Farmer preferences for adopting precision farming technologies: a case study in the North-Western and Central Region of Romania

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Abstract. This study examines farmers' perceptions, attitudes, and preferences regarding the adoption of precision agriculture (PA) technologies in two development regions of Romania, Bistrița-Năsăud and Alba. Using a structured survey combined with a discrete choice experiment (DCE), the analysis evaluates the influence of socio-demographic characteristics, farm structure, and behavioural factors on technology adoption. Results show that younger and more highly educated farmers, as well as those with larger farms, are significantly more inclined to adopt precision technologies. Direct experience with modern equipment strongly increases perceived usefulness, while non-users express more heterogeneous and often sceptical views. Economic and operational constraints, particularly limited access to credit, lack of high-performance machinery, and labour shortages, are perceived as more pressing than environmental concerns, shaping farmers' investment decisions. Mixed Logit (MXL) and Latent Class models reveal substantial preference heterogeneity and highlight the central role of financial capacity, technological familiarity, and professionalised management practices. The findings underline the need for integrated policy interventions combining financial support, advisory services, and hands-on demonstrations to accelerate Romania's agricultural digitalisation.

Key Words: precision agriculture, technology adoption, discrete choice experiment, farmers' perceptions, digitalisation, Romania, farm size, socio-economic determinants, automation preferences, agricultural innovation.

Introduction. Contemporary agriculture is undergoing major transformations driven by climate change, resource constraints, market volatility, and the growing need for sustainable production systems. Precision agriculture (PA) has emerged as a central pathway for modernizing agricultural practices due to its capacity to enhance input efficiency, reduce production costs, and improve economic and environmental performance. Technologies such as GPS-guided equipment, drones, sensors, smart machinery, and digital monitoring platforms enable farmers to make data-driven decisions that increase accuracy and optimize production processes (Godwin et al 2003; Balafoutis et al 2017). The integration of advanced technologies, including Big Data and IoT

applications, further strengthens the potential of digital transformation and reshapes farm management strategies (Wolfert et al 2017; Micle 2023/2024).

International research emphasizes that a combination of socio-economic, technological, and behavioral factors influences the adoption of PA technologies. Education, farm size, professional experience, and perceived usefulness are consistently identified as key determinants of adoption (Adrian et al 2005). Studies focusing on social networks show that interactions among farmers significantly accelerate technology diffusion, as information exchange plays a crucial role in shaping decisions (Bandiera & Rasul 2006; Conley & Udry 2001). Nonetheless, high investment costs, insufficient training opportunities, and perceived technological complexity remain important barriers (Kutter et al 2011; Long et al 2016). At the European Union level, adoption patterns vary widely due to differences in digital infrastructure, policy support, and farm technological readiness (Zarco-Tejada et al 2014; Barnes et al 2019a; Barnes et al 2019b).

In Romania, agricultural digitalization is progressing, yet adoption rates are still lower than in other EU countries. Research points to a growing interest among farmers, but also to persistent challenges such as limited access to training programs, high perceived costs, uneven digital infrastructure, and variability in digital literacy (Zeca 2022; Rodino et al 2023; Fertu et al 2025). Recent studies highlight the importance of behavioral and motivational factors, including perceived usefulness, ease of use, and institutional support (Markovits 2024; Șerban 2024), while technologies such as drones and IoT monitoring systems are increasingly present, particularly in larger and better-capitalized farms (Pop et al 2024; Köllő 2025).

Despite this growing interest, Romanian literature on PA adoption remains limited, and empirical studies examining farmers' perceptions and preferences are still insufficient relative to the pace of technological change. A significant knowledge gap persists regarding how socio-economic characteristics, farm structure, and attitudes toward technology shape adoption decisions, particularly in regions marked by agricultural diversity.

Therefore, this study investigates farmers' perceptions, attitudes, and preferences regarding the adoption of PA technologies in the North-Western and Central developmental regions of Romania, comprising the counties of Bistrita-Nasaud and Alba. This region's diverse agricultural landscape and varying levels of technological development offer a relevant context for analyzing the factors that facilitate or hinder adoption. The study provides a comprehensive examination of farmers' socio-economic characteristics, motivations, and perceived barriers, and situates the findings within the broader international literature, highlighting Romania's specific pathways toward agricultural digitalization.

Material and Method

Study area. The sample used in this research originates from two agriculturally significant counties in the North-Western and Central developmental regions of Romania, namely Bistrița-Năsăud and Alba. Recent studies highlight that regional context plays a crucial role in shaping farmers' adoption behaviour, as differences in infrastructure, farm structure, and access to resources influence technological uptake (Zeca 2022; Rodino et al 2023).

The Bistrita Nasaud region displays a mixture of crop cultivation, permanent grasslands, and subsistence-oriented production, reflecting structural patterns typical of Transylvanian smallholder agriculture, as also described by recent studies on agricultural digitalization in Romania (Markovits 2024). Although mechanization levels vary considerably between farms, younger farmers tend to show a growing interest in digital tools, reinforcing existing findings on the generational dimension of agricultural innovation (Pop et al 2024).

In Alba County, respondents are concentrated in two well-defined micro-regions. The first is the Târnave area. This region is known for its viticultural tradition, complemented by arable crops and mixed farming systems. The presence of technologically advanced commercial farms, particularly around the renowned Jidvei vineyards, creates an environment in which PA technologies are more visible and potentially more accessible. This aligns with the literature showing that commercially oriented farms are often early

adopters of precision technologies (Adrian et al 2005; Lencsés et al 2014). The second micro-region within Alba includes the Alba Iulia-Aiud-Blaj area. This area is dominated by small and medium-sized farms engaged mainly in arable and mixed production systems, benefiting from better infrastructure and closer access to agricultural advisory services.

Bringing together the two counties within the same analytical framework offers a comprehensive perspective on farmers' perceptions and behaviours toward PA technologies. Bistrița-Năsăud reflects a setting marked by small-scale farms with limited financial resources and structural constraints, comparable to mountain and sub-mountain rural environments discussed in international literature (Tey & Brindal 2012). In contrast, Alba combines traditional family farming with technologically advanced holdings, enabling the observation of a broader range of digitalization levels. This diversity is essential for identifying differences in attitudes, barriers, and motivations, and reinforces the conclusions of European studies that emphasize the importance of local context in agricultural technology adoption (Tamirat et al 2018; Barnes et al 2019b).

Altogether, the two counties provide a robust and representative analytical environment for understanding the challenges and opportunities associated with the transition toward digital and PA in Transylvania.

Survey design and data collection. The main research instrument used in this study was a structured questionnaire designed in accordance with established technology adoption frameworks, namely the technology acceptance model (TAM) and the unified theory of acceptance and use of technology (UTAUT), and inspired by international studies on agricultural technology adoption (Davis 1989; Venkatesh et al 2003; Adrian et al 2005; Tey & Brindal 2012; Lencsés et al 2014). The wording and structure of the items were adapted to the Romanian agricultural context, in line with recent analyses regarding the digital transformation of agriculture in Romania (Markovits 2024; Pop et al 2024).

The questionnaire was administered online via a digital form shared through local agricultural networks, professional groups, and farmer associations. Data collection took place between September 2024 and June 2025, as indicated by the automatically recorded timestamps. A total of 104 valid responses were collected.

The questionnaire consisted of 32 items addressing farm characteristics, technological equipment, perceptions of the usefulness and efficiency of PA tools, perceived barriers to adoption, and socio-demographic aspects. Most respondents operate farms between 1 and 50 hectares, while a substantial share manage 50-200 hectare holdings, confirming the structural polarization of farms in Transylvania. Age distribution is dominated by the categories 40-50 years and above 60 years, followed by 20-30 years, indicating a combination of traditional farmers and a younger, innovation-oriented group.

Educational levels vary, with vocational education being the most common (41 respondents), followed by secondary and higher education - patterns consistent with other Romanian studies on agricultural digitalization (Rodino et al 2023). Regarding existing technologies, 44 farmers report using GPS-equipped machinery, and 81 state they are familiar with the concept of PA, revealing a relatively high level of awareness but a moderate level of actual technological adoption. Data quality was ensured through internal validation procedures by verifying logical consistency across related items (such as reported crops and machinery use), and incomplete or contradictory responses were removed. The structure of the sample was compared to publicly available county-level agricultural data, confirming its representativeness for small and medium-sized farms in the region.

This methodological design provides a rigorous foundation for understanding perceptions, motivations, and barriers related to the adoption of PA technologies across two Transylvanian micro-regions with distinct agricultural profiles, setting the stage for a nuanced interpretation of the study's results.

Choice experiment design. To assess farmers' preferences regarding the adoption of PA technologies, the study employed a discrete choice experiment (DCE), a widely used method in agricultural and environmental economics grounded in Lancaster's characteristics theory and the random utility framework. According to Lancaster (1966),

utility is derived from the attributes of a good rather than the good itself, while McFadden (1974) and later Train (2009) formalized the probabilistic structure underlying individual choice. DCEs have become increasingly common in the analysis of technology adoption in agriculture, including precision farming research across Europe (Tamirat et al 2018; Barnes et al 2019b).

The experimental design was inspired by similar studies examining farmers' adoption behaviour in Italy, Germany, and Denmark, where DCEs have been successfully used to quantify preferences for automation levels, costs, and agronomic benefits (Reichardt & Jürgens 2009; Kutter et al 201). The selection of attributes was informed by the international literature and adapted to the realities of Romanian agriculture, ensuring that respondents evaluated scenarios that were both realistic and comprehensible. Attribute categories and level ranges were aligned with the frameworks used by Zarco-Tejada et al (2014), Balafoutis et al (2017), and Barnes et al (2019b), but adjusted to reflect the technological and financial context of small and medium-sized farms in Transylvania.

The attributes included the degree of automation (non-automated, partially automated, and fully automated systems), expected yield increase, reduction in fertilizer use, improvement in groundwater quality, availability of free advisory services, and the initial investment cost. Each attribute was defined across three levels, covering a range of conservative to advanced technological configurations. Investment costs ranged from €1,000 to €75,000, calibrated to current market prices for GPS guidance systems, soil sensors, Real-Time Kinematic positioning (RTK) modules, and remote sensing-based services, in line with the cost structures documented in the European PA literature (Schimmelpfennig 2016; Balafoutis et al 2017).

To maintain internal consistency, combinations deemed unrealistic or contradictory were eliminated following the methodological recommendations of Rose & Bliemer (2009). The final design consisted of 32 choice scenarios split into eight blocks, with each participant randomly assigned to one block to evaluate four choice tasks. Each card presented three technological alternatives and one status quo option. The visual interface was simplified and supported with icons and concise explanations adapted to the local agricultural context, in accordance with best practices for ensuring respondent comprehension in rural populations (Louviere et al 2000; Morey et al 2006).

Before completing the choice experiment, respondents received an introductory section explaining, in accessible language, what PA entails and how different levels of automation, sensor technologies, and monitoring systems operate. This step was essential, as prior knowledge significantly affects farmers' ability to evaluate technology attributes realistically (McBride & Daberkow 2003; Wolfert et al 2017).

Statistical analysis. The statistical analysis of the DCE data was performed within the framework of Random Utility Theory, according to which each respondent associates every alternative with a utility composed of an observable component and a stochastic term (McFadden 1974; Train 2009). The deterministic part of utility was specified as a linear function of the experiment's attributes - degree of automation, expected yield increase, fertilizer reduction, groundwater quality improvement, availability of free advisory services, and investment cost - along with socio-economic characteristics such as farm size, education, age, farming experience, and prior exposure to digital technologies.

Given the substantial heterogeneity in farmers' attitudes and preferences, the analysis relied on two complementary econometric approaches: the Mixed Logit (MXL) model and the latent class logit (LCL) model. The MXL model allows attribute coefficients to vary randomly across individuals, thus capturing unobserved heterogeneity and overcoming the restrictive IIA assumption inherent in standard multinomial logit models (Brownstone & Train 1998; Hensher & Greene 2003). Random coefficients were modeled using normal distributions for non-monetary attributes and log-normal distributions for the cost parameter, reflecting the theoretical requirement of a negative marginal utility of investment cost.

The LCL model was employed to identify distinct segments of farmers with internally homogeneous preferences but differing systematically across classes, an approach well established in the literature on technology adoption and environmental valuation (Morey et al 2006; Scarpa et al 2007). The optimal number of classes was selected using information criteria such as AIC and BIC, complemented by an assessment of the economic interpretability of each class.

Model estimation was conducted via simulated maximum likelihood using 500 Halton draws for the MXL specification, following best practices in applied choice modelling (Train 2009). To explore observed heterogeneity, interaction terms were included between key attributes and socio-economic characteristics, a strategy frequently used in empirical studies on PA adoption (Adrian et al 2005; Tamirat et al 2018; Barnes et al 2019b). This allowed for investigation of how cost sensitivity varies with farm size, how education influences preferences for automation, and how prior technological familiarity affects the valuation of agronomic improvements.

Model performance and robustness were assessed through log-likelihood comparisons, adjusted pseudo-R^2 values, information criteria, and elasticity analyses. The resulting statistical framework provides a rigorous basis for understanding the factors that shape farmers' preferences and willingness to adopt PA technologies across the two Transylvanian counties included in the study.

Representativeness and data validation. To assess the representativeness of the sample and the validity of the collected data, several statistical and consistency checks were conducted to ensure alignment between respondents' answers and the agricultural realities of Bistrița-Năsăud and Alba counties. The final sample of 104 valid responses reflects the dominant characteristics of farms in north-western Transylvania, where small and medium-sized holdings represent the prevailing organizational structure, consistent with national reports on agricultural digitalisation (Rodino et al 2023; Fertu et al 2025).

The distribution of farm sizes in the dataset, with a strong concentration in the 1-50 ha and 50-200 ha categories, matches the structural profile of the region, which is largely characterized by fragmented, family-run farms with moderate levels of mechanization. This pattern is consistent with previous analyses documenting the limited adoption of advanced technologies in Romanian agriculture (Zeca 2022; Pop et al 2024). The age distribution, dominated by the 40-50 and 60+ age groups, also reflects national demographic trends in farming, where population ageing is significant but coexists with a growing cohort of younger farmers engaged in digitalisation (Markovits 2024).

Data validation involved internal consistency checks across logically related variables, such as matching the reported crop types with the machinery used, verifying the coherence between farm size and mechanization levels, or comparing the degree of familiarity with PA with willingness to adopt automated technologies. Incomplete, inconsistent, or contradictory responses were removed from the dataset. Potential outliers, including extreme farm sizes or unrealistic investment estimates, were also examined manually to ensure accuracy.

Furthermore, thematic representativeness was examined by comparing the prevalence of reported technological equipment with national and European data on the uptake of PA. The proportion of farmers using GPS-based machinery (44 respondents) or familiar with the concept of PA (81 respondents) is consistent with European findings indicating increasing awareness but gradual and uneven adoption (Kutter et al 2011; Schimmelpfennig 2016; Barnes et al 2019b).

Overall, the validation procedures confirm that the sample is representative of small and medium-sized farms in the two counties studied, and that the dataset is coherent, reliable, and suitable for the econometric analyses employed in the research.

Results

Socio-demographic and structural characteristics of farmers. The age distribution of respondents (Figure 1) shows a clear predominance of mature and older farmers, a pattern commonly reported in Romanian and European agriculture (Markovits 2024; Albizua et al 2020). The largest age group is 40-50 years (26.9%), followed by farmers older than 60 (25.0%) and those aged 50-60 (18.3%). Younger farmers (20-40) account for only 29.8% of the sample. This demographic structure is relevant because age significantly influences digital technology adoption, with younger farmers typically more open to innovation (Venkatesh et al 2003; Tey & Brindal 2012).

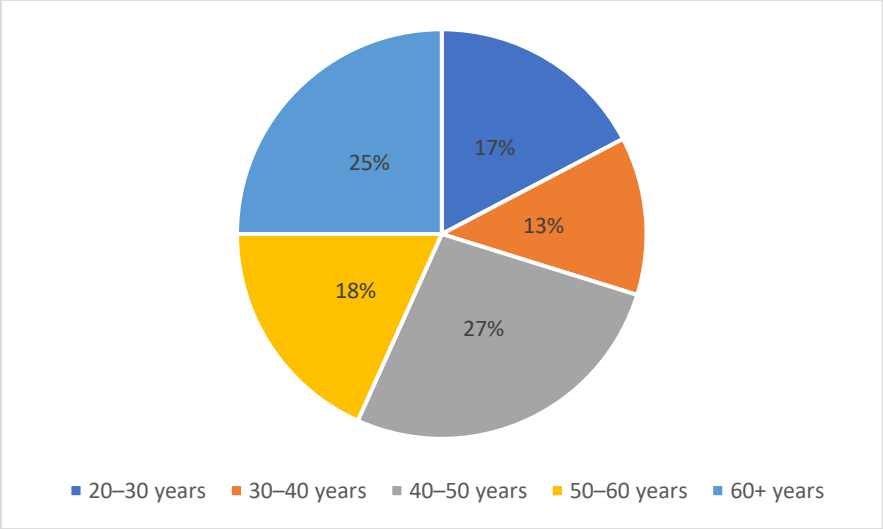

Figure 1. Age distribution of surveyed farmers. The figure illustrates the proportion of respondents in each age category, highlighting the predominance of mature and older farmers within the sample.

The educational profile (Figure 2) is dominated by medium-level education: 42.7% completed vocational training, and 29.2% have high school degrees, while only 16.7% hold university degrees. Since education is a consistent predictor of technology adoption (Adrian et al 2005; Kutter et al 2011), this distribution suggests moderate readiness for the uptake of advanced digital technologies.

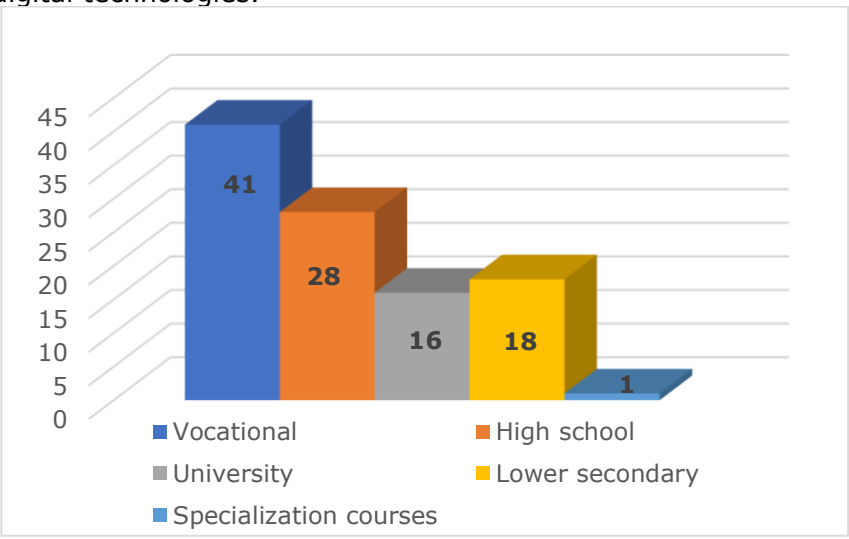

Figure 2. Educational level of farmers. The figure presents the distribution of educational attainment among respondents, showing a predominance of vocational and high school education.

Farm size patterns (Figure 3) reflect the structural fragmentation characteristic of Transylvanian agriculture. More than half of respondents (53.8%) cultivate 1-50 hectares, 19.2% operate 50-100 hectares, and only 9.6% manage over 200 hectares. Previous research indicates that smaller farms face greater barriers to the adoption of PA, largely due to economic and structural constraints (Tamirat et al 2018; Barnes et al 2019a).

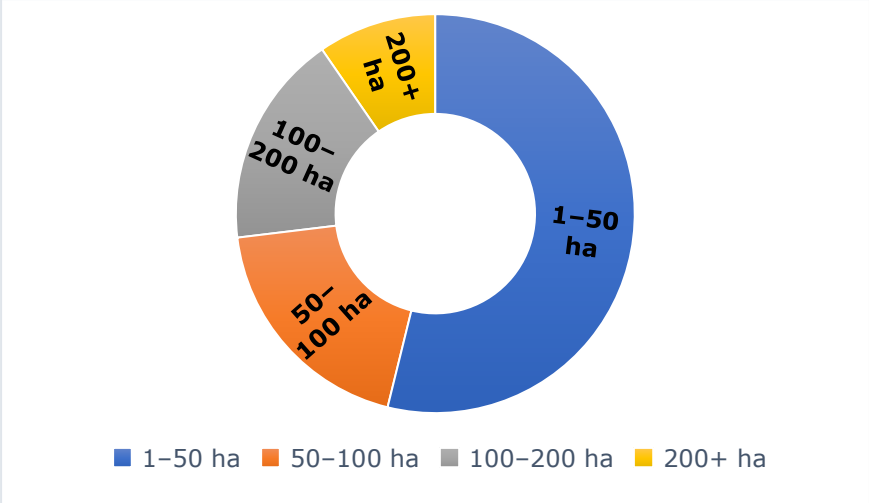

Figure 3. Farm size distribution in the sample. The figure shows the prevalence of small and medium-sized farms, with the majority operating less than 50 hectares.

Property structure and crop distribution further confirm that the region is dominated by family farms, typical mixed and cereal-based systems.

Farming practices and technology use. The agricultural practices reported by farmers indicate a medium level of mechanisation typical of small and medium-sized farms in north-western Transylvania. Most respondents perform key field operations, such as ploughing, disc harrowing, sowing, fertilisation, and spraying, using their own machinery, illustrating a predominantly traditional yet functional technological setup. Some farmers outsource certain operations, especially harvesting or spraying, a behaviour commonly observed in farms with limited technical resources (Long et al 2016; Knierim et al 2018).

The types of agricultural operations carried out are summarised in Table 1 and illustrated in Figure 4, which highlights the dominant activities across the surveyed farms.

Table 1

Types of agricultural operations performed on the farm (multiple responses)

Agricultural operation	*Frequency**
Ploughing	High
Disc harrowing	High
Sowing	High
Fertilisation	Moderate
Spraying (herbicide application)	Moderate
Harvesting	Moderate
Transport	Almost universal
Other operations	Variable

The dataset contains open responses; frequencies reflect consolidated mentions. High = the operation is carried out frequently, in most agricultural cycles; Moderate = the operation is carried out with medium frequency; Almost universal = the operation is carried out almost always, regardless of the crop; Variable = the frequency depends on the crop, farming system, or specific conditions.

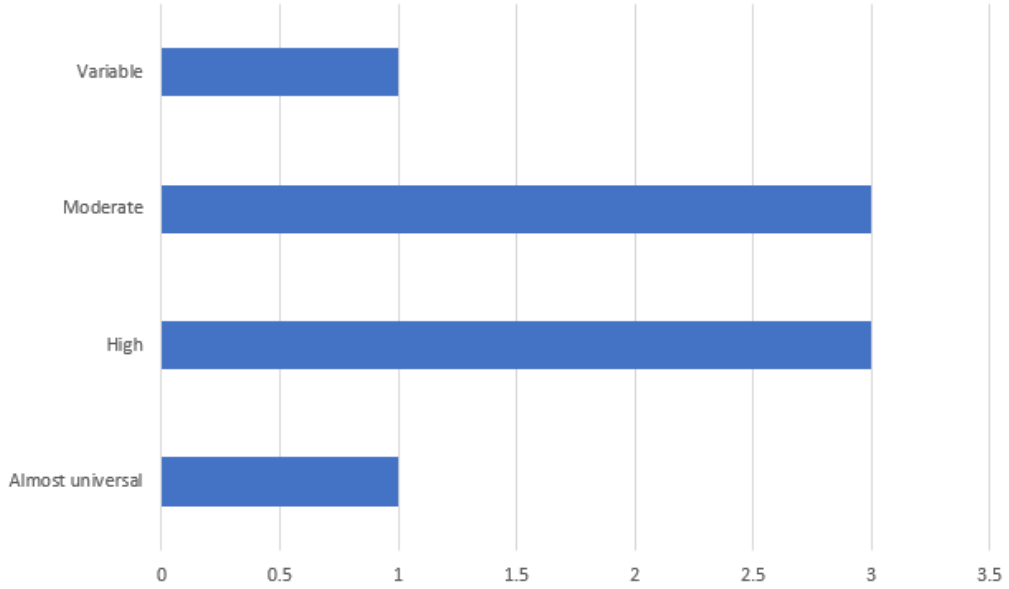

Figure 4. Types of agricultural operations performed on the farm (multiple responses). The figure presents the main field operations carried out by farmers, based on aggregated open responses.

Soil testing practices further illustrate the degree of farm professionalisation. A share of farmers report performing soil analyses, while others do not include this practice in their management routines. Among those who do, the main reason given is to determine the appropriate quantities of fertilisers to apply, indicating a focus on improving nutrient management and avoiding over- or under-fertilisation. Additional motives mentioned include monitoring soil health and improving productivity. The reported frequency of testing varies between 1-3, 3-5, and 5-7 years, with most farmers indicating an interval of 3-5 years, which is consistent with common agronomic practice in small and medium-sized farms.

Regarding technical equipment, the results show that a proportion of respondents use modern machinery, including GPS-guided equipment. According to the data, 43.6% of farmers use GPS-enabled machinery, while 56.4% do not (Figure 5). These adoption levels are consistent with those observed in comparable European farm structures (Lencsés et al 2014; Schimmelpfennig 2016).

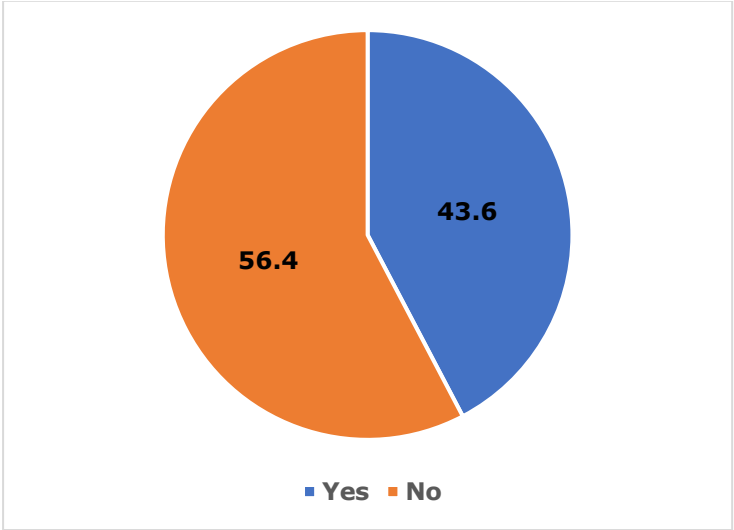

Figure 5. Use of GPS-equipped machinery. The figure displays the share of farmers who currently use GPS-enabled equipment versus those who do not.

Awareness of PA is considerably higher, with 78.6% reporting that they have heard of such technologies (Figure 6). This discrepancy points to a well-known awareness-adoption gap (Kutter et al 2011; Barnes et al 2019), likely associated with financial constraints, technical barriers, and limited access to advisory services.

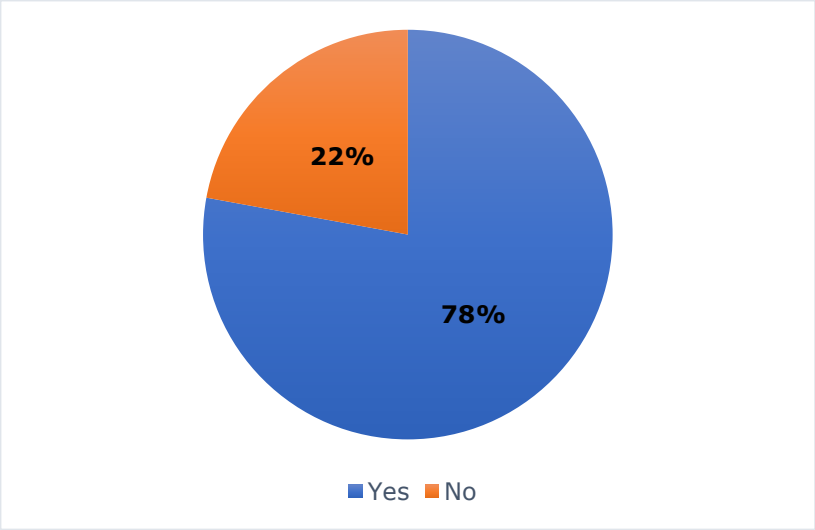

Figure 6. Awareness of PA among farmers. The figure depicts the proportion of respondents familiar with the PA concept.

Farmers' perception of the usefulness of modern agricultural equipment. Farmers' perceptions of the usefulness and impact of modern agricultural equipment are strongly positive, as evidenced by the descriptive statistics presented in Table 3. Among farmers who already use modern technologies, satisfaction levels are exceptionally high: the mean score reaches 4.46, while both the median and mode equal 5, indicating a remarkably consistent evaluation. The low standard deviation (0.87) demonstrates strong agreement within this group, suggesting that the vast majority experience substantial improvements in operational efficiency and reductions in physical labour. The minimum and maximum values (1-5) confirm that extremely low ratings are rare, with responses overwhelmingly concentrated at the upper end of the scale.

These findings align closely with previous research, which shows that direct exposure to advanced equipment enhances farmers' perception of its operational benefits, including improved precision, time savings, and overall work facilitation (Pedersen et al 2004; Adrian et al 2005; Schimmelpfennig 2016).

When considering the general perception of usefulness across the entire sample, the results maintain a strongly positive orientation, though with greater variability. Table 3 shows a mean score of 4.08, with the median and mode again equal to 5, underlining a generally favourable attitude. However, the higher standard deviation (1.18) indicates more dispersed opinions, reflecting the presence of farmers with less experience or uncertainty regarding the applicability of such technologies. Lower scores (1-2) appear more frequently in this group, pointing toward a moderate level of scepticism rooted in factors such as unfamiliarity, perceived financial risk, limited training, or lack of advisory support. This distributional pattern mirrors findings from the literature on digital agriculture adoption, where positive attitudes often coexist with hesitation among non-users (Kutter et al 2011; Lencsés et al 2014).

Taken together, the results illustrated in Table 2 reveal a clear distinction between farmers with direct technological experience - who express a near-unanimous conviction in the usefulness of modern equipment - and those without such exposure, whose perceptions remain positive but significantly more heterogeneous. This contrast highlights the critical role of practical demonstrations, technical training, and advisory services in strengthening trust in digital technologies and in encouraging broader adoption across the sector.

Table 2

Descriptive statistics for the evaluation of equipment usefulness (Likert scale 1-5)

Indicator	*Perceived impact on easing agricultural work*	*Perceived usefulness of equipment*
N responses	96	97
Mean	4.46	4.08
Median	5	5
Mode	5	5
Standard deviation	0.87	1.18
Minimum	1	1
Maximum	5	5

This table presents the descriptive statistics for two sets of Likert-scale evaluations related to farmers' perceptions of modern agricultural equipment. The first column summarises responses from farmers who currently use modern equipment and evaluates the extent to which such technologies ease agricultural work. The second column summarises the general perceived usefulness of these technologies among the entire sample. Both indicators show predominantly positive evaluations, with high mean values and modal scores of 5, though variability is higher among farmers without direct experience.

Farmers' perceptions of key agricultural challenges. Farmers' perceptions regarding the severity of key agricultural problems reveal strong concerns about both environmental degradation and structural constraints within the sector. The five issues assessed, soil degradation, groundwater nitrogen enrichment, limited access to credit, labour shortages, and lack of high-performance machinery, were evaluated on a three-level scale (*Insignificant*, *Medium*, *Serious*). Their consolidated distribution is presented in Figure 7, which synthesises the responses across all categories.

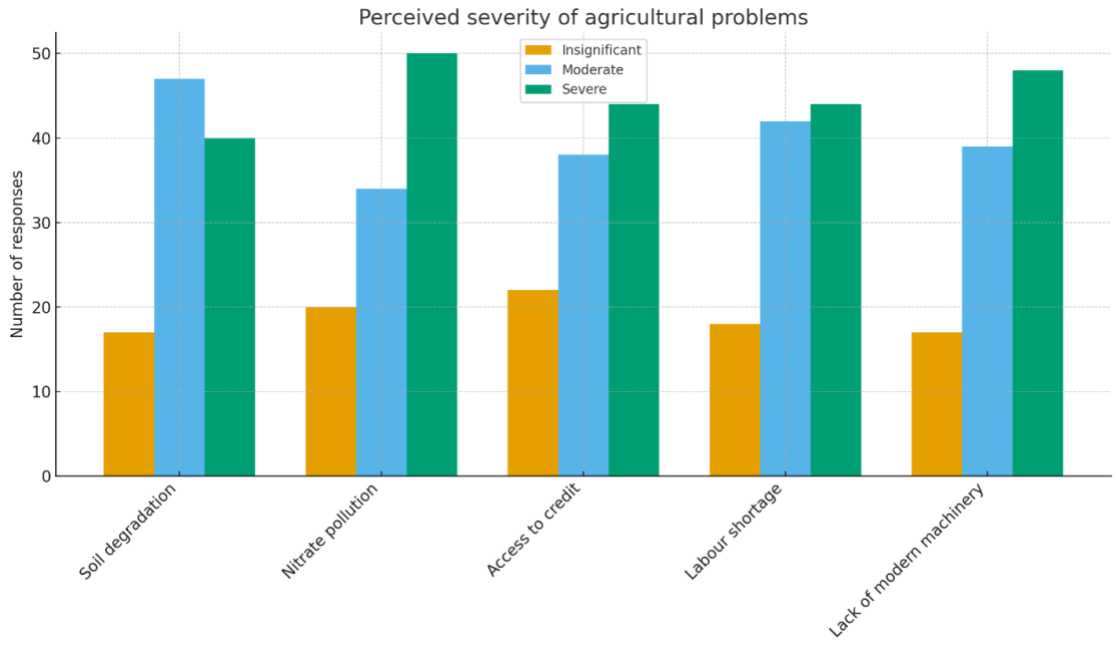

Figure 7. Severity of major agricultural problems as perceived by farmers.

The results indicate that soil degradation is among the most pressing concerns. A high proportion of respondents classify it as a *Serious* problem, reflecting widespread issues linked to declining soil fertility, erosion, compaction, and inadequate nutrient balance. These concerns are consistent with broader European trends, where soil degradation is recognised as a major constraint to sustainable production, particularly in regions dominated by small and medium-sized farms (Panagos et al 2015; Schmidt et al 2018).

Similarly, groundwater nitrogen pollution also receives predominantly *Serious* and *Medium* evaluations. Although a subset of farmers considers it insignificant, the overall distribution suggests growing awareness of environmental risks associated with excessive or poorly managed fertiliser application, an issue widely documented in the EU, where nitrate contamination remains a priority environmental challenge (Grizzetti et al 2017; Eurostat 2023).

The responses regarding limited access to credit illustrate the financial vulnerabilities faced by farmers in Transylvania. A large number of "Serious" responses point to persistent structural barriers such as high collateral requirements, elevated borrowing costs, and limited access to investment capital, which are also highlighted in studies of Central and Eastern European agriculture (Ferto 2009; Ciaian et al 2012; Reti et al 2025). These financial limitations play a crucial role in shaping technology adoption, as PA often requires substantial upfront investment (Schimmelpfennig 2016).

Labour shortages emerge as another critical challenge, perceived by many farmers as highly severe. This reflects demographic changes, aging rural populations, and migration trends that reduce the availability of skilled agricultural labour, factors repeatedly identified as major bottlenecks in European and Romanian agriculture (Kutter et al 2011; Eurofound 2022). Labour scarcity directly increases production costs and often accelerates interest in automation and precision technologies as alternatives to manual work.

The lack of high-performance machinery is also frequently evaluated as *Serious*, confirming previously observed patterns of moderate mechanisation and technological saturation in the surveyed farms. Many respondents operate older or limited-capacity machinery, which constrains efficiency and reduces the ability to adopt advanced precision tools. Similar findings are reported across Eastern Europe, where farm size and capital availability strongly influence the modernisation of agricultural machinery (Lencsés et al 2014; Barnes et al 2019a).

Overall, these results underline a coherent pattern: environmental degradation, financial constraints, labour shortages, and insufficient mechanisation are simultaneously perceived as major obstacles to agricultural performance and as drivers of interest in PA. The alignment between farmers' concerns and documented structural challenges in Romanian and European agriculture reinforces the relevance of digital technologies as potential solutions, while also highlighting the need for targeted policy support, advisory services, and accessible financial mechanisms.

Statistical synthesis and cross-variable patterns. In addition to the descriptive results presented above, several statistical examinations were conducted to identify the relationships between socio-demographic factors, farm characteristics, and farmers' attitudes toward PA technologies. These analyses provide a deeper understanding of the dynamics underlying technology adoption and allow for a clearer separation between structurally driven behaviour and attitudinal determinants.

Descriptive statistics for the two Likert-scale evaluations concerning the perceived usefulness of modern equipment (Questions 18 and 23) reveal a consistently positive orientation within the sample. Farmers who currently use modern equipment reported very high satisfaction levels, with a mean score of 4.46, median and mode of 5, and a relatively low standard deviation (0.87), indicating a strong agreement regarding the extent to which such tools ease agricultural work. In contrast, the entire sample's perception of general equipment usefulness shows a slightly lower mean (4.08) and a higher standard deviation (1.18), suggesting greater attitudinal dispersion among respondents who have limited or no direct experience. The full range of possible scores (1-5) is represented, but the distribution is heavily skewed toward higher values, indicating a favourable predisposition toward adopting modern technologies if structural barriers can be overcome.

The association between education level and GPS adoption reveals a pronounced pattern: respondents with higher education are over-represented among GPS users, whereas lower-educated farmers dominate the non-user category. This distribution mirrors international findings identifying education as a strong predictor of digital technology adoption in agriculture (Adrian et al 2005; Kutter et al 2011). While a formal inferential

test could not be conducted based on categorical data alone, the observed pattern suggests a clear positive relationship between schooling level and technological uptake.

Farm size also appears to influence perceptions of equipment usefulness. Larger farms (above 100 ha) tend to assign maximum usefulness scores, while the lowest evaluations (1-2) were almost exclusively reported by farmers cultivating under 50 ha. This pattern corresponds with well-established empirical evidence indicating that larger, better-capitalized farms are more likely to integrate precision technologies due to investment capacity and scale-related efficiencies (Tamirat et al 2018; Barnes et al 2019a).

The analysis of farmers' classification of agricultural problems reveals additional systematic tendencies. The most severe challenge identified is the lack of high-performance machinery, where responses are overwhelmingly concentrated in the "Severe" category. Lack of access to credit emerges as the second most critical issue, while environmental problems such as soil degradation or nitrate contamination of groundwater receive more balanced distributions across "Moderate" and "Severe." This hierarchy aligns with national studies showing that economic and infrastructural limitations outweigh environmental concerns among small and medium-sized Romanian farms (Zeca 2022; Rodino et al 2023).

A strong positive association is also observed between GPS use and perceived usefulness of modern equipment. Respondents using GPS systems consistently reported maximum usefulness scores, whereas lower evaluations were almost exclusively given by non-users. This finding aligns with key elements of the UTAUT, which emphasises the influence of experience and facilitating conditions on behavioural intention (Venkatesh et al 2003).

Finally, farmers who carry out soil testing regularly tend to report greater concern for soil degradation and a stronger appreciation of advanced equipment. This suggests that more professionalised management practices are accompanied by a heightened awareness of agronomic risks and by greater openness to technological innovation.

Overall, the statistical analysis confirms three overarching trends:

(1) Socio-demographic variables significantly influence technological adoption, particularly education and age;

(2) Farm size plays a major role in shaping both attitudes and adoption capacity; and

(3) Economic and technical limitations are perceived as the principal barriers, overshadowing environmental concerns.

Together, these findings provide a comprehensive understanding of the structural and behavioural factors that shape farmers' preferences for PA in the two surveyed Transylvanian counties and form a solid empirical basis for the interpretative discussion that follows.

Discussion. The results of this study provide a comprehensive insight into the perceptions, attitudes, and behavioural intentions of farmers from two developmental regions of Romania regarding the adoption of PA technologies. When interpreted in conjunction with the existing international literature, several patterns and implications emerge, reflecting both universal determinants of technological adoption and regional specificities that differentiate Romanian farmers from their Western European counterparts.

A first key finding concerns the profile of the respondents, which reflects the demographic structure typical of Romanian agriculture, an ageing farming population, relatively modest educational levels, and predominantly small and medium-sized farms. These structural characteristics have been widely documented as barriers to digitalisation (Adrian et al 2005; Barnes et al 2019b; Rodino et al 2023). In the present study, younger farmers and those with higher education were markedly more receptive to precision technologies, confirming theoretical expectations from TAM and UTAUT frameworks (Davis 1989; Venkatesh et al 2003). The clear association between education level and GPS use further reinforces the assumption that digital literacy plays a central role in early adoption behaviours. This suggests that educational interventions, training programmes, workshops, and field demonstrations remain essential to narrowing the adoption gap at the regional level.

Farm size emerges as another important factor differentiating attitudes and adoption capacity. Larger farms (above 100 ha) consistently evaluated modern equipment as highly useful and expressed fewer concerns regarding investment costs. This aligns with findings from Tamirat et al (2018) and Barnes et al (2019a), which show that economies of scale enhance the relative benefits and reduce the perceived risks associated with precision technologies. In contrast, smaller farms expressed greater scepticism and reported structural limitations such as financial constraints, lack of credit access, and insufficient machinery, barriers also highlighted by Kutter et al (2011) and Schimmelpfennig (2016). These results underscore the critical importance of targeted financial instruments, such as subsidised credit, investment grants, or cooperative machinery-sharing schemes, to support digitalisation in smallholder farming systems.

Perceptions regarding agricultural challenges further illuminate the economic context shaping farmers' technological decisions. The most severe problem identified was the lack of performant machinery, followed closely by the difficulty of accessing credit. Environmental concerns, such as soil degradation and nutrient leaching, while recognised as relevant, ranked lower than economic and operational issues. This hierarchy diverges from many Western European studies, where environmental drivers play a stronger role in technology adoption (Zarco-Tejada et al 2014; Balafoutis et al 2017). In Romania, and particularly in Transylvania, economic vulnerability remains the primary determinant of farm-level investment decisions. This suggests that promoting PA primarily through environmental arguments may be less effective than emphasising cost reduction, labour savings, and economic resilience.

A particularly striking pattern emerges when comparing farmers with direct technological experience to those without. Users of GPS-enabled equipment overwhelmingly rated the usefulness of modern technologies as very high and expressed favourable attitudes towards automation. Non-users, however, exhibited more heterogeneous perceptions, with a wider distribution of sceptical views. This discrepancy illustrates the well-known experiential gap described by Pedersen et al (2004) and Wolfert et al (2017): exposure to precision technologies significantly increases perceived benefits and reduces uncertainty. This finding highlights the importance of demonstration farms, pilot projects, and peer-to-peer learning networks mechanisms shown to be highly effective in accelerating technology diffusion (Conley & Udry 2001; Bandiera & Rasul 2006).

Another notable observation concerns soil testing practices. Farmers who perform regular soil analyses tend to express greater concern regarding soil degradation and assign higher usefulness scores to PA tools. This suggests that more professionalised farm management practices correlate with stronger interest in digital solutions, reinforcing the argument that PA adoption is part of a broader behavioural profile rather than an isolated decision.

Overall, the discussion reveals that the adoption of PA in Transylvania is shaped by a combination of structural constraints (farm size, machinery access), socio-demographic characteristics (age, education), and behavioural dimensions (experience with technology, risk perception). These findings confirm many of the adoption mechanisms identified in the international literature, but also demonstrate several regional specificities:

- The predominance of economic barriers over environmental motivations;
- The critical importance of machinery availability;
- The decisive influence of direct technological experience;
- The strong contrast between larger commercial farms and smaller subsistence or semi-subsistence holdings.

The study, therefore, contributes to a more nuanced understanding of PA adoption in Romania, pointing to the need for integrated strategies that combine financial support, extension services, training programmes, and technological demonstration. Policies focusing solely on subsidies or solely on education are unlikely to be sufficient; instead, an ecosystem approach is required, one that simultaneously addresses technical, financial, and informational barriers. Strengthening advisory networks and facilitating knowledge exchange may be particularly effective, given the demonstrated role of peer interactions in shaping adoption behaviour.

In summary, while the potential for PA adoption in Transylvania is substantial, realising this potential requires coordinated efforts that recognise the socio-economic diversity of farmers, the structural limitations of small and medium-sized holdings, and the decisive role of experiential learning. The findings of this study offer a solid empirical foundation for such strategic considerations and position Romania within the broader European discourse on agricultural digitalisation.

Conclusions. This study examined farmers' perceptions and preferences regarding PA technologies in two developmental regions of Romania. The results show that adoption is strongly influenced by socio-demographic and structural factors. Younger and higher-educated farmers, as well as larger and better-capitalized farms, display higher openness toward digital technologies, confirming findings from international studies (Venkatesh et al 2003; Adrian et al 2005; Barnes et al 2019ab).

A key outcome is the clear difference between farmers with technological experience and those without. Users of GPS-enabled machinery report very high perceived usefulness, while non-users express more diverse and often sceptical attitudes. This highlights the importance of practical demonstrations and knowledge transfer mechanisms, as documented in previous research (Pedersen et al 2004; Wolfert et al 2017).

Farmers perceive economic and operational constraints, lack of machinery, limited access to credit, and labour shortages as more severe than environmental problems. This indicates that, in the Romanian context, economic viability remains the primary driver of adoption decisions.

Overall, the findings suggest that accelerating PA adoption requires integrated strategies combining financial support, advisory services, and training. Strengthening farmer networks and providing accessible demonstration activities could significantly reduce uncertainty and increase adoption rates. The study contributes to a better understanding of Romania's digitalisation trajectory and identifies concrete priorities for supporting the transition towards more efficient and sustainable agriculture.

Limitations. This study acknowledges several limitations that should be considered when interpreting the results. First, the sample is restricted to two counties in north-western Transylvania, which, although agriculturally diverse, may not fully represent all Romanian farming systems. As PA adoption varies across regions depending on farm size, infrastructure, and market conditions, caution is needed when generalizing the findings.

Second, the data were collected through an online questionnaire, which may bias participation toward farmers who are more digitally active or familiar with online tools. This may slightly overestimate the level of technological awareness compared to the broader population of Romanian farmers.

Third, the study relies on self-reported information regarding farm practices, perceptions, and technological use. Such data may be subject to recall bias or social desirability bias, especially in the context of emerging technologies, where respondents might feel inclined to report higher familiarity.

Fourth, the DCE evaluates hypothetical scenarios. Although widely used in adoption research, hypothetical choices may not fully reflect real-world investment decisions, particularly in contexts where financial constraints are strong.

Finally, while the study integrates key socio-economic variables, other factors, such as detailed financial performance indicators, long-term investment strategies, or institutional support structures, were not included and could further refine the analysis.

Despite these limitations, the research offers valuable insights into the factors shaping PA adoption in the Central and North-Western region of Romania and provides a robust foundation for future studies involving larger samples, additional regions, or longitudinal approaches.

Conflict of interest. The authors declare that there is no conflict of interest.

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