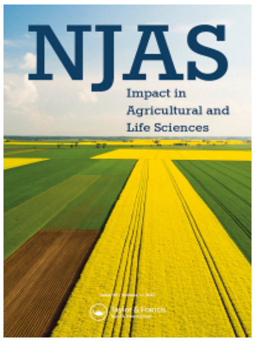

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Digital transformation of fruit farming in Germany: Digital tool development, stakeholder perceptions, adoption, and barriers

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ABSTRACT
The digital transformation of agriculture promises technical solutions for present and future challenges. However, it cannot be assumed that such promises will automatically lead to implementation of the technologies, nor if the technologies meet the user expectations. To this end, the authors conducted a novel review and characterization of over 200 digital tools for fruit cultivation by on-farm functions and 23 interviews with stakeholders related to fruit cultivation in the case-study region of Lake of Constance, Germany. Results indicate strengths and weaknesses in the development of digital tools. A cross-analysis of the available tools, stakeholder expectations, and implemented tools indicates commonalities and discrepancies. Tool characteristics that meet stakeholder expectations and adoption by farmers are identified, as well as those that may be impacted greatest by the reported barriers. An uneven distribution of knowledge on digitalisation in this sector was evident among stakeholders. The authors identify opportunities for technological development and recommendations to support a user-oriented transformation. Unsuitable tool development and an uneven distribution of digital knowledge in the fruit production industry could lead to a consequential sectoral, regional, and/or national digital divide between those with access to cutting-edge technologies and those without. To further improve the sustainability and resilience of food production, technological development must take into account the needs of stakeholders and support a more user-orientated strategy to support the transformation. Further research on stakeholders' perspectives on digital innovations is needed to investigate if the findings match to other fruit growing regions in Germany and abroad.

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KEYWORD Digital technology; stakeholder perceptions; adoption; barriers; Germany; fruit farming

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1. Introduction

Agriculture 4.0, in which physical and virtual objects, or digital tools, are controlled and connected through smart networks along the agricultural value chain, can improve the efficiency and transparency of production, storage, transport, and sales of agricultural goods (Arvanitis & Symeonaki, 2020; Madushanki et al., 2019; Talavera et al., 2017; Uwe et al., 2016; Zambon et al., 2019). Digital tools can improve production efficiency by minimizing the use of water, fuel, and fertilizer through increased precision techniques and by promoting the use of renewable energy (J. Miranda et al., 2019; Van Haarlem, 2020). Digital tools are defined by Bacco et al. (2020a) as a "physical and/or virtual instance relying on digital technologies (or on a set of those, as in a digital paradigm) having a given function as defined in its design phase". Digital technologies, therefore, are a combination of hardware and software to make use of digital data (Bacco et al., 2020b).

There is high hope that digitalization can support the transformation of the agriculture and food sector to become both more efficient and more sustainable. Consequently, environmental impacts and social concerns are to be mitigated. Though agriculture has been attributed as having a leading role in German digitalization (Bitkom et al., 2020), the digitalization of the fruit sector is lagging behind (Ossevoort et al., 2016). A wide range of digitalized tools for fruit farming exists, yet little is known about how or if these meet the needs and expectations of technology users.

The models of digital technology development govern the distribution and availability of technologies across agricultural sectors, geographical regions, farming systems, and farm sizes. Digitalization may be driven by the technology-push (TP) model, fostered by advances in science and technology (e.g. Global Navigation Satellite Systems, sensors, web platforms and app applications on mobile phones), or the demand-pull (DP) model, for which technology development emerges as a response to the perceived market potential (Rothwell & Zegveld, 1985). TP and DP are interdependent because R&D objectives may be demand-selected and market needs may arise in response to innovation (Saviotti & Pyka, 2013).

According to the core assumption of the social construction of technology (SCOT), technology includes the physical hardware as well as the required knowledge and associations to implement the technology (Bijker & Pinch, 1987; Vik et al., 2021). The social construction involves a complex interaction between different social groups, each of which sees future technology as a solution to a problem. These groups have their own unique interests, which are reflected in their varying opinions about the emerging technologies. Whether or not digitalisation actually solves the problem of agriculture, and in this case study of fruit production, is not a question of technical rationality but depends significantly on whether the affected stakeholders believe that the technical innovation can solve their problems. Therefore, understanding if the digital tools available match the expectations of digital technology consumers, such as farmers and other agricultural actors like advisors, marketers, and developers, is critical for the diffusion of innovations. Beyond that, technology use by individual farmers determines their participation in the transformation and the speed of its progression.

Farmers require technological support to tackle the present and future techno-economic, environmental and social challenges of fruit production. The fruit sector in particular is highly unpredictable with workability restraints such as labour shortages (Marinoudi et al., 2021). Other challenges include dependency on labourers for hand-labour such as tree thinning, the political demands on the use of production resources (e.g. pesticides, fertilizers), increasing crop failure due to higher frost rates and water requirements from climate change, and increasing consumer pressure for sustainable, high-quality, and low-cost fruit.

Against this background, the aims of this study are as follows:

- To provide a comprehensive review of available digital innovations in fruit farming based on on-farm tasks
- Investigate expectations for digitalization in fruit production, barriers, and adoption from stakeholders in case study region
- identify commonalities and discrepancies between characteristics of digital tools for fruit production with the expectations of stakeholders and adopted tools

We hypothesize that in times of strong policy support in a technological field, such as digitalization, businesses will focus on providing technical tools and competing in the fast-growing market rather than on the market's needs, therefore following technology-push policies rather than demand-pull.

The digital tool review fills the research gap surrounding characteristics of digital tools in fruit production and serves as a status-quo marker for the timeframe of the analysis. The qualitative interview assessment and the comparative results highlight the extent to which interviewed stakeholder needs are being met, potential for further tool development, and knowledge gaps of stakeholders on abilities of digital tools. This study provides valuable information to future users of the reviewed technologies, tool developers, and policymakers at a critical moment in time, as the transition towards the fourth agricultural revolution is still underway, and deficiencies in digital tool development could create inequalities across agricultural sectors and geographical regions.

The rest of this article is structured as follows. Section 2 introduces a background on previous state of the art (SOTA) studies for digital agricultural tools and technology adoption. Section 3 details the methodologies used for the digital tool review and the stakeholder assessment, interview series, interview content analysis, and cross-analysis. Section 4 contains the results of this article and thus describes the outcomes of the digital tool review, qualitatively assesses technology adoption and barriers among farmers in the case study region, and compares the perceived characteristics of digitalized technologies in fruit production with the characteristics of adopted tools and of those found in the tool review. Section 5 discusses the study limitations, the derived implications from the cross-analysis, the intricacies of the farmer interviews, and identifies opportunities for digital tool development. Finally, Section 6 concludes this paper.

2. Background

2.1. State of the art studies for digital agricultural tools

Terminology, depth of digitalization (e.g. systems perspective versus individual technology categories), and agricultural sector of study differ amongst previously published SOTA studies on digital agricultural tools (see Appendix). For instance, while some studies use the term "precision agriculture technologies" (e.g. Bhakta et al., 2019; Bucci et al., 2018; Lowenberg-Deboer & Erickson, 2019), others have synonymously used "smart farming technologies" (SFTs) (e.g. Balafoutis et al., 2017; Noack, 2019) or "technological enablers" (e.g. Aceto et al., 2019). The complex nature of digitalization in agriculture may be perpetuated through the interchangeable use of synonymous terms. A clear definition of technologies included in precision agriculture (PA) does not exist (Lowenberg-Deboer & Erickson, 2019).

While some research provides a broad spectrum of technologies within smart farming (e.g. Karunathilake et al., 2023; Navarro et al., 2020), others have focused on reviewing technology sub-categories, such as apps (e.g. Inwood & Dale, 2019), Unmanned Aerial Vehicles (UAVs) (e.g. Lan et al., 2017), or robotics (e.g. Aravind et al., 2017; Roldán et al., 2017; Thomasson et al., 2019). Reviews of sub-categories within artificial intelligence (AI) for agriculture such as Big Data, computer vision, digital twins, deep learning, and machine learning (e.g. Bhat & Huang, 2021; Coulibaly et al., 2022; Liakos et al., 2018; Patrício & Rieder, 2018; POPA, 2011; Purcell & Neubauer, 2023) add to existing literature on digital agricultural tools. At the same time, other studies consider the complexity of systems rather than an independent aspect of digital agriculture. Bacco et al. (2020a) conducted a taxonomy and inventory of "Digital Game Changers" (DGC), which are considered based on their ability to change aspects and actors of social and economic life. Similarly, Arvanitis and Symeonaki (2020) used the category "agricultural cyber-physical systems" (ACPSs) in their review of

Agricultural 4.0 technologies to describe interactions within agricultural systems, and Benyam et al. (2021) employed a systems perspective to their review of digital agricultural technologies food loss and waste prevention.

Other SOTAs assessed Internet of Things (IoT) systems of particular sectors or types of agriculture (e.g. Shi et al., 2019; Talavera et al., 2017; Villa-Henriksen et al., 2020). As previously mentioned, the digitalization of the fruit sector lags behind other sectors, and thus fewer SOTAs exist for digital fruit production. Digital agriculture reviews for fruit farming have focused on specific technology solutions such as Unmanned Aerial Vehicles (UAV)s and robotics in orchards (e.g. Adarsch et al., 2018; Stefas et al., 2016; C. Zhang et al., 2021; Q. Zhang et al., 2019), AI in viticulture and horticulture (e.g. J. C. Miranda et al., 2023; Tardaguila et al., 2021), or highlighted current projects and development (e.g. Köhler, 2018; Zoth, 2018).

The most common approach among the reviewed SOTAs was to group and then assess the technologies or tools based on their technology categories, e.g. web-based technologies and cloud-based computing. While SOTAs for digital agricultural tools are numerous, few studies consider tools outside of published research articles, such as on-market apps (see e.g. Inwood & Dale, 2019) and rather reference research articles with experimental data. Furthermore, these systematic reviews have focused primarily on technical specifications of the tools rather than on-farm functions. Exceptions include the studies by Q. Zhang et al. (2019) and Van Haarlem (2020), which reviewed literature on technology applications on fruit farms based on on-farm functions performed by agricultural robots and by digital technologies applicable in the Netherlands, respectively. The present study compliments these outcomes by expanding the review of digital agricultural tools based on on-farm tasks, which increases the practicality of the results and applicability for digitalization's intended end-users, such as farmers.

While it is purposeful to assess the available or researched technologies per technology category or other unique categorization methods, it can be impractical for users and developers of the technologies, as the categorization is not based on the on-farm functions. Therefore, it is unclear what technologies are available per field task and if these technologies can be used across multiple on-farm activities. The studies that categorize based on on-farm activity do not include post-harvest, marketing, or communication opportunities for the farmer. Farmer-to-farmer communication has been named one of the most important sources of information in a cross-country farmer survey (Knierim et al., 2018). Additionally, the lack of on-farm information about the adoption of these tools and expectations of farmers creates a gap between the theoretical versus reality.

2.2. Technology adoption in agriculture

Technology adoption in agriculture, particularly regarding PA techniques, has been researched considerably, though often only a few aspects or farm characteristics have been investigated (Busse et al., 2014; Pathak et al., 2019; Paustian & Theuvsen, 2017). The way in which digital technologies can be used at the farm-level to improve sustainability appears to be inadequately assessed and communicated (Coteur et al., 2016; Knierim et al., 2018). Lowenberg-Deboer and Erickson (2019) argue that data collection methods on PA adoption also vary from country to country, which challenges comparisons among existing studies. The previously mentioned issue of synonymous, interchangeable terminology in this field and lack of a clear definition of tools further complicates comparability.

An approach focused on the perception of potential users and the connection to intended or unintended use of new technology is the Technology Acceptance Model (TAM) methodology (Davis, 1989). This model is widely used to understand new technology adoption (King & He, 2006; Pierpaoli, 2013) and is derived from the Theory of Planned Behavior (Ajzen, 1991; Fishbein & Azjen, 1975), which tests the influencing factors to a potential user's decision regarding when and how new technology is used (Pierpaoli, 2013). Other technology adoption models have a more economic focus, such as the induced innovation theory (Hicks, 1932), the diffusion model by Griliches (1957), or the Net Present Value analysis, the most basic method for investment decisions (Gallardo & Sauer, 2018). However, these econocentric models include limitations: in general, the theories do not consider human aspects of technology adoption, such as uncertainties in the investment decision or decision-maker. This is where empirical studies, including the present study, are advantageous.

Empirical approaches are common among studies on technology adoption in agriculture. Similar to available state-of-the-art reviews, most studies on technology adoption in agriculture focus on industrial cropping systems (Pathak et al., 2019). Several large-scale surveys have been conducted among farmers across Europe (e.g. A. P. Barnes et al., 2019; Blasch et al., 2020; Groher et al., 2020; Knierim et al., 2018). Generally, these studies found that adoption rates varied across branches of agriculture and technology type (Groher et al., 2020) and systems, leading to inequalities in technology access (A. Barnes et al., 2019).

Determining technology adoption factors appear to be demographic factors such as age (A. Barnes et al., 2019). In Germany, technology adoption has previously been determined by demographic factors including age, education, and farm size (Michels et al., 2019). Paustian and Theuvsen (2017) found that German farmers owning farms smaller than 100 ha were less likely to adopt precision technologies. Younger farmers were considered to have positive attitudes towards cloud technologies in their fields (Das et al., 2019). Still, other studies show that farmer demographics were not as important as perceptions and attitudes regarding the farm and technology at hand (e.g. Kernecker et al., 2016; Tey & Brindal, 2012). Das et al. (2019) surveyed 32 Irish farmers with mixed methods (interviews and surveys) and found cost to be the most significant factor influencing SFT adoption, including unavailability of lower-cost technologies for small farms. Similar to Knierim et al. (2018) and Blasch et al. (2020), however using a mixed-methods approach with a survey, interviews, and a workshop, Busse et al. (2014) concluded that German farmers and their communication networks play a significant role in the acceptance and generation of innovations.

Factors that are often studied in other industries are underrepresented among agricultural studies on technology adoption and the complex nature of adoption is poorly explained (Pathak et al., 2019). Research on technology adoption rates and empirical research on the reasons behind the farmers' decisions to adopt must be conducted in all agricultural sectors and regions to avoid inequality in the development and uptake of promising technologies.

3. Methods

3.1. Digital tool review

In order to assess the characteristics of tools in fruit production, a review of available tools was analysed. Selection criteria for these tools were defined. First, the tools must fit the definition of digital technologies by Birner et al. (2021b) as technologies that use binary, or machine-readable, data which embody a physical product (such as an automatic harvester) or technologies to provide disembodied services (such as apps or farm management programmes). Secondly, the tool must be usable in fruit production, either marketed for or compatible for use in fruit production systems. The boundaries of fruit production for this study are defined in Figure 1. These boundaries consider that most fruit grown in Germany is sold and consumed as table fruit and therefore not processed into other products such as alcohol (Statistisches Bundesamt, 2019b). Furthermore, the fruits of interest for this study are those grown commonly in Germany, in particular tree fruits such as apple, pear, cherry, plum, apricot, and peach. Other relevant fruits are wine grapes, currants, raspberries, blueberries, and strawberries (Statistisches Bundesamt, 2019a). Finally, the tools should be considered in the prototype or on-market phase of development. As the development of this industry is rapid, this tool review should be considered as a snapshot into the available tools in and until the spring of 2021, and it is likely that the tools considered at this point to be "prototypes" could quickly be available on-market after the review was conducted.

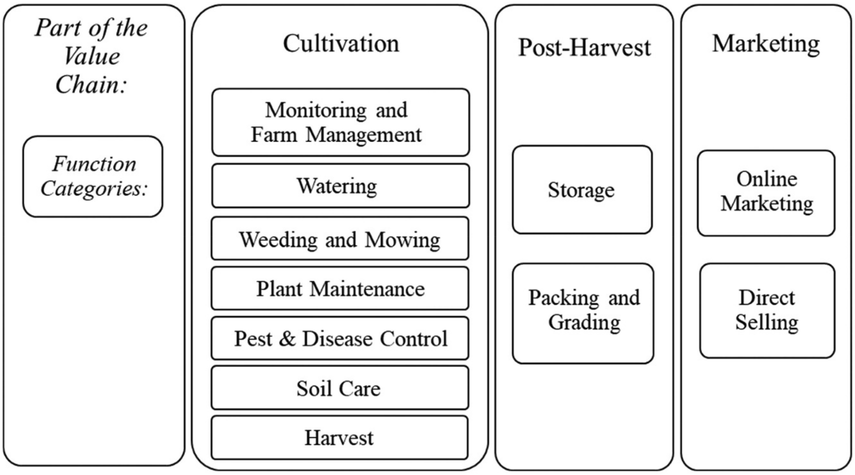

Figure 1. Characteristics of the fruit value chain considered within this study.

Considering these selection criteria, a comprehensive literature and media review was conducted to collect the tool review using the standalone literature review method (Templier & Paré, 2015). The standalone review attempts to interpret the body of existing literature. This review was then further compared against interview responses form stakeholders. Between January and April of 2021, reports on ongoing research projects (running during the year 2021), marketed products and their company websites, conferences and trade fairs, and news articles were searched for in relation to fruit production. These sources are dated until April 2021. Additionally, an internet search was conducted per listed function in the fruit production system boundary (e.g. "digitalized fruit storage") to find sources such as news articles, company websites to ensure that all value chain sections were searched for (Figure 2). The information for the tools that met the previously listed criteria were collected into a spreadsheet (provided as an additional file) for analysis.

3.1.1. Digital tool review categorization

The tool review was systematically organized to assess specific characteristics of the tools. A total of 14 inductive or deductive categories were used to categorize the tools (see Appendix). The deductive categories were determined prior to the review of the tools based on information of value for the interested users, developers, and policy makers regarding digital technologies in fruit production. These categories include stage of development (prototype or on-market), technology type (embodied or disembodied (Sunding & Zilberman, 2001)), part of the value chain (cultivation, post-harvest, and marketing), sector of agriculture (horticulture: fruit, horticulture: vegetables, viticulture, and arable farming), usability (stand alone or

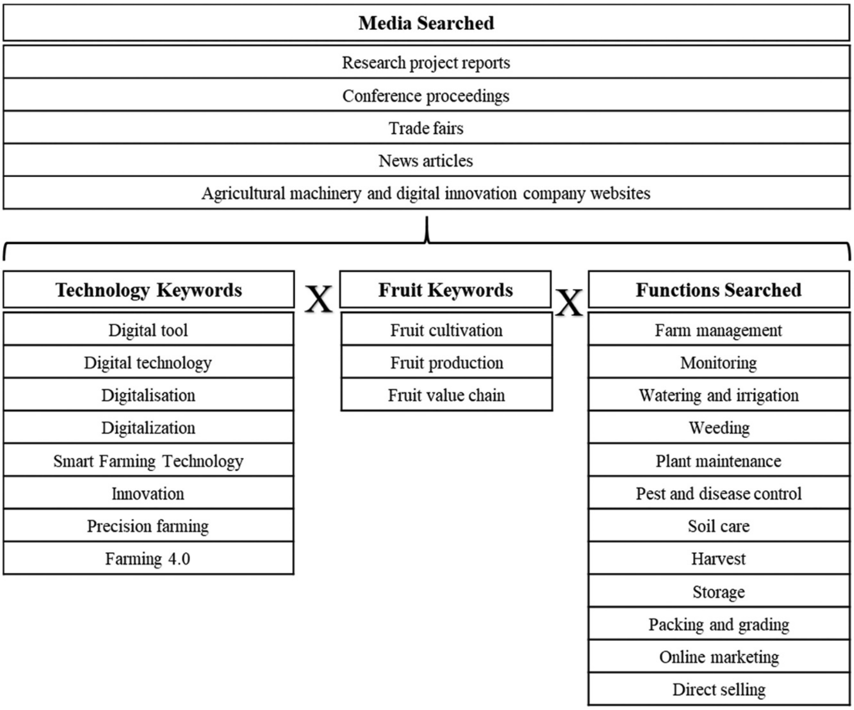

Figure 2. Overview of searched media and keywords for digital tool review.

dependent), form of connectivity (one-to-one, one-to-many, or many-to-many (Porter & Heppelmann, 2014)), and capability (monitoring, control, or autonomous capabilities (Porter & Heppelmann, 2014)).

Some categories required only a binary coding decision of yes or no: German customer/technical support, service, and multifunctionality. Characteristics within inductive categories were established as the tools were assessed: the location of the company, technology category, function, and function category.

3.2. Interviews

3.2.1. Region of study

The region of the study was the Lake of Constance region in southern Germany. This region is the second-largest fruit cultivation region in Germany with 1,017 fruit farms in the counties of Konstanz, Bodensee-Kreis, Ravensburg, and Lindau (Bundesministerium für Ernährung und Landwirtschaft BMEL, 2016). The climatic characteristics of the area, such as mild temperatures and annual precipitation of 900 mm, are advantageous to the fruit growing sector (Landkreis Konstanz, & Landratsamt Bodenseekreis, 2017). Apples, pears, plums, and cherries are the most commonly grown fruits and are produced in orchards for fresh consumption (BMEL, B. für E. und L, 2020). Around 8,500 ha of agricultural land in the region are organically farmed, accounting for about 12 % of the area compared to the national average of 9,6% (Grimminger et al., 2018). The average sizes of fruit farms in Germany and within the state of Baden-Württemberg at 7 ha and 4,6 ha, respectively (LEL Schwäbisch Gmünd, 2017; Statistisches Bundesamt DESTATIS, 2017) are smaller than farms in other sectors.

3.3. Stakeholder mapping and selection

Stakeholders were selected for their relevance to the fruit value chain in the Lake Constance region. Using purposive sampling (Bryman, 2012), potential participants were strategically collected in relation to the research question: stakeholders who are the intended users of the technologies and the developers of the technologies were approached for their interest in an interview. Additionally, experts were consulted and asked to define relevant stakeholder groups in the regional value chain. The stakeholder groups are fruit farmers, fruit cultivation and plant protection products (PPP) advisors, fruit wholesalers or marketers, and agricultural machinery and digital innovation developers (Table 1). When divided into interests or stakes in digital tools for fruit production, the former three groups are considered the intended users of the tools, while the latter group is considered the developer group. Of the intended users, farmers are the most targeted users for agricultural technologies. For this reason, more farmers than other stakeholders were sought to take part in the interviews and were reached through snowball sampling (Goodman, 1961): the authors contacted a regional fruit cultivation advisor and a leader of an agricultural organization with the request to provide contact information of farmers who might be interested in participating. Of these farmers, eight were interviewed for the study: five organic farmers and three integrated production (IP) farmers. This group is not representative of the region, but their participation provided useful insights for the purpose of this study.

3.4. Interview process

A semi-structured interview guideline was developed for the interview series to answer the research questions (see Appendix). This guideline was developed by the authors and tested with two expert interviews in early 2020. The guideline was used for a series of interviews as part of the DESIRA project (DESIRA, 2019) and therefore covers more topics than are relevant for the present study. The interview questions of most relevance for this study were questions 15, 20, and 25 regarding the use of digitalized tools, what the

Table 1. Stakeholder group descriptions ($n = 4$).

Type of interest/ stake	Stakeholder group	Description	#	%
Users	Fruit farmers	Farmers predominantly engaged in fruit production on their agricultural land, employing either Integrated Production (IP) or organic principles.[1]	8	34,7%
	Fruit cultivation and plant protection product (PPP) advisors	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 fertilizers.	5	21,7%
	Fruit wholesalers or marketers	Individuals serving as employees or leaders within fruit wholesale organizations or companies or individuals in similar roles within farm shops that offer local delivery services.	5	21,7%
Developers	Agricultural machinery and digital innovation developers	Individuals working as employees or leaders in agricultural machinery or technology companies, ranging from start-ups to international corporations.	5	21,7%

stakeholders perceive or expect to be digitalization in fruit farming, and the barriers to the adoption/use of digital innovations in fruit farming. In total, 23 stakeholders across the four stakeholder groups participated in 1-hour interviews between October 2020 and March 2021. More farmers identifying as men than women participated in the interviews. The dominant age group was from 30–50 and all participants had completed a form of post-secondary education or training. Seven of the eight farmers had farm sizes of 50 ha or smaller, and all farmers produced pomaceous and stone fruit as their main products, with some farms additionally producing secondary products such as berries, cereals, or providing a communal service such as a rental apartment for seasonal workers or tourists. Further demographic details on the participants per stakeholder can be found in the Appendix.

3.5. *Interview analysis*

The audio recordings of each interview were anonymized and transcribed into text documents, which were subsequently analysed using Qualitative Content Analysis (Mayring, 2000) in MaxQDA 2020 software. The categories used to code the text are the same as those in the digital tool review (see Appendix), as the purpose of the content analysis was to be able to compare

[1]German horticulture is comprised of two production systems: integrated production (IP) and organic. The choice of PPP and the holistic nature of the production system differentiate the two systems (Das Grüne Lexikon Hortipendium, 2021; Landwirtschaftliches Technologiezentrum Augustenberg LTZ, 2023).

Table 2. Deductive categories for the interview result assessment.

Technology Categories		Block chain
		Blower
		Camera
		Computer
		Dosing System
		Drone
		Insect Trap
		Production Line
		Program/App
		QR Code
		Robot
		Satellite Imagery
		Sensor
		Sprayer
		Transmitter
		Web Platform
Functions within Function Categories	*Monitoring and Farm Management*	Field management
		Mapping
		Surveillance
		Climate/weather control
		Employee administration
		Coordination of robots
	Watering	Irrigation management
	Weeding and Mowing	Mowing
		Weeding
		Slashing
	Harvesting	Harvesting
		Transportation
	Plant Maintenance	Pruning
		Thinning
		Defoliation
	Pest and Disease Control	Pest control
		Substance application
		Plant analysis
		Fertilization
		Soil analysis
	Storage	Storage
		Ripening
	Packing and Grading	Sorting/grading
		Packing
		Supply chain management
	Post-harvest quality control	Plant analysis
		Sorting
	Marketing	B2B Marketing
		Online selling
	Other	Cooperation among producers
Part of the Value Chain		Cultivation
		Post-Harvest
		Marketing
Technology Type		Embodied
		Disembodied

with the digital farming tool review. The characteristics that were inductively established during the digital tool assessment therefore became deductive categories (Mayring, 2000) for the interview text (Table 2 Deductive Categories for the interview result assessment Table 2). The tool review's deductive categories *part of value chain* and *technology type* were also able to be coded within stakeholder descriptions and farmer responses to adopted tools, and were therefore included. Other deductive categories stage of development, agricultural sector, usability, connectivity, and capability were not described by stakeholders and therefore excluded from the deductive categories for the interview analysis.

3.6. Cross-analysis

A quantitative approach was used as grounds for qualitative cross-analysis between the results of the digital tool review and interview responses. Specifically, the frequencies of available tools characterized by the deductive categories in Table 2 were collected into an excel spreadsheet. The frequencies of stakeholder descriptions and farmer descriptions of their tool adoption containing these categories were subsequently added to the spreadsheet. In this way, the frequencies of the categories across all data sets could be observed. To conduct an organized comparison across the data sets of varying sizes, authors used quartiles to group the data within each data set. Commonalities and discrepancies across datasets are visualized in Table 3 and defined as follows: Characteristics that were Q3 or above (i.e. the top 25% of the data set) in all three datasets were considered commonalities. Commonalities are characteristics have thus far experienced a suitable development, as they are expected by stakeholders, available for use, and implemented by interviewed farmers without facing significant barriers. Discrepancies highlight mismatches in expectations, supply, and adoption for this case-study. Characteristics that were in Q3 or above for two of the three datasets were considered partial commonalities. Characteristics that were Q3 or above in one dataset and less than Q3 in the other two were considered discrepancies. Characteristics in which all groups had frequencies of Q1 experienced a lack of both commonalities and discrepancies, implying the characteristic was not relevant for digital tools, stakeholders, nor adopted by farmers.

Table 3. Definitions of commonalities, partial commonalities, and discrepancies based on comparisons across dataset quartile groupings.

Cross-analysis of characteristic	dataset 1: digital tool review	dataset 2: stakeholder expectations	dataset 3: tool adoption
commonality	>Q3	>Q3	>Q3
partial commonality	>Q3	>Q3	<Q3
	>Q3	<Q3	>Q3
	<Q3	>Q3	>Q3
discrepancy	>Q3	<Q3	<Q3
	<Q3	>Q3	<Q3
	<Q3	<Q3	>Q3
neither commonality nor discrepancy	<Q1	<Q1	<Q1

4. Results

4.1. Digital tool review results

Characteristics of the reviewed tools have been layered to present the results in a practical format in the following section. Digital tools from the review within their parts of the value chain were assessed for their stage of development (Table 4). As the searched media for the review included research project reports and conference proceedings along with trade fairs and developer websites, both on-market and prototype stages of development were found. Within cultivation, the majority (86%) of tools were found to be on the market, while 90% of post-harvest tools and 94% of marketing tools were on the market. Few tools per value chain section were in the prototype stage, such as in an ongoing research project, with the highest ratio found in cultivation at 13%. Tools regarded as "undetermined" did not disclose adequate information to determine a stage of development.

Digital tools from the review within their value chain parts and functions were further reviewed for hireable services (Table 5). Of all the tools reviewed, only tools within cultivation were found to be hireable, and these tools represent just 5% ($n = 10$) of all tools within cultivation. These tools were distributed relatively evenly across the function categories of monitoring and farm management, harvesting, and pest and disease, with just one tool in the plant maintenance function category.

The intended agricultural sector of use was assessed among the reviewed digital tools (Table 6). The information provided about the tools was, in most cases, very clear as to which agricultural sector the tool was designed for or marketed for; however, in 26% of the reviewed tools, this information was not disclosed and therefore the tools were categorized as undetermined. Some tools were marketed as suitable for multiple sectors. Of the reviewed tools, the greatest number of tools were marketed as suitable for the horticulture: fruit (43%), followed by arable farming (24%), vegetables (18%), viticulture (11%) and all sectors (3%).

The multifunctionality of the reviewed tools was also assessed per value chain section, meaning that tools are designed to have multiple functions

Table 4. Stages of development per part of the value chain.

Part of value chain	Stage of Development	# per value chain	% of tools per value chain
Cultivation	on-the-market	144	86%
	prototype	21	13%
	undetermined	2	1%
Post-harvest	on-the-market	26	90%
	prototype	2	7%
	undetermined	1	3%
Marketing	on-the-market	15	94%
	prototype	1	6%
	undetermined	0	0%

Table 5. Tools that are hirable services per part of the value chain, function category, and function ($n = 10$).

Part of value chain	# of service tools	% of tools in part of value chain	function category	# of service tools	% of tools in function category	function	# of service tools	% of tools in function
cultivation	10	5%	monitoring and farm management	3	1%	field management	1	1%
						mapping	1	1%
						surveillance	1	1%
			harvesting	3	1%	harvesting	3	1%
			plant maintenance	1	1%	thinning	1	1%
			pest and disease control	3	1%	substance application	2	1%
						plant analysis	1	1%

Table 6. Intended agricultural sector of use ($n = 214$).

Agricultural Sector of use	# of tools per sector	% of total tools
All	6	3%
Horticulture: fruit	91	43%
Viticulture	24	11%
Horticulture: vegetables	39	18%
Arable Farming	52	24%
Undetermined	56	26%

and, therefore, a possible investment advantage. Thirteen among the 214 reviewed tools were found to have multifunctional abilities, of which most were found in cultivation (4%) and the rest were found in post-harvest (2%). No tools with multifunctionality were found in marketing.

The usability of tools, if the tools can be used stand-alone or if they are dependent and require the purchase or rental of at least one other tool, was assessed (Table 7). The greatest number of stand-alone tools was found in marketing as 100% of the tools in this value chain part, followed by 85% and 77% of the tools in cultivation and post-harvest, respectively. The greatest

Table 7. Usability of tools per part of the value chain ($n = 214$).

Part of value chain	Usability	# per value chain	% of tools in part of value chain
Cultivation	stand alone	123	85%
	dependent	21	14%
Post-harvest	stand alone	21	77%
	dependent	6	22%
Marketing	stand alone	16	100%
	dependent	0	0%
Other	stand alone	1	50%
	dependent	1	50%

number of dependent tools were found in cultivation as 14% of the tools, followed by 22% of post-harvest tools. Of the two reviewed tools that do not fit adequately into a value chain part and are deemed as "other", the stand-alone and dependent usability characteristics are split evenly across the two tools.

The embedded digital tools within the review were categorized based on their form of connectivity: one-to-one, one-to-many, and many-to-many (Porter & Heppelmann, 2014) (Table 8). Among the determinable tools, the most common form of connectivity was found to be one-to-one in cultivation (56% of the cultivation tools), followed by one-to-one connectivity in post-harvest tools (56% of the post-harvest tools). It was common that the form of connectivity could not be determined (13% and 44% of cultivation and post-harvest tools, respectively). This is due to inadequate information on the tool websites regarding connectivity.

The capabilities of the embedded tools as defined by Porter and Heppelmann Porter and Heppelmann (Porter & Heppelmann, 2014) were also categories within the digital tool review assessment (Table 9). The capabilities – monitoring, control, and autonomy – were easily defined based on information provided for each tool, and only 6% of the tools were unable to be determined. The majority of the tools are considered to have autonomy capabilities, meaning that these tools also conduct all other capabilities. The monitoring capability was second-most common at 24% of tools, meaning these tools are only able to monitor the product's condition,

Table 8. Form of connectivity of tools per part of the value chain ($n = 127$).

Part of value chain	Form of Connectivity[1]	# per value chain	% of tools per value chain
cultivation	one-to-one	61	56%
	one-to-many	20	19%
	many-to-many	13	12%
	undetermined	14	13%
post-harvest	one-to-one	10	56%
	one-to-many	0	0%
	many-to-many	0	0%
	undetermined	8	44%
other	one-to-one	0	0%
	one-to-many	1	11%
	many-to-many	0	0%
	undetermined	0	0%

[a](Porter & Heppelmann, 2014).

Table 9. Capabilities of tools ($n = 127$).

Capabilities[1]	# of capable tools	Percentage of total tools
Autonomy	78	61%
Monitoring	24	24%
Control	12	9%
Undetermined	7	6%

[a](Porter & Heppelmann, 2014).

Table 10. Tools available in the German language per part of the value chain and per function ($n = 69$).

Part of value chain	# available in German	% of tools in part of value chain	Function	# available in German	% of tools per function
Cultivation	42	20%	climate/weather control	6	3%
			field management	7	3 %
			irrigation management	5	2 %
			mapping	3	1 %
			surveillance	4	2%
			irrigation management	5	2%
			mowing	2	1%
			weeding	2	1%
			harvesting	2	1%
			transportation	1	1%
			defoliation	1	1%
			pruning	0	0 %
			thinning	1	1%
			pest control	1	1%
			substance application	2	1%
			plant analysis	5	2 %
Post-harvest	15	7%	surveillance	1	1%
			sorting	7	3%
			supply chain management	3	1 %
			transportation	1	1%
			plant analysis	4	2%
Marketing	12	6%	online selling	12	6%

operation, and external environment. Control was the least common of the three capabilities at just 9% of the reviewed tools.

Finally, the reviewed digital tools were assessed for their technical support in the German language (Table 10). The greatest number of tools with German technical support was in cultivation at 20% of the cultivation tools. The function with most tools available in German was found to be field management ($n = 7$) followed by climate/weather control ($n = 6$). Of the reviewed post-harvest tools, just 7% are available with German technical support, of which sorting and plant analysis functions make up 5%. One function within marketing contained tools that offer German technical support, namely online selling.

4.2. *Qualitative assessment of adoption in German fruit farming among interviewed fruit farmers*

This results section focuses on these interviewed farmers' qualitative responses on barriers to adoption or use of technologies and innovations in fruit production. Eight farmers were interviewed for this part of the study, of which five were organic and three were integrated production (IP) farmers.

This small group cannot represent the fruit farmers in the Lake of Constance region; nonetheless, their participation provided insights into the actual use and perceived barriers of digital tool adoption.

4.2.1. Adoption of digital tools by farmers

The actual use of digital tools varied widely among the interviewed farmers. When asked if they currently use digital tools or technologies on their farm, all farmers answered yes. However, the explanations of the digital tools or technologies used indicate a variety of knowledge levels. For instance, farmer 24 responded with, *"I use a computer, of course. I use my mobile phone, of course. I use geodata, if available and possible … I have a plant protection product app where we more or less do the plant protection product documentation partly through it".,* while farmer 21 responded with, *"Digital? So a photovoltaic system is not going to be a digitalized tool here, is it?"* and farmer 27 with, *"yes … email, exactly"*. Farmers 24, 21, and 27 identify as IP farmers. In contrast, organic farmers tended to have a broader knowledge and "toolbox" of digital tools and technologies. Farmer 26, an organic fruit farmer, responded in detail: *"Yes, well, of course, many machines are now equipped with spraying computers, etc., or something like that. So we already use that … the whole CA storage is of course, completely computer-controlled … The woodchip heating system, for example, is connected via the Internet. So there are also one or two remote maintenance systems … of course, in the administration. Yes. I wouldn't know how to do without it".*

Two other organic farmers mentioned using farm management or administration systems. Farmer 20 used digital tools for crop protection with an automation capability: *"When it detects that the tree is coming here, it switches the fan on or off automatically. Then these data are automatically uploaded right away. So I can follow it almost live on the PC afterwards, (to see) whether it works or not"*. Farmer 28 believed organic farmers are faster to uptake digital tools and attributed this to overall greater interest in on-farm technologies: *"in organic farming … there are more farms that are tech-savvy and willing to move in new directions. That's why I could imagine that we are faster in this area in organic farming"*.

Farmers 28, 25, and 14 used crop management tools via on-board computers with automatic recording through GPS, often referred to as digital field indexes. Tools beyond cultivation, such as post-harvest or marketing, appear to be used less often. Farmer 26 mentioned digitalized CA storage, and farmer 28 reported using a digital merchandise management system for their direct sales.

4.2.2. Barriers to adoption: farmer experience

When asked about barriers to their own technology adoption, interviewed farmers were less detailed in their responses in comparison to their responses to question 25 on the general barriers. Two farmers mentioned their personal choice as the reasons for the lack of uptake of specific technologies. For instance, farmer 24, an IP farmer, mentioned they do not use digitalized technologies in their tractors. They mentioned they are interested, *"as long as the price is right and the technology is right. At the moment, geodata is still quite expensive. And the ones that are freely available are no good"*. Farmer 27, also an IP farmer, did not see the need in certain technologies such as post-harvest sorting and grading machinery because *"that's manual work with us"*. However, organic farmer 28 mentioned infrastructure as the reason they do not use digitalized machinery in their vineyards: *"it's very difficult because (of) these small cells and small plots (of land) to digitize and even then with GPS accuracy, it's all still too inaccurate"*.

4.2.3. Barriers to adoption: farmers report on general barriers

Farmers were also asked about general barriers, not necessarily related to their personal decision to adopt. The most commonly named barrier was the cost of investment. Farmer 14 mentioned, *"One obstacle will certainly be the cost of the machine. Because for me, digitalization often means, as far as production is concerned, something with autonomously working things that will be very expensive"*. Farmer 26 mentioned that the "*technology is only supportive*", and therefore the investment costs for the digital tools or technologies are not the only costs to consider. Regarding post-harvest technologies, farmer 27 noted the extreme costs of the currently available digital machinery: "*We give everything away for sorting, because that is the problem, that the sorting machines are extremely expensive ... We used to have sorting machines. But now it's exactly a matter of percentages of color, whether the apple has 60% or 75% color. And you can't do that with a normal machine anymore. You really have to have a machine that can measure the color exactly by percentage ... We don't have that"*.

The handling of the technology was named second most often as a barrier to adoption. The interviewed farmers described knowledge and the learning curve when adopting new technologies as a significant barrier. Furthermore, the older generation of farmers was described to associate fear through their lack of knowledge in handling new technologies: *"Especially among the older generation. And the associated fear of having to get involved with this technology ... Because some people didn't grow up with computers, even just plain computers, they lack the basics. Or they lack the normal basic knowledge that makes it much easier for our younger generation to grow with technology. That is definitely one of the major obstacles*". (Farmer 26).

Cost, usability, and reliability were concerns for Farmer 20: *"You can have the best technology, a machine that costs 250,000 euros, and still it produces crooked rows. So you have to be able to use the technology or use it correctly"*. Half of the interviewed farmers mentioned lack of reliability as a barrier. Farmer 14 described the early stages of digitalization in fruit production: *"Digitalization is already a bit in its infancy. At least for us in fruit growing ... digitalization can* *mean loss of work, for example, if my farm is only managed with autonomous tractors and the technology fails, I am at a great disadvantage … with digitalization, at some point the technology is so complex that you can't fix it in a hurry".*

Other barriers were mentioned to be acceptance and trust from the farmers, as well as lack of proper infrastructure. The personal choice of the farmer is a deciding factor, according to farmer 14 "*Never change a running system. If apple harvesting has always worked this way or fruit production has always worked this way, why should we rush into something new?*"

4.2.4. Barriers to adoption: regional infrastructure, production system, farm size

Specific to the Lake of Constance region, the poor broadband network in the rural areas where farmers work was a barrier to adoption. When asked if there are different barriers to adoption between organic and IP fruit farming, four (two organic and two IP) of the interviewed farmers said no. However, the two farmers who believe there is a difference were both organic farmers. Farmer 26 thought farmers with organic production systems have to be more careful of the entire system: *"We have to pay more attention to nature… And then, of course, the importance of any prognosis model decreases"*. Five of the interviewed farmers believed farm size influences the barriers to adoption. Specifically, these farmers believed larger farms could afford the investment costs compared to smaller farms. While the farm sizes are relative, farmer 26 mentioned as an example, *"Someone with twenty hectares can't cope. And the other one has it with sixty"*. Still, some of the interviewed farmers believed the farm size does not make a difference in the adoption of digital technologies. Farmer 14 believed it lays more on the personal choice of the farmer than the size of their farm: *"It doesn't matter whether the farm operates 100 hectares or one. There will be no difference. And in my view, it is only up to the farm manager whether he has a certain affinity for using such technology or not"*.

4.3. Cross-analysis: Stakeholder perceptions, tool development, and tool adoption by interviewed farmers

The results of the digital tool review and stakeholder interviews were cross-analysed in order to deduce commonalities and discrepancies across the datasets. Figure 3 visualizes these results and Table 13 in the Appendix provides a more detailed quantitative analysis.

4.3.1. Commonalities and partial commonalities

The commonalities are found in the overlays of the Venn diagram (Figure 3). ***Suitable tools in action:*** The commonalities between all three datasets are represented at the core of the diagram. These common characteristics include tools that belong to the cultivation part of the value chain, tools within the

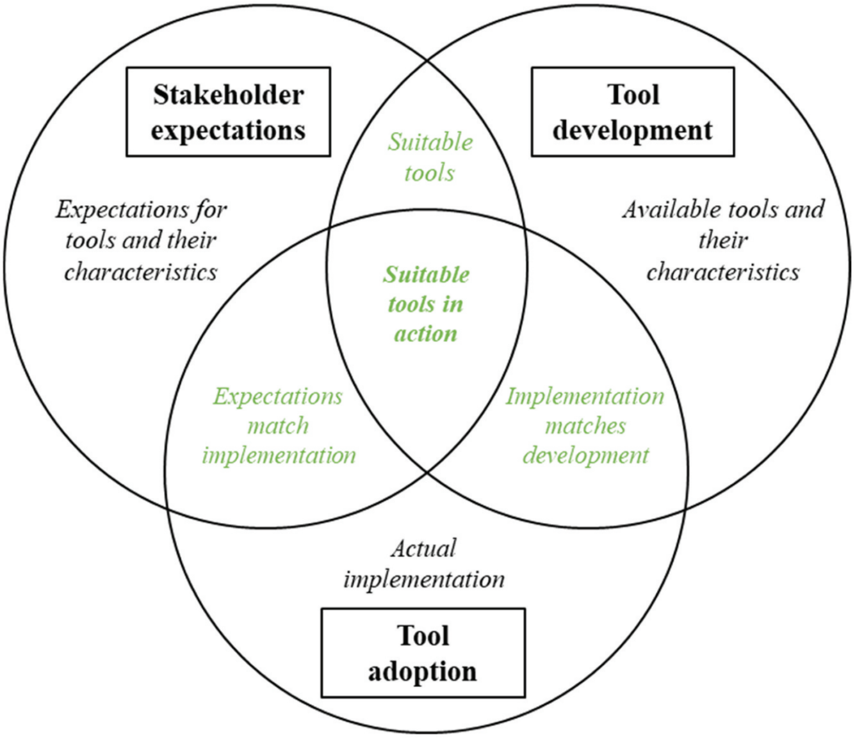

Figure 3. Implications of commonalities and discrepancies between stakeholder expectations, tool development, and tool adoption.

technology categories of programs/apps, robots, and sensors, and tools with the functions of field management, irrigation management, and substance application. ***Suitable tools:*** commonalities between stakeholder descriptions and the available digital tools, implying supplied characteristics that meet stakeholder expectations, include embodied digital tools, and tools with the functions of climate/weather control, plant analysis, online selling. ***Implementation matches development:*** commonalities between adopted tools and available tools are limited to the function of mapping. ***Expectations match implementation:*** commonalities between stakeholder expectations and adopted tools are limited to the function of pest control.

4.3.2. Discrepancies

Discrepancies were considered to be characteristics with high frequencies per category in one dataset, but lower in the other two, suggesting these characteristics were only relevant for one dataset. ***Expectations for tools and their characteristics***: the technology categories QR Code and camera, as well as the function of supply chain management, were

expected by relatively high rates of interviewed stakeholders but were supplied or implemented at lower frequencies. ***Available tools and their characteristics:*** the technology category web platform and the function sorting were provided at higher frequencies than expected or implemented. ***Actual implementation:*** disembodied technologies were by the greatest number of farmers, such as farm management systems or apps, but embodied technologies were more common within the tool review and among stakeholder descriptions. The technology categories blower and satellite imagery, as well as the functions transportation and storage, were implemented at higher frequencies than were found in the tool review and among stakeholder descriptions.
Characteristics that were found to have the lowest frequencies within their category for all datasets were numerous. These include all functions in related to plant maintenance (pruning, thinning, and defoliation), as well as the functions of slashing, coordination of robots and fertilization. Additionally, the technologies categories of block chain, computer, and transmitter were insignificant in all datasets. Marketing tools were the least frequently found or reported among the parts of the value chain category in all datasets. These characteristics are therefore neither supplied by the reviewed digital tools, demanded by interviewed stakeholders, nor adopted by farmers, questioning their relevance in this agricultural sector.

5. Discussion

5.1. Study limitations

Several factors limited the digital tool review. To begin, the review only assessed single tools and technical solutions, not entire systems. Photovoltaic systems, for instance, were considered to be system-level tools and therefore excluded from the review. Furthermore, the post-harvest section of the value chain did not include off-farm transport and logistics, but rather only direct marketing and online marketing, as the farmers themselves can conduct these. Off-farm transport and logistics were considered outside of the "boundaries" of this paper, as visualized in the methodology section. Finally, many digital tools were missing critical information on their websites, which were then described in the analysis as "undetermined". As the review was so large, information was taken only from the publicly available information (websites, technical reports, etc.), and further information was not requested from individual companies.

Stakeholders were not provided with a definition of digitalization in fruit farming prior to the interviews, nor did were they informed on the deductive categories from the digital tool review that were used to code their responses. While this allowed for an empirical lens on the stakeholders' perspectives, it may have limited the quantitative grounds for the cross-analysis: as many characteristics were not mentioned by stakeholders, the zero-frequencies in those characteristics resulted in a skewed the quartile distribution. Still, the quartiles serve only a basis for comparison and the quantitative data should be understood with reservations, considering the small sample sizes of stakeholders and farmers with adopted tools. The nuances found in the qualitative analysis are of greater value for the aims of this study.

The stakeholder mapping and selection process exhausted the limited number of relevant actors in the Lake of Constance region. Due to constraining factors of the funding project, the sample size could not be expanded to represent a more diverse sample. This sample size may lead to criticism within the scientific community. Nonetheless, the interviews provide a valuable snapshot into the perspectives of stakeholders in this region at a critical moment in the digital transformation of agriculture. Furthermore, as research on this transformation continues, the methodology can be used in other regions of Germany, for instance. The detailed characterization of technologies in the tool review (provided as supplementary material) can be used as a blueprint for future studies and to continue as an inventory for digital technologies in fruit production in the ongoing transformation towards agriculture 4.0. Similarly, the cross-analysis provides a valuable lens through which the sustainability of digital transformation can be assessed at a broader scale or in different sectors.

6. Cross-analysis implications

Consideration of the interface between expectations of stakeholders, available technology characteristics, and tool adoption is critical for assessing the sustainability of a technological transformation. Commonalities could point to where development of digital tools for fruit production thus far meets the expectations of interviewed stakeholders and adoption by interviewed farmers, and where barriers have not impeded implementation. Meanwhile, discrepancies emphasize mismatches in expectations, supply, and adoption in the boundaries of this case study. Discrepancies could suggest that the technology-push (TP) model without adequate consideration of user interests has driven development, but they may also suggest low stakeholder knowledge on digitalization, which would require better information diffusion on digitalization in fruit production.

At the core of the cross-analysis (*suitable tools in action* in Figure 3), commonalities were identified, including programs/apps, robots, and sensors, and tools with the functions of field management and substance application. The common characteristics of digital tools can be understood as having met stakeholder expectations and were able to be implemented without significant barriers for the interviewed stakeholders.

Beyond the commonalities, the other findings from the cross-analysis can be grouped into two categories based on their implications. First, the characteristics in the discrepancies *expectations for tools and their characteristics* and *actual implementation*, as well as in the partial commonality *expectations match implementation*, were less frequent in the review than in stakeholder descriptions and/or adopted by farmers. This implies that these characteristics are of interest for stakeholders and farmers and, if adopted, can be implemented without significant barriers. For instance, disembodied tools were implemented more frequently than embodied, yet embodied tools were expected and available more frequently than embodied (*actual implementation*). This suggests that disembodied tools could face fewer barriers to adoption than embodied. While characteristics frequently mentioned by stakeholders may equate to a need, they may also be expectations influenced by external factors, such as marketing schemes for tool characteristics or the existence of technologies in their farming communities.

Second, the characteristics in the discrepancy *available tools and their characteristics* and the partial commonalities *suitable tools* and *implementation matches development* were found more frequently in the developed tools than were described by stakeholders and/or adopted by farmers. These differences could be caused by lack of need, interest, or knowledge by stakeholders and, if not adopted, significant barriers that hinder implementation. For example, web platforms and sorting were provided at higher frequencies than expected or implemented (*available tools and their characteristics)*. If stakeholders are unaware of these technologies and functions, they cannot expect them to exist within digitalized fruit production, nor could farmers adopt them. A similar outcome is likely if stakeholders and farmers do not have an interest or requirement for these characteristics. On the other hand, characteristics that were expected and available at high frequencies, yet seldom implemented (*suitable tools*), such as embodied digital tools and tools with the functions of climate/weather control, could be inhibited by significant barriers to adoption. Ultimately, authors cannot determine the causes behind differences in tool development, stakeholder expectation, and adoption within the boundaries of this study. Further participatory research is encouraged to study these phenomena in order to amend the differences and enable a more sustainable digital transition.

6.1. Farmer interviews

6.1.1. Uneven distribution of knowledge and barriers to adoption

The open approach used to collect stakeholder perceptions on digitalized fruit production allowed for free responses from stakeholders, influenced by stakeholders' current knowledge levels and without suggestive phrasing or categorization. For this reason, definitions of digital technologies in fruit production varied greatly, from computers and email to automated sprayers and irrigation systems. This finding suggests an uneven distribution of experience and knowledge across interviewed stakeholders. Similar to the findings in the cross-analysis, this could be due to a variety of reasons, including inadequate knowledge transfer and marketing strategies of the technologies or stakeholder interest. In this study's group of interviewed farmers, the IP farmers presented lower knowledge on digital technologies in fruit production than organic farmers. While the IP farmers did not believe that production systems do not face different barriers to adoption, two of the three IP farmers reported personal choice as their reasoning behind lack of adoption. It is likely that this knowledge difference influenced the adoption rates between production systems. The reported barriers of acceptance and trust could perhaps be overcome, or at least put into an appropriate, educated context, if user knowledge on digitalization in fruit production increased. Further research should be conducted on a larger scale among fruit farmers and relevant stakeholders to gain insight on the distribution of digital technology knowledge from a representative sample.

Interviewed farmers mentioned the ageing farmer population to be a barrier in the adoption of technologies, similar to the results found by A. Barnes et al. (2019), Michels et al. (2020), Paustian and Theuvsen (2017), Rijswijk et al. (2020), and Knierim et al. (2019). Barriers mentioned by German farmers in the Knierim et al. study and by European farmers in the study by Kernecker et al. (2020) mirror those mentioned most by the farmers in this study as cost and compatibility. Access in relation to cost was also found to be the largest barrier in a study on European farmers by Kernecker et al. (2016). Other dimensions involved in the adoption decision process, such as social needs and cultural aspects, require a specific approach by rural development policies (Bacco et al., 2020a). In the study by Ferrari et al. (2022), the authors also found barriers which hinder digitalization to be socio-cultural (such as fear, competence, and complexity), technical (such as connectivity and dependability), and economic. These authors found another category of barriers that were not mentioned by the farmers in the present study, namely regulatory-institutional barriers like data management and regulations. Regarding the reasons for adoption of digital technologies, the study by Kernecker et al. (2020) found similar results to those in this study: improved ease and quality of work through automation or digital administration.

6.2. Opportunities for digital tool development

Based on the findings in the digital tool review, stakeholder interviews, and cross-analysis, authors have identified opportunities for future digital tool development for fruit production. The results of the digital tool review Digital Tool Review Results demonstrate the great variety of characteristics among the reviewed technologies. Tools fit for use in fruit cultivation (based on the criteria defined in this study) were frequently marketed as usable for arable farming

(24%) or vegetable farming (18%); while this could be advantageous for farmers whose farms are not single-sector, as the majority of fruit farms in the region *are* single-sector, this could be disadvantageous and risk being overseen.

Considering that investment cost is described as the main barrier to adoption by the interviewed farmers in this study, as well as the studies by Das et al. (2019), Knierim et al. (2018), and Schleicher and Gandorfer (2018), tool characteristics assessed in this study, such as usability, multifunctionality, or being a hireable service could be opportunities to reduce the investment cost barrier. In the case of usability, the majority of tools in cultivation (85%), post-harvest (78%), and marketing (100%) were found to be stand-alone tools, meaning they would function without requiring the purchase of one or more other tools. These results are positive regarding cost investment for farmers. However, few tools were found to have multifunctional abilities, which leads to the assumption that tools are often purchased for single tasks, resulting in high investment costs for a farm with numerous functional requirements. Similarly, tools that are hireable services, which could have a smaller initial cost investment, comprised of just 5% of the reviewed tools. These were limited to the cultivation section of the value chain for the functions of monitoring and farm management, harvesting, plant maintenance, and pest and disease control.

Very few digital tools from the review offer German language technical support: 20% of cultivation, 7% of post-harvest, and 6% of marketing tools reviewed offered the German language in addition to English. It cannot be ruled out that German farmers would not be willing to use tools that only provide English technical support. However, it can be assumed that German farmers would prefer tools with technical support in their language. When combined, just one of the hireable service tools and three of the multifunctional tools offer German technical support. Furthermore, only 30 of the 42 tools available with German technical support are marketed for fruit production, while the other 12 are marketed only for arable farming, yet could be functional for fruit cultivation. This is a small collection of available tools for German farmers. The lack of appropriate tools in this sector of German farming indicates evidence of a technology-push development. The failure to meet needs of farmers could lead to a digital divide (Hilbert, 2011), in which fruit farmers would be disadvantaged compared to those in other sectors.

7. Conclusion

Upon consideration of the named barriers to adoption, the characteristics of existing tools in the tool review, and the results of the cross-analysis, the current development of tools is not suitable for the needs and abilities of the stakeholders in the case study. Uneven distribution of knowledge on digitalisation and a lack of tools that can overcome the named barriers to adoption may perpetuate the lag in digitalisation of the German fruit sector. The limited commonalities and various discrepancies among developed tools and stakeholder expectations and implementation leads to the assumption that the current development of digital tools for fruit production has been from a technology-push and not a demand-pull. Reported barriers to adoption are numerous and were found in similar studies in other regions, suggesting greater consideration of stakeholder perceptions and technology adoption strategies is required at a wider geographical and sectoral scale.

Authors recommend actions for a more sustainable and just digital transformation of the fruit sector. First, tools with multifunctionalities and hireable services offer chances to overcome the barrier of cost: technology developers are encouraged to focus on further development of tools with these characteristics to increase inclusion opportunities for technology users. Government policies must provide financial support at the development level as well as support for investment from users to reduce inequalities in development and adoption. This support must consider the reported differences in barriers according to production system and farm size, and should therefore specifically target small farms and share efforts equally across organic and IP production systems. Second, marketing of tools and the diffusion of knowledge regarding digitalized technologies for fruit production must be improved; misguided marketing and inadequate information could be the cause of slow uptake in the fruit sector. Finally, to support the German fruit farming sector, technical support must be available in the national language to allow for equal opportunities for inclusion in the digital transformation. Cooperation between users and developers in the fruit value chain is recommended to understand the causes behind the discrepancies and amend the existing gap between expectations and reality, thus improving usability and technology adoption. All sectors must be equally considered and developed in this fourth agricultural revolution, otherwise the sustainability of this transition is at risk.

List of abbreviations

TP	Technology-Push Model
DP	Demand-Pull Model
SOTA	State of the Art
SFT	Smart Farming Technology
PA	Precision Agriculture
DGC	Digital Game Changer
ACPS	Agricultural Cyber-Physical Systems
IOT	Internet of Things
UAV	Unmanned Aerial Vehicle
TAM	Technology Acceptance Model
PU	Perceived Usage
PEU	Perceived Ease of Use
PPP	Plant Protection Product
IP	Integrated Production
CA	Controlled Atmosphere

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Consent for publication

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