

DRIVERS OF INTRODUCING INNOVATIONS IN THE FIELD OF SUSTAINABLE LAND USE IN SLOVAK AGRICULTURE: EXPLORING THE ROLE OF THE EU COMMON AGRICULTURAL POLICY

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Abstract: Sustainable land use is increasingly recognised as a core condition for climate resilience, soil protection, and long-term agricultural productivity. The main objective of the study is to analyse and evaluate the significance of the European Union's Common Agricultural Policy in supporting the introduction of innovations in agricultural enterprises that contribute to sustainable land use. The research employs a mixed-methods design, combining an exploratory logistic regression model with qualitative analysis grounded in Grounded Theory. Primary data were collected through a nationwide questionnaire survey of Slovak agricultural enterprises. The results show that funding from the second pillar of the Common Agricultural Policy is the main driver of innovation, leading to the delivery of new solutions in sustainable land use. Successful innovation implementation was also explained by the enterprise's technological maturity, collaborative networks, and a general orientation toward ecological agriculture. Qualitative findings further reveal that Slovak farmers face persistent financial, administrative, and knowledge-related barriers to the implementation of eco-innovation.

Keywords: Sustainable land use; Agriculture, Innovation; Common Agricultural Policy; European Agricultural Fund for Rural Development; Logistic regression

Highlights

- 68% of farmers in the sample introduced innovations related to sustainable land use.
- In Slovakia, innovations are most frequently adopted in precision agriculture and regenerative farming.
- The key motive for adopting innovations lies in farmers' ecological values and engagement in organic farming.
- Innovations related to sustainable land use are hindered by financial and administrative barriers.
- EAFRD support is the strongest driver of innovation, tripling the likelihood of sustainability-oriented land-use innovations.

1. Introduction

Agriculture enters the third decade of the twenty-first century under growing structural pressures from population growth, climate change, and land degradation. By 2050, the global population is expected to reach 9.7 billion, implying an approximately 70 percent increase in global food demand. At the same time, climatic extremes, irregular precipitation, and rising temperatures already reduce yields in vulnerable regions by tens of percent, while degradation and soil sealing exclude around 12 million hectares of arable land from production each year (Chen, 2025; Naik et al., 2025). Soil is a non-renewable resource formed over millennia, providing a wide range of ecosystem services, from food production and carbon sequestration to water retention and biodiversity regulation. Its quality changes dynamically under the effects of compaction, salinization, declining organic matter, and biodiversity loss (European Commission, 2020).

Research on land use has been significantly redefined in recent decades (Pašová et al., 2019), while sustainable land use and soil protection have emerged as key topics in both the land use literature and European policies. In the European context, the relationship between agriculture and land is shaped by the Common Agricultural Policy (CAP), whose objectives of sustainable resource management and climate action explicitly rest on the productive capacity of soil. The CAP combines regulatory and financial mechanisms that directly and indirectly support sustainable land management from conditionality and agro-environmental measures to schemes promoting precision and sustainable intensification (European Commission, 2020). At the same time, academic and policy debates increasingly emphasise eco-

innovations as solutions that reduce environmental impacts while maintaining or enhancing productivity and food safety. Their relevance in agriculture continues to grow in relation to climate adaptation and consumer health (Diaz-Garcia et al., 2015; Chabé-Ferret et al., 2019).

Within the new green architecture of the CAP 2023–2027, innovation is defined as a core mechanism for aligning productivity, biodiversity, and climate resilience from baseline conditionality to eco-schemes and multi-annual measures under Pillar II, implemented through nationally adapted strategic plans (European Commission, 2020; Jongeneel & Gonzalez-Martinez, 2023; Zieliński, 2025; Galioto & Nino, 2023). Yet research emphasises that the effects of different CAP instruments on farmers' innovation decisions are heterogeneous and methodologically difficult to identify (Bartolini et al., 2011; Curzi et al., 2022). Knowledge gaps persist, particularly in post-socialist EU countries and in the lack of in-depth qualitative analyses of drivers and barriers of innovation emergence in agriculture (Doran, 2025; Macaneiro et al., 2013).

Building on these insights, this study examines the determinants of innovations supporting sustainable land use in Slovak agriculture, with special attention to the role of investment support from the European Agricultural Fund for Rural Development (EAFRD) and to the interaction between financial, technological, human-capital, and institutional factors. The secondary objective is to examine the structure and character of innovations emerging in Slovak agricultural enterprises within the context of the EU Common Agricultural Policy, and to identify the motives and barriers farmers perceive in their efforts to implement innovations that promote sustainable land use. The original contribution of the study lies in integrating three dimensions that are typically examined separately: (1) innovation adoption at the farm level, (2) the role of public policy support mechanisms – CAP/EAFRD and (3) sustainable land management into a single empirical framework.

2. Theory background and research hypothesis

The theoretical concept of the innovation production function assumes that innovation results from the combination of capital (internal and external), labour, and knowledge within a specific institutional environment. In agriculture, this function materialises through technical, organisational, and institutional adjustments that transform inputs (land, labour, capital, information) into outputs characterised by higher productivity and environmental performance (OECD, 2022; WIPO, 2023). Land represents the fundamental natural capital whose productive and ecological properties evolve in time; management decisions on soil cultivation, crop rotation, nutrient management, water retention, and livestock integration directly shape soil quality and ecosystem services (European Commission, 2020). Within the CAP framework, these activities are influenced by regulatory baselines and incentive mechanisms promoting precision and sustainable intensification.

Agricultural innovation cannot be viewed solely as technological change; it also represents organisational and institutional transformation that enhances productivity and environmental performance while ensuring economic viability (OECD, 2022). However, access to cutting-edge technologies can still limit actors' capacity to deliver sustainable land-use practices. In the context of this study, these technological domains are not examined individually, but serve as a conceptual basis for defining the dependent variable capturing innovation adoption. Specifically, innovations related to sustainable land use are operationalized as the adoption of selected technological and ecological practices falling within these categories. A wide technological frontier is now developing from precision agriculture, including the GPS/RTK, drones, imaging, variable-rate application (Gebbers & Adamchuk, 2010), vertical (Kabir et al., 2023) and new regenerative agriculture methods and procedures (Shennan-Farpón et al., 2025), IoT, automation, artificial intelligence to controlled environments (Javaid et al., 2022), microbial consortia, and nanomaterials (Mridha et al., 2025). This categorization is particularly relevant for the present study, as it forms the conceptual basis for defining and measuring the dependent variable capturing the adoption of these innovation types.

Precision farming employs GPS-guided machinery, satellite and drone imagery, soil-moisture and nutrient sensors, and variable-rate algorithms, thereby reducing agrochemical overuse and optimising

interventions in real time (Gebbers & Adamchuk, 2010; Song et al., 2022). Automation and robotics respond to labour shortages and cost pressures, while controlled-environment agriculture improves water and energy efficiency (Engler and Krarti, 2022). Artificial intelligence and big-data analytics enhance the predictive capacity of risk management (Mridha et al., 2025). At the same time, biological and material innovations move to the forefront: rhizosphere microbial ecosystems are recognised as leverage points of sustainable intensification, and nanotechnologies (nanofertilisers, nano pesticides, nano sensors) show potential for controlled nutrient release and reduced chemical inputs, though they require robust risk–benefit assessment (Allan et al., 2021; Suman et al., 2021; Norton & Alwang, 2020). Together, these innovations form an integrated, data-driven infrastructure for responding to twenty-first-century agricultural challenges (Song et al., 2022).

Empirical evidence on the relationship between the CAP and innovation performance remains diverse. Studies highlight that CAP payments can have both stimulating and constraining effects depending on the instrument and the national implementation context. Investment measures co-financed by the EAFRD generally increase the adoption of new technologies and environmentally oriented practices by reducing capital constraints and perceived risk (Nillson et al., 2021; Quiroga et al., 2024). Conversely, some direct-payment schemes may inadvertently weaken incentives for innovation if they stabilise income without linking support to performance outcomes (Bartolini et al., 2011; Dwyer, 2013). Integrated policy packages that combine investment aid with advisory services and knowledge-transfer actions appear most effective in promoting soil-conservation and climate-resilient practices (Popescu et al., 2025). The overall evidence suggests that financial support improves farms' willingness and ability to innovate, but its effectiveness depends on administrative simplicity, predictability, and the presence of complementary human- and knowledge-capital measures (Curzi et al., 2022; Wieliczko, 2019).

Research analysing the drivers of innovation leading to sustainable land use consistently points to four interrelated domains. These include the policy frameworks (predictable regulation, investment incentives, and platforms for knowledge exchange), human capital (qualified labour), technology (especially AI, drones, and digital tools), and innovation ecosystems (Doran, 2025; Zabala et al., 2025). Our empirical study examines the influence of the European Union's Common Agricultural Policy and external investment funding sources on the capacity of agricultural enterprises to introduce eco-innovations, specifically those related to sustainable land management practices.

The study's analytical framework can be interpreted through the lens of the innovation production function, as well as in the context of technology adoption models and the concept of absorptive capacity. Empirical studies on the adoption of agricultural innovations indicate that firms' decision-making is determined by a combination of economic, institutional, and social factors, such as access to finance, information, human capital, and perceived risk, with adoption occurring heterogeneously across firms and over time (Feder et al. 1985). This approach partially aligns with the concept of absorptive capacity, which holds that a firm's ability to identify, assimilate, and effectively utilize new knowledge depends on its capabilities, prior experience, and organizational competencies (Cohen & Levinthal, 1990). However, within the scope of this study, it is not possible to operationalize absorptive capacity in its full extent, as data on firms' research and development activities, a key determinant in the literature, are unavailable. For this reason, the selected model is also conceptually grounded in the innovation production function (Solow, 1956; Romer, 1990), in which capital, labor, and technological inputs are transformed into innovation outputs, while the examined variables primarily capture firms' ability to absorb and implement these innovations in practice.

The capital will be incorporated into our production function, both in its internal and external forms. External investment capital mitigates financial constraints, enabling enterprises to undertake riskier, longer-term innovation activities, including the acquisition of technologies essential to precision and smart farming. Co-financing from the EAFRD should therefore act as an exogenous stimulus directly determining the outputs of innovative activity (Bartolini et al., 2011; Czyżewski et al., 2019; Severini & Biagini, 2020). We formulate the following hypothesis:

H1: Higher annual income of an agricultural enterprise positively affects the likelihood of implementing innovations related to sustainable land use.

Investment support under the second pillar of the CAP can be expected to play an important role in shaping innovation adoption, as it reduces investment risk and increases the availability of capital for innovation activities. From the perspective of the innovation production function, such support enhances firms' investment capacity by complementing internal financial resources, thereby enabling the implementation of innovations that might otherwise remain unrealized (Criscuoli et al., 2024; Popescu et al., 2025). Therefore, we formulate another hypothesis:

H2: Agricultural enterprises that have received investment support from the European Agricultural Fund for Rural Development (EAFRD) exhibit a higher probability of introducing innovations aimed at sustainable land management.

Another attribute of internal innovation capacity is the availability of educated human capital (Hu et al., 2023). Educated employees contribute to the absorptive capacity and problem-solving ability required to transform knowledge into practical innovations. Their creative and managerial competences, often of an irreplaceable tacit nature, may in some cases serve as the primary source of new ideas and their implementation. We therefore formulate the following hypothesis:

H3: A higher proportion of employees with tertiary education increases the probability that an agricultural enterprise will implement innovations supporting sustainable land and soil management.

The last observed factor of a firm's inner capacity is technological maturity. Enterprises that have already achieved a higher technological level tend to possess previous experience with innovation, higher productivity, and greater absorptive capacity (Kalfas et al., 2024). They are therefore predisposed to adopt innovations in sustainable land management. We formulate the final hypothesis:

H4: Enterprises with a higher level of technological maturity, which reflects their absorptive capacity and accumulated technological experience, are more likely to deliver innovations supporting sustainable land use

To ensure that our empirical study does not focus solely on conventional attributes of the innovation production function, we extend the analysis of innovation adoption determinants by incorporating firms' ability to build linkages with other spatial actors, which may represent an important component of their absorptive capacity (Scuotto et al., 2017). In our empirical analysis, we examine the role of cooperative linkages between agricultural enterprises and various external actors. The benefits of collaboration between firms and universities for innovation adoption are well established in the literature (e.g., Bocchi et al., 2017), which justifies testing this relationship in a specific context: cooperation between agricultural enterprises and universities in the adoption of sustainable land-use innovations. We therefore formulate the following hypothesis:

H5: Enterprises that engage in cooperation with external actors, particularly universities, are more likely to adopt innovations supporting sustainable land use.

To operationalize the above theoretical perspectives, the empirical model integrates elements of the innovation production function, absorptive capacity, and technology adoption frameworks into a unified specification. Specifically, internal resources such as annual income and human capital reflect the capital and labour inputs of the innovation production function, while technological maturity and prior experience capture the firm's absorptive capacity. External financial support from the EAFRD represents an exogenous capital injection that reduces investment constraints, and cooperation variables approximate access to external knowledge networks, as emphasized in technology adoption models. In this way, the selected variables are not treated as isolated determinants but as empirical proxies for broader theoretical constructs that shape innovation behaviour.

3. Data and Methods

The research follows a sequential explanatory mixed-methods design, in which the qualitative component primarily serves an explanatory rather than an exploratory function. Specifically, the quantitative analysis identifies statistically significant determinants of innovation adoption, while the qualitative data are used

to interpret and contextualise these relationships by uncovering underlying mechanisms, such as perceived barriers, institutional constraints, and behavioural factors. The integration of both approaches occurs at the interpretation stage, where qualitative insights are systematically linked to quantitative findings to provide a more comprehensive understanding of innovation processes in Slovak agriculture. The qualitative findings are also partially quantified (e.g., frequency of coded responses), which facilitates their integration with the quantitative results.

The empirical analysis is based on primary data collected through a semi-structured questionnaire survey conducted between January and July 2025. The target population consisted of agricultural enterprises in Slovakia classified under NACE A01 (Agriculture). To ensure the feasibility of data collection and sufficient availability of contact information, the sample was restricted to legal entities with at least 2 employees, as microenterprises with 0 or 1 employees typically lack publicly accessible contact details (e.g., websites or email addresses). No additional restrictions were applied regarding legal form, and both domestic- and foreign-owned enterprises operating in Slovakia were included. Based on data from the Statistical Office of the Slovak Republic (2024), an initial population of 5,914 legal entities was identified, of which 4,243 were agricultural enterprises, filtered using the Register of Institutional Units. Subsequently, applying the employment-size criterion reduced the sample. As a result, a final contact database of 1,821 agricultural enterprises was compiled. These enterprises were approached in multiple waves (four contact rounds) using an online questionnaire, complemented by telephone follow-ups conducted on a randomly selected subset of ventures. In total, 105 valid responses were obtained, corresponding to a response rate of 7.94%. While the sample is not statistically representative, it captures a meaningful segment of the sector, as the responding enterprises collectively employ 2,703 employees, representing approximately 16.6% of total agricultural employment (including individual farmers).

The questionnaire combined closed-ended, semi-closed, and open-ended questions, enabling both quantitative modelling and qualitative analysis. Approximately half of the questions were answered by all respondents, while the remaining items targeted enterprises that had implemented innovations in sustainable land use within the previous 7 years. In line with the literature, a broad definition of innovation was adopted, encompassing technological and non-technological solutions (including process and organisational innovations) that are new at the firm level, not widely diffused across Slovak farms, and have a direct or indirect impact on sustainable land-use.

The processing of qualitative data is based on qualitative content analysis, complemented by coding procedures (Erlingsson & Brysiewicz, 2017). Specifically, open and axial coding techniques were applied to identify and structure key themes emerging from respondents' answers. The aim of the analysis was not to develop a new theory, but to systematically categorize barriers to innovation and assess their occurrence across respondents. The subsequent quantification of qualitative codes (e.g., frequency of occurrence within individual categories) enabled the integration of qualitative and quantitative dimensions of the research, thereby strengthening the robustness and interpretability of the results.

An exploratory econometric analysis is also conducted. Using cross-sectional data from 105 agricultural enterprises in Slovakia, the aim is to verify the assumptions of the innovation production function and, in particular, to clarify the validity of the premise that the European Union's Common Agricultural Policy (CAP) plays a significant role in generating innovations that lead to sustainable land use in the agricultural sector. The research has an exploratory-verificatory character. The hypotheses were formulated on the basis of the production function framework; however, their testing does not aim to inferentially generalize the findings to the entire population of agricultural enterprises. The objective is to verify the internal consistency of the theoretical assumptions and to identify the direction and strength of relationships between selected factors within the sample.

To examine the outlined relationships, we employ logistic regression (given the binary nature of the dependent variable). The general form of the logit function is as follows:

$$\log\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \beta_1 X_{1i} + \dots + \beta_k X_{ki}$$

where:

$$p_i = P(Y_i = 1 \mid X_i)$$

The coefficients of the logistic model are interpreted using the odds ratio, defined as e^{β_j} . This value expresses how the ratio of the probability of an event occurring to the probability of its non-occurrence changes with a one-unit increase in the explanatory variable. Given the specified structure of Models I, II, and III, we formulate the following theoretical models to be empirically tested:

1. $\text{Logit}(P(\text{delivered_innovation}_i = 1)) = \beta_0 + \beta_1 * \text{age_venture}_i + \beta_2 * \text{num_empl}_i + \beta_3 * \text{land_area}_i + \beta_4 * \text{share_EA_land_area}_i + \beta_5 * \text{inv_projects_EAFRD}_i + \beta_6 * \text{tertiary_education}_i + \beta_7 * \text{annual_income}_i + \beta_8 * \text{technological_maturity}_i$
2. $\text{logit}(P(\text{delivered_innovation}_i = 1)) = \beta_0 + \beta_1 * \text{age_venture}_i + \beta_2 * \text{num_empl}_i + \beta_3 * \text{land_area}_i + \beta_4 * \text{share_EA_land_area}_i + \beta_5 * \text{inv_projects_EAFRD}_i + \beta_6 * \text{coop_MARD}_i + \beta_7 * \text{coop_APA}_i + \beta_8 * \text{coop_clusters}_i + \beta_9 * \text{coop_university}_i$

The constructed binary logistic regression model examines the determinants of innovation activity among agricultural enterprises in Slovakia, focusing specifically on the probability that an enterprise introduces innovations contributing to more sustainable land use. The dependent variable indicates whether the enterprise has implemented any innovation related to sustainable land management over the past five years.

Tab 1. Overview of variables of logit model. Source: own processing based on primary data collected through the survey

name of variable	type of variable	description
delivered_innovation	binary	a binary variable that expresses whether the enterprise has introduced innovations in relation to sustainable land management in the last 5 years
age_venture	continous	number of years of the enterprise's existence
num_empl	continous	size of the enterprise measured by the absolute number of employees
land_area	continous	total area of agricultural land in HA
share_EA_land area	continous	share of own agricultural land on which the farmer carries out organic farming activities
inv_projects_EAFRD	binary	a binary variable that expresses whether the enterprise has or has not drawn support from the EAFRD in the last 7 years
annual_income	ordinal	a categorical variable expresses the average amount of enterprise income (EUR) by the categories of total income
teritary_education	continous	number of employees with a higher education degree of I., II., or III. degree
technological_maturity	continous	own assessment of the enterprise's technological maturity relative to competitors in the region, on a scale of 0–10
coop_MARD	ordinal	a binary variable expresses whether in the past 5 years there has been a significant relationship of cooperation between the business and f MARD
coop_APA	ordinal	a binary variable expresses whether in the past 5 years there has been a significant relationship of cooperation between the business and APA
coop_clusters	ordinal	a binary variable expresses whether, in the past 5 years, there has been a significant relationship of cooperation between the business and clusters of businesses in the agro-food complex
coop_university	ordinal	a binary variable expresses whether in the past 5 years there has been a significant relationship of cooperation between the business and universities

The dependent variable is a binary indicator indicating whether an agricultural enterprise has introduced at least one innovation related to sustainable land use during the observed period. The model includes a set of control variables reflecting key dimensions of the innovation production process, combining continuous variables (e.g., number of employees, land area, technological maturity, and share of organically managed land) with binary indicators (e.g., receipt of EAFRD investment support) and ordinal variables (e.g., income categories and cooperation intensity). Potential overlap between variables capturing farm size (number of employees and land area) was carefully assessed. Although conceptually related, these variables represent distinct dimensions of agricultural production and do not exhibit strong correlation in the sample. This reflects the structural diversity of farms, including labour-intensive ecological practices and vertically integrated or non-land-based activities. Diagnostic tests (low VIF values) confirm that multicollinearity is not a concern. Average income was measured using interval-based categories and treated as an ordinal variable, while relational variables capturing cooperation with external actors were constructed similarly, reflecting the intensity of both formal and informal interactions (including information exchange, knowledge transfer, and joint projects) on a scale. The model specification represents a simplified empirical approximation of the innovation production function extended by elements of absorptive capacity and technology adoption theory.

Given the relatively small sample size ($N = 105$), particular attention was paid to maintaining a parsimonious model specification. The number of explanatory variables was limited in relation to the number of observations to ensure statistical stability, and the analysis is therefore interpreted as exploratory rather than confirmatory.

4. Results

4.1 Selected characteristic features of the agriculture sector in Slovakia

In this subsection, we focus on a comparative analysis of selected agricultural characteristics in Slovakia with those of the V4 countries and the EU27 average, with the aim of placing Slovak agriculture in a broader European context. Through selected indicators, we analyse differences in farm structure, land use, economic performance, and the role of the sector within national economies.

Tab 2. Comparison of selected characteristics of agriculture in Slovakia and V4 countries (and EU27 averages) relevant to the objectives of the study. Source: Eurostat (2023); DG AGRI (2020–2024)

	<i>year</i>	<i>source of data</i>	<i>SK</i>	<i>CZ</i>	<i>HU</i>	<i>PL</i>	<i>EU</i>
Total land area (km ²)	2023	Eurostat	49035	78871	93012	311928	4207888
Share of agricultural land in total area (%)	2023	Eurostat	0.401	0.468	0.601	0.501	0.388
Number of agricultural holdings (legal entities and natural persons)	2023	Eurostat	17520	33170	189180	1227020	8746560
Density of agricultural holdings (number per 1,000 km ² of total area)	2023	Eurostat	357.296	420.56	2033.93	3933.66	2078.61
Average size of agricultural holding (ha)	2020	EC (DG AGRI)	95	121	21	11	41
Average economic size of holding (thousand EUR)	2020	EC (DG AGRI)	101.49	191.49	30.46	30.62	39.7
Share of employment in agriculture in total employment (%)	2024	EC (DG AGRI)	0.016	0.0214	0.037	0.0614	0.289
Development of agricultural income compared to the overall economy (%)	2024	EC (DG AGRI)	1.2157	0.9148	0.6409	0.5228	0.5295

	<i>year</i>	<i>source of data</i>	<i>SK</i>	<i>CZ</i>	<i>HU</i>	<i>PL</i>	<i>EU</i>
Entrepreneurial income (including wages) at current prices (AWU)	2023	EC (DG AGRI)	20851	23185	14219	10907	23332
Share of CAP direct payments in agricultural income (factor income)	2024	EC (DG AGRI)	0.3472	0.3237	0.3629	0.2165	0.1856
Share of extensively managed land in UAA (%)	2020	EC (DG AGRI)	0.383	0.42	0.22	0.113	-
Share of organic farming in total utilised agricultural area (%)	2024	EC (DG AGRI)	0.1479	0.1596	0.0607	0.0488	-
Share of land under agri-environment-climate measures (AECM) (% of utilised agricultural area)	2022	EC (DG AGRI)	0.09	0.18	0.1	0.05	0.13

Table X provides an overview of key comparative indicators, with one of the first findings being differences in the share of agricultural land in total area. Slovakia, with a share of approximately 40.1%, slightly exceeds the EU27 average (38.8%), but lags behind the Czech Republic (46.8%) and especially Hungary (60.1%), which ranks among the countries with the highest share of agricultural land in the region. This difference primarily reflects natural-geographical conditions, as Slovakia has a higher proportion of mountainous areas than Hungary, which has a predominantly lowland character.

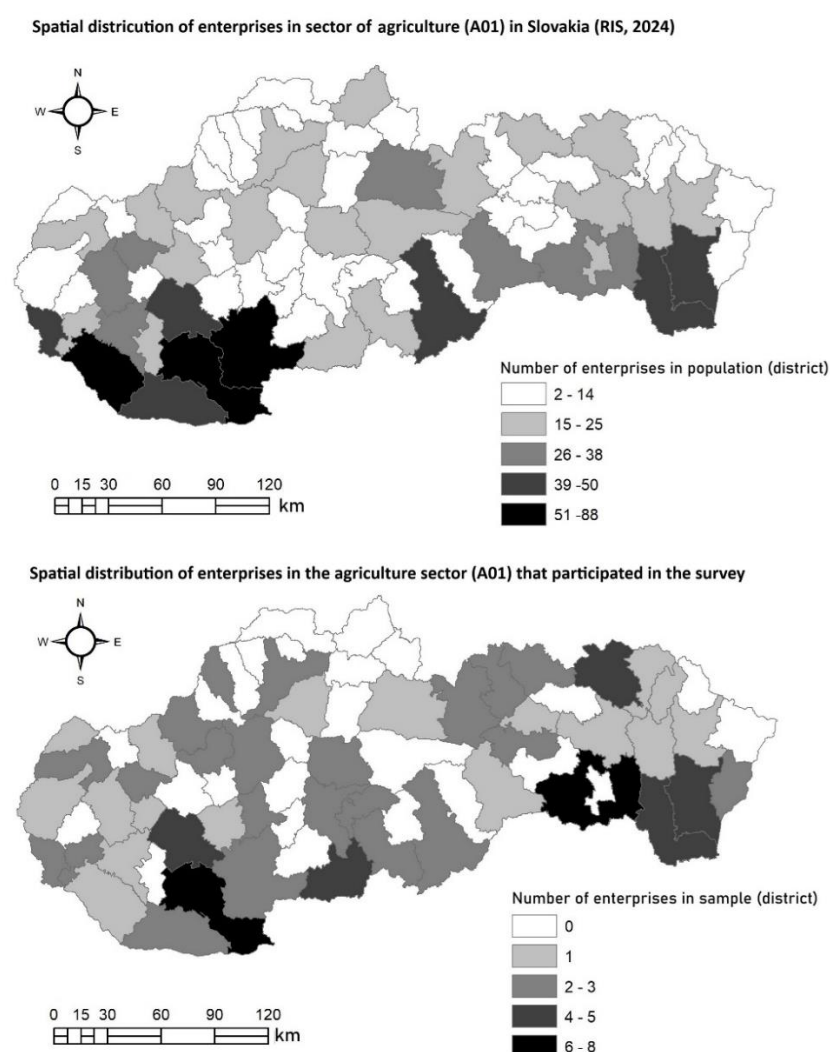
In terms of the number of agricultural holdings, Slovakia is characterised by a significantly lower number of entities (17,520) compared to Poland (more than 1.2 million) or Hungary (nearly 190,000), which is also reflected in the density of holdings per 1,000 km². Slovakia reaches approximately 357 holdings, while Poland exceeds 3,900 and Hungary has more than 2,000 holdings per the same area. This difference points to a fundamentally different sectoral structure, with Slovakia belonging to countries with fewer but larger farms. This is further confirmed by the average farm size, which in Slovakia reaches approximately 95 ha, more than double the EU27 average (41 ha) and significantly higher than in Poland (11 ha) or Hungary (21 ha). A similar pattern is observed in the average economic size of farms, where Slovakia reaches €101 thousand, exceeding the EU average but still lagging behind the Czech Republic, where the average exceeds €190 thousand. It can therefore be concluded that Slovak agriculture is characterised by relatively large and economically stronger enterprises, reflecting the historical development and structural transformation of the sector.

Interesting insights also emerge when examining employment in the sector. The share of agricultural employment in total employment in Slovakia is only around 1.6%, significantly lower than in Poland (over 6%) or Hungary (3.7%), but comparable to the Czech Republic. This low share indicates a high level of mechanisation and labour productivity, but also points to the limited role of the sector in job creation. In terms of income development, Slovakia records a value above 1 when comparing agricultural income to the overall economy, suggesting a relatively favourable income development in the sector compared to other V4 countries and the EU average. This result may be influenced by the structure of subsidies and by farms' capacity to effectively absorb support.

Direct payments under the Common Agricultural Policy also play a significant role, accounting for approximately 34.7% of agricultural income in Slovakia, compared to the EU27 average of 18.6%. This indicates a higher dependence of Slovak agriculture on public support, which may have an ambivalent effect on innovation activity: while it stabilises farm incomes, it may also reduce pressure to improve efficiency. From an environmental perspective, Slovakia shows a relatively high share of organic farming (14.8%), exceeding that of Hungary and Poland, as well as a relatively high share of extensively managed land. On the other hand, the share of land under agri-environment-climate measures is below the EU average, indicating potential for a more intensive use of these instruments.

4.2 Basic characteristics of the sample

Agriculture is a traditional and key sector of rural economies, contributing not only economic but also environmental and social benefits to regional development. The number of agricultural enterprises in Slovakia has sharply declined between 1993 and 2025, a trend not uncommon in Europe. This phenomenon is associated with the rapid development of mechanisation and, in recent years, the digitalisation and automation of agriculture, which have led to increased productivity but also to a decrease in employment and a reduced social-stabilising role of the agricultural sector. Agricultural enterprises were classified according to the filtering criteria described in the previous chapter, yielding a population of 1,846 enterprises. Their spatial distribution across LAU I regions of Slovakia is illustrated in Map 1. The spatial pattern of agricultural activity in Slovakia is largely determined by natural and geographical factors, particularly soil fertility, topography, and climatic characteristics. The southern regions, dominated by lowlands with fertile arable soils, represent the core areas of agricultural specialisation. Conversely, the northern parts of the country, characterised by mountainous terrain, display a lower intensity of agricultural production and greater dependence on natural limitations.



Map 1 and Map 2. Spatial distribution of agricultural enterprises (population) and the sample of agricultural enterprises in Slovakia. Source: own processing based on primary data collected through the survey

Our sample approximately follows the spatial distribution of agricultural enterprises in the population. As shown in Map 2, responses were not obtained primarily from districts with the lowest representation in the agricultural sector. The highest number of responses was recorded in districts belonging to Slovakia's traditional agricultural regions, specifically in selected districts of the Nitra, Banská Bystrica, and Košice regions.

Tab 3. Structure of sample by selected indicators. Source: own processing based on primary data collected through the survey

Size structure (employment)	n	f	Size structure (revenues)	n	f
0–5 employees	16	15.2%	0 – 100 000 eur	12	11.4%
6–10 employees	19	18.1%	100 001 – 500 000 eur	20	19.0%
11–20 employees	30	28.6%	500 001 – 1 000 000 eur	16	15.2%
21–50 employees	26	24.8%	1 000 001 – 2 000 000 eur	26	24.8%
51–100 employees	10	9.5%	2 000 001 – 3 000 000 eur	11	10.5%
100 and more employees	4	3.8%	3 000 001 – 5 000 000 eur	12	11.4%
			5 000 001 – 10 000 000 eur	5	4.8%
Structure of main activities	n	f	Structure of main activities	n	f
0–200 ha	30	28.57%	Animal production	72	68.6%
200–600 ha	21	20.00%	Crop production	85	81.0%
600–1 200 ha	15	14.29%	Forestry	6	5.7%
1 200–2 500 ha	24	22.86%	Processing	23	21.9%
2 500 ha a viac	15	14.29%	Agromechanization	15	14.3%
			Agrotourism	10	9.5%
			Catering / Food services	11	10.5%
			Educational services	15	14.3%
			Construction / technical services	3	2.9%
			Horticulture	4	3.8%

The responded sample of 105 agricultural enterprises reflects a relatively balanced representation of medium-sized and small entities operating in Slovak agriculture. Nearly one-third of enterprises employ 11–20 workers (28,6%), while another quarter have 21–50 employees (24.8%), confirming the dominance of medium-scale farms. Only 3,8% of respondents employ more than 100 workers, which corresponds to the sector's overall structure. The revenue profile shows a similar pattern, with the largest share of enterprises reporting annual incomes between 1 and 2 million EUR (24.8%), followed by the ventures with income between 100,000 and 500,000 (19%). The distribution of agricultural enterprises by land area shows a relatively balanced structure across size categories, with the highest share observed in farms up to 200 hectares (28.57%). At the same time, a substantial proportion of enterprises falls into larger size categories, indicating a heterogeneous farm structure with both small and large-scale holdings represented. In terms of production orientation, the majority of enterprises are engaged in crop production (81%) and animal production (68.6%), while a smaller number combine agriculture with processing (21.9%), agromechanisation (14.3%), or agrotourism (9.5%). The percentages do not sum to 100%, as enterprises may engage in multiple main activities simultaneously; therefore, the categories are not mutually exclusive.

The analysis in Figure 1 illustrates the support structure received by the surveyed agricultural enterprises within the framework of the Common Agricultural Policy (CAP). The majority of respondents reported receiving direct payments (SAPS/BISS), which represent the fundamental income-stabilising instrument of the CAP. A considerable share of enterprises also benefited from complementary and coupled payments, particularly those linked to specific production sectors or environmentally oriented practices. However, a smaller yet substantial group of respondents – approximately one third – declared having implemented investment projects co-financed by the European Agricultural Fund for Rural Development (EAFRD), showing a relatively high level of dependence of enterprises in agriculture on external funding of investment activities.

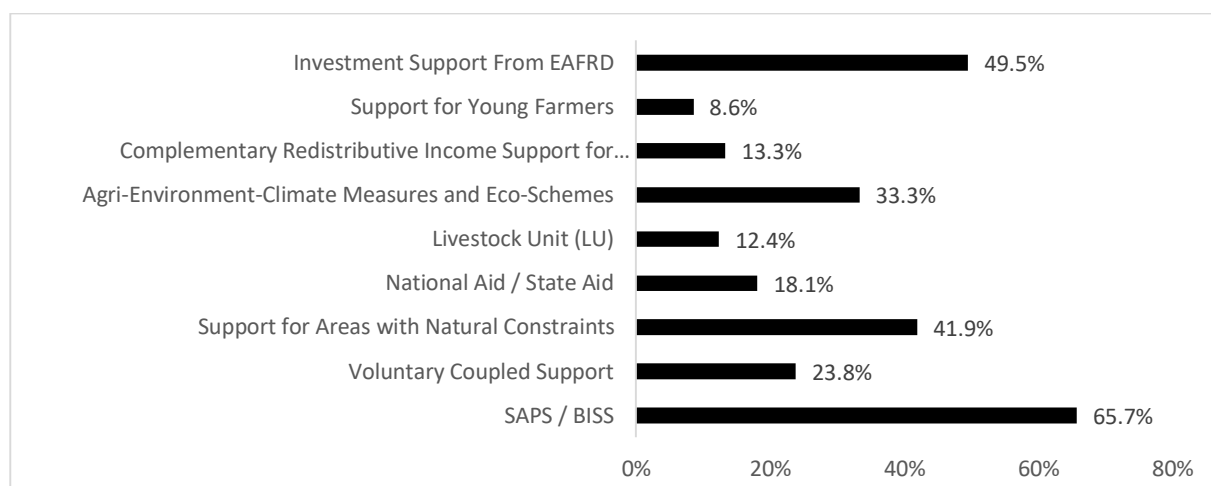


Fig 1. Share of respondents in the sample who received direct, complementary and other payments or investment support from the CAP. Source: own processing based on primary data collected through the survey

This pattern confirms that while direct and complementary payments ensure the economic viability of farms, EAFRD-funded investment support represents a qualitatively different type of intervention. EARDF actively supports innovation and structural modernization. For the purposes of our research design, this dimension is key: access to EAFRD investment support is the principal explanatory factor of innovation activity in our model, capturing the role of external capital in enabling farms to adopt new technologies and sustainable land management practices.

For our research design and subsequent efforts to address the research questions, it is important to note that 68 of 105 surveyed agricultural enterprises (64.8%) reported introducing at least one innovation in sustainable land use in the past five years. This finding indicates a relatively high level of innovation engagement within the sample, suggesting that sustainability-oriented innovations are no longer marginal but have become an integral component of strategic farm management. Such a proportion also provides a solid empirical basis for examining the determinants of innovation adoption and for identifying how financial, institutional, and human-capital factors shape the capacity of Slovak farms to implement environmentally oriented practices.

4.3 The identified innovation action in the area of sustainable land use

Figure 2 summarises the share of responding ventures that delivered individual types of innovation related to sustainable land use. The results show that the most widespread forms of innovation are precision agriculture and regenerative agricultural practices, reported by more than half of respondents who implemented at least one innovation in the past five years. This dominance suggests that technological and environmentally oriented approaches represent the primary direction of innovation in the Slovak agricultural sector. Innovations in **sustainable intensification** and **agroforestry** were less frequent but still notable, while the **application of nanomaterials** remains at the experimental or research stage, adopted by only a limited number of technologically advanced farms.

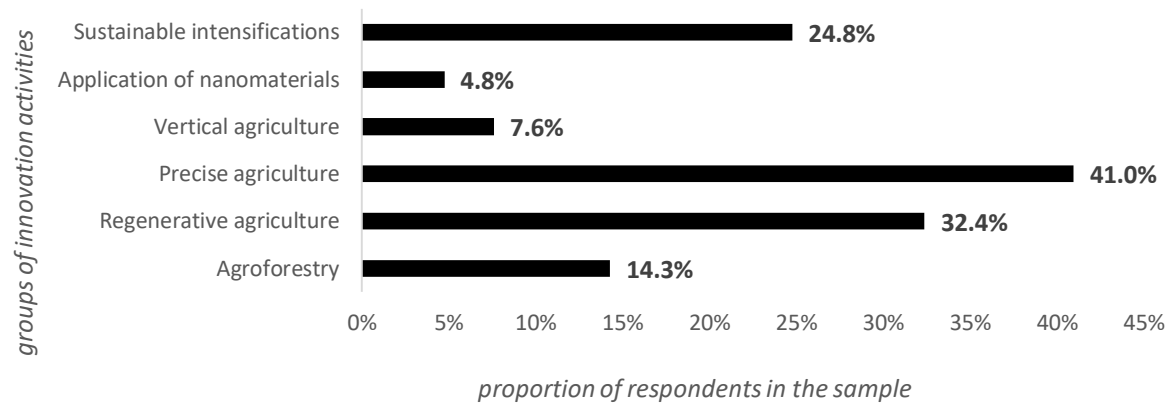


Fig 2. Share of respondents who implemented selected types of innovations in relation to sustainable land use. Source: own processing based on primary data collected through the survey

Table 4 provides a detailed overview of the specific innovations implemented in the observed areas. The frequencies reported in the table are based on open-ended responses; therefore, not all innovations implemented by the enterprises were described or captured in detail. In precision agriculture, the most common practices include GPS and RTK navigation systems, soil variability mapping, and drone-based crop monitoring. These technologies improve production efficiency, optimise input use, and enhance data-driven decision-making. Regenerative practices such as no-till or minimum-tillage, cover crop cultivation, and incorporation of organic matter (compost or digestate) improve soil fertility, water retention, and long-term productivity, reflecting a gradual shift toward more sustainable management of land resources.

Tab 4. Share of respondents who implemented specific innovations in the observed areas (frequencies of anxi and open codes incidence in open answers). Source: own processing based on primary data collected through the survey

Anxial code	Open codes	n	f
Agroforestry	Establishment of shelterbelts, tree lines, and windbreaks	7	6.7%
	A combination of trees and agricultural crops	3	2.9%
	Restoration of landscape-forming elements	2	1.9%
Regenerative agriculture	No-till or minimum tillage practices	5	4.8%
	Cultivation of cover crops and green manuring	3	2.9%
	Increasing soil organic matter (compost, digestate)	3	2.9%
	Mulching and soil moisture protection	2	1.9%
	Use of biological plant protection	2	1.9%
	Sustainable rainwater management	1	1.0%
Precision agriculture	Use of GPS and RTK navigation systems	6	5.7%
	Mapping of soil variability	5	4.8%
	Use of drones for crop monitoring	4	3.8%
	Sensors for variable-rate fertilizer application	3	2.9%
	Automatic steering of agricultural machinery	3	2.9%
	Software and data platforms for yield analysis	3	2.9%
Application of nanomaterials	Testing of nano-fertilizers	2	1.9%
	Experiments with nano-pesticides	2	1.9%
	Research projects using nanoparticles in soils	1	1.0%
Sustainable intensification	Optimization of input and fertilizer rates	5	4.8%
	Breeding of drought- and disease-resistant crops	2	1.9%
	Modernization of technologies reducing fuel and input consumption	2	1.9%

Innovations related to sustainable intensification, such as optimising fertiliser application, adopting energy-efficient technologies, and breeding more resilient crops illustrate farms' efforts to increase productivity while maintaining environmental balance. Agroforestry measures, including the establishment of shelterbelts and windbreaks, and the restoration of landscape-forming elements, remain less common but demonstrate growing interest in landscape-level sustainability and ecosystem services. Finally, the application of nanomaterials, observed in only a few cases, remains largely experimental and tied to research collaborations.

Overall, the results show that precision and regenerative practices dominate innovation patterns, while sustainable intensification and agroforestry play complementary roles. The presence of experimental nano-applications indicates emerging links between farm practice and research. This confirms that innovation pathways in Slovak agriculture increasingly integrate technological advancement with environmental sustainability, with investment projects under the EAFRD strongly supporting this.

4.4 Barriers to innovation action recognized by responding enterprises

In this section of the study, we focus on the identification and interpretation of barriers perceived by surveyed agricultural enterprises in relation to the adoption of innovations supporting sustainable land use.

Tab 5. Perceived barriers of innovation action leading to sustainable land use in selected groups (frequencies of axial and open codes incidence in open answers). Source: own processing based on primary data collected through the survey

Axial code	Open codes	n	f
1. Financial and economic barriers	Lack of own financial resources	37	35.2%
	High investment costs of new technologies	28	26.7%
	Insufficient access to external funding (grants, loans)	25	23.8%
	High investment risk and uncertain returns	14	13.3%
2. Institutional and administrative barriers	Excessive bureaucracy and administrative burden under the CAP	29	27.6%
	Complex system of funding calls and project documentation	22	21.0%
	Poor coordination among institutions (MoA, the Paying Agency, local governments)	13	12.4%
	Unclear rules and frequent legislative changes	11	10.5%
3. Human and knowledge-related barriers	Lack of qualified or skilled labour	18	17.1%
	Insufficient knowledge of innovative technologies and practices	15	14.3%
	Low motivation of employees to adopt innovations	10	9.5%
	Weak links between research institutions and practice	8	7.6%
4. Organisational and value-related barriers	Conservative management attitudes and resistance to change	9	8.6%
	Fear of failure during innovation implementation	7	6.7%
	Limited inter-farm cooperation and experience sharing	6	5.7%
	Lack of time and staff capacity for experimentation	5	4.8%

Table 5 identifies the most significant barriers that agricultural enterprises perceive when attempting to introduce innovations for sustainable land use. Financial and economic constraints emerge as the most dominant factor, mentioned by nearly three-fifths of respondents. These limitations are rooted not only in the overall financial fragility of many farms but also in the structural nature of agricultural markets, where liquidity problems (35.2%) and uncertain returns on long-term investments (13.3%) reduce farmers' willingness to experiment with new technologies. High acquisition costs of modern machinery, precision systems, and environmentally oriented technologies remain a persistent obstacle (26.7%), particularly for small and medium-sized enterprises with limited access to credit or collateral. Even though subsidy schemes under the CAP provide partial relief, respondents repeatedly emphasised that co-financing requirements and delayed reimbursements often hinder the implementation of innovation projects. Consequently, financial barriers are not merely a lack of money, but rather a complex set of

interrelated constraints that shape risk perception, investment behaviour, and innovation timing within the sector.

Institutional and administrative barriers form the second most significant category. These obstacles are largely associated with the procedural complexity of the CAP and national-level funding mechanisms (21%), including excessive bureaucracy, unpredictable rule changes, and insufficient coordination between managing authorities. Farmers often view the administrative environment as both time-consuming and discouraging, especially when preparing project documentation and complying with monitoring requirements that exceed the capacity of smaller enterprises. Several respondents noted that the burden of formalities diverts attention from innovation planning and technical implementation, effectively reducing the efficiency of public support. Moreover, a lack of transparent communication among key institutions, such as the Ministry of Agriculture, the Paying Agency, and regional development actors, further amplifies uncertainty and erodes trust in policy stability (12,4%). This constellation of institutional factors reflects a broader governance challenge: while the CAP provides substantial financial resources for innovation, its accessibility and usability depend heavily on the quality of national-level administrative coordination and policy implementation.

Human and knowledge-related barriers reflect a shortage of qualified labour (17,1%) and insufficient technical know-how (14,3%), particularly in regions where the agricultural workforce is ageing and professional training opportunities are limited. The findings suggest that many enterprises' absorptive capacity to integrate new technologies or ecological practices remains low, slowing the diffusion of innovation. Organisational and value-related barriers, although less frequent (23,8%), reveal important internal and behavioural aspects of innovation resistance. Conservative managerial attitudes (8,6%) and fear of failure (6,7%) often discourage experimentation, especially in enterprises with limited human or financial reserves. A lack of time and personnel dedicated to innovation activities (4,8%) additionally indicates that everyday operational pressures frequently outweigh strategic planning.

It appears that while farmers clearly recognise where public support should be directed, they continue to face systemic financial and administrative obstacles that constrain innovation capacity. The results underline the need for a holistic policy approach that combines investment incentives, simplified administrative procedures, and knowledge-transfer measures to fully unlock the innovation potential of Slovak agriculture and strengthen its transition toward sustainable land management.

4.5 Drivers of production of the sustainable land use innovations in agricultural sector

This section interprets the results of two logistic regression models identifying the key drivers of innovation adoption related to sustainable land use in Slovak agricultural enterprises. The analysis was conducted in Stata 14. The overall diagnostic indicators confirm that both models exhibit satisfactory explanatory power and appropriate specification. The predictive performance of the models, assessed using the ROC curve, reaches AUCs of 0.85 in Model I and 0.87 in Model II, indicating a high level of discriminative ability; however, the robustness of these estimates may be affected by the relatively small sample size. The linktest results show that the predicted values ($\hat{\mu}$) are statistically significant, whereas the squared predictions ($\hat{\mu}^2$) are not, confirming that the models are correctly specified and do not suffer from major omitted-variable bias. Multicollinearity was assessed using the VIF diagnostic, with mean VIFs around 1.5 and no individual VIF exceeding 5, indicating that multicollinearity is not a concern. Overall, the models can be considered statistically reliable and suitable for interpreting the determinants of innovation behaviour within the analysed sample.

Tab 6. Results of logistic regression. Source: own processing based on primary data collected through the survey

	MODEL I				MODEL II			
	coef.	o.r.	conf. interval (odds ratio)		coef.	o.r.	conf. interval (odds ratio)	
<i>age_venture</i>	-0.0688 (0.2743)	0.9335 (0.2561)	0.5453	1.5981	-0.3384 (0.2809)	0.7129 0.2003	0.4111	1.2364
<i>num_empl</i>	-0.2374 (0.3781)	0.7887 (0.2982)	0.3759	1.6549	-0.3237 (0.3342)	0.7235 0.2418	0.3758	1.393
<i>land_area</i>	0.0292 (0.4058)	1.0296 (0.4178)	0.4648	2.2807	0.0136 (0.4829)	1.0137 0.4895	0.3935	2.6116
<i>share_EA_land area</i>	2.7933** (1.0546)	16.3341** (17.221)	2.0674	129.056	2.9475** (1.0514)	19.0585** 20.0374	2.4275	149.62
<i>inv_projects_EAFRD</i>	1.6116** (0.5632)	5.0108** (2.822)	1.6616	15.1109	2.0232*** (0.5825)	7.5628*** 4.4057	2.4145	23.689
<i>tertiary_education</i>	0.0041 (0.0166)	1.0041 (0.0166)	0.972	1.0373				
<i>annual_income</i>	-0.272 (0.4036)	0.7618 (0.3075)	0.3454	1.6805				
<i>technological_maturity</i>	0.7612** (0.2930)	2.1408** (0.6273)	1.2054**	3.8019**				
<i>cooper_MARD</i>					-0.5874 (0.4114)	0.5558 (0.2287)	0.2481	1.2449
<i>cooper_APA</i>					0.5904 (0.4120)	1.8047 (0.7435)	0.8049	4.0465
<i>cooper_clusters</i>					-0.1607 (0.3313)	0.8516 (0.2821)	0.4449	1.6301
<i>cooper_university</i>					0.7817* (0.3828)	2.1853* (0.8364)	1.032	4.6272
<i>_cons</i>	-0.5637 (0.3801)	0.5691 (0.2163)	0.2702	1.1988	-0.7168* (0.3759)	0.4883* (0.1836)	0.2337	1.0202
Number of obs.	105				105			
LR chi2	41.12***				41.54***			
Pseudo R2	0.3017				0.3048			
Mean VIF	1.52				1.56			
Linktest	1.2196***				1.1865***			
	_hatsq	-0.1466			-0.1193			
lroc	0.8529				0.8669			

* indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$. Standard errors are in brackets

The evaluation of the core hypotheses (H1–H5) reveals a differentiated pattern of determinants shaping innovation adoption related to sustainable land use. Hypothesis H1, which assumes a positive effect of annual income, is not supported. The results indicate that internally generated financial resources do not have a statistically significant effect on the likelihood of introducing innovations. This suggests that, in the context of Slovak agriculture, innovation activity is not primarily driven by internal capital accumulation but rather by access to external financial sources. Therefore, we reject hypothesis 1. This finding challenges the standard assumptions of the innovation production function, suggesting that not all forms of capital equally translate into innovation outputs. In this context, the structure and conditionality of financial resources appear more important than their absolute level.

In contrast, hypothesis H2 is strongly supported. The variable capturing investment support from the EAFRD is statistically significant in both models and exhibits a substantial positive effect. Farms that

have received EAFRD investment support in recent years have approximately five to seven times higher probability of introducing innovations with potential impact on sustainable land management. This result justifies hypothesis H2, which we accept. This finding highlights the importance of CAP investment instruments in reducing financial constraints and enabling the adoption of sustainable land use practices. The results also indicate that both the previous Rural Development Programme and the current CAP Strategic Plan of Slovakia provide an important framework for implementing innovations that contribute to sustainable land use. From the perspective of the innovation production function, this finding also confirms the critical role of external capital as a key input enabling innovation outputs, particularly in environments where internal financial resources are insufficient.

Hypothesis H3, focusing on the role of human capital, is not supported. The share of employees with tertiary education does not reach statistical significance, indicating that formal education alone does not directly translate into innovation adoption. This may suggest that the ability to implement innovations depends more on practical experience, access to knowledge networks, or external advisory support than on formal educational attainment. This result may appear counterintuitive at first glance when assessing the adoption of innovations aimed at sustainable land use. Some activities, particularly in precision agriculture, require a higher level of human capital and advanced technical competencies. However, it should be noted that in other types of innovation action, for instance, regenerative practices, the level of human capital may not play a dominant role. Hypothesis H4 is supported, as technological maturity proves to be a statistically significant determinant of innovation behaviour. Enterprises with higher levels of technological advancement are significantly more likely to adopt innovations related to sustainable land use. This confirms the assumption that prior technological development enhances firms' absorptive capacity and their ability to effectively implement new solutions. This result provides empirical support for the concept of absorptive capacity, as technologically advanced enterprises are better able to identify, assimilate, and apply new knowledge, which directly translates into higher innovation performance. Therefore, hypothesis H3 is accepted.

Finally, hypothesis H5, which examines the role of cooperation with external actors, is accepted; however, the overall results suggest that cooperation factors do not constitute a dominant determinant of innovation adoption in sustainable land use. Most cooperation variables do not show statistically significant effects, indicating that relational linkages alone are not sufficient to explain innovation behaviour in this domain. This may be explained by the fact that cooperation with various actors often takes place primarily through information exchange, the transfer of know-how, or the implementation of projects that are not directly related to sustainable land use or do not clearly represent an innovation action. Nevertheless, the expected positive effect of collaboration with universities is confirmed, as this variable is statistically significant, highlighting the specific role of knowledge-intensive cooperation in facilitating the adoption of sustainability-oriented innovations.

Beyond the tested hypotheses, additional variables provide further insights into the structure of innovation determinants. The size of the enterprise, measured by both the number of employees and total land area, does not have a statistically significant effect, suggesting that scale alone is not a decisive factor in innovation. Similarly, the enterprise's age remains insignificant, suggesting that accumulated experience does not automatically lead to higher innovation activity. A strong, statistically significant effect is observed for the share of land managed under organic farming, indicating that enterprises oriented toward ecological production are substantially more likely to introduce innovations that support sustainable land use. This result points to the importance of environmental orientation as an internal driver of innovation behaviour.

5. Conclusion and discussion

The results of the empirical analysis provide a structured yet non-trivial picture of the determinants of innovation adoption related to sustainable land use, revealing a clear dominance of policy-driven financial support while simultaneously challenging several commonly assumed firm-level drivers. While prior research emphasises the role of both internal capacities and external conditions, the findings suggest that,

in the context of Slovak agriculture, innovation behaviour is more strongly shaped by institutional and policy mechanisms than by endogenous firm characteristics (Curzi et al., 2022; Wieliczko, 2019).

The most robust and consistent result across both models is the strong positive effect of EAFRD investment support. This finding aligns with studies showing that CAP investment measures reduce capital constraints and perceived risks associated with innovation (Nilsson et al., 2021; Quiroga et al., 2024). However, the magnitude and stability of this effect across model specifications suggest a potential structural dependency, where innovation activity is not merely supported but effectively enabled by public funding. This extends previous findings by indicating that, in structurally constrained agricultural systems, public investment support may partially substitute for insufficient internal capital accumulation (Severini & Biagini, 2020; Bartolini et al., 2011). At the same time, this result raises critical concerns regarding the long-term sustainability of such innovation dynamics, as excessive reliance on subsidies may weaken endogenous innovation capacity and reduce incentives for independent investment (Dwyer, 2013). These conclusions are further reinforced by the analysis of perceived barriers to innovation, which reveals a strong dominance of financial and economic constraints. The most frequently identified barriers include insufficient own financial resources, high investment costs of new technologies, and limited access to external financing, all of which point to a structurally constrained investment environment. Similar barriers have been widely documented in the literature on agricultural innovation, particularly in regions characterised by lower capital intensity and higher exposure to risk (Bartolini et al., 2011; Severini & Biagini, 2020). Importantly, the persistence of these barriers helps explain why external support mechanisms emerge as such a strong determinant in the econometric models.

Beyond financial constraints, the results highlight the significant role of institutional and administrative barriers, particularly excessive bureaucracy, complex application procedures, and instability of regulatory frameworks. These findings are consistent with studies emphasising that administrative burden and policy complexity can significantly limit the effectiveness of public support instruments, even when financial resources are available (Dwyer, 2013; Curzi et al., 2022). In this sense, the results suggest that the effectiveness of CAP instruments is conditioned not only by their financial volume but also by the institutional environment in which they are implemented. The analysis also identifies barriers related to human and knowledge capacities, including a lack of qualified labour, insufficient awareness of innovative practices, and weak linkages between research and practice. While these factors do not emerge as statistically significant in the regression model, their presence in qualitative responses suggests that they may operate as latent or indirect constraints on innovation adoption. This partially explains the non-significant effect of formal human capital observed in the model, indicating that the issue may lie not in the quantity of education, but in the type and applicability of knowledge available to enterprises (OECD, 2022; Macaneiro et al., 2013).

The absence of a statistically significant effect of annual income directly challenges the assumptions of the innovation production function, which posit a positive relationship between internal financial resources and innovation output. While some studies report a positive link between income and innovation capacity, particularly in capital-intensive sectors, evidence from agriculture remains mixed (Bartolini et al., 2011; Curzi et al., 2022). The present findings support the latter stream, suggesting that income alone does not translate into innovation unless it is channelled into targeted investment. This indicates that the structure and conditionality of financial resources – rather than their absolute level – play a more decisive role in shaping innovation behaviour. The positive and statistically significant effect of technological maturity confirms the importance of accumulated capabilities and prior technological development. This result reinforces findings from studies emphasising cumulative learning processes and the role of prior technological experience (Kalfas et al., 2024; Zabala et al., 2025). More importantly, it provides empirical support for the concept of absorptive capacity, as firms with higher technological maturity are demonstrably better equipped to identify, assimilate, and implement new knowledge (Cohen & Levinthal, 1990).

A similarly strong effect is observed for environmental orientation, proxied by the share of land under organic farming. This finding confirms that enterprises already aligned with sustainability-oriented production systems exhibit a higher propensity to adopt further innovations (Chabé-Ferret et al., 2019;

Diaz-Garcia et al., 2015; Galioto & Nino, 2023). In contrast, the non-significant effect of human capital suggests that the relationship between knowledge and innovation adoption is more complex than often assumed. While previous studies emphasise the importance of education (Hu et al., 2023; Doran, 2025), the results indicate that formal education alone may not capture the relevant knowledge base, particularly in the context of heterogeneous agricultural innovations, where tacit knowledge and practical experience play a key role (OECD, 2022; Macaneiro et al., 2013).

The role of cooperation with external actors presents a differentiated picture. Overall, cooperation does not emerge as a dominant determinant of innovation adoption, which contrasts with literature emphasising network effects (Scuotto et al., 2017; Zabala et al., 2025). However, a statistically significant effect is observed for cooperation with universities, suggesting that knowledge-intensive collaboration plays a distinct role. This supports the argument of technology adoption models that access to relevant knowledge channels is a key driver of innovation decisions (Feder et al., 1985).

Several limitations should be acknowledged. First, the study relies on a cross-sectional survey of Slovak agricultural enterprises, which does not capture how innovation behaviour evolves over time. Second, the dataset is based on voluntary participation and self-reported information. Third, although the logistic regression model provides useful exploratory insights, it cannot fully account for the complex interactions among financial support, institutional conditions, and behavioural factors; omitted-variable bias remains a possibility. Fourth, the national focus on Slovakia and its specific CAP implementation limits the generalisability of results to other European contexts. Finally, the qualitative findings, while valuable, are constrained by the limited depth of open-ended responses. Future research should combine longitudinal data, objective performance indicators, and multi-country comparisons to strengthen and validate these observations.

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