shortages continue to challenge the agricultural productivity [53], interviewed stakeholders in the present study did not mention risks or opportunities related to the potential complete replacement of workers. This could be due to the low adoption of completely autonomous robots in German agriculture, as was concluded in the empirical study of digital technologies and German horticultural workers by Prause [18]. However, technologies with semi-autonomy may be enough to influence the sectoral labour force. The use of robotics or semi-autonomous machines might lead to sectoral job losses [80, 92] through, for instance, a shift from highly skilled labour to temporary, migrant labour [93]. These findings contest the previously mentioned economic opportunities found in the literature and the concerns of exclusive, high-wage digitalized jobs as described by the stakeholders. This contradiction highlights the uncertainties that still exist: the impacts of digitalization in fruit cultivation are yet to be fully understood at this stage in the digital transformation, emphasizing the need for continued research and observation to support a sustainable transition.

When asked about differences in challenges based on farm size and production system, the greatest number of stakeholders reported differences in socio-economic challenges based on farm size. Given the research that has shown the correlation between farm size and adaptability to technological innovations [94–96], Martens and Zscheischler [88] have questioned how European governments will protect smallholders from this digital divide. Prause et al. [80] argue that opposition between small-scale agroecological farming and large-scale industrial farming will be fortified by digitalization. Smaller farms were perceived by stakeholders in this study to face greater challenges to enter the market with their products. Markets and large-scale buyers may favour larger farms, who tend to punctually deliver large volumes of commodities over smaller farms [97, 98]. Digitalization could further exclude small-scale producers from certain markets, as high-cost digital supply chain technologies are being encouraged for regulatory compliance proofing, which may not be affordable for smallholders [80]. Policy makers recognize the advantage that larger farms have over smaller farms in market access: the Agricultural Ministers Conference in 2020 proposed that an International Digital Council should be developed by the Food and Agriculture Organisation of the United Nations (FAO) to, among others aims, reduce the digital-divide and improve access to digital technologies, including for smallholder farmers [99]. Recognition is a helpful first-step towards support, but actions are required to ensure that smallholder farmers, such as those commonly found in the fruit production sector in the Lake Constance region, do not face greater disadvantages than middle- and large- scale farmers. Targeted support that considers the results of this study, such as specific development of affordable supply chain technologies or policies in markets that favour small farms, would aid in reducing the gap in opportunities and challenges based on farm size in digitalized fruit farming.

Most current socio-economic challenges for fruit production in the Lake Constance region reported by stakeholders relate to transition and societal acceptance of agriculture. As consumers have gradually become further removed from the agricultural industry since the industrialization of agriculture [100], their concerns surrounding agriculture have increased [101]. Potential consequences of deficient agricultural knowledge, such as misplaced public support for political campaigns, mistrust of farmers, and a lack of understanding of price politics threaten the sustainability of farming [102]. Many stakeholders described a general lack of knowledge or interest from consumers regarding fruit production, which they described to harbour unfair criticisms and inappropriate expectations for price and seasonal availability. This gap between high expectations from society and the prices consumers are willing to pay is referred to as the citizen-consumer gap [103]. Farmers reported this mismatch less frequently than the other stakeholder groups. One farmer suggested consumers change their expectations for the price of products in order for the farmers to be able to financially manage the increasing environmental and societal demands on fruit cultivation. Stakeholders were hopeful that increased transparency from farm to fork through digital technologies in fruit cultivation could mitigate the most commonly reported challenge of societal appreciation and understanding of agricultural practices such as changing consumer expectations. The German Agricultural Society (DLG) has echoed this optimism by suggesting that the transparency of production processes and traceability that can be simplified through digitalization will create trust and increase appreciation of agriculture [104]. For instance, blockchain technologies can work with IoT-related technologies (such as sensors and digital tags) to collect and upload data along the value chain, from fruit picking to final consumption, for increased traceability and transparency [105]. Digital media tools that use blockchain platforms to allow consumers to trace the transformation of food along the supply chain through, for instance, the scan of a QR code on their product [106, 107]. Beyond this, open-source digital platforms and apps that enable two-way communication between fruit farmers and consumers, such as digital Community Supported Agriculture (CSA) platforms or direct marketing apps, could build trust between the parties [54]. While the related article by Gaber et al. [54] investigated the *perceived* impact that digitalization, including increased transparency enabled through digital technologies, could have on the public opinion of fruit farming, the true impact of increased transparency in fruit production has yet to be researched. Despite the opportunities offered by technologies towards improved transparency and the optimism described by stakeholders on this aspect, little evidence suggests that increased information on practices can alter societal appreciation for farming [103]. In fact, in the case of animal husbandry, as also described by a researcher within this study, critical attitudes have been observed to grow with improved consumer knowledge [69, 108]. Furthermore, based on the results of a survey conducted by Pfeiffer et al. [17] with respondents across Germany, authors reported that it is unlikely that digitalization benefits can impact public acceptance due to the widespread criticism of agriculture among citizens. Weible et al. [69] argue that critical attitudes may rather be improved through the public communication of efforts taken to improve agricultural systems to meet societal expectations. This could include the implementation of digital technologies focused on improving sustainability challenges. Authors build upon this argument to suggest that the narrative surrounding digitalization in agriculture be accessible to the wide public, considering varying levels of foundational agricultural knowledge, and focus on efforts practitioners in the value chain, with a particular focus on farmers, are taking to meet the current environmental and societal issues.

5 Conclusions and recommendations

Current environmental and socio-economic challenges threaten the sustainability of fruit production. This study adds to the limited literature on stakeholder perspectives of digitalization in fruit production. Stakeholders named the reduction of available PPPs, biodiversity support, labour, and societal acceptance of fruit production to be key challenges in fruit production in the Lake Constance region. According to interviewed stakeholders, digitalization can alleviate sustainability challenges in fruit production, particularly regarding environmental challenges, through e.g. increased efficiency, productivity, and transparency. At the same time, stakeholders discussed uncertainties and perceived risks of digitalization, including the impact on the regional and sectoral labour availability and the unseen connection between digitalization and regional socio-economic issues.

It can be questioned if the role of digitalization is indeed to address sustainability challenges. The authors of this study argue that, in light of the the urgency of the current sustainability challenges, the progression of digitalization in agriculture, and the opportunities described by stakeholders in this study, digitalization should be considered as a tool to mitigate current sustainability challenges in the Lake Constance fruit production sector, with some considerations. The authors encourage agricultural policy and funding schemes to give equal attention to environmental and socio-economic challenges, as the latter, particularly related to digitalization, are not adequately supported despite their abundance and complexity. The digitalization of the fruit production sector must be supported through intelligent user-oriented technological design and political and financial frameworks. Moreover, this re-focusing of support should include intentional, user-driven technological design, considering the unique challenges faced by stakeholders in this sector and within their regional contexts. Specifically, support and design must be inclusive of small fruit farms, such as those commonly found in the Lake Constance region, and cater specifically to their reported needs, including non-exclusive market policies and cost-effective technical solutions. Further research on the potential for digitalization to bridge the existing gaps in sustainability challenges between small and large farms, as well as organic and IP farming practices, is necessary. These efforts would allow for equal opportunities across farm size, user demographics, and agricultural sectors to fairly benefit from the chances offered by digitalization. Additionally, research activities aimed at understanding how the technologies that offer to improve transparency along the value chain could impact societal acceptance of fruit cultivation and how the use of technologies may influence the challenges associated with labour availability are required. The improvement of information dissemination on digitalization in fruit cultivation could help to increase digital literacy among intended users, in order for them to be able to make informed choices for or against the implementation of digital tools.

Appendix

Abbreviations

AI	Artificial Intelligence
CSA	Community Supported Agriculture
FAO	Food and Agriculture Association of the United Nations
IOT	Internet of Things
NAC	Nature, agriculture and consumer (associations)
PPPs	Plant Protection Products
IP	Integrated Production
UAV	Unmanned aerial vehicle

Interview guideline

Questions for Interviewees:

1. How old are you?

   a) < 30
   b) 30–40
   c) 41–50
   d) 51–60
   e) 61–70
   f) > 70
   g) No answer

2. What gender do you identify as?

   a) Female
   b) Male
   c) Diverse
   d) No answer

3. Which county do you live in?
4. How would you describe the area you live in?

   a) Mostly rural
   b) Mixed
   c) Mostly urban
   d) No answer

5. What is your highest level of completed education?

a) Primary school
b) Secondary school
c) Post-secondary at a university or technical college (e.g. Diplom, Magister, Bachelor, Master, PhD)
d) Other (please specify)
e) No answer

6. Do you have a specific training in one of these topics?

a) Agriculture
b) Food science
c) Forestry
d) Sustainability
e) Digital technologies (e.g. IT, electrician, engineering, etc.)
f) Other (please specify)
g) No answer

7. Where do you get your information about digitalization in fruit production or in your professional field? (multiple responses are possible)

a) Magazines, newspapers
b) Social media
c) Colleagues and neighbours
d) Agricultural fairs or conferences
e) Training courses
f) Other (please specify)
g) No answer
h) I do not have any information on digitalization in fruit production or my professional field

8. Please self-grade your knowledge on digitalization in fruit production

a) High
b) Rather high
c) Medium
d) Rather low
e) Low
f) No answer

9. Which role do you play in the digitalization of agriculture? (multiple responses are possible)

a) Agricultural production
b) Agricultural advising
c) Agricultural organization or association
d) Mechanical engineering
e) PPP manufacturer

f) Fruit storage and/or processing
g) Wholesaler and/or marketing
h) IT- and digital sector
i) Administration
j) Research
k) Education
l) Technology development
m) Local community initiatives or groups
n) Community service/charitable foundations
o) No professional/institutional area

10. Which sector do you work in? (multiple responses are possible)

a) Private
b) Public
c) Non-profit
d) Civil society
e) Other (please specify)
f) No answer

Questions only for owners or leasers of farming enterprises

11. Which production system do you use on your farm? (multiple responses are possible)

a) Integrated production (IP)
b) Organic production
c) Certified organic production
d) Demeter production
e) No answer

12. How large is your farming enterprise? (answer in hectares)
13. Please provide the main products of your farming enterprise (multiple responses are possible)

a) Plant products

1. Stone fruits
2. Soft fruits/berries
3. Other fruits
4. Cereals
5. Other

b) Animal products

1. Eggs
2. Milk
3. Other

c) Services

1. Lodging
2. Vacation apartments
3. Maintenance work for the community
4. Other

d) No answer

14. Please describe the ownership of your farming enterprise (multiple responses are possible)

a) Own property
b) Lease
c) Community of joint heirs/civil law association/community of farms/cooperative/Ltd
d) Other form (please specify)
e) No answer

15. Do you use digital tools or technologies on your farming enterprise?

a) If yes, which ones? Or rather for which purposes do you use the tools?
b) If no, why not?
c) No answer

16. How do you store your products? (multiple responses are possible)

a) On-site storage
b) Off-site storage
c) Storage in communal storage facility
d) Storage in commercial storage facility
e) Other (please specify)
f) No answer

17. How do you market your products? (multiple options are possible)

a) Direct marketing

1. Farm shop
2. Delivery service
3. Shipping

b) Intermediary trade
c) Wholesaler
d) Communal marketing over e.g. farming cooperative
e) Export
f) Other form (please specify)
g) No answer

Challenges in fruit production (your farming enterprise/the Lake Constance region)

18. Describe the most important environmental challenges of fruit production in the Lake Constance region
    a) Do these differ from those in organic fruit production?
        1. If yes, which challenges differ, and what are the reasons for these differences?
    b) Are there differences based on farm size?
        1. If yes, which challenges differ, and what are the reasons for these differences? Please name the farm sizes in hectare for small/large.
19. Describe the most important socioeconomic and social challenges of fruit production in the Lake Constance region
    a) Do these differ from those in organic fruit production?
        1. If yes, which challenges differ, and what are the reasons for these differences?
    b) Are there differences based on farm size?
        1. If yes, which challenges differ, and what are the reasons for these differences? Please name the farm sizes in hectare for small/large.
20. What do you understand by the term "digitalization in fruit production"? Please give examples.
21. Do you believe that digitalization can help mitigate the previously mentioned ecological challenges? If yes, which challenges and how?
22. Do you believe that digitalization can help mitigate the previously mentioned socioeconomical and social challenges? If yes, which challenges and how?
23. What are the advantages of digitalization in fruit production?
    a) Do these differ from those in organic fruit production?
        1. If yes, which challenges differ, and what are the reasons for these differences?
    b) Are there differences based on farm size?
        1. If yes, which challenges differ, and what are the reasons for these differences? Please name the farm sizes in hectare for small/large.
24. What are the disadvantages of digitalization in fruit production?
    a) Do these differ from those in organic fruit production?
        1. If yes, which challenges differ, and what are the reasons for these differences?
    b) Are there differences based on farm size?

1. If yes, which challenges differ, and what are the reasons for these differences? Please name the farm sizes in hectare for small/large.

25. What barriers do you see to the introduction/use of digital technologies and innovations in fruit production?

a) Do these differ from those in organic fruit production?

1. If yes, which challenges differ, and what are the reasons for these differences?

b) Are there differences based on farm size?

1. If yes, which challenges differ, and what are the reasons for these differences? Please name the farm sizes in hectare for small/large.

26. In your opinion, would the use of digitalized technologies in fruit production change public opinion about the products or production methods? (Yes, no and what reasons play a role here)

a) Does your answer differ when we speak about the use of digitalized technologies in **organic** fruit production? (if yes, how and what are the reasons for these differences)

27. Please indicate which of the following groups of people or organizations you think would benefit (winners), not benefit (losers) or neither benefit nor lose (neutral) from the digitization of fruit growing, and add if any should be missing from your point of view (your farm/region).

a) Organic fruit producers
b) Conventional or integrated fruit producers
c) Small to medium sized farms
d) Larger farms
e) Fruit wholesalers and marketers
f) Production cooperatives/associations
g) Agricultural researchers
h) Manufacturers of agricultural technologies
i) Companies in the field of digitalization/digital technologies in agriculture
j) Consultant for fruit production
k) Consultant for digitalization
l) Crop protection manufacturers
m) Consumers

Environmental and socio-economic challenges and descriptions

See Tables 3 and 4.

Table 3 Environmental challenges and descriptions by stakeholders

Category	Descriptive code of challenge	Description of challenge by stakeholders
Farm management- related challenges and their environmental impacts	Reduction and availability of approved active ingredients	Fewer active ingredients being approved for use as restrictions increase
	Reduction of use of PPPs	Producers are challenged to greatly reduce or complete adhere from use of PPPs in their farming practices
	Untrustworthy active ingredients	Concern over available active ingredients that reach the market without thorough testing
	PPP drift and nitrate leaching	Laws to control potential drift of PPPs and leaching of nitrate into groundwater add complexity to farming activities
	Minimize residues	Environmental and social pressure to reduce the amount of PPP residues on food products
	Control pests sustainably	Challenge to sustainably control pests in orchards and fields
	Need-based fertilization	Farmers challenged to apply correct amount of fertilizer, without over- or under- fertilizing
	Maintain high yield and quality with changing regulations	Maintaining product yield and quality while adjusting practices to fit new regulations and societal pressures to, e.g., reduce use of PPPs in production
	Support of biodiversity, avoidance of species loss	Biodiversity and avoidance of species loss are not prioritized enough and/or increasingly challenged by environmental and social pressures
	Increase resilience	Resilience must be increased and systems such as mixed cultures, crop mixes, must be incorporated for this
	Soil compaction	Soil life is being compromised through the frequent driving of heavy machinery over soils and the associated soil compaction
	Avoiding resistance	Pests and invasive plants are becoming increasingly resistant to PPPs as the active ingredient spectrum becomes increasingly restricted
	High fuel consumption	Frequent use of fossil fuels for tractor and sprayer use, particularly in organic farming when PPPs are applied more frequently and with the increasing weather extremes
Climate and energy	Climate change	Changing climate is leading to consequential effects in fruit production
	Weather extremes	Weather extremes such as extreme cold temperatures or heat waves are increasing in frequency and can have detrimental effects on fruit production
	Access to water	Water is becoming a limited resource but is critical for agricultural production
	Frost	Fruit production in particular can suffer large harvest losses from frost, therefore intensive frost protection actions at farm-level are required
	Hail and precipitation	Increasing rates of hail storms and heavy precipitation, which cause damage to fruit orchards and farms
Insects, pests, and diseases	Disease	Managing plant diseases and adjusting management practices with increasing PPP restrictions
	Intensive permaculture increases pest challenges	Pests and diseases can thrive better and longer in intensive, permaculture farms such as orchards
	Scab pressure	High rates of fungal disease like apple scab, particularly in the humid regions for fruit growing
	Damage from insects	Managing damage from insects and adjusting management practices with increasing PPP restrictions
	Pollination	Loss of insect populations reduces the pollination rates and therefore success of the agricultural area

Table 3 (continued)

Category	Descriptive code of challenge	Description of challenge by stakeholders
Regional environment	Humidity from lake proximity causes increased apple scab	Humidity from Lake of Constance increases rates of apple scab and other fungal diseases
	Problematic, weak young sites	Young farm sites in the region are at greater risk of failure compared to long-established orchards due to pest invasion or failed plant growth
	Lake largest water reservoir, protected area	Lake of Constance, as Germany's largest drinking water reservoir, therefore stricter regulations for PPP use
	High local precipitation	Regional precipitation rates higher than other fruit growing regions, therefore require greater interventions such as hail nets

Table 4 Socio-economic challenges and descriptions by stakeholders

Category	Descriptive code of challenge	Description of challenge by stakeholders
Challenges related to farm labour and management	Wages and housing standards for farm labourers	Paying fair wages for farm workers, considering for instance the rising minimum wage, is a challenge for some farmers. Indirect costs of hired farm workers such as on-farm housing and bureaucracy along with fair wages is not economically feasible for all farms
	Integration of foreign seasonal workers into the community	Foreign seasonal labourers are often not given opportunities to integrate into the local communities and instead can be viewed to overwhelm the communities when many arrive at the same time of year
	Reliability, work ethic, training of the labourers	Fruit production is challenged to find and retain reliable labourers with relevant training
	Labour availability	Local and international workers are increasingly challenging to find. More jobs with better pay and more comfortable working conditions are becoming available in nearby regions
	Dependency on seasonal workers due to shortage of local labourers	Local labourers are, for some tasks such as intense seasonal harvesting, difficult to find. Farms are dependent upon the influx of international seasonal workers. This dependency creates risks, for instance, when seasonal workers are not allowed into Germany or are offered better pay and/or conditions elsewhere
	Bureaucracy	Large amounts of bureaucracy and office work for quality control and bookkeeping in addition to field work, including bureaucracy for international seasonal workers like visa arrangements
Transition and societal acceptance of agriculture	Structural change of farming	General challenge of structural change in agriculture is also faced locally, with an aging population of farmers and small farms being taken over by larger farms or enterprises. Farmers have also become more specialized and focus their production on one or few products, which increases their vulnerability to losses from disease or weather extremes
	Disturbance to tourism industry by certain agricultural practices	The popular tourism industry in the region is affected by unattractive farming practices like hail nets and the spraying of PPPs, and this leads to local conflicts
	Creation of valuable, attractive jobs/retention of employees	Fruit farming is challenged to create and offer attractive jobs with competitive pay in order to find and retain labourers
	Farm succession	Increasing challenge of farm succession in the region as local cities offer higher paying jobs or more comfortable, reliable working conditions than fruit farming
	Lack of societal understanding, acceptance, and appreciation	Lack of societal understanding, acceptance, and appreciation of agricultural practices leads to misguided pressure from society and politics on farmers and their livelihoods, which in turn challenges the existence of fruit farming
Markets and marketing	Power of monopolies	Fewer companies operate along the regional fruit value chain than in previous years due to monopolization, which has given more power to these companies over the farmers
	Price competition and pressure	Competing prices with imported fruits as well as fruits of other production methods, such as IP versus organic products, drives profit margins down
	Inadequate marketing methods/channels	Variety of marketing methods creates a paradox of choice and increasing competition pressures the farmers
	Global competition	The globalised market for fruits challenges the prices of local products

Table 4 (continued)

Category	Descriptive code of challenge	Description of challenge by stakeholders
Socio-econom-ic-environmen-tal nexus	Crop losses due to weather extremes	Crop losses through increasing weather extremes in the region, such as frost, hail, and drought lead to economic challenges
	Land use competition	Land for fruit production competes with, for instance, recreational area, as fruit production regions require optimal climactic conditions. This can cause regional tensions and competition
	Food security	Ensuring high quality, local food production to keep a low food footprint and reduce food imports

Environmental challenges

See Fig. 7.

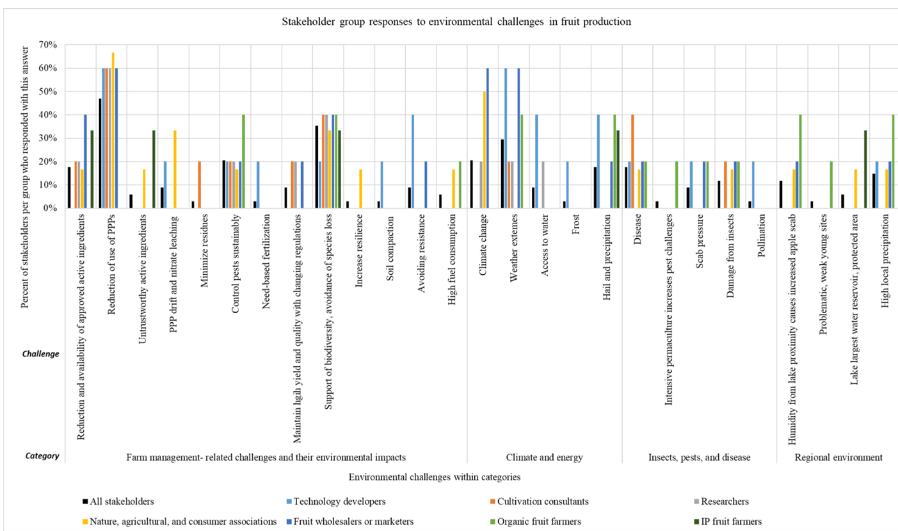

Fig. 7 Reported environmental challenges in fruit production per stakeholder group

Socio-economic challenges

See Fig. 8.

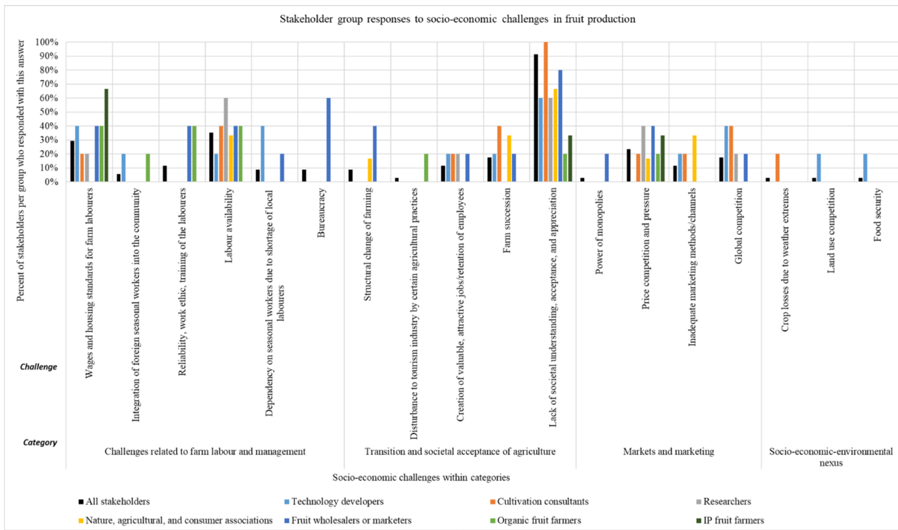

Fig. 8 Reported socio-economic challenges in fruit production per stakeholder group

Author contributions

All authors contributed to the study conception and design. Data collection and analysis were performed by K.G. Material preparation and methodology were led by K.G.; C.R. and C.B. provided guidance and feedback. The first draft of the manuscript was written by K.G.; editing and reviewing were provided by C.R. and C.B. K.G. led the revision; feedback on the revision was provided by C.R. and C.B. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL. This work was supported by the DESIRA Project, funded by the European Commission under Grant Agreement No. 818194.

Data availability

The author confirms that all data generated or analysed during this study are presented within the article and/or the appendix.

Declarations

Ethics approval and consent to participate

This study involved human participants through the use of interviews. The consent form for this study was created through the data protection office of the Karlsruhe Institute of Technology. All participants provided informed consent prior to participation and were assured of confidentiality and the voluntary nature of their involvement. The study design assured protection of study participants and neither included clinical data about participants nor configured itself as a clinical trial. No minors were involved in this study. Participants signed a written informed consent form that confirmed that the recorded and transcribed interviews would be anonymized and used for scientific and teaching purposes. Participants were informed that their participation was voluntary and could be withdrawn at any time.

Consent for publication

Informed consent for publication was obtained from all individual participants interviewed for this study.

Competing interests

The authors declare no competing interests.

Received: 15 November 2024 / Accepted: 27 July 2025

Published online: 12 August 2025

References

1. Stöckle CO, Marsal J, Villar JM. Impact of climate change on irrigated tree fruit production. Acta Hortic. 2011;889:41–52. https://doi.org/10.17660/ActaHortic.2011.889.2.
2. Dierend W. Kulturschutzeinrichtungen im Obstbau. Ulmer. 2009.

3. Krölling C. Optimierung ressourcenschonender Anbau- konzepte zur Qualitätssicherung bei Apfel unter Berücksichtigung des Klimawandels, Freistaat Sachsen, 2021.
4. The European Commission. The European Green Deal: Communcation from the commission to the European parliament, the European Council, the Council, the European economic and social committee and the committee of the regions, Brussels. 2019.
5. The European Commission. The European Green Deal: Annex, Brussels. 2019.
6. Chemnitz C, Wenz K, Haffmans S. Pestizidatlas 2022: Daten und Fakten zu Giften in der Landwirtschaft, Heinrich-Böll-Stiftung. 2022. Available: https://www.boell.de/de/2022/01/04/pestizidatlas.
7. Busse M, et al. Innovation mechanisms in German precision farming. Precis Agric. 2014;15(4):403–26. https://doi.org/10.1007/s11119-013-9337-2.
8. Miranda J, Ponce P, Molina A, Wright P. Sensing, smart and sustainable technologies for agri-food 4.0. Comput Ind. 2019;108:21–36. https://doi.org/10.1016/j.compind.2019.02.002.
9. Walter A, Finger R, Huber R, Buchmann N. Smart farming is key to developing sustainable agriculture. Proc Natl Acad Sci USA. 2017;114(24):6148–50. https://doi.org/10.1073/pnas.1707462114.
10. Basso B, Antle J. Digital agriculture to design sustainable agricultural systems. Nat Sustain. 2020;3(4):254–6. https://doi.org/10.1038/s41893-020-0510-0.
11. Hrustek L. Sustainability driven by agriculture through digital transformation. Sustain. 2020;12(20):1–18. https://doi.org/10.3390/su12208596.
12. Finger R, Swinton SM, El Benni N, Walter A. Precision farming at the nexus of agricultural production and the environment. Annu Rev Resour Econ. 2019;11:313–35. https://doi.org/10.1146/annurev-resource-100518-093929.
13. Hassoun A, et al. The fourth industrial revolution in the food industry—part I: industry 4.0 technologies. Crit Rev Food Sci Nutr. 2023;63(23):6547–63. https://doi.org/10.1080/10408398.2022.2034735.
14. Zscheischler J, et al. Landwirtschaft, Digitalisie- rung und digitale Daten. 2024.
15. Scholz RW, Beckedahl M, Albrecht E, Marx D. DiDaT Weißbuch: Verantwortungsvoller Umgang mit digitalen Daten- Orientierungen eines transdisziplinären Prozesses. Nomos Verlagsgesellschaft. 2021.
16. Scholz RW, et al. Unintended side effects of the digital transition: European scientists' messages from a proposition-based expert round table. Sustainability. 2018. https://doi.org/10.3390/su10062001.
17. Pfeiffer J, Gabriel A, Gandorfer M. Understanding the public attitudinal acceptance of digital farming technologies: a nationwide survey in Germany. Agric Hum Values. 2021;38(1):107–28. https://doi.org/10.1007/s10460-020-10145-2.
18. Prause L. Digital agriculture and labor: a few challenges for social sustainability. Sustainability. 2021;13:5980. https://doi.org/10.3390/SU13115980.
19. Dara R, Hazrati Fard SM, Kaur J. Recommendations for ethical and responsible use of artificial intelligence in digital agriculture. Front Artif Intell. 2022. https://doi.org/10.3389/frai.2022.884192.
20. Gardezi M, et al. Artificial intelligence in farming: challenges and opportunities for building trust. Agron J. 2023. https://doi.org/10.1002/agj2.21353.
21. Ryan M. The social and ethical impacts of artificial intelligence in agriculture: mapping the agricultural AI literature. AI Soc. 2023;38(6):2473–85. https://doi.org/10.1007/s00146-021-01377-9.
22. Ayris K, Jackman A, Mauchline A, Rose DC. Exploring inclusion in UK agricultural robotics development: who, how, and why? Agric Hum Values. 2024. https://doi.org/10.1007/s10460-024-10555-6.
23. van der Burg S, Giesbers E, Bogaardt MJ, Ouweltjes W, Lokhorst K. Ethical aspects of AI robots for agri-food; a relational approach based on four case studies. AI Soc. 2024;39(2):541–55. https://doi.org/10.1007/s00146-022-01429-8.
24. Saleh R, El Benni N, Masson S, Ammann J. Public acceptance and sustainability perceptions of food produced with chemical, digital and mechanical weed control measures. Food Qual Prefer. 2024;113:105079. https://doi.org/10.1016/j.foodqual.2023.105079.
25. Köhler DH. Digitalisierung im Obstbau—Anwendungen und Aussichten. In: Rheinhessischer Obstbautag; 2018, pp. 1–3. Available: https://www.gb-profi.de/fileadmin/user_upload/GBP/Obstbautag_Rheinhessen_2018.pdf.
26. Olum S, Gellynck X, Juvinal J, Ongeng D, De Steur H. Farmers' adoption of agricultural innovations: a systematic review on willingness to pay studies. Outlook Agric. 2020;49(3):187–203. https://doi.org/10.1177/0030727019879453.
27. Feyisa BW. Determinants of agricultural technology adoption in Ethiopia: a meta-analysis. Cogent Food Agric. 2020;6:200. https://doi.org/10.1080/23311932.2020.1855817.
28. Tey YS, Brindal M. Factors influencing the adoption of precision agricultural technologies: a review for policy implications. Precis Agric. 2012;13(6):713–30. https://doi.org/10.1007/s11119-012-9273-6.
29. Degieter M, De Steur H, Tran D, Gellynck X, Schouteten JJ. Farmers' acceptance of robotics and unmanned aerial vehicles: a systematic review. Agron J. 2023;115:2159–73. https://doi.org/10.1002/agj2.21427.
30. Baeten J, Donné K, Boedrij S, Beckers W, Claesen E. Autonomous fruit picking machine: a robotic apple harvester. In: Laugier C, Siegwart R, editors. Field and service robotics: results of the 6th international conference. Berlin: Springer; 2008, pp. 531–539.
31. Zhang J, Kang N, Qu Q, Zhou L, Zhang H. Automatic fruit picking technology: a comprehensive review of research advances, vol. 57. Amsterdam: Springer; 2024.
32. Adarsch A, Pranav PM, Manjunath CR, Soumya KN. Fruit farm surveillance using drones. Int J Trend Sci Res Dev. 2018;2:351–7. https://doi.org/10.31142/ijtsrd12973.
33. Stefas N, Bayram H, Isler V. Vision-based UAV navigation in orchards. IFAC Pap Online. 2016;16:10–5. https://doi.org/10.1016/j.ifacol.2016.10.003.
34. Zhang C, Valente J, Kooistra L, Guo L, Wang W. Orchard management with small unmanned aerial vehicles: a survey of sensing and analysis approaches. New York: Springer; 2021.
35. Zhang Q, Karkee M, Tabb A. The use of agricultural robots in orchard management. In: Billingsley J, editor. Robotics and automation for improving agriculture. Cambridge: Burleigh Dodds Science Publishing; 2019. p. 187–214.
36. Siefen N. Apfel4.NULL: einsatz von sensoren für eine nachhaltige Produktion und Lagerung. Besseres Obst. 2021;16–17.
37. Siefen N, McCormick RJ, Vogel AM, Biegert K. Effects of laser scanner quality and tractor speed to characterise apple tree canopies. Smart Agric Technol. 2023;4:100173. https://doi.org/10.1016/j.atech.2023.100173.
38. Biegert K. Smart Horticulture: application of sensors and modelling to predict fruit growth, quality and storage behaviour of 'Braeburn' apples. 2022.

39. Miranda JC, et al. Fruit sizing using AI: a review of methods and challenges. Postharvest Biol Technol. 2023. https://doi.org/10.1016/j.postharvbio.2023.112587.
40. Barbole DK, Jadhav PM, Patil SB. A review on fruit detection and segmentation techniques in agricultural field BT. In: Second international conference on image processing and capsule networks; 2022, pp. 269–288.
41. Kodors S, Lacis G, Zhukov V, Bartulsons T. Pear and apple recognition using deep learning and mobile. Eng Rural Dev. 2020;19(May):1795–800. https://doi.org/10.22616/ERDev.2020.19.TF476.
42. Nordmark L, et al. Launch of IoT and artificial intelligence to increase the competitiveness in Swedish apple and grapevine production. Acta Hortic. 2021;1314:235–40. https://doi.org/10.17660/ActaHortic.2021.1314.30.
43. Hassoun A, et al. Implementation of relevant fourth industrial revolution innovations across the supply chain of fruits and vegetables: A short update on Traceability 4.0. Food Chem. 2023. https://doi.org/10.1016/j.foodchem.2022.135303.
44. Ossevoort R, Verdouw C, Frans De Jong P, Hennen En W, Robbemond R. Fruit 4.0: De vruchten van meer technologie Technologie-roadmap. 2016. Available: http://library.wur.nl/WebQuery/wurpubs/fulltext/385030.
45. Gaber K, Rösch C, Bieling C. Digital transformation of fruit farming in Germany: digital tool development, stakeholder perceptions, adoption, and barriers. NJAS Impact Agric Life Sci. 2024. https://doi.org/10.1080/27685241.2024.2349544.
46. Spykman O, Emberger-Klein A, Gabriel A, Gandorfer M. Autonomous agriculture in public perception—German consumer segments' view of crop robots. Comput Electron Agric. 2022;202:107385. https://doi.org/10.1016/j.compag.2022.107385.
47. Langer G, Kühl S. Perception and acceptance of robots in dairy farming—a cluster analysis of German citizens. Agric Hum Values. 2024;41(1):249–67. https://doi.org/10.1007/s10460-023-10483-x.
48. von Veltheim FR, Theuvsen L, Heise H. German farmers' intention to use autonomous field robots: a PLS-analysis. Precis Agric. 2022;23:670–97. https://doi.org/10.1007/s11119-021-09854-3.
49. von Veltheim FR, Heise H. German farmers' attitudes on adopting autonomous field robots: an empirical survey. Agriculture. 2021;11:216. https://doi.org/10.3390/AGRICULTURE11030216.
50. Wilmes R, Waldhof G, Breunig P. Can digital farming technologies enhance the willingness to buy products from current farming systems? PLoS ONE. 2022;17:1–20. https://doi.org/10.1371/journal.pone.0277731.
51. Tranchina M, et al. Exploring agroforestry limiting factors and digitalization perspectives: insights from a european multi-actor appraisal. Agrofor Syst. 2024;98(7):2499–515. https://doi.org/10.1007/s10457-024-01047-x.
52. Argente García JE, et al. Digitalising governance processes and water resources management to foster sustainability strategies in the Mediterranean agriculture. Environ Sci Policy. 2014. https://doi.org/10.1016/j.envsci.2024.103805.
53. Knierim A, Kernecker M, Erdle K, Kraus T, Borges F, Wurbs A. Smart farming technology innovations—Insights and reflections from the German Smart-AKIS hub. NJAS Wageningen J Life Sci. 2019. https://doi.org/10.1016/j.njas.2019.100314.
54. Gaber K, Rösch C, Bieling C. The impact of digitalization on the public opinion of fruit farming: stakeholder perspectives in Germany. NJAS Impact Agric Life Sci. 2025. https://doi.org/10.1080/27685241.2025.2508139.
55. Bundesinformationszentrum Landwirtschaft. Wie viele landwirtschaftliche Betriebe gibt es in Deutschland und wie groß sind sie? 2024. Available: https://www.praxis-agrar.de/service/infografiken/wie-viele-landwirtschaftliche-betriebe-gibt-es-in-deutschland.
56. Statistische Ämter des Bundes und der Länder. Landwirtschaftliche Betriebe mit Anbauflächen gartenbaulicher Erzeugnisse 2016. 2019. Available: https://www.statistikportal.de/en/node/266.
57. Landwirtschaftliches Technologiezentrum Augustenberg. Integrierter Pflanzenschutz 2023: Erwerbsobstbau. 2023.
58. Das Grüne Lexikon Hortipendium. Gemüseanbau: Bio oder Konventionell. 2021. https://hortipendium.de/Gemüseanbau:_Bio_oder_Konventionell.
59. Bundesministerium für Ernährung und Landwirtschaft. Der Gartenbau in Deutschland: Auswertung des Gartenbaumoduls der Agrarstrukturerhebung 2016, Berlin. 2016. Available: https://www.bmel.de/SharedDocs/Downloads/Broschueren/Gartenbauerhebung.pdf?__blob=publicationFile.
60. Statistisches Landesamt Baden-Württemberg. Pressemitteilung 2015/2022: Äpfel dominieren den Obstanbau in Baden-Württemberg. Größstes Anbaugebiet am Bodensee, Stuttgart. 2022. Available: http://www.statistik-bw.de/Presse/Pressemitteilungen/2022205.
61. Kösler J. Statistisches Monatsheft Baden-Württemberg: Der Baden-Württembergische Baumobstanbau. 2023.
62. Fanzo J. From big to small: the significance of smallholder farms in the global food system. Lancet Planet Health. 2017;1(1):e15–6. https://doi.org/10.1016/S2542-5196(17)30011-6.
63. Grasswitz TR. Integrated pest management (IPM) for small-scale farms in developed economies: challenges and opportunities. Insects. 2019. https://doi.org/10.3390/insects10060179.
64. Bodensee-Stiftung. Zukunftsfähiger Bodensee: Jahresbericht 2013, Radolfzell. 2013. Available: https://www.bodensee-stiftung.org/wp-content/uploads/BoSti_Jahresbericht_13_0.pdf.
65. Bodensee-Wasserversorgung. Die Bodensee-Wasserversorgung: Wasser aus dem See- Trinkwasser aus dem Hahn. https://www.bodensee-wasserversorgung.de/startseite.html. Accessed 10 Dec 2023.
66. Bodensee Biene and Obst vom Bodensee. Ja zu Bienen und Artenvielfalt. 2019. https://www.bodenseebiene.de/wp-content/uploads/2019/09/bodenseebiene-flyer.pdf. Accessed 15 May 2024.
67. Moderner Landwirt. Stiller Protest der Landwirte auf der Fruchtwelt Bodensee. 2024. https://moderner-landwirt.de/stiller-protest-der-landwirte-auf-der-fruchtwelt-bodensee/. Accessed 18 May 2024.
68. Matthews A. Farmer protests and the 2024 European parliament elections. Intereconomics. 2024;59(2):83–7. https://doi.org/10.2478/ie-2024-0018.
69. Weible D, Christoph-Schulz I, Salamon P, Zander K. Citizens' perception of modern pig production in Germany: a mixed-method research approach. Br Food J. 2016;118(8):2014–32. https://doi.org/10.1108/BFJ-12-2015-0458.
70. Bundesministerium für Ernährung und Landwirtschaft. Deutschland, wie es isst: Der BMEL-Ernährungsreport 2022. 2022. Available: https://www.bmel.de/SharedDocs/Downloads/Broschueren/Ernaehrungsreport2019.pdf?__blob=publicationFile%0Ahttp://www.bmel.de/SharedDocs/Downloads/Broschueren/Ernaehrungsreport2017.pdf?__blob=publicationFile.
71. Bryman A. Social research methods, vol. 4. New York: Oxford University Press; 2012.
72. Goodman LA. Snowball sampling. Ann Math Stat. 1961;32(1):148–70. https://doi.org/10.1214/aoms/1177705148.
73. Johnson G, Scholes K, Whittington R. Stakeholder mapping: the power/interest matrix. 2008.
74. Mendelow AL. Environmental scanning—the impact of the stakeholder concept.In: Proc. int. conf. inf. syst.; 1981, pp. 407–417.

75. Bundesministerium für Ernährung und Landwirtschaft. Landwirtschaftliche Arbeitskräfte, Landwirtschaft, 2020. https://www.bmel-statistik.de/landwirtschaft/landwirtschaftliche-arbeitskraefte. Accessed 25 Jul 2024.
76. DESIRA. The Project: about DESIRA. 2019. https://desira2020.eu/the-project/.
77. Mayring P. Qualitative content analysis. Forum Qual Soc Res. 2000;1:10.
78. Saldaña J. The coding manual for qualitative researchers. 2013.
79. Bronson K. Looking through a responsible innovation lens at uneven engagements with digital farming. NJAS Wageningen J Life Sci. 2019;90–91:100294. https://doi.org/10.1016/j.njas.2019.03.001.
80. Prause L, Hackfort S, Lindgren M. Digitalization and the third food regime. Agric Human Values. 2021;38(3):641–55. https://doi.org/10.1007/s10460-020-10161-2.
81. Jankowski P, Hoffmann ML, Rohde F, Rehak R. Shaping digital transformation for a sustainable society—Contributions from Bits und Bäume.2023.
82. Granatstein D, Kupferman E. Sustainable horticulture in fruit production. Acta Hortic. 2008;767:295–308. https://doi.org/10.17660/ActaHortic.2008.767.31.
83. Medici M, Canavari M, Toselli M. Interpreting environmental impacts resulting from fruit cultivation in a business innovation perspective. Sustain. 2020;12(23):1–14. https://doi.org/10.3390/su12239793.
84. The European Commission. Proposal for a regulation of the European parliament and of the council: establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law). Brussels. 2020. https://doi.org/10.1017/CBO9781107415324.004.
85. The European Commission. Farm to Fork Strategy. 2020.
86. Bundesministerium für Ernährung und Landwirtschaft. Biodiversity: Protecting bees and insects. Topics >Farming >Species Diversity. 2023. https://www.bmel.de/EN/topics/farming/species-diversity/biodiversity-protecting-bees-insects.html.
87. Rentenbank. Förderung des BMEL-Investitionsprogramm Landwirtschaft. Landwirtschaft, 2023. https://www.rentenbank.de/bmel-zuschuesse/landwirtschaft/#:~:text=Die. Landwirtschaftliche Rentenbank bietet im 2024.
88. Martens K, Zscheischler J. The digital transformation of the agricultural value chain: discourses on opportunities, challenges and controversial perspectives on governance approaches. Sustainability. 2022. https://doi.org/10.3390/su14073905.
89. Purvis B, Mao Y, Robinson D. Three pillars of sustainability: in search of conceptual origins. Sustain Sci. 2019;14(3):681–95. https://doi.org/10.1007/s11625-018-0627-5.
90. Hilbert M. The end justifies the definition: the manifold outlooks on the digital divide and their practical usefulness for policy making. Telecomm Policy. 2011;35:715–36. https://doi.org/10.1016/j.telpol.2011.06.012.
91. Bundesministerium für Ernährung und Landwirtschaft. Ackerbaustrategie 2035; 2019, p. 68.
92. Carolan M. Automated agrifood futures: robotics, labor and the distributive politics of digital agriculture. J Peasant Stud. 2020;47(1):184–207. https://doi.org/10.1080/03066150.2019.1584189.
93. Rotz S, et al. Automated pastures and the digital divide: how agricultural technologies are shaping labour and rural communities. J Rural Stud. 2019;68:112–22. https://doi.org/10.1016/j.jrurstud.2019.01.023.
94. Kernecker M, Knierim A, Wurbs A, Kraus T, Borges F. Experience versus expectation: farmers' perceptions of smart farming technologies for cropping systems across Europe. Precis Agric. 2020;21(1):34–50. https://doi.org/10.1007/s11119-019-09651-z.
95. Kutter T, Tiemann S, Siebert R, Fountas S. The role of communication and co-operation in the adoption of precision farming. Precis Agric. 2011;12(1):2–17. https://doi.org/10.1007/s11119-009-9150-0.
96. Daberkow SG, McBride WD. Farm and operator characteristics affecting the awareness and adoption of precision agriculture technologies in the US. Precis Agric. 2003;4(2):163–77. https://doi.org/10.1023/A:1024557205871.
97. Ricciardi V, Mehrabi Z, Wittman H, James D, Ramankutty N. Higher yields and more biodiversity on smaller farms. Nat Sustain. 2021;4(7):651–7. https://doi.org/10.1038/s41893-021-00699-2.
98. Wiggins S, Kirsten J, Llambí L. The future of small farms. World Dev. 2010;38(10):1341–8. https://doi.org/10.1016/J.WORLDDEV.2009.06.013.
99. Bundesministerium für Ernährung und Landwirtschaft. Klöckner: Farmers must be winners in trade Background. Press Release. 2020. https://www.bmel.de/SharedDocs/Pressemitteilungen/EN/2020/abschluss-gffa-2020.html.
100. Zimbelman RG, Wilson LL, Bennett MB, Curtis SE. Public image of animal agriculture in the United States. Livest Prod Sci. 1995;43(2):153–9. https://doi.org/10.1016/0301-6226(95)00040-R.
101. Rumble JN, Irani T. Opening the doors to agriculture: the effect of transparent communication on attitude. J Appl Commun. 2016. https://doi.org/10.4148/1051-0834.1030.
102. Igo C, Frick M. A case study assessment of standard benchmarks for implementing food and fiber systems literacy. 1999.
103. Zukunftskommission Landwirtschaft. The Future of Agriculture A common agenda. 2021.
104. Deutsche Landwirtschafts-Gesellschaft. Digitale Landwirtschaft: Ein Positionspapier der DLG. Frankfurt am Main, 2018. Available: https://www.dlg.org/fileadmin/downloads/fachinfos/DLG_Position_Digitalisierung.pdf.
105. Zhang Y, et al. Blockchain: an emerging novel technology to upgrade the current fresh fruit supply chain. Trends Food Sci Technol. 2022;124:1–12. https://doi.org/10.1016/j.tifs.2022.03.030.
106. FAO and WFF. Digital technologies for multidimenstional youth engagement in agrifood systems transformation, Rome. 2024.
107. Matzak F. Eine technologie sorgt für transparenz. In: Ökologie und landbau; 2021, pp. 28–30.
108. Sonntag WI, Ermann M, Spiller A, von Meyer-Höfer M. Im Streit um die Nutztierhaltung: Gesllschaftsorientierte Kommunikationsstrategien für die Agrar- und Ernährungswirtschaft. Ger J Agric Econ. 2021;10:1–16.

Publisher's Note