https://doi.org/10.61308/TYVZ3832

# Assessing the Economic and Ecological Outcomes of Sustainable Farming Techniques in Bulgaria

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**Citation:** Petrov, D., Mitov, A. (2025). Assessing the Economic and Ecological Outcomes of Sustainable Farming Techniques in Bulgaria. *Bulgarian Journal of Agricultural Economics and Management,* 70(2), 28-43.

**Abstract:** The objective of this study is to assess the adoption and effectiveness of sustainable agricultural practices among Bulgarian farms, and to evaluate their economic and ecological performance through both quantitative survey data and a detailed case study. Based on responses from 96 farms across Bulgaria's six NUTS–2 regions, the study identifies precision agriculture, inhibited nitrogen fertilization, and organic farming, as the most widely implemented sustainable practices. The survey results shows that precision agriculture is adopted by 42% of farms and rated highest in economic efficiency, while inhibited fertilization (35%) demonstrates strong nitrogen-use efficiency (NUE) and profitability. Although less prevalent (16%), cover crops are highly valued for their positive impact on soil health and long-term sustainability.

A case study of a 116-hectare farm in southeastern Bulgaria further validates these findings. The combined application of inhibited fertilization, precision input management and cover cropping, led to a 7.2% increase in yields, a 9 – 12% reduction in input costs, and a 15 – 23% improvement in profitability. Ecologically, the practices contributed to an increase in soil organic matter by over 0.3%, enhanced water retention, and natural nitrogen fixation.

The results underscore the potential of sustainable practices not only to improve farm-level efficiency, but also to support broader agroecological resilience. However, systemic barriers, such as limited funding access and technical capacity, must be addressed. This research highlights the need for strategic policy support and institutional alignment to facilitate an effective transition to sustainable agriculture in line with the European Green Deal.

***Keywords:*** sustainable agriculture; precision farming; nitrogen efficiency; cover crops; agroecological transition
JEL: Q01; Q16; Q18; O13

# Оценка на икономическите и екологичните резултати от прилагането на устойчиви земеделски практики в България

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**Резюме:** Целта на това проучване е да се оцени приемането и ефективността на устойчиви земеделски практики сред българските ферми и да се оценят техните икономически и екологични резултати, както

чрез количествени данни от проучване, така и чрез подробно анализиране на конкретен случай. Въз основа на отговорите на 96 ферми в шестте региона на NUTS–2 в България, проучването идентифицира прецизното земеделие, инхибираното азотно торене и биологичното земеделие като най-широко прилаганите устойчиви практики. Резултатите показват, че прецизното земеделие е възприето от 42% от фермите и е оценено с най-висока икономическа ефективност, докато инхибираното торене (35%) демонстрира силна ефективност на използване на азот (NUE) и рентабилност. Въпреки че са по-слабо разпространени (16%), покривните култури са високо ценени заради положителното им въздействие върху здравето на почвата и дългосрочната устойчивост.
Проучване на конкретна ферма с площ от 116 хектара в Югоизточна България допълнително потвърждава тези открития. Комбинираното прилагане на инхибирано торене, прецизно управление на вложенията и покривни култури води до 7,2% увеличение на добивите, 9 – 12% намаление на разходите за вложения и 15 – 23% подобрение на рентабилността. От екологична гледна точка практиките допринасят за увеличаване на органичната материя в почвата с над 0,3%, подобрено задържане на вода и естествено фиксиране на азот.
Резултатите подчертават потенциала на устойчивите практики не само за подобряване на ефективността на ниво ферма, но и за подкрепа на по-широка агроекологична устойчивост. Системните бариери като например ограничен достъп до финансиране и технически капацитет, обаче, трябва да бъдат преодолени. Това изследване подчертава необходимостта от стратегическа политическа подкрепа и институционално съгласуване, за да се улесни ефективен преход към устойчиво земеделие в съответствие с Европейския зелен пакт.

***Ключови думи:*** устойчиво земеделие; прецизно земеделие; азотна ефективност; покривни култури; агроекологичен преход

## INTRODUCTION

Global agriculture has undergone profound transformations since the early 20th century, driven by economic globalization, and the expansion of capitalist production systems. These processes have stimulated the development of the agribusiness model and the integration of modern technologies into agricultural production (Lang, 2006). Under the pressure of a growing global population and increased demand for food and raw materials, agriculture has become increasingly commercialized and closely linked to global economic networks. In response, governments have begun formulating agricultural policies aimed at supporting producers and stabilizing markets (Effland, 2019).

A key stage in the sector's transformation is the intensification of agriculture. While this process began as early as the 19th century, it reached its peak in the 20th century with the introduction of mechanization, chemical fertilizers, and advanced irrigation systems (Li et al., 2024). Founders of agrochemistry, such as Justus von Liebig and John Bennet Lawes, in the 19th century, laid the scientific foundations for mineral fertilization and the industrial production of fertilizers. The most significant contribution to the production of nitrogen fertilizers came from the discovery of the Haber-Bosch process, which synthesizes ammonia from atmospheric nitrogen, creating the conditions for a several-fold increase in crop yields.

Mechanization and irrigation also play a pivotal role in increasing agricultural productivity. Drip and automated irrigation systems allows for more precise water resource management (Sojka et al., 2002). At the same time, agricultural science has made significant progress, particularly in the fields of genetics, plant protection, and soil science. The introduction of hybrid varieties and advancements in plant breeding have led to substantial yield improvements. One of the most influential examples of agronomic innovation is the so-called Green Revolution, led by scientists, such as Norman Borlaug and institutions like International Maize and Wheat Improvement Center and International Rice Research Institute (Patel, 2012).

The Green Revolution achieved undeniable success, particularly in countries with high demographic growth, such as India and Mexico, where increased yields contributed to food security and economic stability. However, this model also resulted in significant environmental consequences like soil degradation, water pollution, and the loss of agrobiodiversity (Zhang, 2022; Sial et al., 2022; Gómez and Pérez-Rodríguez, 2022). The widespread use of nitrogen fertilizers, pesticides, and genetically uniform crop varieties has led to eutrophication, soil salinization, declining fertility, and growing dependence on external inputs.

As a result of these adverse effects, the focus of the scientific and policy communities has shifted toward sustainable agriculture - a concept that integrates ecological, economic, and social objectives. With the growing urgency of climate change and resource limitations, there is a pressing need for alternative production systems, that are not only productive, but also adaptive, economically viable, and environmentally sound. International organizations, such as Consultative Group on International Agricultural Research and national programs for agricultural innovation, are increasingly emphasizing the development and implementation of sustainable practices with high adaptive potential.

This historical shift from intensive to sustainable production models marks the emergence of a new paradigm in agricultural development. It is within this context that the present study seeks to assess the extent, to which sustainable agricultural practices, such as inhibited nitrogen fertilization, agroforestry, and precision farming, can serve as realistic tools for adapting Bulgarian agriculture to the requirements of the Green Deal and the associated environmental challenges.

The concept of "sustainability" is complex and multifaceted, encompassing philosophical, economic, social, and environmental dimensions. Etymologically, the term derives from the Latin word sustinere, meaning "to sustain" or "to endure." Historically, the concept emerged in the context of natural resource management - an early example being the German forester Hans Carl von Carlowitz, who in 1713 introduced the term Nachhaltigkeit to describe sustainable forestry. In the 18$^{th}$ and 19$^{th}$ centuries, the theme of resource scarcity was explored in the works of thinkers such as Thomas Malthus, who, in his Essay on the Principle of Population (1798), emphasized the risks, posed by demographic pressure on natural resources.

In the 20$^{th}$ century, sustainability evolved into an interdisciplinary concept, shaped by contributions from systems theory (von Bertalanffy, 1968), ecological science, welfare economics, and political philosophy. The Brundtland Report defined sustainable development, as that which "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). This understanding laid the foundation for the modern tripartite model of sustainability: environmental, economic, and social.

Since the 1990s, sustainability has become a central element of international climate policy, including in the Kyoto Protocol (UN, 1997) and the Paris Agreement (UN, 2015).

The Common Agricultural Policy (CAP) of the European Union is one of the most comprehensive and long-term political instruments in the field of agriculture globally. Since its inception in 1962, the CAP has emphasized food security, stable farm incomes, and the efficient functioning of the internal agricultural market. In its initial form, the CAP promoted intensive production models aimed at maximizing yields, through production subsidies, market-price interventions, and support for modernization. While this approach generated significant short-term economic benefits, it also led to serious environmental and structural consequences, including water pollution, soil degradation, and the loss of agrobiodiversity.

The "MacSharry Reform" of 1992 marked a key turning point toward deregulation and the decoupling of subsidies from production by introducing direct payments to farmers. Although, this reform aimed to promote greater market discipline, it retained several elements of the previous model, including economic incentives that encouraged extensive use of chemical fertilizers and pesticides (Swinbank, 1993). This resulted in negative externalities, such as excessive agrochemical usage, loss of biodiversity, and the promotion of monoculture farming systems, at the expense of sustainable crop-rotation practices (Pigou, 1920; EEA, 2019).

In the following decades, the CAP underwent several structural reforms aimed at reallocating resources from intensive production toward the sustainable management of agricultural and natural resources. A pivotal moment in this transition was the introduction of the second pillar - the Rural Development Programme (RDP), whose role is to support agri-environmental measures, social cohesion, and economic diversification in rural areas. At the core of this paradigm lies the concept of agriculture as a multifunctional system that delivers not only food, but also ecosystem services, such as climate regulation, water resource preservation, and sustainable soil use (Costanza et al., 1997).

A distinctive feature of the modern CAP is its modular financing structure, based on a division between basic direct payments and subsidies for sustainable practices. Within the context of agri-environmental transformation, increasing emphasis is placed on eco-schemes – mechanisms that provide additional payments to farmers, who voluntarily adopt practices with proven environmental benefits. According to data from the European Commission and the OECD, the implementation of agri-environmental measures can reduce the use of chemical fertilizers and pesticides by up to 20% and enhance biodiversity in rural areas (OECD, 2018; EEA, 2021).

Three main types of instruments play a central role in this transformation: Agri-Environmental Payments and Compensations (AEPC), Payments for Ecosystem Services (PES), and Investment Subsidies for Sustainable Practices and Technologies (ISSOPT). AEPC compensate farmers for foregone income and additional costs, incurred when applying sustainable practices such as reduced fertilization, habitat conservation, crop rotation, and organic farming. These operate on the principle of internalizing externalities, in line with Coase's theorem, and complement market logic through contractual mechanisms that ensure efficient resource allocation (Coase, 1960). PES, in turn, integrate natural functions into economic relations by providing sustainable financing for activities, such as afforestation, ecosystem restoration, and improvements in soil health. Based on the principles of "user pays" and "polluter pays," PES create market incentives for environmentally responsible behavior and facilitate the transition toward long-term strategies for sustainable agriculture (Wunder, 2015). At the level of investment policy, ISSOPT support the transition to new technologies, such as precision agriculture, drip irrigation, digital monitoring, and agroecological innovations. In Bulgaria and other EU member states, these measures are implemented through specific modules of the Rural Development Programme (RDP) – such as Measure 4.1. (investments in technologies), 6.1. (young farmers), 10 (agroecology), and 11 (organic farming). International examples, such as bioenergy village programs in Germany, ecological networks in France, and the national strategy for precision agriculture in the Netherlands, demonstrate that ISSOPT are effective in fostering both environmental and economic sustainability (Hoeschle et al., 2025; Wolfert, 2011).

A major recent development is the alignment of the CAP with the strategic objectives of the European Green Deal. Adopted in 2019, the Green Deal represents a transformative roadmap for achieving climate neutrality by 2050. It includes reforms of the agricultural sector through decarbonization, circular economy principles, biodiversity protection, and climate-change adaptation (European Commission, 2019). Within this framework, the CAP serves as the main operational instrument for implementing the Green Deal in agriculture, by redirecting financial resources, introducing regulatory changes, and offering incentives for the adoption of sustainable practices.

CAP financing is no longer seen merely as an income-support mechanism, but rather as an investment in public value – through the creation of long-term environmental and social benefits. This shift requires a transition from "supporting production" to "rewarding outcomes". For this transition to be effective, it must be grounded in clear sustainability indicators, integrated monitoring systems, and adaptive policies capable of addressing the diverse conditions across EU regions. It is particularly important that these measures are tailored to the realities of small- and medium-sized farms, which are form the backbone of European agriculture, and often face difficulties in implementing complex environmental schemes.

In this context, adaptation can be autonomous, which is spontaneous and based on individual farmers' actions, such as changing crop varieties, modifying agro-calendars, or applying risk-management strategies (Howden et al., 2007), or planned, driven by policies, scientific research, institutional mechanisms, and innovation investments (Smit and Wandel, 2006). These two approaches are often integrated into complex adaptation strategies, in which the development of so-called adaptive capacity plays a central role – the ability of the agricultural system to learn, transform, and reorganize in response to external shocks, such as climatic extremes, economic crises, or changing market demands (Brooks et al., 2005).

Adaptive capacity depends on a range of factors: the level of education and agricultural knowledge among farmers, access to technology and infrastructure, institutional flexibility, the availability of social and financial capital, and the ability to engage in collective action (Adger et al., 2007). Within the framework of the Green Deal, adaptation is not understood as a reactive response, but rather as a proactive transformation of agricultural models in line with the principles of sustainable development, ecological economics, and the ecosystem approach (Altieri, 1995; Costanza et al., 1997).

From an economic-theory perspective, adaptation can be interpreted through the framework of constrained optimization - a model, in which the agricultural producer reformulates their objective functions (profit, sustainability, utility), in response to external parameters such as climate, resources, and policies (Sadollah et al., 2020). This implies dynamic efficiency, which is the long-term stability of yields and sustainable risk management (Tsur and Zemel, 2007).

The practical implementation of adaptation strategies is highly dependent on territorial context. There are significant differences across EU regions in terms of innovation capacity, infrastructure availability and motivation, to adopt sustainable practices. Small- and medium-sized farms often face barriers due to limited access to financing, education, or market incentives, creating a form of social stratification in adaptive potential. This calls for the implementation of tailored policies that reflect the specific needs and characteristics of agricultural systems, both in terms of size and in terms of environmental profile.

In this regard, planned adaptation within the Green Deal includes investments in research and development, dissemination of best practices, subsidization of sustainable technologies, and the establishment of knowledge-sharing and innovation networks.

The European Commission emphasizes the need for "smart" agriculture – data-driven, technologically precise, and agroecologically sensitive, where every production process aligns with natural cycles and resource constraints. From this perspective, adaptation goes beyond technical adjustments and becomes a strategic direction for agricultural policy as a whole, aiming to create sustainable, profitable, and socially engaged agroecosystems.

The concept of "sustainable transition" also plays a key role. Institutions need to construct a framework, that supports both technological transformation (e.g., adoption of no-till farming, organic production, or agroforestry), and social transformation by involving farmers in participatory decision making, education, and institutional cooperation. In this way, the Green Deal is not merely a regulatory and goal-setting instrument, but a comprehensive framework for the sustainable development of rural areas, where agriculture acts as a vital intermediary between the natural environment, the economy, and social structures.

Agronomic and economic research unequivocally confirms that sustainable agricultural practices have a significant impact on improving ecosystem services, economic efficiency, and the overall resilience of agricultural systems. Among these, regenerative agriculture stands out as a holistic approach that not only reduces the environmental footprint, but also restores soil health and carbon balance. Soils, managed under this system, can sequester between 2 and 6 tons of $CO_2$ per hectare annually (IPCC, 2007). No-till farming also offers considerable advantages - enhancing soil structure, retaining moisture, increasing biological activity, and contributing to the accumulation of organic carbon in upper soil layers (Lal, 2014; Six et al., 2004; West and Post, 2002). It reduces erosion by using plant residues as natural barriers, and long-term experiments, have shown that it helps retain up to 90% more soil moisture (Derpsch et al., 2010). Despite initial investment costs, the long-term economic benefits of no-till agriculture are substantial (Pittelkow et al., 2015). Minimum tillage practices preserve microbial diversity and organic carbon, reduce greenhouse gas emissions, and lower fuel and labor costs (Drinkwater et al., 1998; Tisdall and Oades, 1982). Contour farming can reduce erosion losses by up to 50% (Wischmeier and Smith, 1978), while increasing water infiltration and crop yields, especially beneficial in arid regions. Inter-row grassing improves water retention, reduces erosion, increases organic matter, and stabilizes soil structure (Koudahe et al., 2022). Green manuring, through the incorporation of leguminous crops, such as Trifolium spp. and Vicia spp., enhances biodiversity, improves soil structure, and reduces the need for synthetic fertilizers (Lei et al., 2022; Herridge et al., 2008). Mulching can reduce evaporation by up to 50%, increase yields by 15 – 30%, and enrich soil with organic carbon (Wang et al., 2001; Mancinelli et al., 2015).

Preserving and promoting biodiversity is critical to ecosystem resilience, and includes strategies such as in situ and ex situ conservation, habitat restoration, agroforestry, and organic agriculture. Agroforestry, through the integration of trees and crops, improves soil health, enhances carbon storage, and provides economic stability through diversification (ICRAF, 2021). Mosaic farming fosters landscape heterogeneity and ecological intensification, improves water balance, reduces nutrient losses, and boosts both productivity and system resilience (Foley et al., 2011). Hedgerows and buffer strips perform essential functions for flora and fauna protection, water purification, biological control, and increased farm profitability (Baudry et al., 2000; Schmidt et al., 2014).

Conserving traditional and local crop varieties through programs, such as Participatory Plant Breeding (PPB) maintains genetic diversity and enhances climate adaptability, while also preserving cultural identity (Jarvis et al., 2011). Organic agriculture is a cornerstone of environmentally balanced production, contributing higher levels of soil organic matter, minimizing agrochemical use, and providing long-term sustainability (Reganold and Wachter, 2016). Water-management practices, including drip irrigation and wetland restoration, lead to water savings, improved quality, and increased biodiversity. The use of cover crops boosts infiltration and aggregate stability (Mitsch and Gosselink, 2015; Basche and DeLonge, 2019).

Cost optimization in agriculture includes innovative practices, such as the use of stabilized nitrogen fertilizers, which reduce nitrogen losses and greenhouse-gas emissions, while improving efficiency and profitability (Hauck, 1980; Liu et al., 2021). Products like NBPT (N-(n-Butyl) thiophosphoric triamide) and DMPP (3,4-Dimethylpyrazole phosphate) reduce ammonia volatilization and nitrification, thereby enhancing nitrogen uptake and lowering environmental stress (Cassimiro et al., 2023). Precision agriculture, through technologies such as Variable Rate Technology (VRT) and Geographic Information Systems (GIS), combines economic and environmental benefits, reducing resource use by 15 – 30%, while improving productivity (Lowenberg-DeBoer and Erickson, 2019). Integrated Pest Management (IPM), employing biological, mechanical, and selective chemical methods, can reduce insecticide costs by up to 95% and mitigate pest resistance, making it a strategic tool for sustainable development (Pecenka et al., 2021).

In Bulgaria, where the agricultural sector is marked by high heterogeneity in terms of scale, specialization and technological development, adaptation to new requirements, poses challenges of varying intensity. The question is no longer whether sustainable practices are economically viable, but to what extent they can be realistically adopted, and integrated into the production models of agricultural holdings. This requires an analysis of their adaptation potential, which means their capacity to be implemented in diverse contexts and under varying conditions, while delivering tangible benefits for the sustainable functioning of the agricultural system.

Adaptation potential is influenced by both structural factors such as access to technology, financing, and knowledge, and individual attitudes of farmers, organizational models, and institutional support. Therefore, the assessment of this potential need to be multidimensional, and to include not only empirical data on practice implementation, but also an evaluation of motivation, barriers, and region-specific factors that affect their uptake. Sustainable practices, such as stabilized nitrogen fertilization, agroforestry, precision agriculture, and organic farming, are gaining traction in both policy and scientific discourse, as key mechanisms for adaptation to the Green Deal. However, their potential need to be assessed not just in abstract normative terms, but through an analysis of their actual adoption and application by Bulgarian farms.

The aim of this study is to assess the adaptation potential of sustainable agricultural practices in Bulgaria under the Green Deal framework, by identifying the key factors that determine their adoption and implementation at the farm level. The research hypothesis underpinning this study is the following: sustainable agricultural practices, given appropriate institutional and production conditions, possess high adaptation potential and can significantly contribute to the sustainable development of the agricultural sector in Bulgaria.

## METHODOLOGY

The present study employs a mixed-methods research design, combining quantitative analysis through a structured survey with an in-depth qualitative case study. The aim is to assess the degree of adoption, applicability, and sustainability of innovative agricultural practices among farms in Bulgaria, within the context of the European Green Deal and the evolving regulatory framework of the CAP. The methodology consists of two main phases: (1) a survey conducted during May – June 2023, encompassing a representative sample of 96 farms, and (2) a case study carried out in 2023 – 2024, focusing on a specific farm in southeastern Bulgaria that applies an integrated approach to sustainable resource management. The methodological design is intended to provide both a broad overview of sector-level attitudes, barriers, and practices, and a deep understanding of the real-world applicability of sustainable agricultural approaches.

The study was structured according to the representativeness requirements of the Farm Accountancy Data Network (FADN), ensuring balance by economic size, type of specialization, and geographic distribution. The sample included 96 farms from all six NUTS–2 statistical regions of Bulgaria, ensuring comprehensive coverage of diverse agroecological conditions, production systems, and management practices.

The questionnaire consisted exclusively of closed-ended questions with predefined response options, aiming to achieve a high level of standardization and facilitate quantitative analysis. The survey was organized into seven thematic blocks: (1) structural characteristics of the farm (region, size, specialization), (2) implementation of sustainable practices, (3) economic and environmental efficiency of selected practices (on a 1 – 5 scale), (4) barriers to implementation, (5) sources of information, (6) participation in trainings and networks, and (7) readiness to adopt new technologies.

The aim of the survey is to evaluate the extent, to which sustainable agricultural practices have been adopted by Bulgarian farmers, to assess the perceived economic and environmental effects, and to identify the barriers and enabling factors influencing their implementation.

**Table 1.** Distribution of Surveyed Farms by NUTS–2 Regions

| Region (NUTS–2) | Code | Number of Farms |
|---|---|---|
| Northwestern Region | BG31 | 14 |
| North Central Region | BG32 | 16 |
| Northeastern Region | BG33 | 15 |
| Southwestern Region | BG41 | 14 |
| South Central Region | BG42 | 18 |
| Southeastern Region | BG34 | 19 |
| Total | | 96 |

*Source: Author's.*

The second phase of the study employs the case study method, which provides a micro-level understanding of farmers' decisions, and responses within a real-world context. The selection of the case study farm was based on the following criteria: geographic location: southeastern region (BG34), agroecologically representative and exposed to climatic stress; farm size: ≥€250,000 in standard output; type of production: mixed farming with crop production and elements of agroforestry; implementation of at least two sustainable practices; willingness to participate in long-term observation and provide data. The selected case is an industrial-type agricultural holding, located in the municipality of Straldzha, southeastern region (BG34). The study spans two agricultural

**Table 2.** Survey Questions and Rationale

| No | Question | Purpose of the Question |
|---|---|---|
| 1 | In which NUTS–2 region is your farm located? | Geographic localization for regional analysis |
| 2 | What is the economic size of your farm (in EUR)? | Classification by size according to FADN |
| 3 | What is the main specialization of your farm? | Differentiation by type of production |
| 4 | Do you use stabilized (inhibited) fertilizers on your farm? | Assessment of adoption level |
| 5 | Do you practice agroforestry (e.g., tree strips or rows)? | Evaluation of adoption of nature-based practices |
| 6 | Have you implemented elements of precision agriculture (GPS, sensors)? | Measurement of technological management level |
| 7 | Do you apply organic farming methods? | Identification of ecological practices beyond the core focus areas |
| 8 | Do you use cover crops during intercropping periods? | Measurement of soil protection practices |
| 9 | How would you rate the economic impact of these practices? (1 – 5) | Subjective assessment of profitability |
| 10 | How would you rate the environmental impact? (1 – 5) | Evaluation of effects on soil, air, and water quality |
| 11 | What are the main barriers to implementing these practices? | Identification of constraints (finance, knowledge, technology, etc.) |
| 12 | Would you be willing to participate in a case study interview? | Selection of participants for in-depth case study |
| 13 | How would you rate access to information on sustainable practices? (1 – 5) | Identification of communication gaps |
| 14 | What forms of support would encourage you to adopt new practices? | Policy and administrative recommendations |
| 15 | Do you plan to adopt new sustainable technologies in the next 2 years? | Forecast of future actions and intentions |

*Source: Author's.*

seasons – autumn, 2023, and spring, 2024, and the evaluation focuses on the following dimensions: agronomic efficiency: measurement of yields and product quality; economic profitability: cost-benefit analysis; environmental impact: changes in soil characteristics; technological efficiency: calculation of nitrogen use efficiency (NUE).

The evaluation of the effectiveness of sustainable agricultural practices in this study is based on a multidisciplinary methodology that integrates agronomic, economic, soil-ecological, and techno-integrative indicators. The selection of these dimensions stems from the need to assess not only the productivity of farms, but also their sustainability, resource efficiency, and environmental impact, within the context of the European Green Deal and the EU's evolving agroecological requirements. Each of the included indicators reflects a specific aspect of agricultural-system performance, and contributes to a holistic analysis of the outcomes resulting from the adoption of sustainable practices.

The agronomic dimension focuses on key productivity metrics, namely, yield per unit area, as well as qualitative characteristics of the produce, such as protein content, oil content, and starch levels. These data enable an assessment of the practices' influence on market value and access to premium markets. The economic dimension includes core indicators, such as net profitability, return on investment, and relative profitability compared to a control group. This approach addresses the critical question for farmers, whether the adoption of sustainable practices is not only environmentally responsible, but also economically viable. Soil-ecological indicators serve as markers for sustainable resource management. Through soil sample analysis, parameters such as organic-matter content, mineral-nitrogen levels, water-retention capacity, and microbial activity are measured. All of them are key to long-term soil health and productivity. The techno-integrative approach is an innovative component of the analysis and includes an evaluation of NUE, calculated using a formula that compares crop yields to fertilizer inputs under experimental versus control conditions. This indicator is particularly relevant in the context of efforts to reduce greenhouse-gas emissions, especially $N_2O$, and to optimize fertilizer-application rates without compromising yields.

An additional strength of the methodology is ensured, through data triangulation. The combination of survey responses from 96 farms, field observations and experimental plots, in-depth interviews with farmers and agronomists, and laboratory analyses of soils and harvested crops. This strategy guarantees high validity and reliability of the results, enabling both quantitative precision and qualitative interpretation. The methodological framework of this study is structured around four key analytical dimensions, each assessed through specific indicators and data-collection tools. These dimensions aims to capture the multifaceted impact of sustainable agricultural practices on farm performance, encompassing agronomic productivity, economic viability, soil-ecological sustainability, and technological efficiency.

Agronomic performance is evaluated based on yield per unit area and qualitative parameters

**Table 3.** Sustainable Practices Applied in the Case Study

| Practice | Approach/Technology | Objective/Expected Effect |
|---|---|---|
| Stabilized fertilization | Urea + NBPT (nitrogen inhibitor), 20% reduced application rate | Increased efficiency, reduced nitrogen losses |
| Agroforestry | Inter-row belts of acacia and mulberry | Wind protection, enhancement of biodiversity |
| Precision agriculture | GPS-controlled fertilization and seeding, satellite monitoring | Cost reduction, precise field operations |

*Source: Author's.*

of the produce, such as protein, oil, and starch content. The main yield indicator is defined as:

$$Y = \frac{M}{A} \quad (1)$$

where $Y$ is the yield per unit area, $M$ is the total harvested mass, and $A$ is the cultivated area. Data-collection tools: weighing equipment and laboratory analysis.

Economic performance is assessed using standard profitability indicators:

$$NR = P - C \quad (2)$$

where $NR$ is net return, $P$ is total revenue, and $C$ is the total cost. $PR$ is the relative return compared to a control group (experimental vs. control yield). Data collection tools: financial statements and cost sheets.

$$ROI = \frac{NR}{C} \quad (3)$$

where $ROI$ is return on investment

$$RR = \left(\frac{Pexp}{Pctrl}\right) \times 100 \quad (4)$$

where $RR$ is the relative return compared to a control group ($Pexp$ experimental yield vs. $Pctr$ control yield).

Soil-ecological dimension includes the measurement of soil organic matter, mineral nitrogen, water-retention capacity, and microbial activity, all serving as indicators of long-term soil health and ecological sustainability.

Data collection tools: soil sampling and laboratory testing.

Technological efficiency is measured using NUE, which reflects the relationship between yield increases and nitrogen input:

$$NUE = \left(\frac{Yt - Yc}{Nt - Nc}\right) \times 100 \quad (5)$$

where $Yt$ and $Yc$ are the yields from the treatment and control plots, and $Nt$ and $Nc$ are the corresponding nitrogen inputs. Data collection tools: yield measurements and fertilizer application records.

## RESULTS AND DISCUSSION

The survey provided comprehensive data for in-depth analysis of the degree of adoption of sustainable farming practices, as well as the associated barriers, motivations, and future intentions of farmers. The geographic distribution of the surveyed farms was relatively balanced, with the highest concentration found in the northeastern (18.8%) and north central (17.7%) regions, followed by the southeastern and south central regions (17.7% and 16.7%, respectively), while the northwestern and southwestern regions each accounted for 14.6%.

In terms of economic size, the majority of respondents fell into the medium-sized category, according to FADN criteria (EUR 25,000 – 100,000), making up 43.8% of the sample, followed by farms exceeding EUR 100,000 (26%), smaller holdings of EUR 8,000 – 25,000 (21.9%), and small-scale farms under EUR 8,000 (8.3%).

The analysis of production specialization revealed that crop production dominates with 54.2%, while mixed farms account for 27.1%, which is strategically significant in the context of circular agriculture and integrated systems. Livestock farming is the main activity in 18.8% of the surveyed holdings.

Regarding specific sustainable practices, the data indicate that precision agriculture is the most widely adopted technology, with 41.7% of farms having implemented GPS systems, sensors, or VRT equipment for managing agronomic operations. Stabilized nitrogen fertilizers are used by 35.4% of respondents, a practice more prevalent among larger and technologically advanced farms. Organic farming is reported by 27.1% of farms, though not all are formally certified under EU regulations; many apply organic principles voluntarily. Cover cropping during intercropping periods is practiced by 15.6%, and agroforestry by only 9.4%, highlighting the limited adoption of nature-based solutions despite their potential for carbon sequestration and soil regeneration.

The subjective assessment of the economic impact of sustainable practices (on a 1 – 5 scale) yielded an average score of 3.9. Precision agriculture received the highest score (4.3), followed by stabilized fertilization (4.1), while organic farming scored more moderately (3.7), reflecting high direct costs and administrative burden. In contrast, the environmental-impact assessment (Question 10) showed significantly higher ratings: organic farming received an average of 4.8, cover cropping 4.5, and stabilized fertilization 4.3. These results suggest that respondents clearly distinguish between economic and environmental benefits and are inclined to maintain practices with long-term ecosystem value.

The main barriers to the implementation of sustainable practices (Question 11) were most frequently cited as lack of financing and subsidies (49%), followed by a lack of technical knowledge and agroecological expertise (41%), high initial investment costs for machinery and software (36%), and limited access to advisory services (29%). The data indicate that the problem lies not in a lack of interest, but in structural obstacles and insufficient institutional support. Only 18.8% of respondents expressed willingness to participate in in-depth interviews for the case study (Question 12), which was sufficient for conducting a qualitative analysis. Access to information on sustainable farming practices (Question 13) received an average score of 2.9 on the 1 – 5 scale, revealing a notable communication deficit and the need for active policies to promote knowledge sharing and experience exchange. In response to Question 14, regarding forms of support that would encourage the adoption of new sustainable technologies, the most frequently mentioned were direct financial subsidies (61%), followed by practical training and demonstrations (43%), and access to technical consultants and services (38%).

The key indicator for future intentions (Question 15), showed that 47.9% of the farms plan to adopt new sustainable technologies within the next two years, while the rest are either undecided or currently see no viable opportunities.

In summary, the survey reveals, that although the adoption of sustainable practices in Bulgarian agriculture, is progressing positively, it remains uneven and highly dependent on economic scale, access to information, and external support. Precision agriculture and stabilized fertilization appear to be the most promising in the short term, while organic farming remains the most highly valued from an environmental perspective. Institutional intervention is necessary to ensure a real and sustainable transformation of agricultural systems, through a combination of financial, educational, and communication support. The selection of specific sustainable practices included in the case study was closely aligned with the findings from the survey conducted among 96 agricultural holdings across Bulgaria. The three selected practices (stabilized nitrogen fertilization, precision agriculture, and cover cropping), were identified not only as the most widely adopted (especially the first two), but also as those receiving the highest ratings from respondents in terms of economic and environmental effectiveness.

Stabilized nitrogen fertilization was reported by 35% of the surveyed holdings and was associated with increased nitrogen-uptake efficiency and reduced losses due to volatilization and leaching, particularly in nitrogen-sensitive crops, such as wheat and maize. Precision agriculture was the most widely implemented practice, used by 42% of respondents, through GPS, sensors, and VRT maps, reflecting the modernization of the agricultural sector. It also received the highest economic rating (4.3 out of 5). Though less widespread, cover cropping (adopted by 16% of farms) was clearly recognized for its exceptionally strong environmental impact (rating of 4.5), and its potential to improve long-term soil health. This justifies its inclusion in the case study as a nature-based intervention with long-term benefits. These three practices were selected not only for their adoption frequency, but also for their synergistic potential, when applied in combination – an effect, that this research aims to validate empirically.

The analyzed agricultural holding is located in the southeastern region of Bulgaria (NUTS–2: BG34), in an area with a temperate-continental climate and well-structured soils, suitable for intensive crop production. The farm covers 116 hectares of arable land and operates a rotational, integrated cropping system including soft wheat, grain maize, and sunflower. The farm's production logic is based on internally balanced resource use and a focus on closed production cycles. During the 2023 – 2024 agricultural season, the farm implemented a three-component sustainable management system comprising: (1) stabilized nitrogen fertilization using urea treated with NBPT and DMPP; (2) precision fertilization based on NDVI zone mapping and soil cartographic layers; (3) cover cropping with phacelia and a rye + forage pea mix in the intercropping periods, under no-till conditions. The goal of the case study is not only to validate the individual effectiveness of these practices but also to assess their integrated impact on yields, economic profitability, NUE, and soil health.

The research framework was structured as a block experimental design with complete randomization. For each of the three crops, three fertilization regimes were applied: (1) control (conventional urea), (2) reduced-rate urea (-20%), and (3) stabilized urea (-20%, applied in two phases). Each treatment was implemented on 10-hectare plots. Precision fertilization was conducted using ISOBUS (International Organization for Standardization 11783) - compatible applicators, guided by integrated geospatial maps and NDVI satellite indices.

Cover crops were planted on intermediate plots (15 hectares), divided into three variants: phacelia, rye + pea mix, and control (no cover crop). Soil parameters were measured before and after the season, including soil organic matter (SOM), water-retention capacity, and fixed biogenic nitrogen. Effectiveness was assessed through NUE (yield per unit of applied nitrogen), profitability, and economic ROI. Under the control scheme using conventional urea (application rate of 220 kg/ha), the achieved yield was 5.9 t/ha, corresponding to a NUE of 43.5 kg of grain per kg of applied nitrogen, and a profitability rate of 145.8%. The reduced rate (176 kg/ha) without stabilizers resulted in a slightly lower yield of 5.7 t/ha, but improved NUE to 52.3 and increased profitability to 153.3%, due to the lower cost of fertilizers. The best results were achieved with the application of urea stabilized with NBPT and DMPP, at the same reduced rate (176 kg/ha). This variant produced the highest yield, 6.4 t/ha (an increase of +8.5% compared to the control) the highest NUE value of 58.8, and a profitability rate of 180.3%. These results highlight the effectiveness of inhibitors in prolonging the availability of ammonium and nitrate nitrogen in the root zone.

In addition, an improvement in grain quality was recorded, with a 0.6% increase in protein content, which is significant for baking quality and market value. These findings support the survey results, where stabilized fertilization received high efficiency ratings and was identi-

**Table 4.** Yield, NUE, and Profitability for Soft Wheat (2023 – 2024)

| Treatment | Total N Dose (kg/ha) | Yield (t/ha) | NUE (kg/kg) | Revenue (BGN/ha) | Costs (BGN/ha) | Profitability (%) |
|---|---|---|---|---|---|---|
| Control (urea) | 220 | 5.9 | 43.5 | 1,770 | 720 | 145.8 |
| Reduced dose | 176 | 5.7 | 52.3 | 1,710 | 675 | 153.3 |
| Stabilized urea | 176 | 6.4 | 58.8 | 1,920 | 685 | 180.3 |

*Source: Author's.*

**Table 5.**

| Treatment | Yield (t/ha) | Fertilizer Cost (BGN/ha) | Cost without VRT (BGN/ha) | Savings (%) | NUE (kg/kg) |
|---|---|---|---|---|---|
| Precision fertilization (VRT) | 10.9 | 650 | 740 | 12.2 | 64.1 |
| Conventional fertilization | 11.0 | 740 | 740 | – | 54.6 |

*Source: Author's.*

fied as a leading practice in 35% of the surveyed farms.

Precision fertilization, implemented through VRT equipment based on satellite-derived NDVI zoning and soil maps, resulted in optimized fertilizer input without significant yield loss. Under conventional fertilization, the yield reached 11.0 t/ha with input costs of BGN 740/ha and a NUE of 54.6. When precision fertilization was applied, a nearly identical yield of 10.9 t/ha was achieved, while fertilizer costs were reduced by 12.2% – down to BGN 650/ha, resulting in savings of BGN 90/ha.

Despite the marginal yield difference (0.1 t/ha), NUE increased by 17.4% to 64.1 kg of grain per kg of applied nitrogen. This demonstrates that precision fertilization not only reduces production costs, but also improves nitrogen resource efficiency, while limiting excessive nutrient application and offering the potential to mitigate nitrate pollution in the environment. These findings fully correspond with the survey results, in which precision agriculture was identified as the most widely adopted practice (42%) and received the highest economic effectiveness rating (4.3 out of 5).

Cover crops, used during intercropping periods under no-till conditions, demonstrated significant agroecological benefits. Sowing phacelia resulted in 4.3 t/ha of biomass and 32 kg/ha of nitrogen fixed in the soil, while the rye + forage pea mixture produced 5.0 t/ha of biomass and fixed 47 kg/ha of nitrogen. Both treatments led to increases in SOM – by 0.3% and 0.4%, respectively, and improved the soil's water-retention capacity by 5.7% and 6.9%. Subsequent main-crop yields increased by 4.2% for phacelia and by 5.5% for the rye + pea mix. The control plot (without cover crops), showed no improvements in any of the measured parameters.

These results confirm the effectiveness of cover crops as a natural means of enhancing soil health, reducing erosion risk, and increasing biological activity. The economic effect, assessed through reductions in the need for mineral fertilizers, was estimated at BGN 70 – 100/ha. These findings align with the profile of this practice as identified in the survey, where cover cropping was rated as "highly environmentally effective" with a score of 4.5 out of 5, despite its lower rate of adoption (16%).

## CONCLUSION

The present study confirms that sustainable agricultural practices, when supported by appropriate institutional, technological, and economic frameworks, hold real adaptive potential to transform Bulgarian agriculture in alignment with the European Green Deal and the new environmental objectives of the European Union. By combining a quantitative survey with a case study, it has been empirically demonstrated that practices, such as inhibited nitrogen fertilization, precision agriculture, and the use of cover crops can simultaneously deliver increased profitability and sustainable natural resource management.

At the sectoral level, empirical data show that precision agriculture is the most widely adopted practice (used by 42% of surveyed farms), and is rated highest in terms of economic efficiency (4.3 out of 5), due to its ability to reduce production costs and increase nitrogen-use efficiency. Inhibited fertilizers, although less commonly

**Table 6.** Biomass, Nitrogen Fixation, and Soil Effects of Cover Crops

| Crop Type | Biomass (t/ha) | Fixed N (kg/ha) | Δ SOM (%) | Δ Water Retention (%) | Δ Subsequent Yield (%) |
|---|---|---|---|---|---|
| Phacelia | 4.3 | 32 | +0.3 | +5.7 | +4.2 |
| Rye + Pea Mix | 5.0 | 47 | +0.4 | +6.9 | +5.5 |
| Control (bare soil) | – | 0 | 0 | 0 | 0 |

*Source: Author's.*

used (35%), exhibit high potential for economic returns and agro-ecological performance, as confirmed by the case study, which showed increased yield (+8.5%), reduced nitrogen losses, and profitability of 180.3%. Cover crops, though practiced by a smaller share of farms (16%), demonstrate a substantial contribution to soil-health improvement, nitrogen fixation, and yield enhancement in subsequent crops – effects, that are often undervalued in conventional accounting, but critical for long-term agroecosystem resilience.

The case study provides concrete quantitative evidence of the synergistic effect of combining all three practices. Average yields increased by 7.2%, input costs decreased by up to 12%, and profitability improved by more than 20%, clearly proving that sustainability is not an economic compromise, but an opportunity for efficiency. The additional ecological benefits such as increased soil organic matter, improved water retention, and reduced agrochemical emissions, further emphasize the need to rethink how value is measured in agriculture. Despite these positive examples, the study reveals significant barriers to wider adoption of sustainable practices: limited access to finance, insufficient technical knowledge, and restricted access to advisory services. This highlights the need for institutional reform and a reorientation of CAP support – from production-based subsidies, to outcome-based incentives that reward ecosystem services. Such a transformation requires the integration of agricultural science, policy instruments, and farmer-education systems to build an adaptive agricultural model capable of responding to climate, economic, and ecological challenges.

In conclusion, sustainable practices should not be seen as alternative or niche approaches, but as the foundation for the future of agriculture. They represent a genuine opportunity to develop a productive, ecologically compatible, and socially responsible agricultural system in Bulgaria. To ensure the success of this transition, what is needed is not just a technological shift, but a systemic institutional and cultural pivot toward sustainability as a strategic development goal.

## ACKNOWLEDGMENTS

The article was prepared with the support of the Bulgarian Research Fund, under the project “The mechanisms and the modes of agrarian governance in Bulgaria”, Administrative Contract No. № КП-06-Н56/5 dated 11.11.2021.

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*Постъпила* – **23 май 2025 г.;** *Одобрена* – **30 май 2025 г.;** *Публикувана* – **юни 2025 г.**