

Review

Enhancing Precision Agriculture for Climate Change Mitigation in Visegrad Countries: Factors Shaping Adaptation

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Abstract: As climate change intensifies, organic agriculture faces new challenges in maintaining sustainability and environmental health. Precision agriculture offers climate-smart solutions by enabling resource efficient and data-driven farming. However, the adoption of precision agriculture technologies (PATs) is influenced by various socio-economic factors, behavioral factors, financial factors, institutional factors and technological factors. Adaptation factors for precision agriculture technologies and their application in response to climate change were identified through a systematic literature review (SLR) of 58 papers from journals indexed in Scopus and Web of Science. The investigation was performed for the Visegrad group countries: Czechia, Slovakia, Poland, and Hungary. Some of these technologies include satellite imaging, remote sensing, soil moisture sensors, and precision irrigation systems, which enable more efficient use of water, fertilizers, and energy. Through a comparative analysis of the application of precision agriculture technologies in the V4 countries, this review underscores the importance of tailored PA approaches to address a specific climate challenge and promote sustainable agricultural practices in the V4 countries.

Keywords: climate-smart agriculture; agriculture technology; environmental sustainability; climate resilience; management practices; climate change adaptation



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1. Introduction

Climate change poses significant and complex challenges to the agricultural sector [1], with increasing temperatures, altered precipitation patterns, and more frequent extreme weather events threatening food security and sustainability worldwide [2]. For the Visegrad Group (V4) countries (Czechia, Slovakia, Poland, and Hungary), these climate impacts are particularly concerning due to the region's heavy reliance on agriculture as a key economic sector [3]. The V4 countries collectively account for approximately 22.5 million hectares of the Utilized Agricultural Area (UAA) in the European Union, which is nearly 20% of the EU's arable land [4,5]. Additionally, in 2020, there were about 9.1 million agricultural holdings in the EU, and the V4 countries are indeed significant contributors to the EU's agricultural output [4,5]. These nations (V4) are significant contributors to the EU's agricultural output, showcasing a diverse range of agricultural systems, from small family-run farms in Poland to large-scale operations in Czechia. Economically, the Visegrad countries face pressures to remain competitive in global markets while addressing labor shortages and rising input costs. Despite their contributions, the agricultural sectors of the V4 face distinct challenges, including vulnerability to climate-induced risks, digitalization gaps, and the complexities associated with adopting organic farming practices. In addition, V4 countries

face unique climate vulnerabilities [6], including heightened droughts in certain regions, soil erosion, and uneven rainfall patterns, which directly affect crop yields and the overall resilience of their agricultural systems. These challenges stem from geographic and climatic conditions, socio-economic transitions, and the region's historical reliance on agriculture. For example, Poland's small-scale farms struggle to integrate precision technologies due to cost and technical barriers [7], while Hungary's drought-prone plains necessitate advanced irrigation systems [8]. These factors make the V4 an important case study for understanding precision agriculture's potential to address climate and sustainability challenges in transitional economies.

In response, precision agriculture technologies (PATs) have emerged as promising solutions to address climate adaptation in agriculture by enhancing resource efficiency and supporting data-driven decision-making [9]. PATs, which encompass technologies such as GPS-guided machinery, remote sensing, and variable rate technology (VRT), enable farmers to optimize water use, improve soil management, and reduce greenhouse gas emissions [9–11]. These technologies, however, have not been universally adopted in the V4 countries, with varying degrees of integration depending on different adaptation factors unique to each country. In organic farming systems, where the use of synthetic chemicals and fertilizers is restricted, the adoption of PATs presents unique challenges and opportunities [12]. Organic farming prioritizes preventative measures, such as diverse crop rotations and ecological pest control, rather than direct interventions. Organic farmers may benefit from PATs in areas such as precision irrigation, soil health monitoring, and targeted pest management [13,14]. This approach aligns with principles of environmental conservation and sustainability but often faces challenges such as lower yields and labor intensity. Despite their differences, precision agriculture and organic farming share common objectives, particularly in promoting sustainable agriculture and mitigating climate change impacts [15]. By carefully managing resources like water, fertilizers, and pesticides, precision agriculture reduces waste, lowers environmental impact, and supports sustainable farming practices [16].

For organic farming, precision agriculture (PA) is especially advantageous because it enhances resource use efficiency and supports soil and plant health through meticulous monitoring and management techniques [17,18]. For instance, soil sensors and precision irrigation systems can optimize water use and soil fertility in organic systems [19], while drones and remote sensing can enhance monitoring and pest control without compromising organic principles [20].

However, the diffusion of technology is not uniform, i.e., it does not occur with the same speed and intensity among farmers in V4 countries. Also, the compatibility of PATs with organic farming principles [21] such as minimizing environmental impact and enhancing ecological balance requires careful consideration. Despite these potential advantages, the uptake of PATs in organic farming is often hindered by the perceived cost of investment, limited access to appropriate technology, and a lack of sufficient knowledge regarding the best practices for integration [22]. These include socioeconomic variables such as education and farm size, financial constraints like high initial investment costs, institutional support for technology integration, and technological factors such as compatibility with organic farming practices. Furthermore, a critical gap exists in understanding how various adaptation factors influence the successful application of PATs in these systems. By addressing socioeconomic, behavioral, financial, institutional, and technological factors, this study aims to provide a comprehensive framework to guide PAT adoption tailored to the needs of the V4 countries. The research question, therefore, focuses on how these factors collectively shape the integration of PATs into organic farming to enhance sustainability and productivity in the face of climate change.

This manuscript provides a comprehensive review of the factors influencing the adoption of PATs in the V4 countries and their response to mitigate climate change impacts. One of the challenges in focusing on the V4 countries is the relative scarcity of robust, consistent data compared to Western Europe. To address this issue, we employed the systematic literature review (SLR) methodology, which included only peer-reviewed articles and reputable sources from recognized databases such as Scopus and Web of Science. This approach ensured the inclusion of high-quality evidence despite data limitations. By conducting an SLR of research on PATs in Visegrad countries, this study identifies five key adaptation factors: socio-economic, behavioral, financial, institutional, and technological. Understanding these factors is crucial for tailoring technology adoption strategies to each country's specific needs, ensuring that PATs can support sustainable agricultural practices and contribute to climate resilience. In addition, this study aims to inform policymakers, stakeholders, and agricultural practitioners on the best practices and potential interventions that could enhance PAT adoption, promote climate adaptation, and foster sustainable agriculture within the Visegrad region. The paper is structured as follows: The first section provides a comprehensive literature review covering climate change and organic agriculture in V4 countries, precision agriculture in organic farming systems, and the factors affecting the adoption of precision agriculture. The second section details the methodology, which is based on an SLR. The third section presents the results obtained from SLR data, emphasizing the factors influencing the adoption of PA technologies across the V4 countries and their adaptation to climate change. The final section concludes the study with insights for policymakers and recommendations for future research.

1.1. Climate Change and Organic Farming in the Visegrad Group

In the Visegrad group countries (V4), agroecology and organic farming in particular has been accepted and supported since the 1980s with financial subsidies, technical trainings and knowledge resources provided to organic farmers to promote sustainable agriculture practices [23]. The V4 was created because these four countries had similar goals, the most important of which were successful social transformation and joining the process of European integration [24], and they present a are significant contributors to the agricultural sector in Central and Eastern Europe. However, in recent years, there have been growing differences in opinion among the Visegrad countries, including on issues such as energy policies and strategies [25]. Agriculture in the V4 countries is increasingly vulnerable to the effects of climate change [26]. Rising temperatures, more frequent droughts, and extreme weather events such as floods are becoming common across the region, presenting significant challenges to the agricultural sector. For organic farming, which relies on natural processes and minimal synthetic inputs [27], these changes pose unique risks. In addition, the organic sector struggles with issues related to scalability and certification [28]. Many countries recognized and tried to reduce the dangers, but the European Union (EU) seemed to be the most innovative group at the forefront of environmental protection and climate governance [29]. The EU's climate goals showed progress toward a substantial shift in climate policy; nevertheless, doubts and concerns arose in adaptation and mitigation [30]. According to Brożyna et al. [24], V4 countries would need to revise their policies and funds allocated for green transformation which, in turn, might change their projections of the EU climate package targets for 2030. Kovács et al. [31] outline three problem groups influencing climate policy implementation in V4 countries: economic interest, lack of will, and institutional failure (instability). However, other factors, such as the Ukrainian–Russian conflict, also pose significant risks to Hungary and Poland's implementations of Climate and Sustainable Development (CSD) strategies [32]. Both countries are currently navigating the EU constitutional process, and until this process is completed, the European

Commission is withholding funds. The loss of these funds could have a substantial effect on their future climate ambitions.

The initial climate policy paradigms (CPP) regarded climate change as a straightforward environmental issue, with this phase of the United Nations Framework Convention on Climate Change culminating in the Kyoto Protocol [33]. Czechia and Hungary were the first among the V4 countries to develop climate strategies aimed at meeting the Kyoto Protocol's goals. These strategies were updated in 2017, with a focus on reducing fossil fuel consumption, lowering energy intensity, and increasing the share of renewable energy sources [34]. While the Czech, Hungarian, and Slovak strategies emphasized adapting to the impacts of climate change, Poland's strategy primarily focused on mitigating the costs associated with adaptation failures [31]. In the V4 countries, organic agriculture with climate change strategies presents an opportunity to enhance sustainability and resilience in the agricultural sector. Organic farming practices align well with the goals of mitigating climate change and adapting to its impacts.

1.2. Precision Agriculture in Organic Farming Systems

Precision agriculture (PA) represents a significant technological development in the agricultural sector. This modern approach aims to optimize management at the field level by considering variations in crops, weather, soil and other environmental factors [35]. PA is a globally applied approach to improving agricultural resources such as quality and yield [35], crop productivity and resource management [36,37], reducing labor inputs [38], reducing overall pesticide use [39], and ensuring effective management of fertilizers and irrigation [13]. This innovative method enables farmers to make data-driven decisions based on specific conditions in different parts of their fields, improving yields and resource use, or animal performance [40]. Organic farming is a scientifically proven, environmentally friendly method for preserving ecological balance [12]. Characterized by its emphasis on natural processes and minimal synthetic inputs, organic farming presents unique challenges and opportunities for precision agriculture [13]. Organic farming helps to reduce soil, water, and air pollution because of its environmentally friendly approach [41]. According to one study [42], organic food consumption may be one strategy to reduce dietary exposure to pesticides and associated health risks. Conventional systems have been able to increase yields with the adoption of precision agricultural techniques (PATs). A similar strategy could be implemented in organic farming by, for example, mapping yields and optimizing the planting rates of nitrogen-fixing cover crops and subsequent cash crops, to optimize the cash crop yields [43]. The integration of precision agriculture into organic farming systems represents a promising intersection between technology and traditional agricultural principles [41]. While organic farming and precision agriculture use different methods, combining these approaches can lead to greater overall benefits [44]. The application of precision agriculture in organic farming is driven by the growing realization that it can complement and support organic principles [45]. In addition, advanced monitoring techniques can improve the effectiveness of organic pest control methods [46] by providing detailed insights into pest populations and crop conditions [14]. By adopting precision agriculture technologies and organic farming practices, farmers can significantly reduce the agricultural sector's carbon footprint and enhance the resilience of their farming systems against climate change. In addition, improving water efficiency and soil health by reducing greenhouse gas emissions, enhancing carbon sequestration, and creating more resilient agricultural systems can contribute to the reduction of climate change impact. Some of the PATs are listed in Table 1 based on widely recognized practices in modern agriculture.

Table 1. Precision agriculture (PA) technologies and their applicability in organic farming systems.

Technology	Description
GPS-Guided Tractors	Used in organic farms to ensure precise planting, cultivating, and weeding without disturbing the soil unnecessarily.
Drones	In organic agriculture, drones monitor crop health and assist with targeted interventions like organic pesticide application or beneficial insect release.
Soil Sensors	These are crucial in organic farming for monitoring soil moisture, organic matter, and nutrients, helping manage fertility without synthetic fertilizers.
Satellite Imagery	Used for large-scale monitoring of crop health by capturing data on vegetation indices like NDVI, and helps farmers to assess soil moisture levels, organic matter content, and overall soil health.
Variable Rate Technology (VRT)	In organic farming, VRT can be adapted to apply organic fertilizers or amendments precisely where needed. Also it could include site-specific seeding, soil cultivation, or crop protection.
Data Analytics Platforms	Organic farmers use data analytics to track crop performance, soil health, and the impact of practices, enabling informed decisions for sustainability.
Geographic Information Systems (GIS)	Organic farmers can use GIS to plan crop rotations, manage field variability, and maintain records of organic certification requirements.
Automated Weed Control	Organic farming often relies on mechanical weeding, using high-precision GPS and computer vision to locate crops and remove weeds.
Weather Monitoring	These systems help organic farmers make better decisions on planting, harvesting, and managing pests and diseases, crucial without synthetic chemicals.
Robotics	It can perform tasks like weeding or planting cover crops, reducing the need for manual labor and supporting organic practices.

Authors' own investigation.

Increasing food production while preserving the environment is one of the ways to meet the needs of a growing population. The rapid increase in population poses major challenges for food production systems worldwide [47]. The total area of agricultural land under organic farming in the EU was estimated at 16.9 million hectares (ha) in 2022. This latest data confirms the continuation of a rapid and strong expansion of organic farmland in the EU: between 2012 and 2022, there was an estimated increase of 7.4 million hectares, an increase of 79% [48]. Recently, increases in organic production have also been observed in the V4 countries. According to the European Environment Agency [49] and the European Commission [50], Czechia accounts for around 15% of the total agricultural area, Slovakia for around 10%, and Hungary for around 6.1%, while Poland accounts for around 3.5% of the total agricultural area [51]. However, the integration of PATs into organic farming is not without its challenges. Issues such as the cost of introducing the technology and the need to educate and train farmers are important considerations. Balancing the use of modern technology with adherence to organic principles requires careful navigation to ensure that the benefits of precision agriculture are realized without compromising the core values of organic farming.

1.3. Factors Affecting the Adoption of Precision Agriculture

Integrating precision agriculture into organic farming presents a promising pathway to enhance the efficiency and productivity of organic systems, which traditionally rely on natural processes and input [52]. There have been many studies regarding factors affecting the adoption of PATs [53,54]. The qualities of the technology, the farmer's goal, and the socioeconomic, biological, and physical context in which the technology is introduced are some of the elements that influence the degree of technology adoption [55]. Factors such as networks and education [56], age [57], family size [58], and activity experience [7] play important roles in the adoption of precision agriculture technologies (PATs). Dessart et al. [59] provided a policy-oriented review of behavioral factors influencing the adoption of various sustainable farming practices in Europe, such as organic farming and conservation agriculture. Understanding these factors is crucial for stakeholders to make informed decisions about adopting these technologies in organic systems. Studies showed that application of PATs is generally higher in the US, Australia, and South America than in Europe [60]. In Europe, the highest user rates of digital farming technology are in Germany, France, the Netherlands, and the United Kingdom [17]. In general, Germany and Czechia are leaders in the application of precision agriculture, while Austria, Poland, Slovakia, Slovenia, and Hungary still need to improve the application of technologies [61]. The adoption of technologies in organic farming within the Visegrad Group is on the rise, supported by a combination of government policies, market dynamics, and technological advancements [62]. These countries, with their rich agricultural traditions and significant contributions to the European Union's agricultural output, face unique challenges and opportunities in integrating PATs [62]. Thus, the study aims to analyze different adaptation factors influencing integration of precision agriculture into organic farming in the V4 countries (Czechia, Slovakia, Poland, and Hungary), as well as which PATs are the most effective for addressing climate change in V4 countries.

1.4. Purpose of the Study

Investigating the different adaptation factors for the application of PATs in organic farming systems is a crucial and evolving area of research and application.

The study was based on the following objectives:

1. Based on a systematic literature review, we established the different adaptation factors influencing the application of PATs in organic farming systems in V4 group countries.
2. We explored which precision agriculture technologies are the most useful in V4 countries in response to climate change.

2. Methodology

The influence of different adoption factors of PA and key technologies for application in response to climate change is documented in this paper. The study area for investigation included the V4 countries (Czechia, Slovakia, Poland, and Hungary). The study was conducted using an SLR, and these countries were chosen to reflect the diversity in the application of PA within the context of a shared V4 policy framework. The SLR approach was chosen for its ability to integrate findings from diverse studies, offering a comprehensive understanding of the topic. The key factors for PA adoption and their response to climate change were identified through an SLR based on the final sample of 58 articles from the total database of 220 papers after thorough reading. The study incorporated the relevant literature to provide context and establish its theoretical foundation. References were sourced through targeted searches in academic databases, including Scopus, Web of Science, and ResearchGate, using keywords such as "climate change", "organic farming", "adaption factors of PATs", "precision farming", "smart agriculture", "agriculture 4.0" and "name

of selected countries". The selection emphasized studies presenting empirical evidence or conceptual insights on the adoption of precision agriculture technologies, particularly within organic farming systems. The articles were selected based on predefined criteria, which included: relevance to precision agriculture, organic agriculture, focus on climate change, geographical scope (the focus was on the V4 countries), and publication date. This method ensured the inclusion of pertinent and up-to-date perspectives to support the survey findings. To capture recent advancements in the field, the search was restricted to peer-reviewed articles published between 2019 and 2024. Figure 1 shows the selection process for extracting research articles based on abstracts and keywords. In addition, according to Aquilani et al. [63], some specific agricultural technologies (GPS, sensors, robots) were used as keywords, as well as some factors affecting the adoption level of PA. Then, the references in the reviews and the articles on climate change, organic agriculture, and precision agriculture were studied. This approach was used to determine if additional articles could be considered for the selected topic. The search was performed in several scientific databases, without restriction of date, but with restriction of country. Table 2 showcases the diversity of the sources utilized in the study, highlighting the thorough and systematic approach taken to select relevant articles. It emphasizes the inclusion of high-quality, peer-reviewed articles from reputable e-resources, ensuring a solid foundation for the research. It includes the years covered and the quality of the journals (Q1/Q2) for each e-resource.

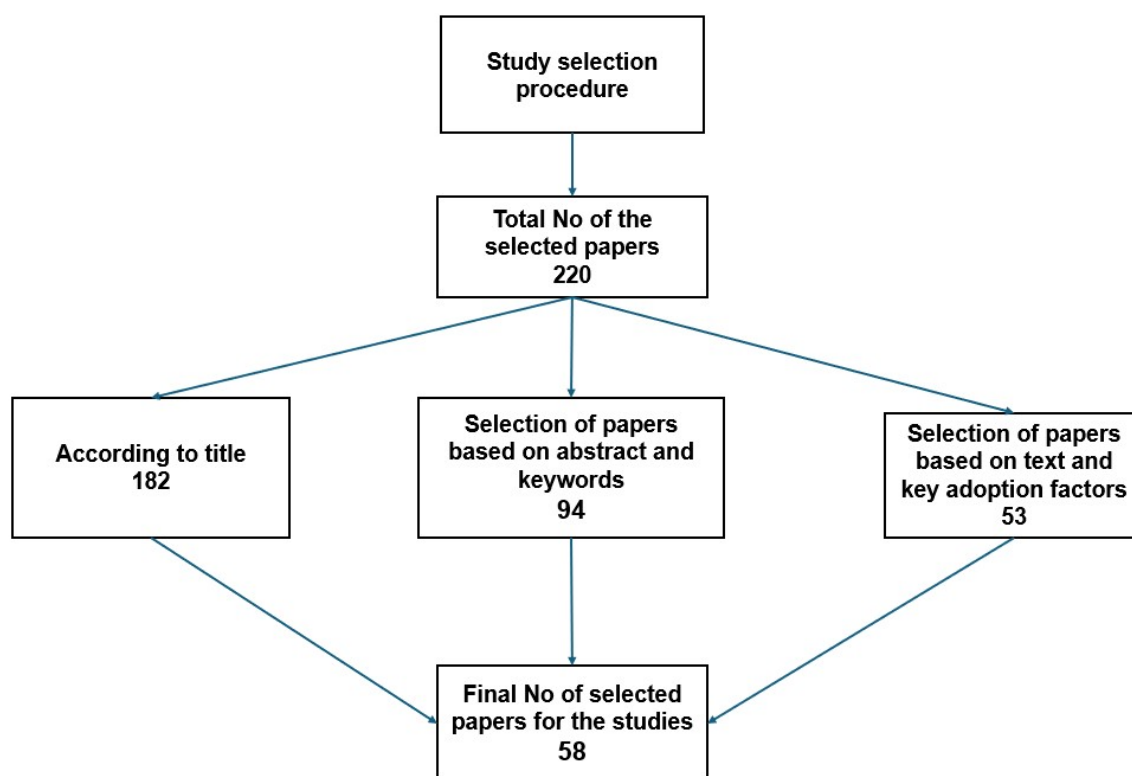


Figure 1. The selection procedure of the 58 studies was included in the systematic review.

The total number of selected articles was 220. Out of these, 182 articles were published in Q1 and Q2 journals. These 182 articles were divided equally among the authors for the first screening phase. Articles that had no mention of PA, adaptation factors, or climate change were eliminated. After the second screening phase, 94 works were excluded, while after third screening phase, 53 articles were included for analyzing. However, citation searching added a further 5 records, for a total of 58 records to be admitted for inclusion in the final review. These 58 articles include research based on case studies, surveys and

questionnaires, focus group discussions (FGDs), as well as interviews with farmers in V4 countries. All of the papers included in the analysis were reviewed in full-text format. All articles were discussed, analyzed, and assigned to the selected countries.

Table 2. Summary of the data from papers selected based on predefined search criteria.

Sr.No E-Resource	Content	Years Covered	Journal Quality
https://www.sciencedirect.com/ https://www.webofscience.com/wos/woscc/basic-search https://www.researchgate.net/ https://www.elsevier.com/ https://onlinelibrary.wiley.com/ https://www.academia.edu/ https://www.proquest.com/ https://www.scinapse.io/	Journals, proceedings, databases, magazines, conferences, and books	2019–2024	Q1/Q2

3. Results and Discussion

After reviewing the literature, five key categories were identified (Table 3) as crucial for the adaptation of PATs in organic farming: socio-economic, behavioral, financial, institutional, and technological factors. These categories were drawn from studies by Souza Filho et al. [64] and Tey and Brindal [53]. In addition, Pierpaoli et al. [35] provided a comprehensive understanding of the various influences on PAT adoptions.

Table 3. Categories of different adaptation factors of PATs.

Categories	Variables	References
Socio-economic factors	Network, education, age	[7,53,58,65–68]
Behavioral factors	Producer behavioral profile; intention to adopt new technology	[69–74]
Economic factors	Credit availability, application of fertilizers, value of production, farm size	[53,54,65,66,75–78]
Institutional factors	Distance from the main market	[57,72,76,79–81]
Technological factors	Adaptation of various technologies, integration with organic practices	[54,68,72,73,77,80,82–84]

Additionally, variables were assigned to quantify these factors, based on adaptations from Antolini et al. [85] and Yrashynskaya [7]. However, the successful integration of these technologies in organic systems will depend on their alignment with organic principles, economic viability, user-friendliness, and demonstrated effectiveness in enhancing sustainability and productivity. Organic farming focuses on maintaining soil health, promoting biodiversity, and avoiding synthetic chemicals [27,86]. Any technology adopted in organic farming must adhere to these core principles. For precision agriculture technologies (PATs) to be successful in organic systems, they need to support and enhance these organic farming practices, rather than contradict them. For example, technologies that optimize natural pest control methods, monitor soil health, or aid in the efficient use of organic fertilizers are aligned with organic principles. Table 4 summarizes the main factors influencing the adoption of precision agriculture technologies (PATs) across the Visegrad group countries (Czechia, Slovakia, Poland, and Hungary). It focuses on above-mentioned five key categories of factors: socio-economic, behavioral, financial, institutional support, and technological.

Table 4. Key factors influencing precision agriculture technology (PAT) adoption in Visegrad countries.

Country	Socio-Economic Factors	Behavioral Factors	Financial Factors	Institutional Support	Technological Factors	References
Czechia	Higher adoption among larger farms; challenges with older farmers' reluctance	Younger farmers more open to adopting new tech; varied interest in older farmers	High initial costs, with limited credit for smaller farms	Government incentives for new machinery; support for climate forecasting tools	Emphasis on soil and water management, VRT for precision fertilization	[57,72,87,88]
Slovakia	Small farms interested but limited by high costs; support from training programs	Strong peer influence within farming communities encouraging adoption	Limited funding; reliance on government subsidies	Institutional support for digital tools; initiatives for crop-specific drought tolerance	Focus on mechanization and GIS for soil erosion prevention and water conservation	[74,82,83,89]
Poland	Education level correlates with higher PAT adoption; small farms face funding barriers	Positive perception in tech-savvy regions; adoption encouraged by local community	Funding mostly accessible to larger farms; subsidy gaps for small farms	Moderate support for PATs and drought resilience	High use of satellite imaging and data analytics for climate impact tracking	[69,88,90–93]
Hungary	Younger farmers and large farms lead adoption; financial constraints for smaller farms	Generally supportive, but smaller farms remain risk-averse	High technology costs; lack of accessible credit for smallholders	Strong support for irrigation systems and weather monitoring	Focus on real-time monitoring tools for drought resilience, automated irrigation	[57,67,71,94–97]

3.1. Socio-Economic Factors

Socio-economic factors such as networking, education, age, and experience play a critical role in influencing farmers' decisions to adopt PATs [98]. A stable and reliable internet connection is essential for the adoption of PATs, as it underpins the wireless communication necessary to integrate various PAT devices into a cohesive and functional network [77]. Without dependable internet access, the effective operation and integration of these technologies would be compromised, rendering the system ineffective [84]. In Hungary, the adoption of precision farming technologies is predominantly observed among younger farmers who possess higher education levels and manage larger farms (over 300 hectares) [70]. Furthermore, Balogh et al. [67] found that the largest farms in Hungary exhibit the highest propensity to innovate, and have the second-highest educational attainment among the five identified clusters of adaptation factors. Conversely, in Czechia, the transition to organic production is hindered by factors such as the older age of farmers and high labor productivity, which are perceived as barriers [90]. In Poland, higher education levels significantly enhance farmers' willingness to implement environmental measures, highlighting the importance of education in promoting sustainable agricultural practices [89]. Similarly to other V4 countries, Slovakia also benefits from practical training, workshops, and field demonstrations, which are effective in familiarizing farmers with the benefits and application of PATs [61]. In the V4 countries, larger farms typically generate higher revenues, which enable them to invest in precision agriculture tools such as GPS-guided equipment, sensors, and data analytics platforms [75]. This correlation between income and technology adoption highlights the need for financial support and incentives for smaller farms, which may struggle to bear the high costs associated with PATs. In the V4 countries, organic farming is more likely to be adopted on small family-run farms [99], while the adaptation of precision agriculture technologies is more common on the large farm size. Larger farms (of 50 ha or more) are more common in, Czechia (27.8% of the total) and Slovakia (17.9% of the total), while small farms of under 5 ha are typical in Hungary

and Poland [66,72]. However, larger farms tend to benefit more from economies of scale, which makes the investment in precision technologies more cost-effective [35]. Variability in soil types across regions necessitates specific PA solutions. Several factors, such as the differences in soil texture and fertility and the occurrence of pests, diseases, and nematodes, can cause spatial variability in the growth and development of crops within a field [100].

3.2. Behavioral Factors

Behavioral factors very often overlap with economic and technological factors, and play a critical role in the adoption of new technologies, including PA [101]. Farmers who perceive PA technologies as beneficial for their productivity, cost savings, or environmental impact are more likely to adopt them [102]. In Poland, for example, studies show that households with a favorable attitude toward sustainability and innovation are more likely to adopt information and communication technologies (ICTs) encompassing computer and network hardware and software [69]. However, the influence of others' opinions, such as family members, farming peers, and local experts, are also important for the adaptation of new technologies. If the farming community or advisors strongly advocate for PA adoption, this social pressure can increase a farmer's intention to adopt [70]. Berenyi et al. [87] conducted research on technology adoption among Hungarian business students. Many of the students have an optimistic approach to new technologies, and a significant part of them showed higher than medium-level proficiency. Parallely, fear of vulnerability is remarkable among the respondents, which suggests cautious behavior. In addition, the positive attitude of Hungarian food business leaders towards innovation, and the strategic intention of placing innovative products and processes on the market have a positive relationship with innovation performance [71]. In Czechia, the adoption of precision agriculture technologies is relatively high [83] and, according to Vrhota et al. [72], farmers are willing to adopt new technologies. It may be due to the Czech government supporting the adoption of precision technologies through financial incentives for new machines [73]. Slovakia experiences a similar situation, where digitalization significantly influences agricultural development [74]. This refers to the farmer's perception of their ability to adopt and use PA technologies. If farmers feel that they have sufficient skills, knowledge, and financial resources, their intention to adopt is stronger.

3.3. Economic Factors

Economic factors are critical for organic farmers, particularly in adopting PATs. These farmers, like others, must justify the financial investment in PATs by ensuring that these technologies can reduce input costs (e.g., water and organic fertilizers) and increase crop yields, ultimately boosting profitability. However, access to credit remains a significant barrier to PATs adoption due to high initial investment costs and limited public funding availability [18,103,104]. In V4 countries, credit availability is essential for financing these initial costs and investing in technologies that enhance operational efficiency and productivity. Yet, disparities in credit access often resulting from stringent loan requirements and high-interest rates hinder small and medium-sized farms from investing in PATs [53]. To mitigate these challenges, some V4 countries have introduced supportive measures. For example, the Czechia government has incentivized the adoption of precision technologies through financial support for new machinery [89]. A survey by Baraniak and Starzyńska [88] of 150 individual farms in Poland's Łódź region revealed that 33.3% of respondents faced financial challenges in adopting innovative agricultural practices. PATs enable precise fertilizer application based on real-time soil and crop requirements, reducing waste and boosting crop yields. In V4 countries, the economic benefits from efficient fertilizer use are a strong motivator for adopting precision farming techniques [67]. The

value of agricultural production is also a significant factor influencing PAT adoption. Farms with high-value crops or larger overall production tend to invest in precision agriculture to enhance profitability and maintain market competitiveness [35]. In the V4 countries, the potential for higher economic returns from high-value crops like wine grapes, fruits, and specialized vegetables drives the use of precision technologies to ensure quality and optimize yields [77]. In Hungary, the most innovative firms mentioned that financial factors are the major barriers to innovation, and that the shortage of skilled employees is also a problem [67]. The main innovation in Slovakia is the introduction of the PA concept, which involves all key stakeholders for better understanding the adoption and use of technologies in the country and government support for adaption of new technologies in organic farming systems.

3.4. Institutional Factors

Institutional factors significantly shape agricultural productivity and economic stability in the V4 countries. The impact of geographical distance from markets on agricultural outcomes has been well-documented. Research indicates that increased distances can lead to higher transportation costs, which negatively affect farmers' access to competitive prices and market opportunities [105,106]. For example, a study by Stringer [107] and Eldridge et al. [108] highlights how market access constraints can exacerbate regional inequalities in agricultural productivity. This is especially important in Slovakia's rural areas, where main challenges are the lack of job opportunities and limited access to basic services. On the other hand, due to glaciation, Polish farms are characterized by high spatial variability in topography and soil properties, enhancing the potential for adopting precision agriculture solutions [109]. Proximity to fertilizer distributors is similarly crucial for optimizing agricultural productivity. Efficient access to fertilizers is essential for enhancing crop yields and maintaining soil fertility. Studies have shown that long distances to distributors can increase input costs and reduce farmers' ability to access necessary resources, which in turn impacts overall productivity [110]. According to Ženka et al. [111], in Czechia, the highest agricultural labor productivity can be expected in fertile lowland areas, which allow for intensive agricultural production with high capital inputs in terms of machinery and fertilizers. On the other hand, extensive agriculture in higher altitudes oriented to pastoral farming can also exhibit relatively high labor productivity levels due to low labor inputs into such kinds of activity. In Hungary, based on the National Chamber of Agriculture's 2019 estimates, the adoption of precision technologies is increasing year by year [97], and farmers closer to urban centers often have better access to financial institutions, enabling them to secure loans and credit lines needed to purchase advanced agricultural equipment and technology [96].

3.5. Technological Factors

In our research, we explore three key technological factors: mechanization of technology, adaptation of various technologies (satellite imaging, remote sensing, soil moisture sensors, and precision irrigation systems), and integration with organic practices, which are essential for enhancing agricultural efficiency and sustainability in the V4 region. Research indicates that mechanization can lead to higher crop yields and better resource management [83], yet the rate and extent of mechanization vary significantly across the V4 countries due to differences in economic development and infrastructure. In Czechia, studies focus on optimizing different doses of fertilizers [108], mapping soil and crop variability, creating application maps for crop fertilization, and optimizing different doses of herbicides [29]. Adaptation of various technologies involves the incorporation of diverse technological solutions to address specific agricultural challenges. This includes preci-

sion agriculture, data analytics, and innovative breeding techniques, which collectively contribute to more efficient and sustainable farming practices [36]. In Hungary, only 38% of farms used some kind of digital tool in 2020, with farmers mostly handling matters related to banking and e-government electronically [95]. Technological advancement and the increasing availability of affordable precision tools are facilitating their adoption by Polish farmers [112]. In Slovakia, despite the lower use of cloud computing services by agricultural enterprises compared to other EU countries [89], the potential for increased efficiency and long-term cost savings makes a strong case for the adoption of precision agriculture technologies [113]. Public institutions in Slovakia primarily use satellite data to produce free data for observing general production patterns. Meanwhile, large companies in Hungary leverage satellite data within software to measure fields, process data, identify specific areas, and create detailed maps [114].

3.6. Precision Agriculture Technologies: Adaptation to Climate Change in V4 Countries

The adoption of PA is tailored to each region's specific climate risks and agricultural needs. In the V4 countries, climate variability, including heatwaves and drought, is a growing concern. Precision irrigation systems are increasingly used to ensure efficient water usage [19,115,116]. PA tools, like satellite monitoring, help farmers track soil moisture levels and optimize water distribution to mitigate drought stress [117]. This enables farmers to maximize crop yield, improve resource efficiency, and reduce environmental impact. By integrating advanced tools such as remote sensing, precision irrigation, soil moisture sensors, and variable-rate technology, today's agricultural practices are becoming more intelligent and sustainable. Together, these technologies form a connected ecosystem that enables farmers to manage crops with precision and adaptability, leading to more productive, resource-efficient, and sustainable agriculture. In addition, by optimizing the use of water, chemicals, and energy, precision agriculture enhances the sector's resilience to climate change, particularly in the face of droughts, extreme weather events, and climate-related pests and diseases [118]. Decision support systems, integrated with field equipment, enable farmers to make informed choices about fertilizer application, timing of spraying, and irrigation needs. This technology allows for remote management of key processes, resulting in significant savings of time, energy, and resources [118].

3.6.1. Czechia

Czechia faces increasing temperature variability, drought risks, and heavy rainfall, particularly during critical growing seasons [119,120]. These climatic changes directly impact crop productivity, especially in the central and southern regions [19]. PA adoption here focuses on technologies such as soil moisture sensors, irrigation management systems, and remote sensing to optimize water use in drought-prone areas [121,122]. Variable-rate technology (VRT) for fertilizer application is also widely used to improve soil health and nutrient management, which are essential for maintaining crop yields in a changing climate [123,124]. Moreover, the integration of climate forecasting tools enables Czech farmers to better predict extreme weather events, such as heavy rains or heat waves, and adjust their farming practices accordingly. In addition, in Brno, Czech Republic several climate forecasting tools are used to help farmers adapt to climate variability and improve agricultural productivity, such as the Czech Hydrometeorological Institute, (CHMI), Integrated Drought Monitoring System (ISNO), and CzechGlobe (Global Change Research Institute).

3.6.2. Slovakia

Slovakia's agricultural sector is increasingly impacted by soil erosion, drought, and irregular rainfall patterns, which affect the country's crop yields and pasture lands. PA

adoption in Slovakia is driven by the need to optimize the use of water and nutrients in response to these climate challenges [125]. Technologies like GPS-guided machinery for precision planting, and drone technology for monitoring field conditions, allow farmers to manage large areas more efficiently [126]. The adoption of these technologies in Slovakia has a direct impact on helping farmers adapt to climate variability. For example, drought-tolerant crops combined with precise soil moisture monitoring are making farming more resilient to unpredictable rainfall patterns [127]. Thus, drought-tolerant crop varieties, combined with PA tools that monitor soil moisture levels, are becoming increasingly relevant in the southern lowland regions, where water scarcity is a growing concern [128]. PA in Slovakia also aims to minimize soil erosion through targeted soil management practices supported by GIS mapping and sensor-based technologies [129]. According to Kumar et al. [130], technologies like agricultural drones and GIS mapping systems are also essential for reducing soil degradation and optimizing the use of fertilizers and pesticides, which helps mitigate the environmental impact of farming.

3.6.3. Poland

In Poland, the northern and eastern regions are vulnerable to excessive rainfall and flooding, while southern areas face increasing droughts. The country's large agricultural sector, particularly in cereal production, requires robust PA technologies to deal with this climatic diversity [131]. Satellite imaging and drone-based remote sensing are used to assess large-scale crop health, while yield monitoring systems help optimize input use and improve field management [132]. In Poland, since October 2019, the Institute of Meteorology and Water Management—National Research Institute (IMWM-PIB) has made available the precipitation maps generated on the basis of observations conducted by ground-based radar stations that are part of the POLRAD network [133]. PA tools such as precision irrigation and water management technologies are critical for mitigating the effects of both excessive rainfall and water shortages. According to Konstantina et al. [134], precision irrigation technologies could increase crop yields and productivity, optimize water use efficiency, and minimize environmental impact. Poland also places a strong emphasis on data analytics in PA, using historical climate and crop data to predict and respond to emerging weather patterns, ultimately improving decision-making for crop protection and nutrient management.

3.6.4. Hungary

Hungary experiences some of the most severe drought conditions in the V4 countries, particularly in the Great Hungarian Plain [135]. Traditionally, Hungarian agriculture is based on dryland farming, with irrigated farming practiced in a few areas [136]. The adoption of PA technologies here focuses on managing water resources and mitigating the effects of frequent droughts. Technologies like automated irrigation systems and weather stations are widely used to ensure efficient water usage, while crop-monitoring drones provide real-time data on plant health and soil conditions [136,137]. Real data such as soil nutrient levels, soil type, pH, pest emergence, etc., can be extracted by application of PATs [138]. This fine data allows farmers to monitor changes in soil and crop conditions and react to events with lightning speed, after thorough and properly instrumented soil sampling. In addition, Hungary's adoption of yield prediction models based on climate data allows farmers to adjust their planting schedules and input use based on the expected seasonal rainfall. The emphasis on precision nutrient management helps in minimizing fertilizer use while optimizing crop yields, especially in drought-prone areas [139].

3.7. Limitations of the Study

There are several limitations related to this research. While the SLR method ensures the inclusion of high-quality evidence, it is limited by the availability of the existing literature and potential regional disparities in research focus. These limitations underscore the need for further primary data collection to validate the findings in a specific context. Also, data availability and reliability across the V4 countries vary, and inconsistencies may affect the accuracy of findings related to PATs adoption and climate adaptation. Additionally, PATs adoption rates can vary widely within each country based on factors like farm size, crop type, and financial resources, which the authors in this study were not able to fully capture. Rapid advancements in PATs may also quickly render some recommendations outdated as new, cost-effective technologies emerge. Additionally, socio-economic and cultural factors unique to each country, as well as financial barriers, are noted but not fully explored, limiting the understanding of the specific social and economic drivers affecting adoption. Lastly, while institutional factors are considered, the study may not thoroughly address specific policy or regulatory barriers across the V4 countries, which could significantly influence PAT integration. These limitations suggest areas for further research to deepen the understanding of PAT adoption in the context of climate adaptation in the V4 region.

4. Conclusions

This study examined the factors shaping the adoption of precision agriculture technologies (PATs) in the Visegrad (V4) countries—Czechia, Slovakia, Poland, and Hungary—and their potential to mitigate the impacts of climate change while promoting sustainable farming practices. Guided by an SLR of 58 peer-reviewed articles, we identified five key factors influencing PAT adoption: socio-economic, behavioral, financial, institutional, and technological. Although each country faces unique climate challenges, such as droughts, soil erosion, and rainfall, PA technologies offer a wide range of solutions, including satellite imaging, remote sensing, soil moisture sensors, and precision irrigation systems, to address these issues effectively. Our findings highlight the importance of tailored strategies to address country-specific challenges and leverage PATs to enhance sustainability and resilience in agriculture. As these countries continue to develop their agricultural sectors, the role of technology in organic farming is expected to grow, further enhancing the sustainability and productivity of their agricultural systems.

4.1. Practical Recommendations for Farmers, Stakeholders, and Policymakers

Each V4 country should implement training programs focused on the specific PATs most relevant to their climate challenges (e.g., moisture sensors in drought-prone areas of Czechia, and erosion control in Slovakia). These programs should target conventional and organic farmers, emphasizing practical techniques and benefits to encourage adoption.

Given the high upfront costs of PATs, particularly for small-scale farmers, V4 governments could consider subsidies, grants, or low-interest loans specifically for climate-relevant technologies. Financial incentives should be tailored to support PATs that align with each country's climate adaptation needs, such as water management systems in Poland and temperature monitoring in Hungary.

Regional cooperation among V4 countries could also enhance knowledge-sharing and the development of standardized guidelines for PAT usage. PATs should be adapted to be compatible with organic farming principles, where feasible, to expand their use in organic systems.

To drive further PAT innovations that align with each V4 country's climate needs, governments, and academic institutions should support R&D collaborations with technology companies. These partnerships could focus on developing affordable and accessible versions of key technologies, such as portable moisture sensors or simplified remote sensing tools.

4.2. Future Research Directions

Future research should evaluate the long-term effectiveness of PATs in enhancing agricultural resilience to climate change in the V4 region. This could include studies that track crop yields, resource efficiency, and soil health over multiple growing seasons to measure the sustained impacts of PAT integration.

More research is needed to explore how PATs can be effectively integrated into organic farming practices while remaining compatible with organic principles. Investigating adjustments or modifications to PATs that could better meet the needs of organic farmers could facilitate wider adoption in this sector.

To address financial constraints in PAT adoption, future research should focus on the development of low-cost, scalable versions of essential PAT tools. Innovations in affordable moisture sensors, remote sensing devices, and VRT systems could increase adoption rates, especially among smaller farms and those with limited resources.

Further research could assess the environmental benefits of PATs when applied to specific climate challenges, such as erosion prevention, water conservation, and carbon footprint reduction. Such studies would help quantify the sustainability gains from PAT use, providing additional motivation for farmers and policymakers to invest in these technologies. In addition, future studies in this area could benefit from incorporating statistical methods, such as descriptive statistics, cluster analysis, and bibliometric analysis, to provide a more comprehensive and data-driven understanding of the adaptation factors of PATs and their response to climate change.

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