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REVIEW

How can precision farming work on a small scale? A systematic literature review

Tamás Mizik[1]

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Abstract
The agri-food industry faces a great challenge due to the growing global population. When considering land scarcity, this can be solved only by a higher production efficiency. Precision agriculture (PA) provides a potential answer. Most farms, especially in developing countries, are small-scale units that have difficulties in applying precision agriculture technologies. On the basis of the systematically selected articles, major benefits and constraints were identified, and solutions were provided. Due to the low economic performance of smallholdings, (demonstrated) economic benefits are essential; however, it should be added that PA also provides potential environmental benefits. The five main constraints of precision agriculture technologies at the small-scale level are small land size, high cost of adoption, technology-related difficulties, lack of professional support and lack of supporting policy. The solutions provided by the literature are various, including, among others, joint/collective actions, zone delineation/field boundary detection, cooperation-cooperatives; low-cost technology, common machinery usage; education, (common) knowledge, use of standards, simple and user-friendly technology; professional support of vendors, advisors, agricultural contractor services; and policy-initiated investments and adequate regulations, respectively. Lower cost, modular technologies can help to accelerate PA uptake.

Keywords Precision farming · Precision agriculture · Small-scale · Technology · Profit

Introduction

The global population is continuously increasing at an accelerating rate. According to the latest projection of the United Nations, there will be 8.5 billion inhabitants on the Earth in 2030, growing to 9.7 billion by 2050 (United Nations 2019). Feeding more and more people is a great challenge for the agri-food industry. As the land, which is one of the most

✉ Tamás Mizik
tamas.mizik@uni-corvinus.hu

1 Department of Agribusiness, Corvinus University of Budapest, Budapest, Hungary

important factors of agricultural production, is limited, achieving a more efficient production is essential. How can the same amount of land feed a significantly higher population? Precision agriculture (PA) is a potential solution. Nevertheless, it should be kept in mind that most farms (84%) are smallholdings, especially in low- and lower-middle-income countries, and normally they cultivate less than 2 hectares (FAO 2020). Their estimated number is 500 million (Lowder et al., 2016), and they provide income and food for the poorest people in developing countries (Bogdanski 2012). Small-scale (family) farming is an important characteristic of the European agriculture as well (Pindado and Sánchez 2017).

According to the official definition of the International Society for Precision Agriculture, "Precision Agriculture is a management strategy that gathers, processes and analyzes temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production." (ISPA 2021). This definition clearly points out the crucial importance of human resources, although this is based on the continuous interactions of farmers (users) and different IT tools (machine). Information is undoubtedly essential even in the case of the simplest activities (e.g. GPS data for using an automated steering system); however, the specific technologies differ greatly. Being site specific is essential that requires data on soil (e.g. quality, fertility, nutrient profile, water absorption capacity, weed density) and weather conditions (e.g. rainfall, temperature) (Bhakta et al. 2019). Although the term "precision agriculture" is well defined, its implementation is fundamentally different between the developed and developing countries. In the former countries, a wider range of available elements are in use, especially by larger farms(Finger et al., 2019), while in the developing countries adoption is limited due to difficulties in accessing technology, capacity problems, and financial difficulties (Onyango et al. 2021). In addition, socio-economic barriers do matter, such as openness to innovation, knowledge sharing, age, complexity and cost of technology, available financial support, and farm size (Blasch et al., 2022). These are among the reasons why PA adoption shows different characteristics compared to other agricultural innovations, such as a slower adoption process for some technologies and greater divergence between the different farms (Erickson and Fausti, 2021).

There is a consensus in the literature that larger farms are more likely to adopt different precision farming methods and tools compared to smaller farms. Based on interviews with 40 precision farmers and 40 traditional banana farmers in India, Franco et al. (2018) found that land size has the highest positive impact on PA adoption. Among the other factors analyzed (working members, farming experience, risk orientation, education, and age), only age had a negative impact on the adoption process. That is the reason why countries with generally larger farms (e.g. Australia, Brazil, Canada, the USA) have higher adoption of different precision farming technologies (Say et al. 2018). However, one should be aware of the fact that the term "large" or "small" in relation to PA may differ from country to country. For example, farms below 2 ha can be considered small in Africa (Persello et al. 2019), while the same term "small" can also be applied to a 50 ha farm in Switzerland (Groher et al. 2020), 200 ha in Hungary (Takacsne Gyorgy et al. 2018) or 250 ha in Germany (Reichardt and Jürgens 2009; Tamirat et al. 2018). International organizations also provide definition of small farms. Their threshold is 10 ha by the FAO (2013) definition, which also emphasized the importance of family-orientation (workforce, own consumption, etc.). The EU has no fixed definition (Eurostat, 2018), since size can be measured by physical size (utilized agricultural area) or economic size (standard output). The US definition concentrates on farm income and considers a farm small if its income is below USD 250,000 (USDA, 2021). However, only physical size data is available worldwide; therefore, only this can be used as a measurement for small farms. This also means that direct country-specific comparisons are not possible.

Based on a detailed literature review, Bhakta et al. (2019) summarized the benefits and limitations of these technologies. They provide a huge amount of real-time, useful, and relevant information, but most of them are not cost-effective at the small-scale level. According to their results, variable rate technologies provide an excellent opportunity for waste reduction and optimal input use (potential environmental benefits). However, these systems require further research on their design to be cost-effective for small producers. Being case/site-specific is of utmost importance due to the enormous heterogeneity of smallholdings (Mizik, 2021). In general, the most important motive for PA adoption seems to be the increased profit; however, the cost of PA technologies may exceed their benefits (Batte et al., 2003). In addition to the economic benefits of PA technology measured in net returns, Brown et al. (2016) further emphasized the environmental benefits related to lower input use (seeds, pesticides, fuel, working hours, etc.) as part of long-term sustainability. Due to savings in GHG emissions, PA can contribute to climate change mitigation (Balafoutis et al. 2017). Thompson et al. (2019) added convenience, which can be an influential argument for adoption. In general, PA technologies result in higher and better quality output with lower production costs due to lower input use (Beluhova-Uzunova and Dunchev 2019, 2020; Brown et al. 2016; Franco et al. 2018). Based on 146 questionnaires, Jochinke et al. (2007) identified higher managerial knowledge based on the big data collected, higher work and input use efficiency, lower greenhouse gas (GHG) emissions, as well as higher time efficiency. Cost reduction and greater accuracy are always the most frequently mentioned reasons for adopting PA, independent of the actual state of PA adoption(Barnes et al. 2019a).

However, even internet access, a minimum for the use of many precision technologies, can be a problem. Smartphones can be expensive for the poorer farmers and, due to continual advancements in technology, may be inappropriate for collecting information, or may even soon be obsolete. For example, only about 25% of the Kenyan mobile phone owner farmers used their devices for their production (e.g. search for production-related data or use of farming-related applications) (Krell et al. 2020). Furthermore, farmers often face difficulties during the decision-making process due to the high level of uncertainty (benefits and costs) and/or the high managerial skills required (Tamirat et al. 2018). But it is surprising that, e.g., Tamirat et al. (2018) were not able to confirm the linkage between the availability of information on PA and the probability of adoption. However, it should be added that they analyzed the Dutch and German farmers who generally have a higher level of knowledge about PA. Therefore, having more information may not have a further impact on their attitude towards the adoption. Franco et al. (2018) classified the different constraints of adoption into environmental, infrastructural, extension, economic, administrative, social, and technological categories. According to their results, the main reasons in each category were high/frequent rainfalls, access to credits, inadequate technical support, expensive inputs, high bureaucracy, lack of self-confidence, and small farm sizes, respectively. It should be noted that the learning curve of PA adoption is more of an S-shape, meaning that farmers experience smaller initial gains and the majority of the benefits can be realized only when the necessary skills and data are available (Castle et al. 2017).

High investment costs are generally a burden on the PA adoption rate (Beluhova-Uzunova and Dunchev 2019, 2020; Reichardt and Jürgens 2009). That is one of the main reasons why PA adoption is much higher in larger farms in developed countries (Finger et al., 2019). Therefore, off-farm incomes are important for small farms for the successful adoption of new technologies (Hammond et al., 2017; Mango et al., 2018). Barnes et al. (2019b) justified the farm size-income-PA adoption connection in their database and emphasized the role of the government in promoting PA technologies. Balogh et al. (2020) conducted 604 interviews and 30 semi-structured interviews in Hungary. They also found that smaller farm sizes are an obstacle to the faster spread of PA. Jaafar and Kharroubi (2020) interviewed 577 farmers in Lebanon and experienced a high willingness for adoption, especially in the case of younger farmers. The majority of farmers were open-minded to a free, mobile smart irrigation application, but this interest goes significantly down if they have to pay for that, mostly because they are not clearly aware of the value added of such a smart irrigation management system. However, Balafoutis et al. (2017) carried out 504 interviews with different Brazilian farms and found that acquisition costs of precision and digital agriculture are challenging even for large farms. Jacobs et al. (2018) carried out 36 questionnaires in the Schweizer-Reneke region of South Africa and found that, besides high costs and small cultivated area, homogenous fields were important limiting factors of PA adoption. Additionally, it should be kept in mind that PA is a constantly evolving technology, e.g., nanoparticle materials make even more targeted and controlled way of intervention possible by carrying bioactives, providing time-controlled release, or being nanosensors (Lang et al., 2021).

Besides farm sizes, it should be distinguished between mechanized and non-mechanized farms, as they have different opportunities to adopt PA technologies. The lack of mechanization could be an obstacle to the uptake of these technologies (Cammarano et al., 2020). Lowenberg-DeBoer and Erickson (2019) identified that non-mechanized, small and medium-sized farms in developing countries have the lowest PA adoption. It should be highlighted that most of the African and Asian small-scale farms are generally non-mechanized; therefore, nondigital-based PA technologies are particularly important for them (Erickson and Fausti, 2021). Although this problem of mechanization and/or adoption is more significant in developing countries, some of the smallholdings in developed countries can also be concerned. According to Schimmelpfennig and Lowenberg-DeBoer (2021), small, mechanized US farms are significantly lagging behind larger farms in PA adoption, in part because in the US smaller farmers buy used equipment and it takes time for PA technology to filter into the used equipment market.

From a social point of view, Hüttel et al. (2020) underlined the importance of key farmers (members of a reference group with practical experience) in the PA adoption process. The physical demonstration of well-working technology is very important to farmers. Without this, the chances of adoption can be negligible (Li et al. 2020). Therefore, it would be useful for PA technology providers to involve farmers in the design and implementation of their products (Lamb et al.,, 2008; Ferrández-Pastor et al., 2018). This interlinkage turned out to be important for the Chinese farmers, too (Li et al., 2020). It can be claimed that PA adoption is a sensitive issue and contains more than a pure cost-benefit point of view. Trust is of utmost importance, especially when the huge amount of partly sensitive datasets are concerned (Jakku et al. 2019).

The research question of this article is how precision farming can work on a small scale. How can small-scale farms benefit from the use of PA? What are the main constraints and motivating factors for PAT adoption? What are the most common solutions? In order to reveal these differences, the selected articles were analyzed according to their methodology. The article is organized as follows. The next section introduces the article selection procedure, i.e., which databases were searched and how the identified articles were determined. The third section provides the results of the systematic review of the literature. The final section presents discussion and conclusions.

Materials and methods

The articles were selected using the following sources: ScienceDirect, Scopus, and Web of Science. The keywords used for this search were precision farming, precision agriculture, small scale (with and without a hyphen), smallholder, small farm, crop, crop production, technology, and profit with the Boolean operator "OR" and "AND" as it is shown in Table 1.

As precision farming and precision agriculture are frequently used interchangeably, it was important to incorporate both into the analysis. It has been observed that native English speaking scientists prefer to use the first, while scientists from other countries often opt for the last (Gusev et al. 2019). All the other keywords are related to the research question, which is whether precision farming works on a small scale, including technological and profit aspects. Crops and crop production were added to concentrate on the core segment of the PA that fits the ISPA definition the most. Unlike commodity crops, higher added-value segments of agricultural production, e.g. vegetables or flowers, can be easily profitable on a small scale. These keywords should be part of the title, keywords, or abstract of the article. However, it should be highlighted that small scale is a relative term. This means that the size of a small-scale farm significantly differs regionally, e.g., much smaller in Asia and much larger in North America.

To focus on high-quality articles, the selection was restricted to refereed scientific and review articles published in English. There were 5,163 results in ScienceDirect; therefore, they were sorted by relevance, and the first 1,000 were used for further analysis. The same method was used for the 122,078 results in Web of Science. With these parameters, there were 2 articles in the Scopus database. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method was applied for the article selection (Moher et al. 2009). After sorting out duplications, 1,904 articles remained for the screening stage of the selection process. Although they contained the selected keywords, their topics were only indirectly related to the applicability of precision farming methods in small-scale farms. Figure 1. gives an overview of the stages of the literature selection process.

After sorting out the non-relevant items, 54 articles remained for the in-depth screening. Most of the non-relevant articles analyzed non-agriculture issues, mostly industry and

Table 1 Keywords of the literature selection

precision farming	AND	small scale, small-scale	AND	crops	AND	technology	AND	profit
		OR						
OR		smallholder		OR				
precision agriculture		OR		crop production				
		small farm						

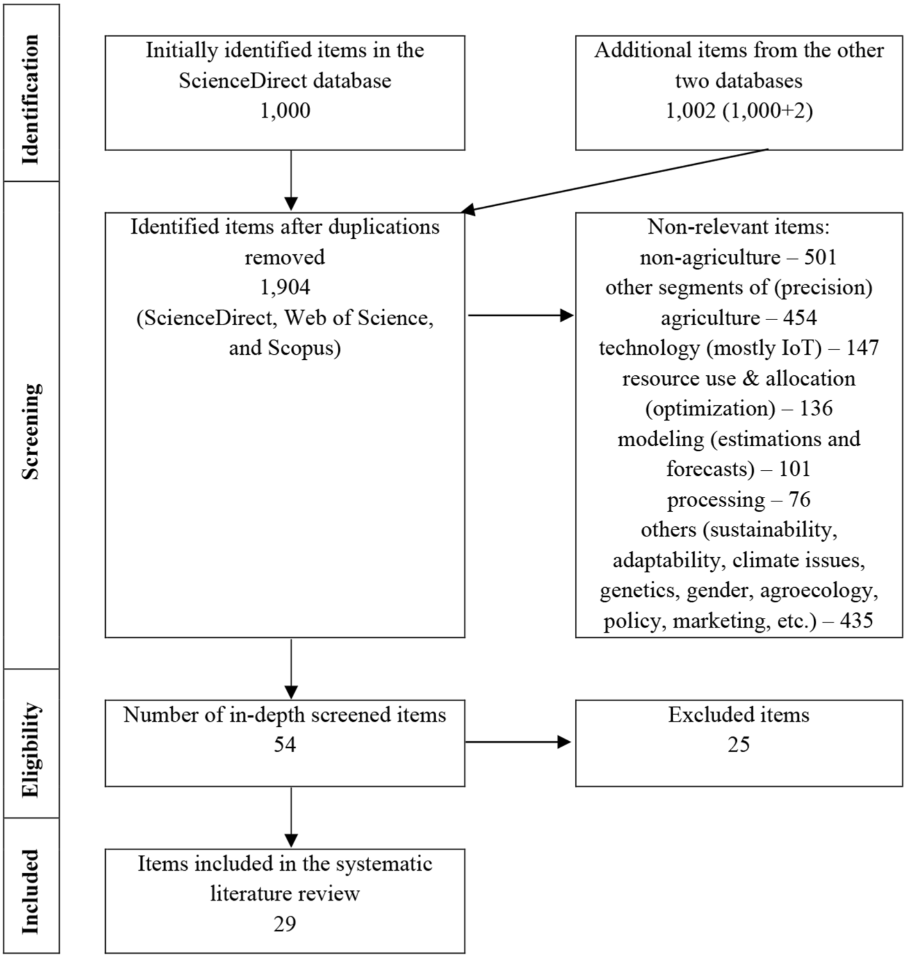

Fig. 1 Stages of the literature selection process

service. 454 articles concentrated on other segments of (precision) agriculture such as on the animal, aquaculture, fruit & vegetables sectors. The following category in non-relevant items were technology (mostly Internet of Things and smart devices), resource use & allocation (mostly optimal use of different inputs, such as fertilizer or irrigation), modeling (estimations and forecasts), and processing. Finally, 435 articles were placed in an "other" category as they dealt with divergent topics, e.g. sustainability, adaptability, climate issues, genetics, gender, agroecology, policy, marketing). It should be mentioned that non-relevant items were often interrelated as modeling and/or forecasting applications rely on datasets provided by the different smart devices. The large number of non-relevant items dealing with non-agriculture from both the Scopus and ScienceDirect databases clearly demonstrate that the processing of the first 1,000 articles were absolutely adequate.

Out of the 54 in-depth screened articles, 29 were selected for the systematic literature review. The common characteristic of the 25 excluded items was a focus on other commodities than crops, or profit aspects were excluded.

With regard to literary sources, great diversity can be observed. The most frequent journal was the *Precision Agriculture* with 5 articles. This is followed by the *Computers and Electronics in Agriculture* with 4 articles. 2 articles were published in the *Field Crops Research*. The other 18 articles were published in 18 different journals.

As the processed articles used a lot of different methods, they were grouped into three categories. 9–9 articles formed two distinctive groups as they collected primary data from either field experiments or surveys and interviews (survey, questionnaire, semi-structured or in-depth interviews). The other 11 articles used many different methods, such as descriptive analysis, gap analysis, literature review, or applied different models. These are combined under the term of mixed methodology.

Results

In general, small-scale farmers are worse off compared to the large holdings due to their lower economies of scale, lower value of collateral which may limit their financial opportunities, etc. They typically generate less revenue and have less valuable assets that can be used for mortgage purposes. Even if they can buy any PA technologies, they suffer further from the higher additional fixed costs per production unit due to their smaller production. This affects their price competitiveness. But sometimes, precision agriculture can be a modular system that allows farmers to introduce this gradually, element by element – according to their financial opportunities and farming needs. The widespread adoption of PA among small-scale farms depends on three things: people (awareness, education, skills), technology (simple, functional, affordable, reputation), and efficiency (performance, results in higher yields/incomes). Price/affordability is essential for small-scale farmers as they often face financial constraints due to their lower income generation (lack of own resources and low credit repayment capacity) and lower level of assets (low level of collateral). Moreover, the good reputation of the technology (e.g., it smoothly works at a neighboring farmer) is also important because most small-scale farms cannot take more (mostly financial) risks. This reputation is particularly exposed to the early phases of adoption (Lamb et al., 2008).

Based on the processed literature, two directions can be identified on how precision farming can work on a small scale. These two directions are: 1) opportunities dependent on the farmers' abilities and needs and 2) opportunities dependent on the technology, such as simpler and, more importantly, cheaper technology. The selected articles are classified into two groups based on their methodology. Site experiments differ significantly from the other methodologies; therefore, they are analyzed separately.

Field experiments for the greater adoption of precision agriculture on small-scale farms

Boundary and/or zone detection for PA is the basis for site-specific measures, which is an even more significant challenge in developing countries, especially in Africa and Asia. As this is a key issue in the adoption of many PA technologies, inexpensiveand easy-to-use solutions are essential. Zha et al. (2019) set up a satellite-based yield model in China that allows delineation of management zones at the village level. This could help small-scale farmers optimize inputs and provide better returns. It should be noted that 80% of Chinese farms are small, and mismanagement of nitrogen fertilizer is a general problem for them (Cammarano et al. 2020). Therefore, Cammarano et al. (2020) proposed a satellite-based system that can delineate a small number of management zones instead of the huge number of farms. Compared to the large number of individual fields, having only 3–4 zones would provide more economic benefits; however, the spatial coherence of these zones should be high. This zone delineation would be the first step for applying precision fertilizer management and achieving improved financial performance even for non-mechanized farms. Yang et al. (2020) also proposed satellite-based, automated field boundary detection algorithms for smallholder farms in Bangladesh. Systems like this can help to collect relevant data on small-scale farms to provide the opportunity of yield forecasting or resource allocation. It should be distinguished between management zone delineation and the cadastral use of PA. Persello et al. (2019) emphasized that the unclear field boundaries of smallholder farms in Nigeria make automatic delineation almost impossible. To solve this serious cadastral problem, the authors suggested a satellite-based system that significantly outperformed the currently used techniques in a cost-effective way. This would make it possible to use some elements of PA technologies that cannot be used otherwise.

Site-specific measures are the key to PA. Dobermann et al. (2002) revealed the importance of site-specific nutrient management based on on-farm experiments at 179 Asian sites. In addition to cost savings, the prevention of excessive nitrogen use contributed to a reduction in pest incidence. Furthermore, field-specific macronutrient management resulted in significantly higher rice yields. At the profitability level, an average growth of 12% can be expected. However, this method needs to be tailored at the country level. Cao et al. (2012) also emphasized the importance of site-specific nitrogen management for the Chinese small-scale farms. With precision nitrogen management, not only significant savings can be achieved on fertilizer costs, but also under- or over-fertilization could be avoided. According to Natcher et al. (2016), fertilizer microdosing is a widely used method in SSA countries due to high and unaffordable fertilizer prices. A microdose is about a fourth of the recommended amount, but it is used with better timing and placed optimally (distance from the plant and depth).

Park et al. (2018) identified the attitude of small-scale farmers as a constraint of precision technologies, for example, low-level fertilizer use. Historically, Nepalese farmers did not experience a significant profit impact of increased fertilizer use, which discouraged them to do so. The authors recommended the implementation of low-cost, simple mechanization (a chest-mounted seed and fertilizer spreader) instead of the commonly used hand distributed practices.

Godwin et al. (2003) compared the costs and benefits of different PA technologies in the UK. According to their results, basic systems can be economically viable from 78 ha, while the most expensive system requires 308 ha. The benefits of PA from the application of nitrogen at a variable rate outweighed the costs of the technology. Additionally, PA can contribute to other economic benefits (e.g. lower herbicide need) and avoidance of penalties (e.g. fertilizer application errors).

In general, the vast majority of field experiments in this review took place in developing countries and their proposals were cheap and simple technologies (Table 2.). This is of crucial importance for smallholdings.

Analyis of small-scale PA adoption with survey and interview data collection

In the case of survey and interview data collection, the major question is whether the results are generalizable or not. Although the results of the studies based on non-representative data collection methods cannot be generalized, they could provide useful information about PA

Table 2 Characteristics of selected articles based on site experiments

Authors	Regional coverage	PA adoption level	Drivers of PA	Barriers to PA	Suggested solution(s)
Cammarano et al., (2020)	China	low	improved crop management	small farm size, low mechanization	zone delineation, variable rate of N use
Cao et al., (2012)	China	low	savings on costs	relatively expensive	precision nitrogen management
Dobermann et al., (2002)	Asia	low	savings on costs, higher yields	complexity	site-specific nutrient management
Godwin et al., (2003)	UK	medium	higher yields, other benefits	high acquisition costs	variable rate of N use
Natcher et al., (2016)	Benin	low	perceived benefits	expensive inputs	fertilizer microdosing
Park et al., (2018)	Nepal	low	economic benefit	attitude	simple mechanization
Persello et al., (2019)	Nigeria	low	clear field boundaries	cadastral problems	satellite-based delineation
Yang et al., (2020)	Bangladesh	low	economic benefits	small farm size	automated field boundary detection
Zha et al., (2019)	China	low	economic benefits	small farm size	satellite-based yield model

knowledge or PA adoption (drivers and barriers). However, their results should be used with caution. Table 3. provides a detailed overview of the generalizability of the reviewed studies based on primary data collection.

PA adoption depends on many different factors, and farm size is definitely one of them. Groher et al. (2020) pointed out that different PA technologies provide higher advantages for small farms with greater production heterogeneity in Switzerland, e.g. field vegetable crops, compared to the more homogeneous arable fields. This also relates to their higher production value and profit. Larger farms (in their sample, this was 50 ha or more) are more likely to adopt PA as even an expensive PA technology costs less relative to their profit. However, size categorization depends on the country; therefore, PA adoption related country-specific results cannot be directly compared. They also laid down that simpler PA technologies, such as Driver Assistance Systems, are more frequently adopted than the difficult systems, e.g. Electronic Measuring Systems. Paustian and Theuvsen (2017) examined the adoption of PA technologies among 227 German crop farmers. They identified that most of the non-adopters are small holdings, mostly because they cannot afford PAtechnologies and are less high-tech oriented. According to their specific needs, they recommended simpler and

Table 3 Generalizability of the reviewed studies using survey and interview data collection

Authors	Type of data collection	Methodology	Generalizability
Aubert et al., (2012)	Questionnaire (438 farm operators)	contact through a professional association	high for the cereal and oleaginous sectors
Barnes et al. (2019)	Survey (971 farmers)	non-random selection	medium for wheat producers (representative for size and income)
Groher et al., (2020)	Questionnaire (827 farmers)	two-stage random sampling	high (representative)
Higgins et al., (2017)	Semi-structured interviews (20+59)	purposive sampling for rice growers	low (non-representative)
Kendall et al., (2021)	In-depth interviews (27)	qualitative in-depth interviews	low (non-representative)
Li et al., (2020)	Personal interviews (449 out of 456 were used)	random sampling combined with snowball sampling by applying the “ten-time rule”	high (representative)
Paustian & Theuvsen (2017)	Questionnaire (227 farmers)	standardized online questionnaire	low (non-representative)
Takacsne Gyorgy et al., (2018)	Survey (656 farmers)	sampling based on the FADN database	high (representative for market-oriented farms)
Vecchio et al., (2020)	Questionnaire (non-random sample of 174 farmers)	non-random sample	medium for those who have knowledge on PA (non-representative)

cheaper solutions. It should be noted that the authors used data from volunteers responding to an online questionnaire; therefore, their results, unlike those of Groher et al. (2020), cannot be generalized.

Barnes et al. (2019) analyzed PA adoption by surveying 971 farmers from five European countries (UK, Germany, the Netherlands, Belgium, and Greece). They identified different barriers as well as facilitators of PA uptake. Agricultural education, different government regulations, and advisors positively influence the adoption of current adopters. Regarding non-adopters, older age, smaller farm size, and lower household income are the most important limiting factors as some PA technologies are expensive with long payback periods, while different subsidies and supports (training and technical) are the major incentives. Concerns about the high costs of precision technologies are prevalent in both groups; however, adopters also emphasized the importance of ease of use. Based on 27 in-depth interviews, Kendall et al. (2021) identified five factors of PA adoption in China. Similarly to Barnes et al. (2019), farmers with agricultural education can be characterized by greater awareness and participation in PA. Kendall et al. (2021) also pointed out that Chinese farmers have short-term orientation because they focus only on the economic benefits of the technology and leave other, mostly potential environmental, benefits aside. Low economic performance of small-scale farms and high costs of PA turned out to be the major barriers. Therefore, low-cost technologies are essential for smallholdings. Takacsne Gyorgy et al. (2018) assessed PA adoption in Hungary. They also found that the purchase of new machinery may not be feasible, but the update of existing ones is a promising option due to the integrated, built-in PA technologies. They also noted that common machinery usage and PA services provide good opportunities for small holdings. Aubert et al. (2012) surveyed 438 farm operators in Quebec, Canada. They highlighted that PA uptake is relatively low, although its benefits are widely accepted. Therefore, knowing the factors influencing PA adoption should be the basis of targeted policies or incentives. Farmers' perceptions are economic in nature, which emphasizes the importance of usefulness and ease of use. Both require compatibility among the different tools of PA. One of their most important results was the negative impact of voluntariness on PA adoption. This can be solved with adequate regulations, e.g. reporting on input use which can be easily performed with PA.

The access to information and cooperation between farmers are indispensable. Li et al., (2020) used 456 personal interviews from the North China Plain for their analysis. One of the major characteristics of the sample is the extremely low average farm size (1.306 hectares), 89.1% of the respondents have less than 1 ha. In addition to perceived benefits, the authors highlighted the potential role of cooperatives in the adoption of PA as an option for small farms. According to their results, this was important as 62.4% of the farmers would rely on cooperatives in PA adoption. This could be generally recommended for small-scale agricultural producers worldwide; however, cooperating is not always an easy issue. Another remarkable result of their study was why farmers stopped the adoption process. Based on the responses, this was caused by financing difficulties and the lack of service providers. Higgins et al., (2017) identified commercial-technological and biophysical modes of PA ordering in the Australian rice industry. The first refers to the potential compatibility problems, while the second is related to uncertainties (e.g. drought and water problems) which decreases spending on PA. Alternative ordering practices are especially important for small-scale farmers to increase their ability to use PA.

National agricultural policies have one of the most influential impacts on PA adoption. In addition to the potential environmental benefits, PA can contribute to higher competitiveness and profitability of small and medium-sized farms mostly due to their increased efficiency; therefore, agricultural policies should support collective actions (Vecchio et al., 2020). However, a policy-based push itself in PA adoption is not always enough. Production of high value-added products can also be a promising option for small-scale farms.

In contrast to the previous sub-chapter, the analyzed articles based on survey and interview data collection in this review are focused mainly on developed countries. Table 4 summarizes the main characteristics of these articles.

Analyis of PA at small-scale with mixed methodology

As the Japanese agriculture is characterized by smallholdings, Sasao and Shibusawa (2000) draw attention to scale-free precision technologies that can be applied to all farms regardless of their sizes. The term "scale free" could also be labeled "scale neutral." They found only manual control feasible below 1 ha. Automated machinery and different sensors can be used between 1–10 ha, GPS-based technologies work between 10 and 50 ha, while VRT technologies can be applied over 50 ha. Besides increased productivity, therefore profit, PA results in a lower environmental impact. Farmer's knowledge can work well on a small area with

Table 4 Characteristics of selected articles based on survey and interview data collection

Authors	Regional coverage	PA adoption level	Drivers of PA	Barriers of PA	Suggested solution(s)
Aubert et al., (2012)	Canada	relatively low	usefulness, ease of use	incompatibility, using difficulties	adequate regulations, standards, vendors
Barnes et al. (2019)	Belgium, Germany, Greece, the Netherlands, and the UK	medium	education, different government regulations, advisors	older age, smaller farm size, lower household income	subsidies and supports
Groher et al., (2020)	Switzerland	high	larger farm size	high acquisition costs	simpler PA technologies
Higgins et al., (2017)	Australia	medium	larger farm size	high acquisition costs	alternative ordering practices, knowledge
Kendall et al., (2021)	China	low	economic benefits	low economic performance, high acquisition costs	education, low-cost technologies
Li et al., (2020)	China	low	perceived benefits	small farm size, financing difficulties, lack of service providers	cooperation-cooperatives
Paustian & Theuvsen (2017)	Germany	medium	high-tech orientation, work experience, large farm size	small farm size	simpler and cheaper solutions
Takacsne Gyorgy et al., (2018)	Hungary	low	economic benefits	high acquisition costs	common machinery usage and PA services
Vecchio et al., (2020)	Italy	low	large farm size, supportive national policy	small farm size	collective actions

a limited number of parcels; however, this becomes harder with the larger farm size and the greater number of fields. Therefore, Shibusawa (2001) suggested regional precision farming for small-scale Japanese farms. This method is based on between-field variability and land use diversity. Auernhammer (2001) suggested "virtual land consolidation" for smallholdings where only the way of farming changes while the ownership remains the same. This method could lead to significant savings on cultivation costs. Well-performing farms may achieve smaller benefits than the costs of the technology, especially small-scale farms. In their case, savings on different inputs are lower, as well as yield increase is limited. PA often means basically the redistribution of the similar amount of inputs. However, even in this case, one should be aware of the potential environmental benefits of PA and the advantages of having more accurate information on production.

Based on a systematic review of the literature of 32 empirical studies, Shang et al., (2021) found that larger farm size and higher level of education have the largest positive impact on PAT adoption among the most frequently analyzed factors. Interestingly, age does not turn out to be a linear predictor of adoption due to other important characteristics such as experience or innovativeness.

In general, cheaper PA tools would lead to higher levels of adoption. Oliveira-Jr et al., (2020) proposed an Internet of Things (IoT) sensing platform for small-scale farms. This is based on affordable, widely available components in a frame of a modular system that follows the do-it-yourself way, e.g. this can be managed by a smartphone. This implies a trade-off between the costs and quality, e.g. the low-cost sensors are not suitable for high precision, but even the poor farms of rural Africa can afford and use them. However, the use of these technologies could lead to higher yields and lower fertilizer costs as well, so both of them contribute to higher profits which could make up for the purchase costs even in the short run. Nevertheless, both can contribute to higher revenues. However, cheaper technology itself cannot automatically lead to higher PA adoption. There are many other influential factors, especially in developing countries. Onyango et al., (2021) highlighted that the adoption of PA is often impeded by the lack of electric power and network connectivity in the SSA. According to the authors, relying on common knowledge and experience can also help to increase farming efficiency in the SSA region. In addition to the dominance of small-scale farms, a relatively low share of Internet accessibility is a significant problem in many African and Asian countries. Therefore, Mehrabi et al., (2021) recommended the following tools:

- policy initiated and/or supported investments into infrastructure;
- affordable handsets and reduced device costs;
- available and affordable access to Internet for the farmers funded by different institutions (public or donor financed);
- solutions between low- and high-level services (e.g. between SMS and 4 or 5G networks).

Site-specific soil maps provide the basis for any variable rate PA; however, only a small share of farms have them even in developed countries (Lowenberg-DeBoer & Erickson, 2019) identified three issues related to the adoption of variable rate technology: its price, its reliability, and its demonstrated value. Adoption rates of PA differ across the world and by technologies. For example, the Global Navigation Satellite Systems guidance shows rapid adoption, while variable rate technology shows slow adoption. They also pointed out that small-scale, non-mechanized farms are lagging behind because there are almost no PAtechnologies for them and there are limited investments into the commercialization of these technologies.

Adamides et al., (2020) proposed a special Smart Farming as a "Service as a methodological framework" that applies an annual fee proportional to the farmer's area. This may help with the fragmented land structure, as well as the undereducated farmers and unskilled workers of Cyprian agriculture. However, this system requires the participation of a high

Table 5 Characteristics of selected articles with mixed methodology

Authors	Methodology	Regional coverage	PA adoption level	Drivers of PA	Barriers of PA	Suggested solution(s)
Adamides et al., (2020)	Pilot application	Cyprus	relatively low	High education	Risk-aversion, low education	Information services
Auernhammer (2001)	Descriptive analysis	Germany	medium	field heterogeneity	fragmented land structure	virtual land consolidation
Lamb et al., (2008)	Gartner Hype-Cycle	Australia	medium	involvement of end-users	complicated technology	use of end-users' expectations
Lowenberg-DeBoer & Erickson (2019)	Traditional literature review based on knowledge of the topic.	Mostly developed countries	medium-high	motorized mechanization, demonstrated value	non-mechanization	cost reduction-commercialization, PA as a toolkit
Mehrabi et al., (2021)	Gap analysis	World	low	High service coverage	missing prerequisites	digital inclusion agenda
Oliveira-Jr. et al. (2020)	IoT Sensing Platform	Africa	low	information and communication technology	expensive technology	cheap sensing platform
Onyango et al., (2021)	Literature review	SSA countries	low	user-friendly technology	missing prerequisites	common knowledge/experience, increased precision
Sasao & Shibusawa (2000)	Descriptive analysis	Japan	relatively low	economic benefits	small farm size	scale-free precision technologies
Shang et al., (2021)	Literature review	Global	-	education, large farm size	small farm size	suitable digital technologies
Shibusawa (2001)	Descriptive analysis	Japan	relatively low	large farm size	small farm size and fragmented land structure	regional precision farming
Torky & Hassanein (2020)	Integration model (blockchain & IoT)	Global	-	high-tech openness	IT difficulties	blockchain technologies

number of small farms in order to be profitable for the provider. It should also be mentioned that data collection and advisory services based on the collected data themselves will not necessarily lead to the desired result of optimization. Regarding new technologies, Torky & Hassanein (2020) give an overview of how blockchain technologies can be used in PA. They identified five areas: farm overseeing, monitoring of supply chain processes, land registration, food safety information, and real-time agricultural remittance. The latter could be particularly useful for small-scale farmers.

Lamb et al., (2008) draw attention to an important characteristic of PAT development, namely its developer push nature rather than user pull. This may cause a huge knowledge gap between them. Therefore, it is advisable to take into account the expectations of end users during the development process of these technologies. This could significantly improve the adoption of PA.

Some of the methods different from field experiments and human subjects data collection, such as gap analysis and literature review, could make it possible to expand the regional coverage of analyses, and PA adoption could be analyzed even at global level. Table 5. gives an overview of the main characteristics of the reviewed articles using different methods for analysis.

Discussion

Agricultural production should be significantly increased to keep up with the continuously growing global population. Using approximately the same amount of land, this will only be possible with substantial efficiency growth. More efficient production, especially input optimization, is the core element of PA. In general, larger farms have better opportunities to introduce PA due to many reasons (e.g. better financial position and access to financing, larger economies of scale, etc.), but most production units are small-scale farms. From this point of view, the extremely small size of the farmland seems to be the major obstacle to the increasing spread of precision farming technologies. However, PA can be used modularly; therefore, they can be introduced step by step. This is a great advantage for small-scale farms, as they often do not have sufficient financial resources (either own resources or access to external sources). Moreover, PA can contribute to achieve higher production efficiency, either by lower/optimized input use or by higher outputs; therefore, they can result in higher revenues and/or profits. Higher profits are important for small-scale farms as they have fewer financial resources compared to large(r) farms.

Based on in-depth analysis of the articles, the major motivating factor of small-scale farms for higher PA adoption is simple and cheap technology. Because PA is a relatively new set of technologies, many of its elements are continuously becoming cheaper. In addition, modularity makes possible the gradual introduction of the technology, while built-in technology allows for the future connection of new technologies easily. However, all these things matter only if the human factor is satisfactory, i.e., farmers are educated, skilled, and aware of the benefits of PA. In this process, information is of crucial importance. There are many different options to inform the farming community, such as through education, extension services, cooperatives, farmer associations, and different fairs/exhibitions. The demonstrated value of PA is extremely essential for small-scale farmers. The agricultural policies play an important role in the adoption of PA by providing incentives, initiatives, access to information, and financial resources. Finally, PA should work well either alone or as a system, as nothing is more convincing to farmers than a demonstration of a well-working technology (efficiency). Table 6 summarizes the main factors for PA adoption based on the systematic review of the literature.

Table 6 Overview of the main factors of PA adoption

Pillars of adoption	Constraints	Solutions	References
People	Lack of awareness, lack of skills, lack of information	(Agricultural) Education, (common) knowledge, extension services, involvement of end-users in the development process, supportive national policy, encourage cooperation (cooperatives, farmers' associations)	Adamides et al., (2020), Barnes et al. (2019), Higgins et al., (2017), Kendall et al., (2021), Lamb et al., (2008), Li et al., (2020), Onyango et al., (2021), Shang et al., (2021)
Technology	Simple, functional, affordable	Modularity, built-in technology, economies of scale in production, low-cost & user-friendly, scale-free, regional precision farming, demonstrated value, use of standards, supportive national policy	Adamides et al., (2020), Aubert et al., (2012), Cammarano et al., (2020), Lowenberg-DeBoer & Erickson (2019), Mehrabi et al., (2021), Oliveira-Jr. et al. (2020), Onyango et al., (2021), Park et al., (2018), Paustian & Theuvsen (2017), Persello et al., (2019), Sasao & Shibusawa (2000), Shang et al., (2021), Shibusawa (2001), Takacsne Gyorgy et al., (2018), Yang et al., (2020), Zha et al., (2019)
Efficiency	Lack of information, lack of personal experience	Education, extension services, modularity, built-in technology, exhibitions/fairs, higher yields – lower costs	Adamides et al., (2020), Groher et al., (2020), Li et al., (2020), Oliveira-Jr et al., (2020), Takacsne Gyorgy et al., (2018), Van Vecchio et al., (2020)

Barriers of higher PA uptake were a central element of the analyzed articles. Table 7 summarizes these difficulties together with potential solutions for small-scale farms. These categories are small land size, high cost of adoption, technology-related difficulties (applicability/feasibility of PA technologies), lack of professional support and lack of supporting policy.

In the people–capital matrix, the interconnections create four different dimensions of PA usage. The optimal case (high adoption of different PA technologies) occurs when farmers have sufficient knowledge and capital. If sufficient knowledge or capital is lacking, PA use

Table 7 PA-related difficulties and potential solutions among small-scale farms

Difficulties	Potential solutions	Supporting literature
Small land size	Joint/collective actions, virtual land consolidation, zone delineation, automated field boundary detection, cooperation-cooperatives	Adamides et al., (2020), Auernhammer (2001), Cammarano et al., (2020), Li et al., (2020), Vecchio et al., (2020), Yang et al., (2020), Zha et al., (2019)
High cost of adoption	Modularity, joint actions, subsidies and supports, precision/site-specific fertilizer management, other benefits, low-cost and scale-free technology, common machinery usage, microdosing	Adamides et al., (2020), Barnes et al. (2019), Cao et al., (2012), Dobermann et al., (2002), Godwin et al., (2003), Groher et al., (2020), Kendall et al., (2021), Natcher et al., (2016), Oliveira-Jr. et al. (2020), Onyango et al., (2021), Park et al., (2018), Paustian & Theuvsen (2017), Sasao & Shibusawa (2000), Takacsne Gyorgy et al., (2018)
Difficult technology	Education, (common) knowledge, standards, involvement of end-users in the development process, simple and user-friendly technology, regional precision farming	Adamides et al., (2020), Aubert et al., (2012), Higgins et al., (2017), Kendall et al., (2021), Lamb et al., (2008), Onyango et al., (2021), Park et al., (2018), Paustian & Theuvsen (2017), Shibusawa (2001),
Lack of professional support	Professional vendors, advisors, agricultural contractor services, demonstrated value	Aubert et al., (2012), Barnes et al. (2019), Lowenberg-DeBoer & Erickson (2019), Paustian & Theuvsen (2017)
Lack of supporting policy	Adequate regulations, policy-initiated investments, supportive policy, digital inclusion agenda	Aubert et al., (2012), Mehrabi et al., (2021), Shang et al., (2021), Vecchio et al., (2020)

cannot be optimal. Farmer's awareness, along with insufficient capital, leads to partial use of PA. Sufficient capital with insufficient knowledge results in suboptimal use of the technology. Finally, when the farmer is unaware of PA and has few financial resources, they are unlikely to be adopters of PA. Figure 2. gives an overview of these cases.

Several future research directions can be identified based on the analyzed articles, such as focusing on policy-related issues (supportive policy, policy incentives), on the linkages between PA and food safety/food security, or on the geographical differences in the constraints and motivating factors of PA adoption. Development opportunities as well as adaptation characteristics of the different PA technologies are of high interest. The development of PA for non-mechanized farms is also an important issue, especially in developing African and Asian countries. The relationship between PAT adoption and the ageing of the farming community would also be an interesting research path.

Conclusions

Regarding the research question, it was possible to provide evidence how precision farming can work on a small scale. It also turned out that adopting different elements of precision farming technologies could be the only way to survive by producing more on the same amount of land. The use of cheap or no-cost technologies is more common in the case of small Asian or African farms as those farmers have almost no financial resources. However, it should always be kept in mind that the basis of any crop technology is the proper soil information. Farmers should be aware of this information; otherwise, site-specific treatments are impossible. But cheaper technology itself cannot guarantee higher adoption of different PA technologies as there are many other influencing factors such as how simple the

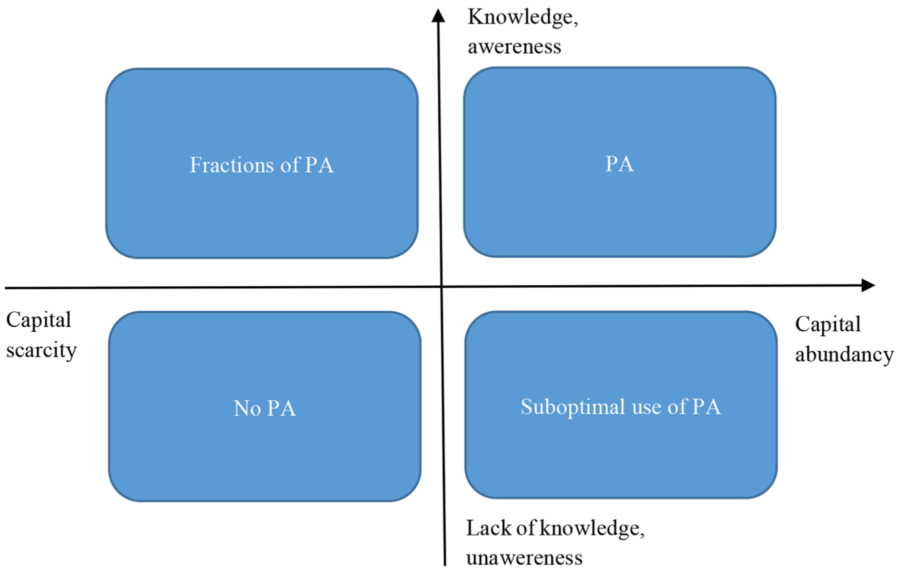

Fig. 2 Theoretical matrix of PA usage

given technology is, what education and skills the farmers have, and how high the level of the supporting factors (e.g. stable electric power and internet access) are. Cheaper technologies organized in a modular way can help accelerate this process. Financial support of this process in developing countries seems to be advantageous globally as precision technologies result in more optimal input use and higher, or at least more stable, output.

Many potential solutions can be identified for the most common difficulties of the smallholdings. Collective actions and cooperation between farmers can help to deal with the small land size. Automated solutions based on artificial intelligence can help with zone delineation/field boundary detection. Among others, there are low-cost and scale-free technologies, such as precision/site-specific fertilizer management or common machinery usage, that offer a solution to the high cost of adoption. Technology-related difficulties can be bridged by education, the use of standards, or simple and user-friendly technology. Professional vendors, advisors, or agricultural contractor services can provide professional support to farmers. Policy-initiated investments and adequate regulations can enhance the further adoption of PA.

From a policy perspective, a stable and supporting environment is essential to achieve higher PA adoption. This is particularly important in low- and lower-middle-income countries where most smallholdings can be found. Different forms of financial support can be justified by the potential environmental benefits of PA related to lower input use. It should be also kept in mind that supporting institutions (e.g. the financial sector) are also less developed in these countries. However, there are many cost-effective elements of PA such as optimal timing of planting harvesting, or proper soil management. Additionally, it makes no sense to introduce any advanced PA technologies without using these cost-effective elements. This draws attention to the importance of education, which is also a matter of public policy. Agricultural education is particularly important. Based on the analyzed articles, this explains why mechanization is one of the most important issues in developing countries, while automation or IoT systems are more relevant in the case of developed countries. PA provides many benefits mostly linked to optimized input use; however, these benefits cannot be equally realized, or realized at all, on all farms. In addition, potential environmental benefits are supported by many articles; however, their quantification is hardly possible.

The main limitation of this study is the selection process, more specifically the keywords used. The results will be significantly different if other, more or fewer keywords are used. This study focused on the applicability/feasibility of precision farming technologies on a small scale. The most important keyword is small scale. As was outlined in the introduction part, small scale is country (or at least region) specific term. Generally, this means a remarkably smaller farm size in the African or Asian region, while a larger one in Europe or South America and a much larger one in North America. These differences should always be taken into account. Carrying out a farm size-related study requires the use of additional keywords to cover smaller farms in Asia and Africa, such as medium scale or family farms.

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Conflict of interest The author has no conflict of interest to declare.

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