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OBSTACLES AND STRATEGIES FOR EU AGRICULTURAL INDEPENDENCE, EU FOOD SECURITY AND THE UTILIZATION OF DIGITAL SOLUTIONS

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D1.2 OBSTACLES AND STRATEGIES FOR EU FOOD SECURITY AND INDEPENDENCE, AND USE OF DIGITAL SOLUTIONS

Pathways to EU Agricultural Independence and Food Security

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Abstract	This document's main objective is to outline the policy landscape associated directly with agricultural independence and food security, and serve as the basis for further project deliverables. To achieve that, the report examines on the practices, policies, and strategies that encourage farmers to ensure sustainability, resilience, and food security. Increasingly, these efforts depend on digital aggregation, digitalisation, the implementation of innovative technology, precision agriculture (PA), and enhanced data usage in agriculture. The deliverable addresses the challenges of agricultural independence and food security in the European Union (EU). Agricultural independence refers to mitigating issues arising from reliance on agrochemicals, fluctuating prices, and external trade pressures. EU-level policies and strategies have been analysed to form the foundation of this report, including the Common Agricultural Policy (CAP), the European Green Deal, the Farm-to-Fork Strategy, the REPower Initiative and the One Health initiative that encompasses four pillars of resilience. Additionally, the EU Digital Strategy, the Chemicals Strategy for Sustainability, and Digital Education policies play important roles. Priorities obtained from this work will be considered in further deliverables by the Nostradamus project. These priorities involve data and technology independence at the EU level; compatibility and interoperability of various data collection systems, digital tools and databases; the priority of sustainability at the farm level; and socioeconomic priorities impacting digitalisation in small-scale farms.
Keywords	Agricultural Independence, Food Security, Digital Solutions, Data Aggregation, Common Agricultural Policy, Farm to Fork Strategy, Digital Literacy, Agrochemical Reduction

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EXECUTIVE SUMMARY

This document, Nostradamus project Deliverable 1.2 "Obstacles and Strategies for EU Agricultural Independence, EU Food Security and the Utilization of Digital Solutions", outlines the policy landscape associated directly with agricultural independence and food security, and serve as the basis for further project deliverables. The information presented herein has been compiled using mixed methods, including a literature review, analysis of policy documents, and examination of EU-wide statistics alongside regional examples.

To achieve the objective of outlining the policy landscape associated with agricultural independence and food security, the report focuses on the practices, policies, and strategies that encourage farmers to ensure sustainability, resilience, and food security. Progressively, these efforts depend on digital aggregation, digitalisation, the implementation of innovative technology, precision agriculture, and enhanced data usage in agriculture.

The report addresses the challenges of agricultural independence and food security in the European Union (EU). Agricultural independence refers to mitigating issues arising from reliance on agrochemicals, fluctuating prices, and external trade pressures. Food security is defined by the aspirational efforts of the EU to achieve self-sufficiency in food production, which requires investments in digitalisation and modernization of agriculture while ensuring that farmers remain competitive.

Agriculture and farming significantly contribute to declining soil health, environmental degradation, and health costs associated with the current land use practices in the EU. At the same time, agriculture faces challenges from climate change, water scarcity and droughts. There is a growing recognition of the urgent need for policies, strategies, targeted farm advisory programs, and networks of demonstration farms to encourage farmers and land managers to adopt sustainable practices. Additionally, policies must focus on building agricultural resilience to address these interconnected crises effectively.

The policies and strategies at the EU level that have been analysed to form the foundation of this report include the Common Agricultural Policy (CAP), the European Green Deal, the Farm-to-Fork Strategy, the REPower Initiative and the One Health initiative, which encompasses four pillars of resilience. Additionally, the EU Digital Strategy, the Chemicals Strategy for Sustainability, and Digital Education policies play important roles. In terms of the CAP, we have summarized some of the achievements and problems in the status quo associated with the CAP Pillar 1 direct income support, CAP Pillar 1 Good Agricultural and Environmental Conditions (GAEC) Standards, CAP Pillar 1 eco-schemes, CAP Pillar 2 agri-environment payments, and CAP Pillar 2 Investments in physical assets. While a detailed analysis regarding effectiveness was beyond the scope of this report, we noted that some issues regarding the delivery of sustainability and agricultural resilience are present within these policies. The report highlights key interventions and approaches to enhance soil health, advance precision and organic farming practices, and support the implementation of nutrient management plans.

Effective digital data management is critical for guaranteeing data quality, accessibility, processing, data interoperability and security within the agricultural sector. A step change is needed in effective data management as the sector continues to generate increasing volumes of data from diverse sources. Such data is instrumental in guiding crucial decisions related to planting, fertilising, and harvesting, directly impacting agricultural productivity and food availability. Precision agriculture will be a key approach at the farm level, characterized by information-intensive procedures, generating vast amounts of valuable data that can optimize food production and minimize losses, thereby strengthening food security. Digital literacy among rural populations extends beyond operating devices; it encompasses a comprehensive understanding of data privacy, cybersecurity, and integrating digital tools into traditional farming practices. As technology continues to evolve, the gap in digital literacy expands, requiring more complex strategies to educate farmers and rural communities effectively. This capacity building is essential for navigating the increasing emergence of digitalisation. The high costs of installing and implementing digital technologies are another barrier to sustainability, resilience and food security.

The priorities derived from this work could be taken into account in further deliverables by the Nostradamus project. These priorities involve data and technology independence at the EU level; compatibility and interoperability of various data collection systems, digital tools and databases; the sustainability priority at the farm level; and socioeconomic priorities impacting digitalisation in small-scale farms. In particular, the sustainability priority at the farm level is a bundle of measures including strengthened efficiency and effectiveness of implementing agricultural policy support measures; increasing the targeted support to technology investments for farmers and land managers; stimulating a task-force group at the EU level to clarify the various criteria for defining the eco-scheme targeted to PA, appropriate to different regions, in a way that complies with the policy requirement of controllable criteria; exploring the use of market-based instruments instead of policy supports targeted to sustainability; developing digital supply chains that enhance the understanding of sustainability by interconnecting suppliers and consumers of agricultural products.

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ABBREVIATIONS

AMS	Area Monitoring Systems
CAP	Common Agricultural Policy
CSA	Climate-Smart Agriculture
DCs	Data Cubes
DIH	Digital Innovation Hubs
EU	European Union
FADN	Farm Accountancy Data Network
FAS	Farm Advisory Services
FS	Food Security
FSDN	Farm Sustainability Data Network
GAEC	Good Agricultural and Environmental Conditions
GNSS	Global Navigation Satellite Systems
LOM	Liquid organic manures
NECP	National Energy and Climate Plans
NIRS	Near Infrared Spectroscopy
PA	Precision Agriculture
RRF	Recovery and Resilience Facility
RRPs	Recovery and Resilience Plans
SDGs	United Nations Sustainable Development Goals
UNCCD	United Nations Convention to Combat Desertification
UNCCD	United Nations Convention to Combat Desertification
VRA	Variable Rate Application

1 INTRODUCTION

This deliverable presents the Nostradamus project's vision for advancing the EU's agricultural independence, enhancing food security, and promoting digital solutions. It outlines key challenges and strategies for reducing agrochemical dependence, improving resilience, and harnessing digital innovations while ensuring alignment with EU regulatory frameworks.

1.1 PROJECT OVERVIEW

The Nostradamus project, funded under the Horizon Europe Programme, aims to enhance food security and reduce dependency on agrochemical inputs across the European Union (EU). It aligns with key EU strategies, including the Farm to Fork Strategy (F2F), the Common Agricultural Policy (CAP), and the European Strategy for Data. The project emphasizes multi-actor collaboration to develop a scalable and robust digital platform for near-real-time data collection and analysis, supporting sustainable agricultural practices.

By integrating various datasets such as Copernicus Earth Observation (EO) data, Internet of Things (IoT) technologies, and open-access databases, Nostradamus seeks to provide actionable insights that improve the agricultural sector's sustainability, competitiveness, and resilience. The Data Cubes (DCs) are central to this initiative, which serves as one-stop shops designed to offer continuous support to stakeholders, empowering informed decision-making and effective policy development. The project employs cutting-edge technologies to promote an inclusive, data-driven approach that addresses key challenges, uncovers opportunities, and contributes to sustainable ecosystems and resilient communities. It strives to enhance agricultural productivity by developing edge, cloud, and mixed digital solutions while reducing input costs and mitigating environmental impacts, even in areas with limited connectivity infrastructure.

In addition, the project will strengthen administrative and monitoring capacities, making agricultural practices more efficient and transparent. With a commitment to ethical standards, gender sensitivity, and cultural inclusion, the Nostradamus Project ensures that its processes and outcomes are accessible to diverse user groups, paving the way for a more sustainable and equitable future.

1.2 DELIVERABLE OVERVIEW

The deliverable aims to set the ground for understanding the current and planned strategies aimed at achieving EU agricultural independence, enhancing food security, and utilizing digital solutions to create a more sustainable and resilient agricultural system. This deliverable maps the obstacles and strategies associated with the EU's agricultural independence and food security, focusing on the challenges arising from agrochemical dependency, fluctuating prices, and external trade pressures.

Digital agriculture plays a crucial role in this transition by employing digital techniques to harmonize and aggregate various databases while optimizing agricultural production through precision agriculture. The EU agriculture sector has undergone increasing digitalisation, driven by the need for data collection, assessment, synthesis, and utilization in CAP-related policymaking. However, the adoption of digital solutions in agriculture is hindered by key barriers, including limited infrastructure, lack of standardization, low digital literacy, concerns over data privacy, and high implementation costs. By analysing these obstacles and proposed strategies, such as nutrient management, precision agriculture, and organic farming, this deliverable aims to provide recommendations for strengthening the resilience and sustainability of EU food systems in line with EU-level strategies like the CAP, Green Deal, Farm to Fork Strategy, and REPowerEU.

This deliverable provides an overview of measures under the CAP that have so far made equivocal steps to meet its overarching goals of environmental sustainability, resilience, and food security. We examine how digitalisation interacts with the range of strategies within the CAP, as the drivers of digitalisation originate from various technologies outside the agricultural sector. This sector faces numerous farm size and structure challenges, raising legal and socio-ethical questions. This deliverable focuses on CAP strategies struggling to drive sustainable farming practices across the EU, particularly their impact on farmers and land managers.

We explore the objectives set forth by the European Green Deal, the Farm-to-Fork Strategy, and various other strategic policies and principles of good practice. This deliverable also situates the European context within the Sustainable Development Goals framework, with a particular emphasis on SDGs 2, 3, 4, 6, 12, and 15.

The review outlines various policy measures and approaches related to rapid technological advancements in big data analytics and cloud computing. It highlights that the collection and processing of data within the analysed policy framework is anticipated to bring significant changes to the roles of farmers, land managers, and other stakeholders involved in policymaking. The deliverable illustrates how various technological trends could influence the EU policy framework. It analyses the issues that need to be addressed in light of the forthcoming debate regarding the future of the CAP.

A comprehensive analysis of the EU legal and policy landscape examines various aspects of agricultural policy and related areas, including environment, health, and climate change. The deliverable also includes a clear list of priorities in digital agriculture for sustainability, resilience, and food security. These priorities include data and technology resource independence at the EU level, compatibility and interoperability of digital tools and databases, sustainability at the farm level and return on investment challenges, and the socio-economic impact of digitalisation on small-scale farms.

1.3 CHAPTER OVERVIEW

The structure of the Deliverable is as follows: Chapter 2 focuses on the policy landscape shaping agricultural independence and food security in the EU, providing an overview of relevnat frameworks, initiatives, and regulaory efforts. Chapter 3 addresses the mapping of obstacles and socio-economic challenges, while Chapter 4 presents scientific and strategic perspectives to support transition. Chapter 5 identifies priorities derived from current research, and Chapter 6 offers concluding remarks and a synthesis of the main findings.

2 POLICY LANDSCAPE FOR AGRICULTURAL INDEPENDENCE & FOOD SECURITY

2.1 ANALYSIS OF EU STRATEGIES & POLICIES

2.1.1 INTRODUCTION TO EU AND INTERNATIONAL STRATEGIES FOR FOOD SECURITY AND AGRICULTURAL INDEPENDENCE

The European Union has established several key strategies to promote agricultural sustainability, digital transformation, and food security.

These strategies made some initial steps to improve the resilience of the agricultural sector, reduce dependence on external agrochemical inputs, and integrate digital technologies to optimize production efficiency.

Table 1 provides an overview of the most relevant strategies and their contributions to food security and agricultural independence. This structured overview provides a foundation for the detailed discussion in the following sections, where each strategy's role in shaping EU agricultural policy is explored in depth.

TABLE 1: OVERVIEW OF EU AND INTERNATIONAL STRATEGIES FOR FOOD SECURITY AND AGRICULTURAL INDEPENDENCE

Strategy/Policy	**Key objectives**	**Relevance to food security and agricultural independence**
Common Agricultural Policy[1]	Support for farmers, sustainability, rural development	Encourages innovation, digital adoption, and resilient food production
European Green Deal[2]	Climate neutrality, biodiversity protection, sustainability	Calls for reducing environmental impact and promoting resource efficiency
Farm to Fork Strategy[3]	Sustainable food systems, pesticide reduction, fair trade	Aspires to promote resilient food production and reduce dependency on agrochemicals
Green Economy[4]	Circular economy, sustainable resource use	Supports sustainable agricultural practices and waste reduction
REPowerEU[5]	Energy independence, renewable energy in agriculture	Reduces reliance on fossil-fuel-based agrochemicals and enhances energy security
One Health & Resilience Pillars[6]	Integrated health approach for humans, animals, and ecosystems	Strengthens agricultural resilience to climate change and disease outbreaks

2.1.2 COMMON AGRICULTURAL POLICY

2.1.2.1 THE ROLE OF THE COMMON AGRICULTURAL POLICY

In 2023, a reframed format of the Common Agricultural Policy (CAP)[7] was launched in Europe, based on legislation from the European Commission's 2018-2020 mandate. This reform aimed to align EU agri-food systems with the land services needed by citizens, addressing the growing pressures on agricultural land use (Mottershead et al., 2018; European Commission, 2020; Schürings et al., 2024). The CAP is financed with a public budget of approximately 260 billion EUR. The focus has shifted from simple income support to implementing diverse measures that improve land services, particularly in response to increasing droughts and extreme weather events that threaten food

[1] https://agriculture.ec.europa.eu/common-agricultural-policy_en
2 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640&qid=1690884927805
3 https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf
4 https://www.unep.org/regions/asia-and-pacific/regional-initiatives/supporting-resource-efficiency/green-economy
[5] https://commission.europa.eu/publications/key-documents-repowereu_en
[6] https://www.who.int/health-topics/one-health#tab=tab_1
[7] https://agriculture.ec.europa.eu/common-agricultural-policy_en

security, alongside the priorities for natural resources associated with land management, ecosystems, biodiversity, the environment - soil, water, atmosphere, carbon and nutrient cycles, and greenhouse gases (Cooper et al., 2009; Poláková et al., 2022). Member States must strategically use funds through CAP Strategic Plans tailored to their land use. However, the funds specifically dealing with environmental protection cannot fully address sustainable land use, and CAP policies have been criticized for not sufficiently considering localized agronomic conditions affecting soil and the environment (Hessel et al., 2022).

Twenty years ago, in 2003/2004, the CAP was divided into two pillars. The first pillar provides farmers with flat-rate payments per hectare of land, independent of production. The second pillar focused on rural development and environmental protection through land-based measures. To qualify for Pillar 1 payments, farmers have to meet Good Agricultural and Environmental Condition (GAEC) standards, including soil conservation and water management. The 2014 reform introduced "greening" measures in Pillar 1, which included crop diversification and the protection of permanent grassland (Erjavec et al. 2015). However, crop diversification faced criticism from European auditors (ECA 2017). The current CAP has since introduced eco-schemes, enhancing greening measures for different land uses in each Member State. Pillar 1 payments, including eco-schemes, are annual payments fully funded by the EU budget, whereas Pillar 2 subsidies involve co-financed projects and environmental protection through land-based commitments (Poláková et al. 2024). Eco-schemes may involve measures for implementing precision agriculture techniques.

FIGURE 1. MAINTENANCE OF LANDSCAPE FEATURES

From left to right, GAEC 8 requires the maintenance of landscape features such as terraces and woody elements; GAEC 4 regulates water quality by banning the use of fertilizers and pesticides within a specified width alongside watercourses; and all GAECs seek to contribute to rural resilience.

Investments in land-based measures that support sustainability are considered essential for rural development in the EU (McAreavey, 2012). Pillar 2 agri-environmental schemes began in 1992 as a pilot program and became available to all member state farmers in 2004. By 2015, a goal was set to reduce greenhouse gas emissions from land use through these schemes (Barral et al., 2023). However, many scientists believe the CAP is not being effectively utilized, with Pe'er et al. (2020, 2024) highlighting a gap between the policy's goals and results on the ground.

With the advent of the new format termed "CAP Strategic Plans", the policy allows national or regional governments to implement investments and land-based measures through strategic plans and choose and suggest their own measures and specific objectives. One of the major changes under the Strategic Plans is that they cover measures of both Pillar 1 and Pillar 2. Another crucial aspect is that the Strategic Plans intend to support climate priority, although European Court of Auditors (2022) have been sceptical about the outcomes. The Regulation (EU) 2021/2015 on CAP Strategic Plans emphasizes the importance of tackling climate change in line with the Union's commitments to implement the Paris Agreement and the United Nations Sustainable Development Goals (SDGs). Therefore the Regulation emphasizes that "the CAP should contribute to mainstreaming climate action in the Union's policies and to the achievement of an overall target of 30 % of the Union's budget expenditures supporting climate objectives, while actions under the CAP are expected to contribute 40 % of the overall financial envelope of the CAP to the achievement of climate-related objectives". One needs to be careful in assessing the potential of the CAP Strategic Plans (ECA 2022). Further, if agricultural resilience and food security is prevailing priority, then sustainability aspects are not fully considered in the food provisioning services (La Notte et al., 2022).

The Regulation (EU) 2021/2115 further specifies the CAP's mandate to "foster a smart and resilient agricultural sector." Public funding should be directed towards investments in farm restructuring, modernization, innovation, diversification, and the adoption of new practices and technologies to enhance farmers' market rewards. This aligns with the CAP's objective of supporting the digital transition. Specifically, the CAP Strategic Plans promote the development of digital technologies in agriculture and rural areas. This objective can be accomplished through funding provided to Member States for the implementation of new technologies, such as area monitoring systems (AMS) and geo-spatial project applications. Furthermore, supporting precision agriculture techniques and initiatives aimed at digitizing rural life will benefit the broader community. AMS is a new provision under the CAP under the Regulation (EU) 2021/2115. AMS involves the regular and systematic observation, tracking, and assessment of agricultural activities and practices across agricultural areas using Copernicus Sentinel satellite data or other data of equivalent quality. AMS serves as a tool to enhance the efficiency of control and monitoring processes. Data obtained through AMS should be utilized to simplify on-the-spot checks at the farm level concerning all land-based payments and commitments.

2.1.2.2 HISTORICAL PERSPECTIVE: THE CAP'S EVOLUTION AND ITS IMPACT ON EU AGRICULTURE

Agricultural objectives in the EU have long focused on ensuring farmers receive a fair and stable income while protecting the environment, including land management, ecosystems, biodiversity, and various environmental components such as soil, water, and nutrient cycles. When the CAP was established in 1957/58, its primary aim was to support productivity, the purchase of equipment, seeds, fertilizers, and farm renewal. However, by the 1960s, concerns about sustainability, biodiversity, and ecosystems began gaining attention on the policy agenda.

The implementation of the CAP between 1960 and 1980 modernized the agricultural economy, reinforced production, and supported markets. However, this period also led to overproduction and significant negative impacts on landscapes, ecosystems, and environmental factors. In 1992, the McSharry reform shifted the emphasis towards ecosystems and sustainability. It sought to end market support, reduce overproduction, and establish mandatory environmental standards. This was accompanied by the Nitrates Directive, adopted in 1991, which became the first piece of European legislation specifically targeting agriculture.

The most significant CAP reform occurred in 2003/2004, introducing the “decoupling” principle, whereby Pillar 1 payments were no longer tied to production quotas. Additionally, compliance with environmental standards, such as Good Agricultural and Environmental Condition (GAEC), was mandated. While the CAP has undergone only minor adjustments over the past decade, climate protection has become one of its more recent priorities. In 2021, the policy introduced "eco-schemes" as part of direct payments under the CAP Strategic Plans, establishing new criteria for justifying funding. However, recent farmer protests led to simplification of legislation, which has weakened sustainability standards under GAEC.

FIGURE 2. SUSTAINABLE LAND MANAGEMENT LEFT – ADVERSE EFFECTS ON SUSTAINABILITY FROM LARGE FIELD BLOCKS; RIGHT – BUFFER ZONE TO PROTECT SOILS FROM EROSION AROUND A FIELD PLANTED WITH MAIZE

2.1.2.3 THE CAP AND GREEN ECONOMY

The Nostradamus project generates and utilizes multiple data sources, including Copernicus Earth Observation (EO) data, Internet of Things (IoT) sensor datasets, stakeholder-generated content, and AI-processed insights. Proper management of Intellectual Property Rights (IPR) and access permissions ensures that partners can collaborate effectively while protecting proprietary data.

Since 1972, when the Club of Rome published the book "Limits to Growth", it has become clear that our society is undergoing a major transformation that requires structural changes. (Meadows et al., 1972). The concept of "green transformation" evolved from two interrelated concepts: "green growth" and "green economy“. The "green economy" became more prominent in the EU agriculture after the 2003/2004 reform with the decoupling of direct payments from production and the reshaping of Pillar 1 as hectare subsidies. The „green economy“ captures the combination of economic and social realities aimed at strengthening knowledge base about land management, ecosystems, biodiversity, the environment - soil, water, atmosphere, carbon cycles, nutrients, and greenhouse gases.

The basic measure to shape the "green economy" under the CAP is the Good Agricultural and Environmental Condition (GAEC) standards. The standards have been mandatory since 2003/2004 and, hence, are applied on 100% agricultural land. Although these standards are rather basic, the wide coverage of agricultural land in the EU is their strength. GAECs continued the political tradition of guild standards, recommended codes of practice and became mandated to level the economic playing field for economic competition. Thus, GAEC standards became the ultimate metric of the subsidy system (Nowicki et al., 2009; OECD, 2008; OECD, 2012).

These are standards that are intended to contribute to sustainability both in terms of economics (at a reasonable cost to business) and environmental protection. Regulation (EU) 1782/2003 and Regulation (EU) 2021/2115 talk about "minimum" standards and also that GAEC topics should be defined in such a way that they are applicable within the farm, controllable in practical situations and should not conflict with local management norms. Effectiveness of GAEC needs to be studied in site-specific conditions (Borrelli et al. 2016). Recently, the simplification regulation has led to the weakening of the GAEC framework. The CAP transition to green economy also involves digitalisation of CAP management, monitoring and evaluation (Table 2).

TABLE 2: REQUIREMENTS FOR THE DIGITALISATION OF CAP MANAGEMENT, MONITORING AND EVALUATION

Requirements	Reference
Setting up electronic information systems for CAP	Article 130 of the CAP Strategic Plan Regulation (Regulation (EU) 2021/2115) relates to the purposes of monitoring and evaluation. Chapter II of the CAP Horizontal Regulation (Regulation (EU) 2021/2116) pertains to the integrated administration and control system. Several articles within the regulation address finance, management and control systems, as well as clearance and conformity procedures.
Setting up measures to reduce the administrative burden of the CAP and ensure simplification	Article 6 of the CAP Strategic Plan Regulation
Automatic claim system	Article 69 of the CAP Horizontal Regulation
Regular collection of the EU statistics mandatory for agricultural policies	Regulation (EU) 1217/2009 for Farm Accountancy Data Network (FADN) and its amendments
CAP strategies and measures to digitalise agriculture	Article 114 of the CAP Strategic Plan Regulation

Source: ITU & FAO, (2024)

Integrated Administration and Control System (IACS). According to Article 65 of the CAP Horizontal Regulation, each Member State is required to establish and operate an Integrated Administration and Control System. This system must be applicable to area- and animal-based interventions. Furthermore, it should be utilised, as necessary, for managing and controlling conditionality and interventions in the wine sector. In line with Article 66, the integrated system will include the following elements:

- an identification system for agricultural parcels;
- Integrated Administration and Control System (IACS)
- a geo-spatial application system and, where applicable, an animal-based application system;
- an area monitoring system;
- a system for the identification of beneficiaries of the interventions and measures referred to in Article 65(2) of the CAP horizontal regulation;
- a control and penalty system (ITU & FAO 2024).

Measures to reduce administrative burdens and ensure simplification. These measures are outlined in Article 6 of the CAP Strategic Plan Regulation. It states that Member States, with support from the European Commission, should implement appropriate actions to minimise administrative burdens and simplify the execution of the CAP.

Automatic claim system (pre-filled application). Article 69 of the CAP Horizontal Regulation allows Member States to establish an automatic claims system and determine whether it will cover area-based and animal-based interventions. If a Member State chooses to implement an automatic claims system, it must create a system that enables the administration to make payments to beneficiaries based on the information available in official digital databases.

Farm Accountancy Data Network and Farm Sustainability Data Network. The Farm Accountancy Data Network (FADN) is an important source of farm-level data essential for monitoring and evaluating the CAP. In November 2023, Regulation (EU) 2023/2674 transformed FADN into the Farm Sustainability Data Network (FSDN), broadening its scope to include environmental and social dimensions through harmonized farm identifiers. FADN collects physical, economic, and financial data of agricultural holdings, serving as a key resource for understanding the impacts of CAP measures. It is the only source of microeconomic data based on standardized book-keeping principles, relying on national surveys. Article 2 of Council Regulation (EC) No. 1217/2009 established FADN as a community network for collecting farm accountancy data. Member States, often with agricultural research institutes, are responsible for collecting, processing, and submitting this data electronically to the European Commission (ITU & FAO, 2024) .

CAP strategies and measures to digitalise agriculture. The CAP is increasingly favouring the transition to digital agriculture within the European Union. There are various CAP measures that can facilitate this transition, as defined in the three current Regulations for the CAP 2023 - 2027. One key requirement is the mandatory inclusion of a strategy for digitalisation in the CAP Strategic Plans, as specified in Article 114 of Regulation 2021/2115. To fulfil this policy requirement, Member States have the option to utilise various CAP interventions aimed at promoting digitalisation in agriculture, namely:

– ***Eco-schemes*** are basic measures for sustainability under Pillar 1 (Article 31 of R2021/2115), which may include options at the discretion of Member States, to support the precision agriculture. However, for financial compliance purposes, it has proved difficult to define criteria for a land-based precision agriculture eco-scheme, as precision farming is critically characterized by variable rates of application of fertilizers, rather than by any strict and controllable criteria. Thus far, only Belgium-Flanders, Italy and Sweden were able to define precision farming for eco-schemes (EC, 2024b);

– ***Farm advisory services*** on the use of digital technologies in agriculture and rural areas, as well as the use of a Farm Sustainability Tool for Nutrients from 2024 at the latest (Article 15 of R2021/2115);

– ***Investments***, for instance, in digital technologies in agriculture, forestry and rural areas, such as through investments in precision farming, smart villages, rural businesses and information and communication technology infrastructures, such as for broadband (Article 73 of R2021/2115);

– ***Knowledge exchange and dissemination of information*** (Article 78 of R2021/2115);

– ***Cooperation*** in the preparation and implementation of local development strategies and Smart Village strategies, as determined by the Member States (Article 77 of R2021/2115), including support to ***operational groups under European Innovation Partnerships (EIP)*** for innovative and digital solutions in agriculture (Article 127 of R2021/2115) and support also other forms of cooperation enabled by the use of digitalisation (ITU & FAO, 2024).

Member States are required to develop strategies to enhance digitalisation in agriculture and rural areas, as stated in Recital 85 of Regulation 2021/2115. These strategies should include actions and financial tools that go beyond CAP Strategic Plans and may cover areas such as research, innovation, education, and telecommunications. While there are no specific CAP guidelines for these strategies, the European Commission provided recommendations during the 2020 reform process on developing effective CAP Strategic Plans that incorporate digital technologies in agriculture and rural areas. The emphasis is on:

– The use of the European Union's digital and spatial infrastructure, and collaboration with Horizon Europe

– Increased effectiveness of knowledge flows and the uptake of applicable research and innovative solutions, as well as experience in the use of good agricultural practices

– Support of innovation in agriculture and other activities related to farming and rural areas (European Innovation Partnership, EIP-Agri)

– Support of smart specialisation strategies

– Development of the potential of the Integrated Administration and Control System (IACS)

Improvements to e-government and other administrative systems ((ITU & FAO, 2024).

2.1.2.4 DIGITAL AGRICULTURE AS A PRIORITY UNDER THE COMMON AGRICULTURAL POLICY

European Green Deal emphasized the digital transition, along with smarter and greener use of technologies, to help in climate-neutrality by 2050. This is among important objectives of the Green Deal. Technology can enhance energy and resource efficiency, promote a circular economy, improve resource allocation, and reduce emissions, pollution, biodiversity loss, and environmental degradation all of which are critical for maintaining long-term food security. By supporting shift to sustainable agricultural practices, digitalisation helps mitigate risks to food production caused by soil degradation, water shortages, and declining biodiversity, which are fundamental to EU food security. Additionally, digitalisation may strengthen agricultural independence by reducing dependence on external agrochemical inputs while ensuring stable food production. The technology sector must also prioritize the environmentally sound design and implementation of digital technologies.

In a state-of-the-art review of digital agriculture by European Parliament (2017), it is stated that digital data management is essential for ensuring data quality, accessibility, processing, and security in the agricultural sector, which continues to generate increasing volumes of data from various sources. This data plays a significant role in guiding decisions related to planting, fertilising, and harvesting, directly influencing agricultural productivity and food availability. Precision agriculture (PA) is characterised by an information-intensive approach that generates large amounts of valuable data, which can help optimize food production and reduce losses, thereby strengthening food security. Various stakeholders, including producers, data collectors, and data cooperatives, collaborate to collect and share this data, which often relies on site-specific information like maps and images. The use of drones equipped with advanced sensors has expanded aerial data collection, but it also raises considerations regarding privacy and data protection, alongside concerns about aerial use of agrochemicals. Importantly, not all agricultural data pertains to PA, which primarily benefits larger farms, hence there are specific challenges for small and large farmers and solutions related to digitalisation. Many other entities, including agricultural payment organizations and advisory services, are involved in digital data management and digitalisation. However, for small farmers, the high cost of digital tools, lack of access to necessary infrastructure, and technical expertise gaps pose barriers to adoption. Overcoming these challenges is essential to ensuring that all farmers, regardless of size, can contribute to food security and agricultural independence through digitalisation.

Authorities managing agricultural data for CAP payments face the challenge of overseeing a wide array of data, including geographical and regulatory information related to environmental and health standards, soil, animal welfare, food safety, climate change, and water management. Digital agriculture services have the potential to significantly enhance value and efficiency in implementing interventions through digitalisation, including cooperation, virtual producers' organisations, and rural services. By fostering more inclusive access to these digital tools, the EU can ensure that both large-scale and small-scale farmers benefit, ultimately reinforcing food security and reducing reliance on external agricultural inputs.

Farming practices increasingly rely on data. The rapid accumulation of data from individual agricultural operations and specific fields creates significant challenges for PA providers. The sheer volume and complexity of this data can easily exceed the capabilities of farmers and land managers in carrying out traditional analysis methods.

This influx of information, which includes everything from soil health metrics to crop yield statistics and weather patterns, requires advanced analytical tools and techniques to interpret effectively. Without the proper resources and strategies in place, farmers and land managers may struggle to extract meaningful insights, supporting their ability to make informed decisions that optimise agricultural productivity and sustainability.

Since food security depends on stable and efficient agricultural production, overcoming these data-related challenges is crucial to ensuring consistent food availability in the EU. For PA providers, creating treatment maps requires significant data collected from connected sensors, valves, and tractors, leading to the development of new data supply chains. As smart machines and sensors become more common on farms, farming practices will increasingly rely on data. Large quantities of various types of data are collected by drones, robots, and sensors. This data includes climate information, satellite imagery, digital photos and videos, transaction records, and GPS signals. The complexity arises from the fact that these technologies enable very detailed data capture. This data can, in principle, be shared using cloud technology and analysed with advanced techniques.

By linking and combining data from various sources—such as real-time nitrogen sensors and GPS-connected prescription maps—farms generate a wide range of data that can be categorised into several types. These include agronomic data, financial data, compliance data, meteorological data, environmental data, machine data, staff data, personal data, and operational data. Operational data encompasses employee data, usage data related to inputs like fertilisers, and other mapping, sensor, and related data that are necessary for operations. This also includes raw data, field data, and experimental data (European Parliament, 2017). Ensuring the integrity and accessibility of such data is vital for maintaining food security by enhancing farm productivity and resource efficiency while minimizing waste and environmental impact. By addressing digital inclusion and ensuring that data-driven advancements are accessible to farms of all sizes, the EU can strengthen both agricultural independence and food security in the long term.

2.1.3 EUROPEAN GREEN DEAL

The European Green Deal is a comprehensive plan to make Europe carbon-neutral by 2050 (Wolf et al., 2021; Kotyza et al., 2024). It addresses climate change and environmental degradation through policies aimed at significantly reducing greenhouse gas emissions. In response, EU member states and the parliament have adopted a detailed agenda that includes measures focused on renewable energy, energy efficiency, greening of agriculture, sustainable transportation, and the circular economy. A key goal is to cut carbon emissions by 55% by 2030 compared to 1990 levels (Sikora, 2021). Achieving this requires cooperation among all member states, government bodies, industries, and citizens. The Green Deal also sought to enhance sustainability in agriculture, ensuring food security while reducing dependence on agrochemicals through greener farming practices, biodiversity protection, and digital transformation (Fayet et al., 2022; Schebesta et al., 2020; Boix-Fayos et al., 2023).

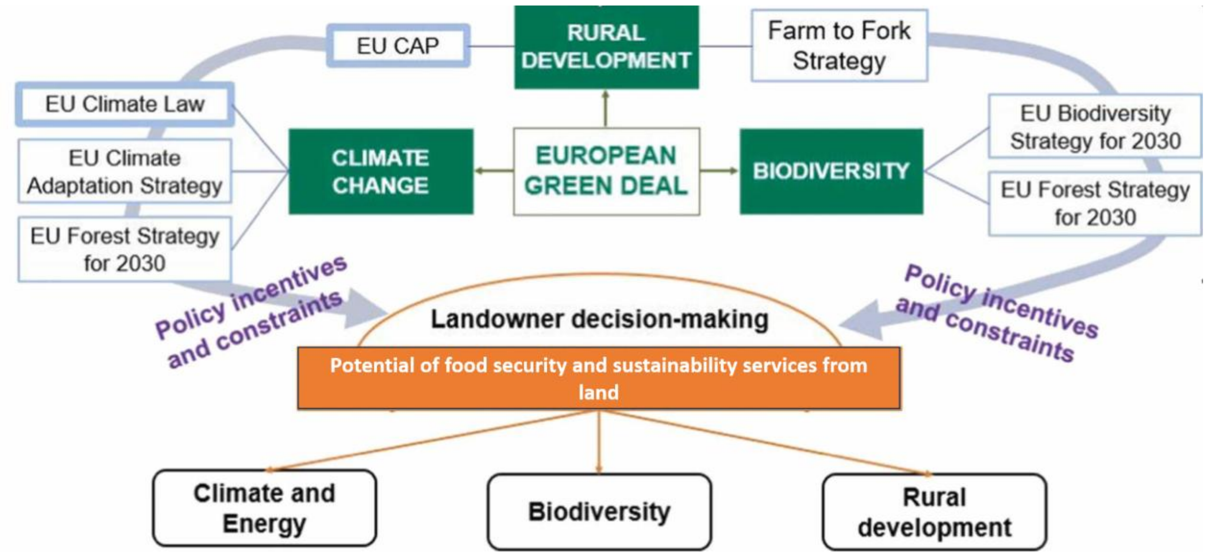

FIGURE 3: AN OVERVIEW OF EUROPEAN GREEN DEAL AND THE POSITION OF THE CAP AND FARM TO FORK STRATEGY. SOURCE: FAYET ET AL., 2022

Key areas of the Green Deal include two foci for agriculture:

- greening the Common Agricultural Policy through 'Farm to Fork' Strategy that addresses enhancing sustainability in agriculture and food systems
- conservation and protection of biodiversity by 2030

Several policies within the European Green Deal contribute to these goals by addressing different aspects of sustainable agriculture, food security, and environmental resilience. The Farm to Fork Strategy focuses on making food systems more sustainable by reducing the use of fertilizers, pesticides, and antimicrobials while promoting organic farming and improving food production methods. The Zero Pollution Action Plan and the EU Chemicals Strategy for Sustainability are designed to minimize harmful chemical inputs, of importance also in agriculture, by regulating pesticide use, promoting safer alternatives, and reducing contamination in soil and water. Similarly, the Circular Economy Action Plan promotes resource efficiency, which could help reduce agricultural waste, boost recycling to improve the sustainability of the food chain and support sustainable material usage (**Error! Reference source not found.**).

The EU Biodiversity Strategy for 2030, which aims to restore natural ecosystems, support pollinato rs, and include agroecological methods that lessen dependency on chemical inputs, makes biodive rsity protection another top priority. Given the increasing threats posed by climate change, the EU Strategy on Adaptation to Climate Change aims to ensure resilience in farming by promoting climate-smart agricultural practices such as water conservation, drought-resistant crops, and precision agriculture. Moreover, by encouraging monitoring, erosion prevention, and regenerative land management techniques to reduce reliance on synthetic fertilizers, the Directive on Soil Monitoring and Resilience highlights soil health, which is crucial for sustainable food production.

In order to enhance sustainability, the Green Deal also uses big data, artificial intelligence, and cutting-edge agricultural technologies. To monitor crop and soil health, optimize resource utilization, and lessen reliance on external inputs, digitization is essential. Digital tools help reduce costs, increase productivity, and promote more sustainable food production methods by increasing efficiency throughout the agricultural value chain. Despite not having legal force behind it, the Green Deal framework impacts policies and shapes futures that member states forecast (Sikora, 2021; Solanke, 2022). The Green Deal aims to transform European agriculture into a more resilient, independent, and environmentally conscious system by integrating sustainability, food security, and digital innovation. The following table summarizes the key policies under the Green Deal and their specific contributions to food security and reducing dependence on agrochemicals (**Error! Reference source not found.**).

TABLE 3:KEY POLICIES OF THE EUROPEAN GREEN DEAL AND THEIR ROLE IN FOOD SECURITY AND REDUCING AGROCHEMICAL DEPENDENCE

Strategy/Policy	**Key objectives**	**Relevance to food security and agricultural independence**
Zero Pollution Action Plan[8]	Minimize pollution in water, air, and soil, with a focus on reducing harmful chemicals	Aims to reduce agrochemical usage by regulating pesticides and promoting safer, sustainable alternatives.
EU Chemicals Strategy for Sustainability[9] [10]	Promote the use of safer chemicals and reduce harmful substances in agriculture.	Focuses on reducing harmful agrochemicals, improving the sustainability of inputs in agriculture.
Circular Economy Action Plan[11]	Encourage sustainable production and consumption through recycling, reuse, and reducing waste.	Promotes the recycling of agricultural waste and the efficient use of resources, reducing the need for chemical inputs.
EU Biodiversity Strategy for 2030[12]	Protect biodiversity, restore ecosystems, and ensure that agricultural practices are ecologically sustainable.	Supports pollinators and ecosystems that are vital for sustainable food production, reducing the reliance on chemical inputs.
EU Strategy on Adaptation to Climate Change[13]	Enhance the resilience of agriculture to climate change impacts.	Promotes water conservation, drought-resistant crops, and precision agriculture, helping to reduce the need for external inputs.
Directive on Soil Monitoring and Resilience[14]	Improve soil health and monitor land resilience against environmental pressures.	Ensures healthy soil, reducing the need for synthetic fertilizers and improving long-term agricultural productivity.

[8] https://environment.ec.europa.eu/strategy/zero-pollution-action-plan_en
[9] https://environment.ec.europa.eu/strategy/chemicals-strategy_en
[10] https://echa.europa.eu/hot-topics/chemicals-strategy-for-sustainability
[11] https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en
[12] https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en
[13] https://climate.ec.europa.eu/eu-action/adaptation-climate-change/eu-adaptation-strategy_en
[14] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0416&qid=1706624227744

2.1.4 FARM TO FORK STRATEGY

The Farm to Fork Strategy engages farmers and land managers to make a significant transition in agricultural practices by maximizing the social and economic benefits of climate action. The Strategy highlights the importance of addressing the challenges of shaping the food chain in a way that works for consumers, producers, climate and the environment, ensuring sustainable food production, and ensuring food security (European Commission, 2020).

Specific changes proposed in the strategy include stricter regulations on the use of pesticides, nutrients and feed additives to promote safer food production and reduce environmental impacts. It also updates animal welfare protocols to ensure ethical and sustainable treatment of livestock. Among the key components, there is also the Carbon Farming Initiative, which encourages farmers to adopt practices that improve carbon sequestration and soil health.

Implementing these changes poses significant challenges for the farming and supply sectors. Farmers must adapt to new regulations and practices, requiring substantial investments in training and technology, including digitalisation. The reforms aim to transform agricultural practices in Europe, altering food production and consumption. Consequently, stakeholders must navigate these challenges while complying with the Farm to Fork Strategy.

The Farm to Fork strategy encompasses four areas of action: (i) use of pesticides; (ii) nutrient management and use of fertilizers; (iii) feed additives and (iv) organic farming.

(i) The use of pesticides contributes to pollution in soil, water, and air. The Farm to Fork Strategy aims to reduce soil pollution by cutting chemical pesticide use by 50% by 2030. This objective was included in the Proposal for the Sustainable Use of Pesticides but was blocked by the European Parliament in December 2023. The blockage was due to protests from farmers and land managers, as well as from Member States that had already made significant reductions in pesticide use. For instance, Czechia reduced its pesticide use by 38% over the decade leading up to 2021. Achieving an additional 50% reduction was considered unrealistic for these early adopters. Following the European Parliament's decision, Commission President Von der Leyen announced in February 2024 that the Commission would retreat from the quantitative goal and instead allow Member States to develop their own plans for pesticide reduction as they see fit.

(ii) The presence of excess nutrients in the environment is a significant contributor to pollution in the air, soil, and water, negatively impacting biodiversity and climate. The Farm to Fork Strategy aims to reduce the use of fertilizers by 20% by 2030 and to decrease nutrient losses by at least 50%.

(iii) Antimicrobial resistance linked to the use of feed additives is a significant factor in premature health decline. Farm to Fork Strategy calls for reduction in the use of feed additives for livestock and aquaculture by 50%.

(iv) Organic farming is considered by the Farm to Fork Strategy with the aim of at least 25 % of the EU's utilised agricultural area to be organically farmed by 2030.

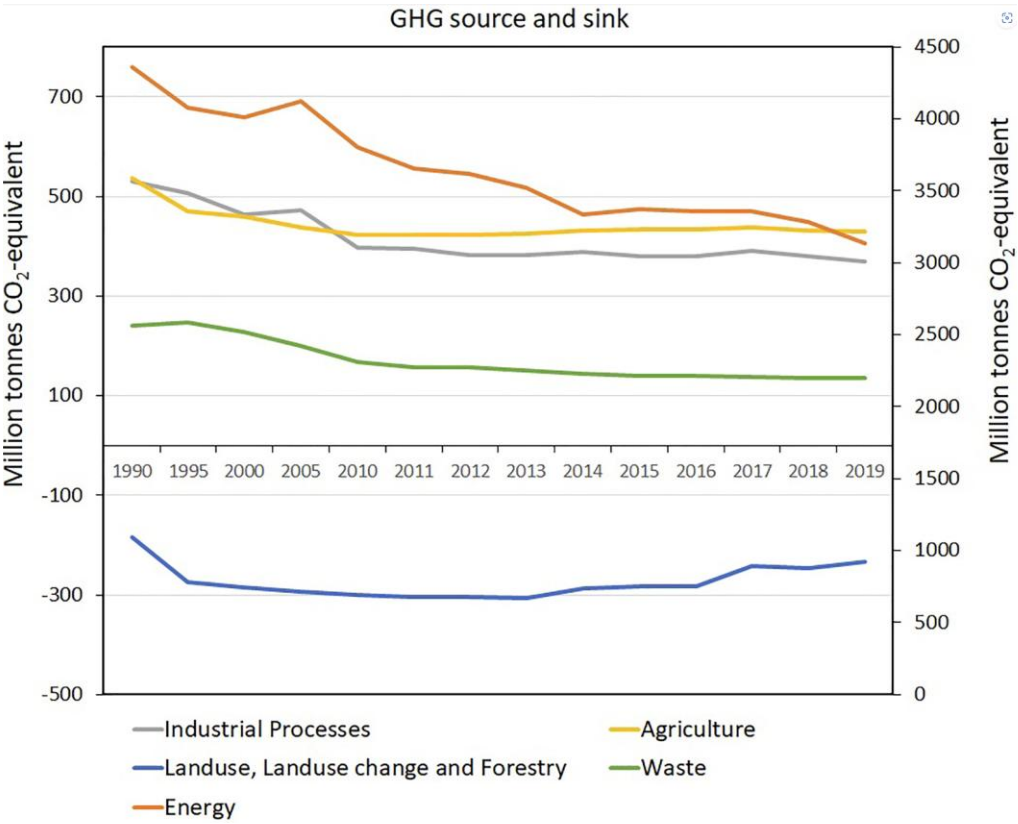

FIGURE 4: GREENHOUSE GAS EMISSIONS AND SINKS ASSOCIATED WITH AGRICULTURE, FROM 1990 TO 2019. SOURCE: EUROSTAT, 2024

The Farm to Fork strategy is the instrument for the farming sector to address decarbonization. Agriculture in the EU is responsible for greenhouse gas emissions (nitrous oxide and methane) that over the past thirty years were in a declining trend, but recently plateaued, and currently are at levels comparable to Energy use (Figure 4). On the other hand, agriculture has the potential to remove carbon dioxide from the atmosphere by sequestering carbon in soils. Carbon farming is the method of building up on the carbon sequestration potentials of different soil management practices and is linked to the EU´s commitment to carbon neutrality in 2050, as well as the knowledge base about atmosphere, carbon and nutrient cycles and greenhouse gases. While carbon farming is an opportunity for a carbon-conscious approach to agriculture, the Green Deal proposal to reduce greenhouse gases by 90 % by 2040 has been revised after farmers´ protests and the passage on agriculture has been removed from the section. Further evolution of decarbonization in agriculture will be influenced by the new European Parliament.

2.1.5 REPOWER EU AND ITS ROLE IN AGRICULTURE AND DATA DRIVEN DECISION

The European Commission has revealed the REPowerEU (Figure 5) Plan, a strategic response to the disruptions caused by Russia's invasion of Ukraine. REPowerEU aims to rapidly reduce EU dependence on Russian fossil fuels by accelerating the clean energy transition, strengthening energy security, and achieving a more resilient Energy Union.

The REPowerEU Plan, while broadly focused on reducing reliance on fossil fuels and addressing climate change, has significant implications for agriculture. Agriculture, a highly energy-intensive sector, heavily depends on fossil fuels for machinery, irrigation, and heating. This makes it vulnerable to fluctuations in energy prices but also provides an opportunity for transformation through REPowerEU's emphasis on sustainable practices and renewable energy adoption. By collaborating as a Union, Europe can expedite the phase-out of Russian energy dependency, a goal supported by 85% of Europeans who advocate for a swift reduction in reliance on Russian gas and oil to show solidarity with Ukraine.

The REPowerEU Plan outlines measures such as energy conservation, diversification of energy supplies, and the accelerated deployment of renewable energy to replace fossil fuels across homes, industries, and power generation sectors. This transition will enhance economic growth and energy security while bolstering climate action within Europe and among its global partners. The Recovery and Resilience Facility (RRF)[15] is central to coordinating the planning and financing for cross-border and national energy infrastructure projects and reforms.

As part of the REPowerEU initiative, agriculture will undergo a significant energy transition, shifting away from fossil fuel dependency toward more sustainable practices. Agriculture's reliance on fossil fuels for machinery, irrigation, and heating makes it an ideal sector for transformation.
The overarching aim of these initiatives is to effect a structural transformation of the EU's energy system. Achieving this objective requires robust coordination across several dimensions: harmonizing European regulatory and infrastructure measures, aligning national investments and reforms, and fostering cohesive energy diplomacy[16].

[15] https://commission.europa.eu/business-economy-euro/economic-recovery/recovery-and-resilience-facility_en
[16] https://commission.europa.eu/publications/key-documents-repowereu_en

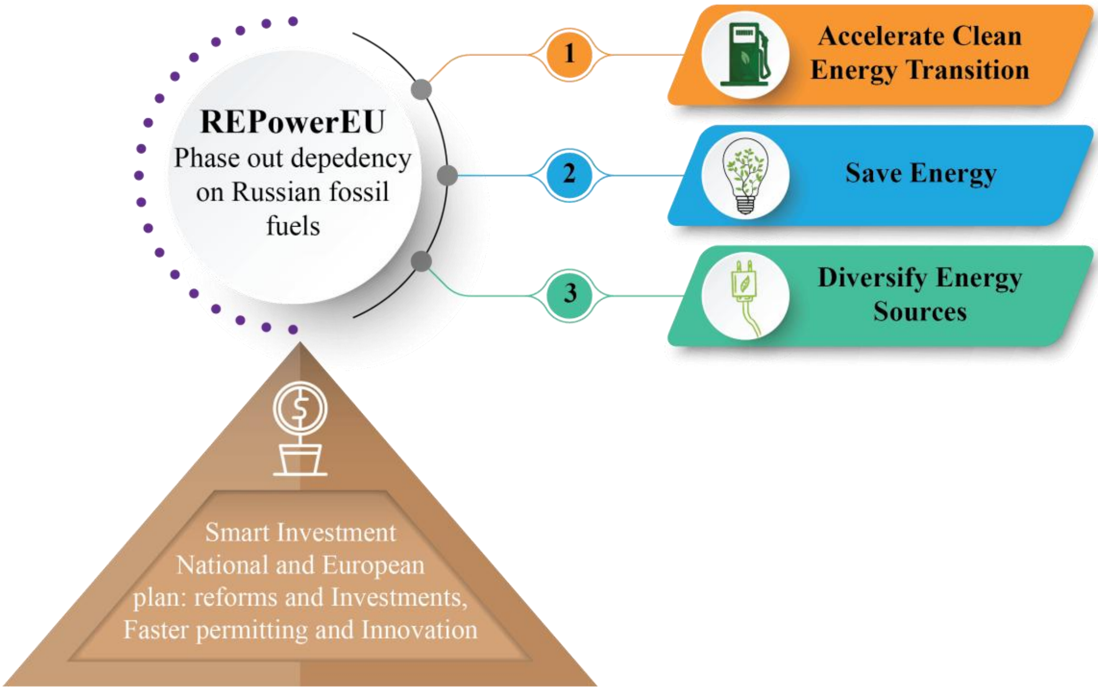

FIGURE 5. REPOWEREU PLAN. SOURCE: OWN GRAPHICS BASED ON EUROPA COMMISSION REPOWER EU PLAN

2.1.5.1 ENERGY TRANSITION IN AGRICULTURE

Agriculture is one of the most energy-intensive sectors, heavily reliant on fossil fuels to use agri-tolls, machinery, irrigation systems and heating, which increases greenhouse gas emissions and makes the sector vulnerable to fluctuations in energy prices. Although agriculture accounts for approximately 2–3% of the EU's total final energy consumption, its dependence on fossil fuels is particularly high compared to other sectors, emphasising the need for a transition to more sustainable energy practices. REPowerEU aims to promote sustainable and efficient alternatives to energy use in agriculture.

Using renewable energy sources on farms is one of the key strategies that reduces the dependency on fossil fuels while lowering operational costs for farmers. Additionally, REPowerEU promotes precision agriculture technologies, which leverage real-time monitoring and data-driven decision-making to optimize energy and water consumption. This approach conserves resources while increasing efficiency. Another important objective is supporting the production and use of biomethane, with an ambitious target of 35 billion cubic meters (bcm) by 2030.

2.1.5.2 DATA DRIVEN DECISION MAKING AND POLICY DEVELOPMENT

REPowerEU emphasizes the critical role of data aggregation and digitalisation in monitoring energy usage and optimizing resource allocation within the agricultural sector to achieve its energy transition goals. By integrating real-time data and predictive analytics into farming operations, REPowerEU aims to not only improve energy efficiency but also optimize resource allocation, helping farmers make smarter decisions about energy use, water conservation, and crop management. This data-driven approach is central to ensuring sustainability and resilience in agriculture under the energy transition.

One of its key aspects is smart energy management, where digital platforms will track energy consumption across farms, providing valuable insights that help policymakers set efficiency targets and allocate subsidies more effectively. This data-driven approach ensures that resources are directed where they are needed most, promoting cost savings and sustainability.

Climate and yield data integration will also play a crucial role in adapting agricultural practices to shifting environmental conditions. Improved weather modelling and soil monitoring technologies will enable farmers to plan their crops more effectively, ensuring resilience against climate change while optimizing energy use.

Furthermore, energy audits and forecasting will help farms and agribusinesses minimize energy waste and better integrate renewable energy sources into their operations. Through predictive analytics, businesses can anticipate energy demands, streamline their supply chains, and make informed decisions about adopting sustainable energy solutions.

2.1.5.3 POLICY SHAPING AND THE ROLE OF DATA AGGREGATION

REPowerEU aligns with agricultural policies by fostering data-sharing mechanisms between farmers, policymakers, and research institutions to support evidence-based policy design. The REPowerEU initiative fosters data-sharing mechanisms among farmers, policymakers, and research institutions, enabling more targeted and efficient policy development. This collaboration ensures that subsidies, tax incentives, and renewable energy adoption strategies are aligned with the specific needs and circumstances of farmers, ultimately driving energy transition and improving the sustainability of agriculture.

The RRF works with REPowerEU to fund energy transition projects in agriculture, with some assistance from the CAP. These financial instruments support the adoption of renewable energy and energy-efficient technologies. These mechanisms provide the strategic application of incentives and subsidies for adopting renewable energy, such as tax adjustments for low-carbon energy and grants for energy-efficient equipment, by leveraging data insights to enable more successful policy decisions. Ultimately, these data-sharing projects assist a more sustainable and energy-independent EU agriculture sector by enabling more accurate tracking of energy efficiency advancements and integrating renewable energy into agricultural systems. By integrating renewable energy solutions and leveraging data-driven insights, REPowerEU has the potential to transform agriculture into a key player in Europe's energy transition, ensuring both environmental sustainability and economic resilience in the sector.

2.1.6 KEY GOALS: SUSTAINABILITY, FOOD SECURITY, AND RESILIENCE IN AGRICULTURE

The European Union's strategic frameworks, such as the European Green Deal, the Farm to Fork Strategy, REPowerEU, and the CAP, should have guided the shift to secure, resilient, and sustainable agricultural systems. It remains to be seen how effective the programs will be in the short term and the medium term, as there are signs to exercise caution. These programs were proposed to address the interrelated issues of food security, biodiversity loss, and climate change, in order to strengthen the EU's ability to guarantee long-term food security and support resilient agricultural systems in the face of new challenges. The following sections look at important frameworks, such as the resilience pillars, sustainability practices, and specific policy actions.

2.1.6.1 ONE HEALTH AND FOUR RESILIENCE PILLARS

Central to the European Green Deal, the European Commission's strategies on biodiversity, zero pollution, and the farm-to-fork approach aim to create a better balance between human health, food systems, and ecosystems, acknowledging their interdependence. In the coming decade, Europe will invest billions of euros in research and innovation to transition to safe and sustainable food systems (Bronzwaer et al., 2022). EU researchers can play a crucial role in advancing the European research agenda by uniting their expertise to inform policymakers. Traditionally, EU research has addressed human, animal, plant, and ecosystem health separately. However, it is essential for researchers to adopt a One Health approach. There is an urgent need to define transdisciplinary research requirements and develop a One Health research agenda, supported by governance at the national and EU levels.

One Health is an integrated approach that aims to balance and enhance the health of people, animals, and ecosystems. By linking these elements, One Health addresses disease control from prevention to management and supports global health security. This framework can be applied at various levels—from community to global—and relies on effective governance, communication, and collaboration. It helps individuals understand the co-benefits, risks, and opportunities for developing equitable and holistic solutions.

As digitalisation continues to accelerate, the WHO (2022) emphasises the importance of considering public health perspectives in digital food environments. There is a negative correlation between the digital marketing of unhealthy food products and areas that promote health and well-being.
Addressing this is key for achieving the Sustainable Development Goals, particularly SDG 3 which aims to ensure healthy lives and promote well-being for everyone at all ages. This priority is also reflected in the European Programme of Work 2020–2025: United Action for Better Health.
The four pillars of agricultural resilience rely on nature-based management options. These pillars include: land management, resource management, human interface and ecosystem interface.

Land management is a fundamental pillar of nature-based agriculture that includes principles of crop management, such as minimum soil disturbance (no-tillage), maintaining permanent soil cover through crop residues or cover crops, and implementing crop rotation. Several agronomical practices fall under the land management pillar including agro-forestry, intercropping, crop rotations, tillage management, and landscape management. Land management involves soil science, creative solutions to common agricultural challenges and policymaking (Shelef et al., 2018).

Resource management emphasizes the principles of low external input farming. It involves managing inputs such as energy, water, and nutrients, along with practices to combat pests, weeds, and pathogens. Key actions include enhancing water conservation and storage techniques, promoting the use of drought-tolerant crop species, implementing low-volume irrigation systems, and managing crops and land to minimize water loss and reduce overall water requirements (Shelef et al., 2018).

Human interface is a pillar directly connected to the One Health concept. Consumers are demanding initiatives to reduce pollution in the air, soil, and water, as well as to address socioeconomic issues in food production, with a strong focus on human health and well-being. This demand is influenced by personal values, culture, norms, and habits (Shelef et al., 2018).

Ecosystem interface is a pillar focusing on the reduction of the impacts on biodiversity by preserving ecosystem services, protecting wildlife, and supporting animal livelihoods. To address these issues, interventions include selecting species and varieties that are well-suited to the local environmental conditions, diversifying crops (including livestock), and implementing cultural practices to enhance both the biological diversity and economic stability of the farm.
The transition toward One Health and agriculture based on the four pillars of resilience would possibly focus on two main priorities: 1) increased use of nature-based agriculture such as precision and organic farming, and 2) a shift towards sustainable diets. This requires a coordinated approach that aligns production and consumption, backed by improved institutional capacities, research and advisory. Policymakers must address farmers' declining economic conditions and provide the necessary knowledge and support for adopting alternative practices.

2.1.6.2 SUSTAINABILITY

The European survey on citizens' views regularly explores opinions on the CAP and agriculture. According to the results from the 2022 survey, citizens generally share a similar perspective on the CAP's role in promoting the sustainable management of natural resources. The survey included 1,000 respondents from each Member State, who expressed varying levels of agreement or disagreement with the relevant statement. The data presented in Figure 6 indicates that 70% of citizens (and 63% in Northern countries, 73% in Southern countries, 69% in Central and Eastern Europe, and 76% in North-Western Europe) agree with ascribing the goal of sustainable management to the CAP. This survey highlights that CAP reforms are essentially driven not only by farmers and land managers whose interests are mainly to retain the direct income support from public funds but also are influenced by societal priorities with regard to sustainability, which in turn places pressure on policymakers and land managers (Eurobarometer, 2022).

QA8.8 Do you agree or not that the Common Agricultural Policy (CAP) contributes to...?
Ensuring sustainable management of natural resources (%)

	Totally agree		Tend to agree		Tend to disagree		Totally disagree		Don't know	Total 'Agree'		Total 'Disagree'	
	Feb/Mar 2022	Diff. Feb/Mar 2022 - Aug/Sep 2020	Feb/Mar 2022	Diff. Feb/Mar 2022 - Aug/Sep 2020	Feb/Mar 2022	Diff. Feb/Mar 2022 - Aug/Sep 2020	Feb/Mar 2022	Diff. Feb/Mar 2022 - Aug/Sep 2020	Feb/Mar 2022	Feb/Mar 2022	Diff. Feb/Mar 2022 - Aug/Sep 2020	Feb/Mar 2022	Diff. Feb/Mar 2022 - Aug/Sep 2020
EU27	25	0	45	0	17	-1	3	-1	10	70	0	20	-2
BE	24	-5	49	12	19	-8	5	1	3	73	7	24	-7
BG	25	3	42	4	13	-3	4	-2	16	67	7	17	-5
CZ	22	2	47	-1	22	6	3	-1	6	69	1	25	5
DK	21	1	40	-2	25	6	6	1	8	61	-1	31	7
DE	20	-1	43	-2	23	1	6	1	8	63	-3	29	2
EE	19	1	51	-2	19	-6	2	-1	9	70	-1	21	-7
IE	33	10	50	-2	5	-18	1	-1	11	83	8	6	-19
EL	14	-3	51	3	24	1	3	0	8	65	0	27	1
ES	21	-3	46	6	14	-11	4	1	15	67	3	18	-10
FR	14	-6	37	0	24	2	6	-1	19	51	-6	30	1
HR	31	3	56	3	10	-5	1	0	2	87	6	11	-5
IT	40	7	46	-2	8	-2	0	-2	6	86	5	8	-4
CY	32	-4	46	2	12	3	2	1	8	78	-2	14	4
LV	25	3	47	3	20	3	2	-2	6	72	6	22	1
LT	18	3	53	-2	14	-2	3	2	12	71	1	17	0
LU	26	-7	50	8	16	-5	4	0	4	76	1	20	-5
HU	36	-3	48	4	11	1	2	0	3	84	1	13	1
MT	49	10	39	3	6	-1	1	0	5	88	13	7	-1
NL	34	-1	43	6	16	-5	2	-1	5	77	5	18	-6
AT	21	-8	48	4	18	1	5	1	8	69	-4	23	2
PL	31	2	55	0	7	-1	1	-1	6	86	2	8	-2
PT	24	-4	49	-1	6	-2	1	1	20	73	-5	7	-1
RO	32	-1	44	5	16	-3	2	-1	6	76	4	18	-4
SI	27	1	46	3	18	-1	3	-2	6	73	4	21	-3
SK	28	12	46	-9	15	-3	3	0	8	74	3	18	-3
FI	12	1	56	0	23	-7	3	1	6	68	1	26	-6
SE	17	0	46	0	25	-6	5	0	7	63	0	30	-6

FIGURE 6. CITIZENS VIEW ON SUSTAINABILITY AS THE CAP PRIORITY. SOURCE: EUROBAROMETER (2021)

Sustainability is the goal primarily associated with the baseline standards under CAP Pillar 1, and agri-environment schemes under CAP Pillar 2. The Good Agricultural and Environmental Conditions (GAEC)[17], referring to a set of environmental protection standards that have been in place since 2003. The GAEC framework consists of "a set of standards aimed at achieving sustainable agriculture" (Regulation (EU) 2021/2115). Maintaining soil in good agricultural and environmental condition is closely linked to several critical issues, such as minimum maintenance levels, water conservation and management, soil erosion prevention, soil organic matter preservation, and soil structure. It is imperative that European farmers who receive basic income direct payments or support for rural development must comply with these standards (Eurostat, 2021). Currently, it is concerning that

[17] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Good_agricultural_and_environmental_conditions_(GAEC)

under pressure from farmers, GAEC standards have undergone simplification that reduces the benchmarks.

On the scale of Europe, GAEC has set a baseline for the funding of the budget of Heading 2 of the EU Multiannual Financial Framework 2021-2027 - Sustainable Natural Resources. The relevant expenditure consisted of the line for Basic Income Support for Sustainability (EUR 40 368 billion) and the line for Rural Development (EUR 15 345 billion). In total, the items accounted for 96.3 % of the final budget of Heading 3 - Natural Resources and Environment 2021-2027. The remaining expenditure was applied to Pillar 1 market interventions, Horizon 2020 scientific and research support, assistance to EU pre-accession candidates and administrative support.

In the post-2021 planning period, there are twelve GAEC standards. Four of these standards specifically focus on soil health: GAEC Standard 3 (maintaining soil organic matter levels), GAEC Standard 5 (minimum soil management reflecting site-specific conditions to protect against erosion), GAEC Standard 6 (minimum soil cover), and GAEC Standard 7 (crop rotations). Additionally, two other GAEC standards also relate to soil health: GAEC 8 (retaining landscape features, including any hedgerows, ponds, ditches, tree planting, trees in groups or isolation, field margins and terraces) which can help to reduce soil in the landscape, soil erosion and maintaining/improving soil organic matter content and GAEC Standard 4 (establishing riparian buffers along watercourses) which, in addition to helping to reduce water pollution, can also help to protect soil along watercourses. These standards collectively aimed to enhance soil health and environmental sustainability. Currently, simplification legislation weakens the mandatory status of these measures.

2.1.6.3 POLICY MEASURES FOCUSING ON SUSTAINABILITY

Since the 2003/2004 reform of the CAP, there has been a noticeable shift in public funding from Pillar 1 direct income payments to farmers towards Pillar 2 rural development policy aimed at promoting sustainability and resilience. Direct income payments still retain the bigger part of the budget. **Error! Reference source not found.** provides an overview of some of the Pillar 2 measures. In particular, agri-environment payment schemes were intended to support the sustainability goals under Pillar 2 (ECA 2011). These schemes are designed to encourage practices that improve soil health, enhance biodiversity, and protect water resources. They also have more rigorous requirements than the basic standards (Hasler et al., 2022).

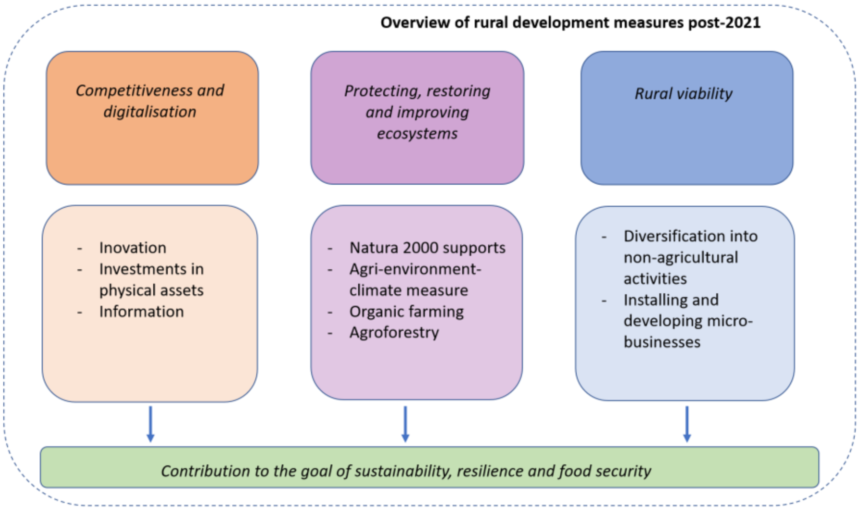

FIGURE 7: OVERVIEW OF REGULATORY MEASURES UNDER CAP PILLAR 2 IN POST-2021. THE MEASURES PROVIDE SUBSIDIES ON A PROJECT BASIS AND ARE VOLUNTARY TO END USERS. EMPHASIZED ARE SUBSIDY MEASURES WITH EFFECT ON SUSTAINABILITY, RESILIENCE AND FOOD SECURITY. SOURCE: POLÁKOVÁ ET AL., 2020, BASED ON REGULATION (EU) 1305/2013[18]

The agri-environment schemes are mandatory for Member States who must introduce them in CAP Strategic Plans and offer a range of agri-environment payments to farmers. However, the adoption of agri-environment payments is optional to farmers, as they adopt the schemes, when it suits their land management plan, as a multiannual contract with the government. While GAEC standards are applied on 100% of agricultural area, agri-environment schemes are applied on 3.5% to 12.4% of agricultural area (when focusing on water and soil priorities). **Error! Reference source not found.** shows the share of agricultural area under basic standards, compared to agri-environment schemes.

[18] https://eur-lex.europa.eu/eli/reg/2013/1305/oj/eng

TABLE 4: SHARE OF AGRICULTURAL AREA UNDER BASIC STANDARDS AND AGRI-ENVIRONMENT SCHEMES

	GAEC Standard (% OF AREA)	Agri-environment practice (% OF AREA)	
		AREA OF WATER	AREA OF SOIL MANAGEMENT
CZECH REPUBLIC	100	11.38	12.41
HUNGARY	100	3.57	8.39
POLAND	100	7.85	10.44
SLOVAKIA	100	9.61	11.43

Source: Poláková et al., 2022

In croplands, agri-environment schemes typically offer two levels of soil health and nutrient management, each serving distinct and important roles. The first level utilizes generic options aimed at encouraging a large number of farmers to implement soil health and nutrient management practices. This includes maintaining unfarmed features such as hedges, field margins, trees, ponds, banks, terraces, ditches, as well as allowing in-field fallow areas and stubbles to remain without fertilizers and pesticides over winter.

These options go beyond GAEC standards, which means that the specific options available under agri-environment schemes may differ across regions, depending on the stipulations outlined in the GAEC standards. The main effect of generic options under agri-environment schemes tends to benefit soil health and quality, e.g. through two-varieties of catch and cover crops.
The second level of soil health and nutrient management can offer management options that are more geographically targeted and tailored to local conditions, aiming to enhance particular soil types and address nutrient loss issues. Some schemes have been notably effective in increasing soil organic matter and preventing soil compaction.

However, the success of these initiatives varies based on location and geographic scale. In certain cases, mixed effectiveness at the regional level may arise because the combination of management practices does not sufficiently meet the pedo-climatic and ecological needs of the soils (Canessa et al., 2024). The agri-environment schemes that aim at improved soil health and nutrient management typically include management actions listed as follows:

- Input reduction to reduce nutrient and pesticide run-off, e.g. no spray zones within arable fields;
- Soil management (minimum or no tillage, green winter cover and catch crops, over-winter stubbles, green cover);
- Introducing or maintaining organic farming practices;
- Introducing or maintaining integrated management;
- Establishment or maintenance of riparian buffer strips;
- Establishment of field margins;
- Maintenance of landscape features;
- Introducing or maintaining extensive arable management;
- Introducing or maintaining extensive grazing practices;
- Introducing legumes in crop rotations; and
- Establishment of grassed waterways, run-off furrows (Poláková et al., 2013)

The European Commission views agri-environment measures positively, as they have met their target in terms of hectares under management. However, several challenges remain: payments are often easily accessible without sufficient validation; results lack systematic monitoring; evaluating the impact on soil health and water quality is difficult; conditions may not align with common farming practices; lasting changes in farmer behaviour are uncertain; greater regional customisation is needed; and advisory services and the non-profit sector play a crucial role (Keenleyside et al., 2012).

2.1.6.4 RESILIENCE AND FOOD SECURITY

Farmers, through their professional associations, need to recognize their responsibility for sustainability as land managers. Each day, they must balance the need for landscape and natural resource protection (Ravallion, 1996; Tovey, 2008; Freshwater, 2015) with their production goals as part of their commitment to food security. Additionally, farmers face challenges such as fluctuations in agricultural commodity prices, factors influencing land use and technology, bioenergy markets, climate change, and demographic shifts (Lobell et al., 2008).

These challenges shape the concept of environmental protection, often referred to as “sustainable”. All policy instruments associated with the CAP since 2003/2004 have connections to the various aspects of sustainability—economic, ecological, and social—although the results on the ground have not been convincing (Pe’er et al., 2017, 2020). In response to these challenges, a new concept of *resilience* has emerged to address the risks facing modern agriculture. Discussions about farm *resilience* began intuitively before it was recognized as a cohesive theme in public discourse (Darnhofer et al., 2014) and subsequently integrated into Pillar 2 rural development policy.

Resilience is defined as the ability of a system to return to a stable state after experiencing a disturbance. Ontologically, it involves the co-creation of foundational elements. In the early stages, various approaches to landscape protection, framed under the concept of sustainability (as seen in Regulation (EU) 1698/2005), became a priority in rural development agendas. During this time, risk management was treated as a separate issue. Farmers and political actors had to negotiate this risk in light of significant biotechnological, bio-economic, or biosocial challenges, which have been regulated for decades through specific agricultural practices that are often complex and not easily understood by the general public. *Resilience* is characterized as a key factor in a farm's ability to address problems typically seen as form of disparity or disadvantage (Barnes et al., 2020). Disparities can arise from natural conditions, such as low fertility in upland and mountainous areas, or from soil characteristics that result in poor water retention and reduced production potential during periods of drought. Recognizing the importance of *resilience* in overcoming these disparities is frequently linked to increasing diversity in agricultural practices (Buitenhuis et al., 2020).

For agricultural economists, public funding such as typically promotes *resilience* by encouraging land management tied to a) diversity of cropping practices, b) robustness of the agricultural enterprise, and c) feasibility of management strategies (Barnes et al., 2020). To enhance *resilience* in agriculture, it is essential for these various factors to coexist in order to effectively address disparities. Therefore, there exists a non-centric set of preconditions necessary for the successful management of these *resilience* factors.

Food security is currently pursued by a new delivery model for the CAP, that emphasizes results over compliance. While direct income support remains important, it will be moderately reduced and better targeted. The goal is to make the EU self-sufficient in food production, which requires investments in digitalisation and modernization of agriculture. Maintaining agricultural entrepreneurship is also crucial during the implementation of the Green Deal (European Parliament, 2023b). Access to financing for farmers is essential for adopting digital technologies and precision farming techniques. This access can lead to increased crop yields while simultaneously reducing pesticide use and water consumption. The European Parliament (2023b) suggests that the EU should establish a new program aimed at modernizing irrigation facilities and promoting innovative water management infrastructure. MEPs view the European Green Deal as a potential milestone in the EU's transition to a sustainable economy and agriculture. However, they caution that some proposed measures may have unassessed unintended consequences at the farm level.

The Commission should ensure that the implementation of the Green Deal supports agricultural activity across the Union to maintain food security. In MEPs´ view, the technology investments should strengthen the EU's food security and farming sector resilience by reducing reliance on external imports and diversifying sources for critical supplies like fertilizers and feed. Furthermore, short and regional supply chains should be sustainably enhanced, particularly in vulnerable countries.

2.2 INTERVENTIONS AND APPROACHES

2.2.1 NUTRIENT MANAGEMENT PLANS (NMPS)

Nutrient management plans have been identified as pivotal in enhancing agricultural systems' sustainability and resilience. These plans concentrate on optimising nutrient usage and ensuring fertilisers are applied to support crop health while minimising negative environmental impacts. The CAP, the Farm to Fork Strategy, and the Green Deal characterise the multifaceted strategy for nutrient management in the EU. Collectively, these policies are designed to ensure that the agricultural sector contributes to the objectives of sustainability, food security and resilience (Table 5).

Key interventions in nutrient management:

Precision agriculture techniques: The Farm to Fork Strategy and CAP's digitalisation agenda encourage the adoption of precision agriculture to optimize nutrient application. In precision agriculture, tools are of pivotal importance in customising nutrient application to suit the particular requirements of crops and soil conditions (Getahun et al., 2024). These technologies, which include soil sensors, GPS mapping and drone monitoring, assist farmers in evaluating the precise nutrient levels across diverse field segments. This, in turn, facilitates more efficient fertiliser application and reduces excess usage (Tsouros et al., 2019). The benefits of precision agriculture include reduced nutrient runoff, decreased input costs, and enhanced environmental sustainability.

Incentivising the use of organic fertilizers: The CAP's agri-environmental schemes provide financial incentives for farmers to replace synthetic fertilisers with organic alternatives such as compost, manure, and biogas digestates. The integration of organic matter improves soil fertility, increases moisture retention, and reduces reliance on fossil-fuel-based fertilisers, supporting the Green Deal's climate and environmental goals (Tian et al., 2022).

Nutrient efficiency training and education: A critical intervention is providing knowledge and skills to farmers, thus enabling them to implement effective nutrient management. Under the CAP, a range of advisory services are available to guide farmers in optimising nutrient use, adopting best practices, and implementing nutrient management plans effectively. These services facilitate a transition towards more sustainable practices by educating farmers on the benefits and techniques of nutrient management, including reducing chemical fertiliser dependency (Kansanga et al., 2021; Di Prima et al., 2022)

Adoption of crop rotation and diversification: Crop rotation, particularly utilising nitrogen-fixing crops such as legumes, constitutes a pivotal intervention in the management of nutrients. The efficacy of these practices in enhancing soil quality and reducing reliance on external inputs has been well-documented. Integrating these practices into nutrient management plans enables farmers to reduce dependency on chemical fertilisers while enhancing soil health, biodiversity, and resilience (Kandel et al., 2023).

Buffer zones and runoff control: To minimise the process of nutrient leaching and the resultant runoff into water systems, the EU has legislated establishing vegetative buffer zones along water bodies under the Nitrates Directive. Such zones act as a natural filter, absorbing excess nutrients before they enter rivers, lakes, and groundwater (Akter et al., 2024). The Nitrate Directive approach is among the oldest approaches as a pivotal intervention to ensure the preservation of water quality. It is closely aligned with the EU's sustainability objectives, as outlined in the Green Deal and Farm to Fork Strategy.

Monitoring and regulatory compliance: Nutrient management plans are subject to monitoring and reporting requirements under EU legislation. This ensures that EU environmental standards regulate agricultural activities, and that nutrient application is done responsibly (Köninger et al., 2021). The EU has established regulatory frameworks for nutrient use, particularly under the Nitrates Directive, which limits the amount of nitrogen that can be applied to farmland. Member States are responsible for implementing the monitoring of nitrate levels and for setting out action plans mandatory for farmers in nitrate vulnerable zones.

Approaches for effective implementation:
Integration with CAP and other EU strategies: The implementation of NMPs is closely linked to the choices by Member States that are quite significant with regard to support mechanisms provided by the CAP. Specifically, CAP's agri-environmental climate schemes may offer, if Member States deems this a priority, financial incentives for farmers who adopt sustainable nutrient management practices, such as reduced fertiliser use or organic farming techniques. This funding mechanism is pivotal in facilitating the widespread adoption of NMPs throughout the EU.

Farm advisory services and technical support: EU Member States provide technical support to farmers through Farm Advisory Services (FAS). Providing personalised advice and assistance in creating and implementing NMPs is central to the role of these services. The services facilitate the adaptation of nutrient management plans to the particular requirements of each farm, thereby ensuring optimal efficiency and sustainability.

Cross-border collaboration and research: The dissemination of knowledge and research findings on nutrient management is encouraged within the EU. Collaborative research initiatives, such as those funded by the Horizon Europe programme, focus on developing new nutrient management technologies, improving soil health, and reducing environmental impacts. Cross-border cooperation on nutrient management facilitates the exchange of best practices between Member States, thereby fostering a more unified approach to nutrient sustainability across Europe.

TABLE 5: COHESION BETWEEN NUTRIENT MANAGEMENT PRACTICES AND EU STRATEGIES

Nutrient management plan	EU strategies and policies*	Key objectives addressed
Precision agriculture techniques	Farm to Fork Strategy, CAP (Investment in physical assets), Green Deal	Optimise nutrient application, reduce fertiliser use, minimise environmental impact
Incentivising the use of organic fertilisers	CAP (Agri-environmental schemes), Green Deal, Circular Economy Action Plan	Reduce dependency on synthetic fertilisers, improve soil health, lower emissions
Nutrient efficiency training & education	Farm Advisory Services under CAP, Farm to Fork Strategy	Improve farmer knowledge, encourage sustainable fertiliser use, enhance soil and water quality
Crop rotation & diversification	CAP (GAEC Standards), Farm to Fork Strategy, Green Deal	Reduce fertiliser reliance, increase soil fertility, enhance biodiversity
Buffer zones & runoff control	Nitrates Directive, Water Framework Directive, CAP GAEC Standards	Prevent water pollution, reduce nutrient leaching, protect aquatic ecosystems
Monitoring & regulatory compliance	Nitrates Directive, Water Framework Directive, CAP Cross-compliance	Ensure responsible nutrient application, enforce environmental standards

Note: The listed strategies and policies call for the specified nutrient management actions; it remains to be seen in future research to what extent the strategies and policies deliver, in practice, on the key objectives. The exception is the Nitrates Directive and GAEC standards that are legislative actions rather than aspirational targets and are in practice controllable.

2.2.2 SOIL HEALTH IMPROVEMENT

Soil health improvement is supported by the forthcoming Soil Monitoring Law through the proposed Directive[19]. The Directive aims to establish a comprehensive soil monitoring framework across the EU to improve soil health and achieve healthy soils by 2050. It seeks to maintain soils in good condition to provide essential ecosystem services, address climate change and biodiversity loss, enhance resilience to natural disasters, and ensure food security. Additionally, the Directive intends to reduce soil contamination to safe levels for human health and the environment (European Commission, 2023a).

[19] https://environment.ec.europa.eu/publications/proposal-directive-soil-monitoring-and-resilience_en

Furthermore, soil health may be benefitted by the Carbon Farming Initiative under the Green Deal. The Carbon Removal and Carbon Farming Certification Framework (European Commission, 2024a) highlights the role of outcome-based payments. This is one of three options to incentivise healthy soil management, the other two being action-based payments and hybrid payments (Smit et al., 2024). Outcome-based payments rely on rigorous monitoring, reporting and verification (MRV) of outcomes for soil carbon and are high risk but having return for farmers (Raina et al., 2024). Action-based payments (essentially similar to agri-environmental programs where the farmer follows prescribed practices) have simple MRV, low risk, but low profitability for the farmer. Hybrid payments combine measurement of outcomes with a commitment to follow practices. This type of payment has low risk and high profitability and links farmers to carbon markets (Raina et al., 2024).

Typically, carbon sequestration potentials are site-specific and must be assessed for specific pedoclimatic conditions. Sequestration potentials are noted for catch/cover crops, crop rotations, reduced tillage, zero tillage, organic amendments and residue management for arable land use; and for grasslands, maintenance of permanent grassland, reducing grassland renewal, optimising manure application, optimizing grazing intensity and conversion of cropland to grassland (Torrus Castillo, et al. 2024).

With respect to carbon sequestration, Aertsens et al. (2013) provide detailed information on both carbon storage and enhancement in agricultural soils; Blanco-Canqui (2021) provides data showing a correlation between vegetation biomass increase and increase in soil organic carbon contents, while Cukor et al. (2017) demonstrates an increase in carbon sequestration for agroforestry, with dependency on stand age (implicitly toward permanent, undisturbed, greater above- and below-ground biomass).

Researchers looked at estimates of how soil water interacts with carbon storage in soil systems. By summarizing estimates of soil carbon sequestration with respect to different agricultural, soil and climatic conditions, it was shown that compared to long-term carbon stocks, the rate of sequestration is limited. Nowicki (2009) reports that the carbon storage capacity of grassland soils exceeds that of cropland soils. Yet, it is equally important to (i) minimize adverse land cover changes to maintain valuable grasslands with carbon contents, as it is to (ii) fine-tune cropland practices to avoid releasing carbon-dioxide emissions from soils (Frelih-Larsen et al., 2017).

Appropriate soil management and agricultural practices are important for soil structure and organic matter. Monitoring, reporting and verifying soil carbon storage, and its changes, is strongly related to the issue of technology, costs and recommended digital solutions for monitoring sequestration. For example, the carbon contents at the baseline level must be simulated with the use of models, verified by soil sampling and in some but not all cases remote sensing. To make effective carbon farming schemes, it may be necessary to apply standardized (regionalized) practice where carbon sequestration fluxes may be compared to long-term soil data from national and European soil survey. For this, digital solutions to bridge various databases (soil data, crop data, farm management data) may be needed.

2.2.3 PRECISION AGRICULTURE

Precision agriculture is an approach using a set of modern technologies to manage in-field heterogeneity. This way, agricultural operations such as fertilizer or pesticide application can be tailored to each part of the field. In the EU, Galileo framework of Earth Observation (Sentinel I and Sentinel II) may provide data fostering the development of PA tools. Where ineffective, pesticide, fertilizer or other inputs may be reduced or completely avoided which not only decrease material cost but also provide ecological benefits and increase sustainability of agricultural production (Stafford, 2000, Godwin et al., 2002). This new approach benefits from the emergence of several technologies, including the Global Positioning System (GPS), geographic information system (GIS), automatic computer control, remote sensors, Unmanned aerial vehicles (UAVs), Internet of Things (IoT), advanced information processing, and telecommunications (Gibbons, 2000, Tsouros et al., 2019).

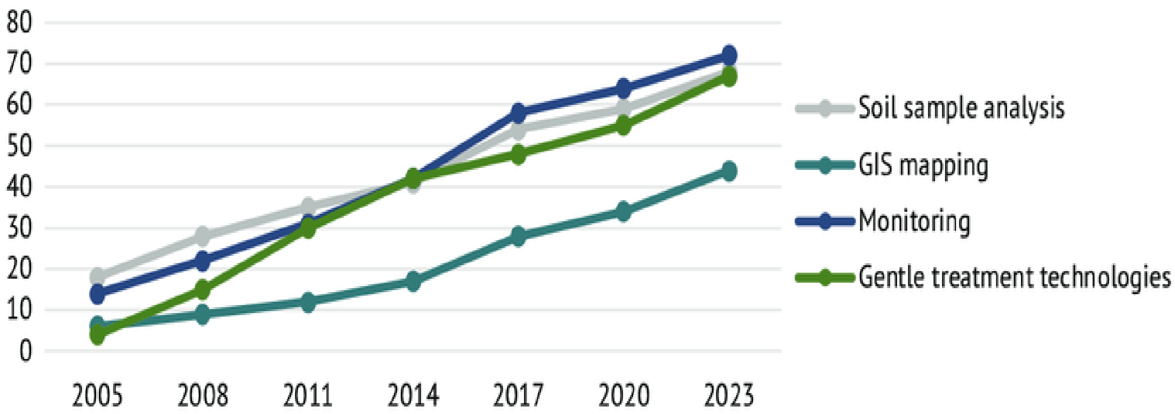

FIGURE 8: RATE OF IMPLEMENTATION OF PRECISION FARMING ELEMENTS IN DEVELOPED EUROPEAN COUNTRIES. SOURCE: EUROPEAN COMMISSION (2023) & DOI: 10.48077/SCIHOR9.2024.110

Although many PA technologies are commercially available and employed by some farmers, broad adoption is still limited. The reasons for this are multiple, but the economic aspects are fundamental for farmers. Many PA technologies require high initial capital investment and added maintenance costs. New technologies also challenge the farmers to change working practices which may result in additional labour costs (Barnes et al., 2019a). Whereas the environmental benefit of PA is apparent, the profitability of these new technologies is not guaranteed for farmers.

Evaluation of the true economic benefits and return to investment is complicated by their application in diverse contexts (Barnes et al., 2019a). Economic returns are dependent on farm related factors and vary on the technology itself, the farm size and whether regular labour is currently employed on the land (Castle et al., 2016). The uncertainties found within the farming community towards PATs, compared to the potential societal gains from their adoption, challenges policy makers to design interventions which encourage their uptake (Barnes et al., 2019b).

The EU has long been struggling to incentivize adoption of sustainable agricultural practices, with precision agriculture serving as part of this effort. Policies under the CAP promote PF technologies only to the extent of providing financial incentives for farmers under CAP Pillar 2 that may be used to adopt advanced tools such as application maps for fertilizing or spraying (European Commission, 2019). The CAP explicitly supports greening measures, but these measures face difficulty in directly prompting farmers to use these technologies to reduce pesticide use, improve water efficiency, and enhance soil health.

A notable intervention is the allocation of funds through CAP Pillar 2 and the European Agricultural Fund for Rural Development (EAFRD), which supports the training and equipping of farmers with precision technologies (European Commission, 2020). Additionally, the EU's Farm to Fork Strategy, part of the European Green Deal, underscores the role of PF in achieving its goals of a 50% reduction in pesticide use and a 20% reduction in fertilizer use by 2030.

The EU has developed frameworks to facilitate data sharing among stakeholders through platforms like the European Digital Innovation Hubs (Kalpaka et al., 2020). These hubs provide enterprises access to real-time data analytics, enabling better decision-making and resource allocation. Policies like the Data Act are key components in ensuring data interoperability and security, building trust among stakeholders across industries, including agriculture. The EU's Horizon Europe program allocates substantial funding to research projects focused on PF. These initiatives emphasize the development of AI algorithms and autonomous machinery tailored to diverse agricultural contexts. For instance, the DEMETER project, funded under Horizon 2020, showcases the integration of PF technologies across various scales of agricultural production (DEMETER, 2020).

An important tool promoting the transfer of precision agriculture technologies and other innovations in the agricultural practice are the EIP-AGRI projects. They are based on an 'interactive innovation' model, bringing together project partners to turn practical problems and creative ideas into innovative solutions. Co-creating solutions stimulates collaboration, knowledge exchange, and effective dissemination and take-up of knowledge and results. The interactive innovation approach is used both in EIP-AGRI Operational Group projects, which are supported under the CAP, and in multi-actor projects (including thematic and advisory networks) funded under EU Research and Innovation Programmes (Horizon 2020 and Horizon Europe). The current CAP for 2023-2027 provides opportunities for preparing and implementing Operational Group projects via national CAP Strategic Plans (European Parliament, 2023a; EU cap network, 2024).

Although the current CAP takes some steps to promote precision agriculture technologies, other measures may be still needed to increase their uptake. Farmer training and higher education providing real knowledge to students and professionals, as well as government support through investments, could lead to an improvement in the application of PA (Petrović et al., 2024).

The concerns of many farmers, however, seem to be mostly related to profitability issues, whereas environmental benefits are secondary for them. For those farmers, regulatory pushes appear to determine willingness to further adopt PA technologies, indicating higher awareness of the roles these technologies can play in meeting compliance with tighter environmental rules. Despite ambitions within Europe to reduce reliance on agrochemical inputs and to increase sustainability of agriculture, there is no direct regulatory push to adopt PA technologies in the EU (Barnes et al., 2019b).

2.2.4 ORGANIC FARMING

The Commission considers organic farming vital for sustainable agriculture and aims for 25% of the EU's agricultural land to be organically farmed by 2030, up from 10.5% in 2022 (Farm to Fork Strategy). From 2014 to 2022, farmers received about €12 billion in support for organic practices via the CAP Policy. EU regulations set the rules for organic farming and the labelling of organic products. Organic farming uses natural substances and processes avoiding synthetic chemicals, ensures high animal welfare standards, and prohibits GMOs. It contributes to biodiversity, soil health, and water quality.

The CAP supports to organic farming are expected to further increase the area of organic farming. Since 2012, the agricultural area under organic farming has grown due to increasing demand and policy support, reaching approximately 16.9 million hectares, or 10.5 % of the total agricultural area, in 2022 (Figure 9). However, the Court of Auditors reported gaps in both EU and national policies for the organic sector. For example, environmental and market objectives were not fully considered (ECA, 2024).

FIGURE 9: SHARE OF THE UTILISED AGRICULTURAL AREA USED FOR ORGANIC FARMING IN THE EU-27 OVER THE PERIOD 2012-2022. SOURCE: EUROSTAT, 2024

Good evidence exists on the benefits of organic farming to water quality and soil functionality. These can be attributed to the ban on the application of artificial fertilisers or pesticides. Organic farming also relies on management actions that are frequently replaced by intensive management in conventional agriculture (such as crop rotation, application of animal manure, minimum tillage, mechanical weed control, hedge management etc).

The use of animal waste and green manures can replace nitrogen and thus reduce nitrate leaching and build up soil organic matter content. Crop rotations with legumes may be particularly effective for providing water and soil benefits. According to the survey by the European Court of Auditors, the positive outcomes of organic farming agri-environment schemes for water were documented in all Member States under survey. 30 studies provided evidence that organic farming practices were effective in achieving their environmental benefits, such as reduced water and air pollution through a decrease in the use of inputs (European Court of Auditors, 2011). Improved water quality beneficially affects the status of wider habitats. For example, organic arable systems in south-west England showed higher plant abundance and species richness than their conventional counterparts (Norton et al., 2009).

2.2.5 EU AND GLOBAL POLICY ALIGNMENT FOR FOOD SECURITY AND AGROCHEMICAL REDUCTION

Beckman et al. (2020) from the US Department of Agriculture assessed the economic implications of the Green Deal and warned Europe about the path to a green transition. They highlight the reduction in agricultural production for regions adopting the Farm to Fork strategy; the increase in agricultural commodity prices; and the reduction in GDP and welfare worldwide.

The green transition may reduce GDP if it does not cover the investment needs of the transition. The cost to GDP is in the order of EUR 11 billion, and may adversely affect the economy, reduce living standards and increase disparities between EU regions. The proposed reduction in the use of pesticides and fertilisers may have a negative impact on production, leading to a decrease of 7-12%, which may affect competitiveness on the domestic and export market. Implementation of the strategy could have global implications and could increase food prices by 9% (if the management mandated by the strategy is adopted only in the EU) or up to 89% (if it is implemented globally). This may in turn affect consumers and reduce social welfare by USD 96 billion depending on the level of adoption in other countries.

The transition towards a more sustainable agricultural system in the EU also aligns with several key international policies and agreements. The United Nations Sustainable Development Goals (SDGs)[20], the Kunming-Montreal Global Biodiversity Framework[21], and the United Nations Convention to

[20] https://sdgs.un.org/goals
[21] https://www.unep.org/resources/kunming-montreal-global-biodiversity-framework

Combat Desertification (UNCCD)[22] all emphasise the urgent need to promote sustainable food systems while minimising environmental degradation. The EU's Farm to Fork Strategy and Green Deal strongly support SDG 2 (Zero Hunger) by fostering sustainable agricultural practices which enhance food security while reducing reliance on pesticides and synthetic fertilisers. Additionally, these policies contribute to SDG 6 (Clean Water and Sanitation) and SDG 15 (Life on Land) by mitigating soil and water contamination from agrochemical runoff. Likewise, the Kunming-Montreal Global Biodiversity Framework's Target 7 supports reducing pesticide risks and excess nutrients. This aligns well with the EU's ambition to halve pesticide use by 2030.

Furthermore, the UNCCD highlights the importance of soil health and land restoration, which are goals that the EU attempted to address. The tools for these goals are CAP eco-schemes (basic measures under CAP Pillar 1), and, under CAP Pillar 2, entry-level agri-environment schemes focusing on agroforestry and conservation agriculture. The international commitments are thus to an extent integrated into the EU's policy framework, but lots of work needs to be done to assess the effectiveness of the various policy measures. Additionally, after the recent simplification changes to GAEC Standards, there are steps to diluting of mandatory measures. This is concerning given the EU's positioning as global leadership on sustainability and ensures coherence between agricultural production, environmental protection and long-term food security. The international linkages may strengthen cross-border collaboration, support knowledge exchange, however the policies would need to be strengthened to enhance the resilience of global food systems in the face of climate change and resource scarcity.

2.3 ASSESSMENT OF POLICY GAPS

2.3.1 KEY AREAS FOR POLICY FOCUS TO REDUCE AGROCHEMICAL DEPENDENCE AND ENHANCE RESILIENCE

In order to reduce dependence on agrochemicals and to build a more resilient and sustainable European agricultural sector, it is necessary to address several key barriers and challenges. These strategies must be aligned with overarching EU frameworks, including the Green Deal, Farm to Fork Strategy, CAP, and REPowerEU, to establish a comprehensive, resilient, and agrochemical-independent agricultural system for the future of Europe. Concentrating on reducing dependence on agrochemicals is vital in the context of EU agricultural independence, food security, and digital solutions. The following section will highlight the main areas that require further attention, as summarized in the table at the end of this section (Table 7).

[22] https://www.unccd.int/

While these areas of intervention are critical for reducing agrochemical dependence, translating these strategies into actionable outcomes faces numerous challenges, which are outlined in the following section.

Integrated pest management and alternative pest control

Integrated Pest Management (IPM) is of pivotal importance in reducing agrochemical usage and can be regarded as a vital strategy for reducing European pesticide dependency. However, adopting IPM practices remains inconsistent due to various barriers, including a lack of knowledge, inadequate infrastructure, and resistance to adopting new, more sustainable, conventional practices. There is an urgent need to reinforce IPM by providing farmers with targeted education, knowledge-sharing platforms, and financial incentives for adopting alternative pest control methods. Furthermore, increasing research into innovative pest control solutions and providing farmer-friendly technology solutions would aid in reducing the reliance on harmful chemicals (Ragunathan & Divakar, 2020). This would require better alignment with existing strategies like the Farm to Fork Strategy and EU Green Deal.

Role of digital solutions in reducing agrochemical use

Digital technologies can play a pivotal role in reducing the use of agrochemicals in European agriculture. Precision agriculture, remote sensing, and crop monitoring technologies have the potential to optimise the use of inputs, including fertilisers and pesticides. However, the full potential of these technologies is hindered by several barriers, including limited digital infrastructure in rural areas, lack of interoperability between platforms, high implementation costs, and concerns over data privacy. To this end, the promotion of widespread adoption of digital solutions is predicated on improving connectivity, implementing cost-reduction strategies for utilising digital tools, and establishing standards across digital platforms. Addressing farmers' concerns about data privacy and fostering digital literacy is also crucial in unlocking the potential of digital tools for sustainable farming practices (MacPherson et al., 2022).

Nutrient management plans and fertiliser reduction

It is imperative to acknowledge the pivotal role of nutrient management plans in curtailing the reliance on synthetic fertilisers, a prominent component of agrochemical dependence (Apostolopoulos et al., 2024). Despite establishing policies within the European Union that promote nutrient efficiency, such as the Nitrates Directive, the implementation of comprehensive nutrient management plans remains inadequate. There is an urgent need for more substantial policy incentives to encourage farmers to adopt comprehensive nutrient management practices. Such measures could include subsidies or financial incentives for practices that optimise nutrient use and minimise fertiliser application. Furthermore, research into alternative nutrient sources, such as organic amendments, is imperative to reduce dependency on synthetic fertilisers and enhance soil health. Existing challenges in implementing nutrient management plans (e.g., lack of comprehensive policies and financial incentives) need to be addressed in parallel with efforts to improve agri-environmental schemes and overcome economic constraints.

Water scarcity and droughts in agrochemical inputs

Water scarcity and drought conditions exacerbate the reliance on agrochemicals in agriculture. Drought conditions reduce soil moisture and impair crop nutrient uptake, often resulting in increased fertilizer use to compensate for nutrient deficiencies (Kandel et al., 2024). Moreover, arid conditions can render crops more vulnerable to pests and diseases, increasing the need for pesticides. Furthermore, the efficacy of agrochemicals is frequently diminished in drought conditions, necessitating increased usage to attain the same level of effectiveness (Subedi et al., 2023). As the challenge of water scarcity persists, it is imperative to incorporate this factor in formulating strategies to reduce agrochemical dependence. The integration of water-saving technologies, improved irrigation practices, and drought-tolerant crop varieties could reduce the pressure on agrochemical usage while concomitantly enhancing the resilience of the agricultural sector as a whole.

Soil health improvement and organic farming

The importance of soil health in reducing the need for agrochemicals by enhancing soil fertility and promoting natural pest control has been well-documented. The EU Green Deal and Farm to Fork Strategy have acknowledged the significance of soil management; however, further efforts are required to incorporate soil health enhancement into conventional agricultural practices (Boix-Fayos & De Vente, 2023). Encouraging practices such as crop rotation, agroforestry, and reduced tillage would help improve soil organic matter and microbial diversity. Organic farming, which relies on fewer chemicals and emphasises soil health, offers an important model for reducing agrochemical use.

Economic challenges and policy alignment

The transition to an agricultural model independent of agrochemicals within the European Union is confronted by substantial economic impediments (Pawlewicz & Pawlewicz, 2023). Rising input costs, fluctuating commodity prices, and increasing competition from non-EU agricultural imports pose challenges for farmers seeking to adopt more sustainable practices. It is imperative to align the Common Agricultural Policy and other relevant EU frameworks more closely with sustainability goals, thereby ensuring adequate financial support to farmers during this transition period. Policies prioritising short-term economic viability and long-term sustainability, such as targeted subsidies for sustainable farming practices, are imperative to affect this transition. In addition, it is essential to incorporate economic models that consider the environmental externalities of chemical-intensive agriculture into EU agricultural policies, thus ensuring that financial pressures do not hinder sustainability efforts.

Digital literacy and knowledge gaps

Despite the increasing significance of digital tools in the agricultural sector, a considerable knowledge deficit remains among farmers, particularly those in rural areas (Ferrari et al., 2022). Having adequate digital literacy and familiarity with the available tools is imperative for farmers to leverage digital solutions to reduce agrochemical use. Enhancing digital literacy through targeted educational and training programmes is crucial to effectively empower farmers to utilise precision agriculture technologies. Furthermore, there is a need for easier access to information on sustainable practices and digital tools, which could be facilitated through online platforms, extension services, and farmer cooperatives.

2.3.2 BARRIERS AND CHALLENGES IN IMPLEMENTING AGROCHEMICAL REDUCTION POLICIES INTO ACTIONABLE OUTCOMES

While several key areas for policy focus have been identified in the above section, significant barriers and challenges still hinder the effective translation of these policies into practical and actionable outcomes. Addressing these challenges is critical to achieving the desired reduction in agrochemical use.

2.3.2.1 CHALLENGES IN AGRI-ENVIRONMENT SCHEMES

Despite the ambitious goals set forth by EU frameworks, the translation of policies into actionable outcomes has been hindered by a variety of challenges. These include issues such as poorly designed agri-environment schemes and barriers to carbon farming initiatives. Several factors, including economic considerations, farmer behavior, and institutional shortcomings, must be addressed to ensure the success of these policies A key challenge with agri-environmental schemes is that direct income support often outweighs environmental goals (Hasler et al., 2022).

Figure 10 compares spending on direct income support versus agri-environment schemes. In 2013, while direct incomes support included a greening requirement, the criteria were usually too easy for farmers to meet, which meant these payments largely acted as income support (Hasler et al., 2022). There has been an overall good assessment of the agri-environment measures as the quantitative objectives (hectares implemented under agri-environment management) were achieved. However, some of the main challenges were: relatively easily accessible payments; no monitoring of results; difficult to assess the effect on soil health and water quality; conditions of measures are not always in line with common practice; whether farmer behaviour change can be more permanent as a result of adoption; the need to regionalise measure conditions; and the accompanying advisory services and the non-profit sector are important (Keenleyside et al., 2012).

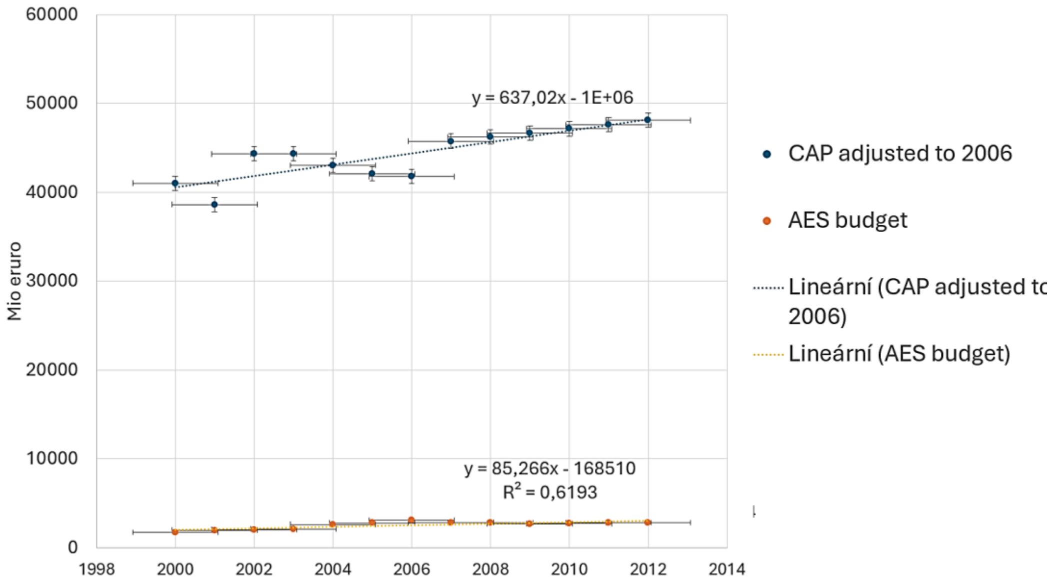

FIGURE 10: COMPARISON OF EXPENDITURE FOR DIRECT INCOME SUPPORT AND AGRI-ENVIRONMENT PAYMENTS. SOURCE: POLÁKOVÁ ET AL. 2022

Despite some notable successes regarding specific results for soil health in certain locations (Borelli, 2016), as well as the maintenance of organic farming systems in many areas, the current suite of policy measures, as designed and implemented by Member States, is insufficient to meet the EU's objectives linked to sustainability, food security and resilience. Evidence from the literature and the case studies conducted (Hasler et al., 2022; Hart et al 2011; Poláková et al., 2013) indicate a variety of reasons for this shortfall. These reasons can be broadly categorized as follows:

- Measure and scheme design at the Member State level;
- Farmer attitudes and the role of advice and vocational training;
- Institutional and political factors;
- Implementation of related policies such as nature directives;
- Other intervening factors outside the control of the farmer or policy (administrative overload; climatic changes; imports from third countries; ambitious climate goals; WTO compliance regime for green box subsidies); and
- Demonstration farms are currently sparse and should be promoted as they contribute to fostering adaptability among farmers and land managers through practical demonstrations on beneficial farming practices. This approach encourages permanent behaviour change based on cognition rather than subsidies. Additionally, Vocational Training Centers could play a key role by offering targeted training programs that further incentivize sustainable practices through education and skill-building, rather than relying solely on financial incentives.

2.3.2.2 CHALLENGES IN CARBON FARMING

The EU understands carbon farming as incentives for ecosystem services specifically for carbon sequestration. This is postulated in Regulation (EU) 2024/3012. Research has examined criteria for sequestration projects since 2001 (Antle et al., 2001). Criteria for sequestration projects are advocated in the Regulation include:

- Additionality to GAEC and other baseline standards
- Carbon leakage (on some fields carbon sequestration is offset by carbon credits while on another field there has been intensification of production and an unwanted increase in emissions)
- Permanence (when the business model pays credit for carbon farming on a particular plot in one year, the question is how to ensure that the farmer keeps up carbon farming practices in the medium and long term so that the carbon content remains long-term) and
- Early adopters (refers to the question of whether it is relevant to pay early adopters who cannot increase already high levels of carbon contents; Smit et al., 2024).

Permanence, additionality and lack of reliable MRV were cited as common barriers for all payment types (Raina et al., 2024). Outcome-based payments face the greatest challenges, including high project and opportunity costs, low-carbon payments, land tenure issues, and the absence of baseline data that are essential for certifying the validity of carbon credits. MRV is therefore a great challenge for the digitalisation of agriculture, including geodata, models, remote sensing technologies.
Table 6 below summarizes the key policy areas, challenges, and required actions for reducing agrochemical dependence in agriculture. It provides an overview of the strategies and policies needed for a sustainable transition.

TABLE 6: INTEGRATED POLICY APPROACHES FOR AGROCHEMICAL REDUCTION IN AGRICULTURE

Key Area	**Barriers/Challenges**	**Required actions & policy attention**	**Strategies & policies to be improved***
Integrated pest management and alternative pest control	Lack of awareness, inconsistent adoption, insufficient infrastructure	Provide targeted education, establish knowledge-sharing platforms, increase research on alternative methods	(a)(b)(c)(d)
Role of digital solutions in reducing agrochemical use	Limited digital infrastructure, high costs, data privacy concerns	Improve rural connectivity, standardize digital platforms, reduce implementation costs, address data privacy issues	(e)(f)(g)(h)(I)

Nutrient management plans and fertiliser reduction	Inadequate implementation of existing policies,	Strengthen nutrient management practices, , encourage research into alternatives	(a)(b)(c)(g)(j)
Soil health and organic farming	Slow uptake of soil management practices, limited organic farming expansion	Promote organic farming, implement practices like crop rotation, agroforestry, and reduced tillage	(a)(d)(g)(k)(l)
Economic challenges and policy alignment	Rising input costs, competition from non-EU imports, inadequate support for farmers transitioning to sustainability	Align CAP with sustainability goals, strengthen mandatory measures, provide cooperation with market-based voluntary measures, consider environmental externalities	(a)(g)(k)
Digital literacy and knowledge gaps	Varying educational levels across regions, especially rural areas	Enhance digital literacy through training, provide easier access to sustainable farming information, create farmer cooperatives	(e)(f)(g)(m)

Note: * The specified strategies and policies call for the identified actions, and typically require these actions directly or indirectly, but it remains to be seen in research to what extent the outcomes in practice have been delivered. Code: (a) Farm to Fork Strategy; (b) EU Green Deal; (c) EU Chemicals Strategy for Sustainability; (d) SDG 15; (e) Digital Education Policies; (f) EU Digital Strategy; (g) CAP; (h) Farm to Fork Strategy; (i) SDG 12; (j) Nitrates Directive; (k) EU Biodiversity Strategy for 2030; (l) Zero Pollution Action Plan; (m) SDG 4 (quality education). Source: OECD 2023

3 MAPPING OBSTACLES AND SOCIO-ECONOMIX CHALLENGES

3.1 DEPENDENCY ON AGROCHEMICALS AND IMPORTS

3.1.1 CURRENT TRENDS IN AGROCHEMICAL USAGE AND IMPORT/EXPORT PATTERNS

This section details how Nostradamus will achieve full FAIR compliance, ensuring that research data remains valuable and accessible beyond the project's lifetime.

European agriculture's reliance on agrochemicals indicates regional disparities, which are driven by climate, practice and structure. The usage of agrochemicals and the extent of reliance on trade vary between Europe's northern and southern regions.

Agrochemical usage - Northern Europe
Northern Europe, comprising countries such as Germany, the Netherlands and Denmark, is characterised by intensive farming practices with a focus on the cultivation of high-yield crops, including cereals, rapeseed and sugar beets. The implementation of precision agriculture practices is more widespread in this region, resulting in comparatively lower pesticide application rates per hectare compared to those observed in Southern Europe. However, utilising fertilisers, notably nitrogen-based products, remains substantial for sustaining productivity. Strict regulatory frameworks, such as the Nitrates Directive, have been implemented in these countries to encourage adopting more sustainable practices. However, the transition to alternative practices, such as organic farming or advanced nutrient management strategies, remains impeded by economic and logistical constraints[23].

Agrochemical usage- Southern Europe
The use of pesticides and herbicides in Southern Europe, comprising Spain, Italy and Greece, is a consequence of the region's warmer climate, which fosters the proliferation of pests and weeds. Crops cultivated in the Mediterranean region, such as olives, grapes, and citrus fruits, are particularly susceptible to these problems, resulting in higher pesticide usage per hectare. Furthermore, fertiliser utilisation is pervasive, particularly in irrigated regions where runoff exacerbates environmental concerns, including water contamination and soil degradation. Despite ongoing efforts to curtail the use of agrochemicals, these endeavours encounter significant impediments due to the fragmented nature of agricultural structures, which leaves numerous small and medium-sized farms lacking the financial wherewithal to adopt alternative practices[25].

[23] https://environment.ec.europa.eu/topics/water/nitrates_en?utm_source=chatgpt.com

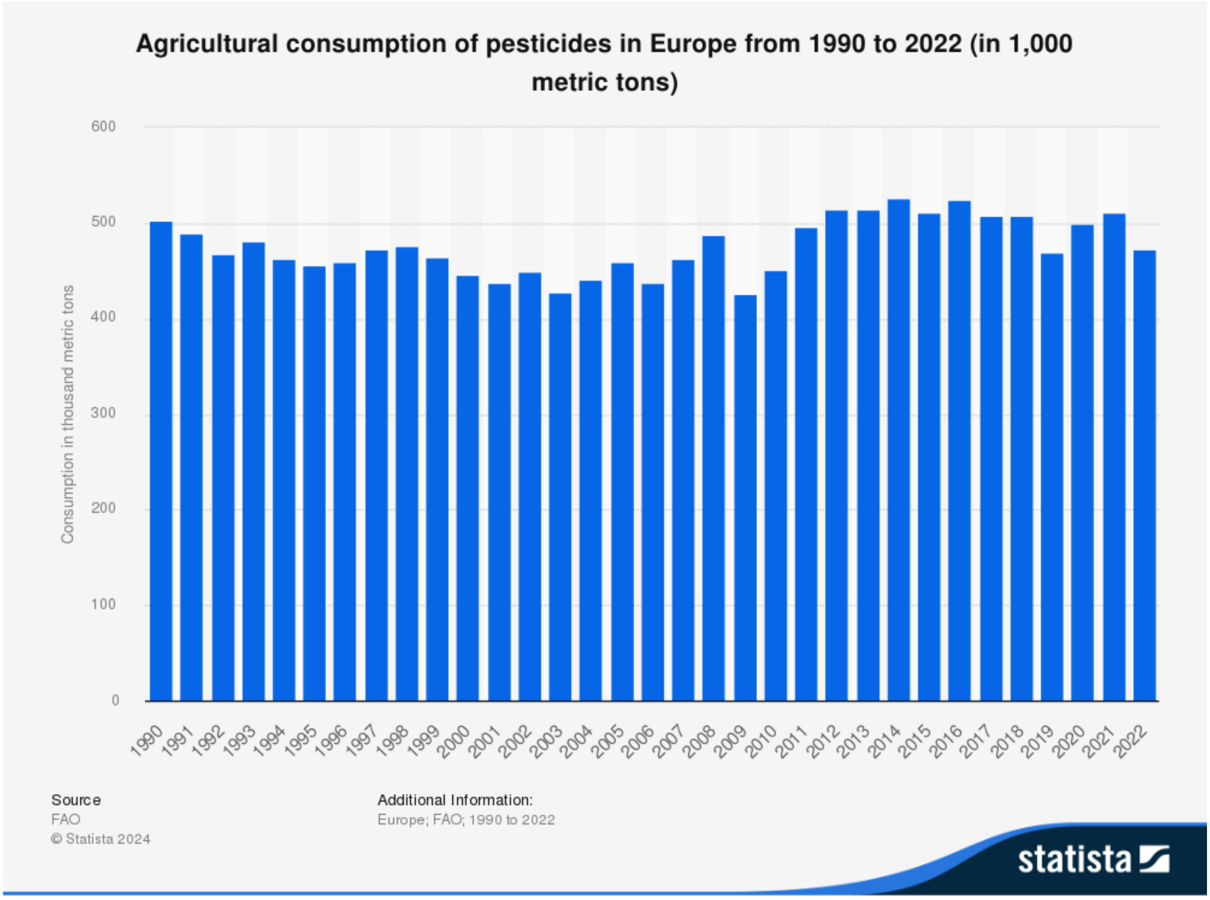

FIGURE 11: AGRICULTURAL CONSUMPTION OF PESTICIDES IN EUROPE. SOURCE: FAO (FAOSTAT.FAO.ORG)

As demonstrated in Figure 11, the necessity of these endeavours is emphasised by the trends in pesticide consumption over the preceding decades. From 1990 to 2022, the utilisation of pesticides in European agriculture exhibited significant fluctuations, with the highest recorded consumption occurring in 2014, reaching 532,710.91 metric tons. By 2022, this figure had declined to 472,902.75 metric tons, reflecting a gradual shift towards more sustainable practices. Nevertheless, pesticide use remains substantial, underscoring the necessity for expedited adoption of alternative solutions.

These statistics highlight the necessity for ongoing innovation and collaboration to reduce agrochemical dependency. As Europe moves towards reducing regional disparities and embracing sustainable agricultural practices, the nexus between technological innovation, regulatory frameworks and trade dynamics is set to assume pivotal importance. A coordinated strategy that capitalises on the strengths of Northern and Southern Europe may be helpful for environmental and economic sustainability, thereby positioning Europe as a global leader in sustainable agriculture.

Import patterns - Northern Europe

The region is a net importer of agrochemicals, particularly fertilisers containing phosphorus and potassium, due to the scarcity of local resources. The importation of pesticides is also driven by the need to adhere to stringent standards for crop protection in intensive farming systems. The impact of global fertiliser market fluctuations on Northern European countries is exacerbated by geopolitical tensions and export restrictions imposed by key suppliers, such as Russia and Belarus[24].

Import patterns – Southern Europe

The high degree of Southern European reliance on agrochemical imports is evident, with considerable quantities of pesticides and fertilisers sourced outside the EU. This region is particularly vulnerable to market volatility, as geopolitical shifts often disrupt supply chains. Spain and Italy, for example, have witnessed an increase in import costs that has a disproportionately negative effect on smaller producers[26].

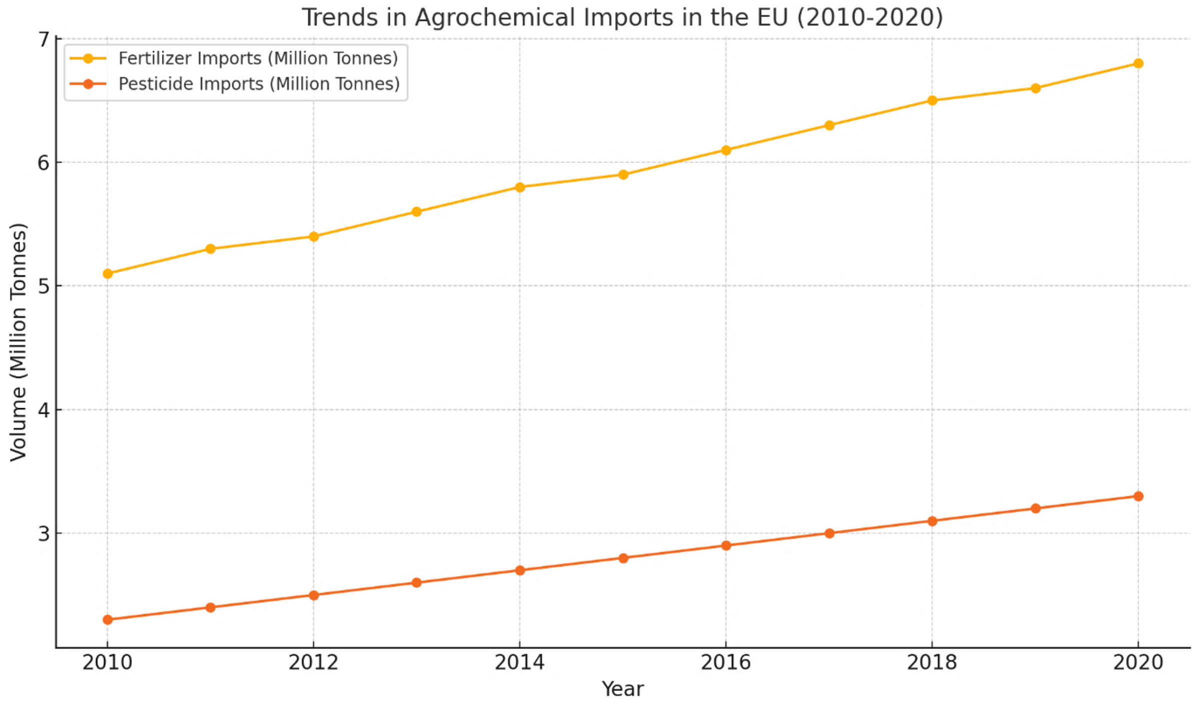

FIGURE 12: TRENDS IN AGROCHEMICAL IMPORTS/EXPORTS (EU-WIDE). SOURCE: EUROSTAT, FAO

The chart of Figure 12 illustrates the trend of agrochemical imports into the EU from 2010 to 2020, which reveals a steady increase in reliance on external sources for pesticides, fertilisers, and other agricultural chemicals. This growing reliance raises concerns regarding the long-term sustainability of Europe's agricultural practices and potential vulnerabilities in supply chains, particularly in the face of geopolitical issues or trade disruptions. Furthermore, the increasing magnitude of importation has been demonstrated to contribute to environmental challenges, including soil degradation and water contamination. In order to address these challenges, Europe must promote sustainable farming practices, including soil management, precision agriculture, organic farming

[24] chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.fertilizerseurope.com/wp-content/uploads/2024/11/Threats-to-the-EU-fertilizer-market-and-agriculture_Nov-2024.pdf?utm_source=chatgpt.com

and circular agricultural models, to reduce reliance on imports. Implementing robust regulatory frameworks and providing support for alternative solutions may facilitate a transition in the agricultural sector towards enhanced self-sufficiency and sustainability.

Challenges - Northern Europe

The challenges associated with this transition include the escalating costs of imported agrochemicals, which disproportionately negatively affect small-scale farmers' profitability. Moreover, the considerable expenses associated with adopting digital technologies have been recognised as a substantial impediment to integrating sustainable practices. Additionally, the inadequacy of agricultural supply chains in terms of external disruption resilience necessitates the exploration of local alternatives and adopting circular approaches, including nutrient recycling[25].

Challenges – Southern Europe

The region is facing a multitude of challenges. A salient vulnerability pertains to the high dependency on imported inputs, which makes the region susceptible to international price fluctuations and trade restrictions. The adoption of alternative practices, such as organic farming, is hindered by economic pressures and inadequate support infrastructure. Digital transformation initiatives encounter substantial impediments, such as inadequate rural connectivity and limited digital literacy[27].

Emerging trends and solutions

Emerging trends and solutions in addressing agrochemical dependence are gradually taking shape across Northern and Southern Europe, with regional differences influencing progress. Northern Europe is at the forefront of the transition towards organic farming, exhibiting higher adoption rates attributable to robust infrastructure, advanced technology, and supportive policies. Conversely, Southern Europe faces structural and financial impediments that hinder its progress despite the growing cognisance of organic practices' environmental and health benefits. This discrepancy has consequences for intra-European trade, as Northern European countries increasingly export organic products, thereby establishing higher market standards that Southern Europe finds challenging to meet (Mohring et al., 2024).

Precision agriculture is becoming a transformative strategy on a global scale, with digital tools being utilised to optimise agrochemical applications to reduce waste and minimise environmental harm. However, the adoption of such technologies remains uneven. Northern Europe benefits from superior infrastructure and funding, facilitating broader implementation, while Southern Europe grapples with cost challenges and limited technological access. This disparity in the adoption of precision agriculture has implications for the competitive dynamics within the European Union, as countries that have adopted advanced precision agriculture technologies gain a competitive advantage in producing higher-quality and more sustainable agricultural products.

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[25] https://agriculture.ec.europa.eu/media/news/eu-agricultural-outlook-2024-35-resilient-sector-adapts-climate-change-sustainability-concerns-and-2024-12-11_en

Circular agricultural practices, including nutrient recycling through composting and the utilisation of waste streams, are examined as promising long-term approaches to reducing agrochemical dependency. Implementing these practices has been demonstrated to enhance soil health, reduce pollution, and present opportunities for cross-border collaboration in technology transfer and resource sharing. As these practices gain traction, they can potentially address the sustainability gap between Northern and Southern Europe, fostering a more balanced trade relationship (Mohring et al., 2024).

Moreover, the EU-wide initiatives of the Green Deal and the Farm to Fork Strategy should have provided a cohesive regulatory framework for reducing agrochemical use and promoting sustainable alternatives, however economic and political difficulties globally have led to farmer protests and weakening of sustainability goals. These policies should have encouraged harmonisation across member states, facilitating fair competition and supporting the development of a unified European market for sustainable agricultural products, however one has seen progressive decentralization of policies and weakening of frameworks. By aligning regional efforts, it remains to be seen whether the EU can drive progress towards a greener agricultural sector while strengthening its position in global trade as a leader in sustainability-focused practices.

3.1.2 THREATS POSED BY PRICE FLUCTUATIONS AND INCREASING COSTS FOR EU CEREAL FARMERS AND THE INDUSTRY

EU cereal farmers face significant challenges due to price volatility and increasing costs. Fertilizer prices have risen substantially, impacting production costs, particularly for cereal farms (Lecuyer et al., 2014). This price risk is exacerbated by the long production cycle of cereals, where inputs are purchased months before harvest (Läänemets et al., 2011).

The volatility in farm incomes has been further intensified by the development of the CAP, which no longer protects and stabilizes prices for products like cereals (Vrolijk et al., 2009). EU cereal producers' competitiveness varies, with higher productivity levels in the UK, Ireland, and France than in Denmark, Germany, and Italy (Thorne, 2005). The opportunity cost of owned resources significantly impacts profitability, and as direct payments become decoupled from production, producers must make decisions based on full economic costs, including adequate remuneration for owned resources (Thorne, 2005).

Price fluctuations and rising costs pose significant challenges for cereal farmers and the broader agricultural industry within the European Union. These challenges are intricate and multifaceted, influencing farming operations' profitability, stability, and sustainability. The ensuing analysis aims to examine these challenges confronting EU cereal farmers and the industry, focusing on fluctuating prices and increasing costs.

Impact of price fluctuations on farmers

As with other agricultural sectors, cereal farmers in the EU are susceptible to price volatility. The prices of essential inputs (e.g. fertilisers, pesticides, and fuel) and cereals can fluctuate due to global market dynamics, weather patterns, and geopolitical events (Berger et al., 2021). Such price fluctuations can harm farmers' incomes and profitability, making it challenging to engage in long-term planning and investment in improvements or technology.

- **Market vulnerabilities**: The price of EU cereals is influenced by international competition and global commodity markets, particularly from major exporters such as Russia, Ukraine and the United States. Fluctuations in production levels, trade policies, or weather conditions in these countries can result in substantial price fluctuations, which in turn can have a notable impact on farmers within the European Union (Berger et al., 2021).
- **Uncertainty in profit margins**: Price volatility makes it difficult for farmers to forecast their revenues with a high degree of accuracy (Berger et al., 2021). This is further exacerbated by escalating operating costs (e.g., labour, machinery, maintenance), which can lead to farmers not covering fixed expenses or investing in their operations.

Rising Input Costs

The increasing costs of essential inputs such as energy, fertilisers, and pesticides represent a significant concern for EU cereal farmers (Sidhoum et al., 2023). The rising costs of such inputs are frequently associated with escalating global energy prices, disruptions in supply chains, and inflationary pressures.

- **Fertiliser Costs**: Fertilisers, particularly nitrogen-based fertilisers, have escalated significantly recently. This has a direct impact on cereal crop yields and farming margins. Farmers experiencing financial constraints may be compelled to reduce fertiliser usage, resulting in diminished productivity and quality of produce. This, in turn, can exert pressure on supply chains and food security (Sidhoum et al., 2023).

- **Energy and Fuel Costs**: The cost of fuel, which is indispensable for agricultural activities, including planting, cultivating, and harvesting crops, has been rising steadily. The ongoing energy crises in Europe, particularly in the context of geopolitical tensions such as the war in Ukraine, have increased operational costs for farmers, further reducing their profitability (Rabbi et al., 2023). This has led to a decline in the viability of cereal production, particularly for smaller, family-run farms that are not well-resourced financially.

- **Labour Costs**: The combination of increasing wages, particularly in more developed regions of the EU, and labour shortages lead to an overall increase in the cost of farming (Christiaensen et al., 2021). This phenomenon can result in farmers reducing their workforce, relying more heavily on technology (which may not always be cost-effective for all farmers) or opting for less labour-intensive farming methods, which may also affect yields and efficiency.

3.2 SOCIO-ECONOMIC CHALLENGES

3.2.1 ANALYSIS OF FLUCTUATING MARKET PRICES, THEIR IMPACT ON FARMERS AND INDUSTRIES

The volatility of agricultural prices and farm incomes has become a significant concern in Europe, particularly following changes in the CAP (Vrolijk et al., 2009). Such price fluctuations have been shown to exert substantial economic and social pressures on the agricultural sector (Lanfranchi et al., 2019). The responses of farmers to these market changes are influenced by several factors, including their country of origin and local environment (Kuipers et al., 2021). The abolition of price support mechanisms, such as intervention purchasing schemes, has exposed producers to greater market signals and uncertainty (Fraser, 1991). Recent studies have demonstrated that short-term price fluctuations can reach up to 100%, which poses a considerable challenge to individual agricultural companies and the broader economic system (Lanfranchi et al., 2019). These market dynamics can influence farmers' attitudes towards organisational and institutional measures, which may vary depending on the prevailing market situation and policy context (Kuipers et al., 2021).

Price volatility in cereals and agricultural commodities poses a substantial challenge to the EU agricultural sector, jeopardising economic stability and disrupting rural social structures. The impacts of price volatility vary across northern and southern Europe, owing to differences in agricultural practices, resource availability, and socio-economic conditions.

3.2.1.1 REGIONAL DISPARITIES IN CHALLENGES

A. Northern Europe: socio-economic impacts in mechanised and export-oriented agriculture

Rural labour and employment challenges

Economic aspect: The mechanisation of agriculture in northern Europe reduces reliance on manual labour, thereby enabling higher productivity. However, this process has also been demonstrated to create job vulnerabilities for seasonal and migrant workers. During periods of price volatility, farm owners may scale back operations or reduce hiring, leading to economic instability in rural labour markets (Olesen, 2016).

Social aspect: Job reductions frequently have an unequal impact on marginalised groups, such as migrant workers, who may encounter difficulties in relocating to other sectors or regions. Rural depopulation is exacerbated as young workers migrate to urban centres for better opportunities (Olesen, 2016).

Mental health and farmer well-being

Economic aspect: The economic challenges farmers face in the northern regions are due to three main factors. Firstly, market prices are subject to significant volatility. Secondly, substantial investments made costly machinery. Thirdly, many agricultural enterprises' viability is contingent on export markets' stability (Arnalte-Alegre & Ortiz-Miranda, 2013). Price declines can precipitate profitability and difficulties in debt repayment, engendering heightened economic vulnerability among agricultural enterprises (Olesen, 2016).

Social aspect: The financial pressures exerted on individuals can have a deleterious effect on mental health, with anxiety and depression being the most common consequences. The impact of social isolation, a particularly salient feature in rural areas characterised by constrained access to comprehensive psychological healthcare, contributes to this complex set of circumstances (Olesen, 2016).

Market concentration and farm consolidation

Economic aspect: The Northern European region is distinguished by substantial agribusinesses. This has resulted in elevated levels of competition, which has directly impacted smaller agricultural enterprises. The consolidation of the market within the region is another contributing factor to the reduction of diversity and the weakening of economic resilience exhibited by smallholders (Olesen, 2016).

Social aspect: The consolidation of farms disrupts the established rural communities. This diminishes local cultural identity and weakens community solidarity due to the abandonment of smaller farms (Olesen, 2016).

B. Southern Europe: socio-economic impacts in resource-constrained and smaller-scale farming

Family farming pressures

Economic aspect: The agricultural sector of Southern Europe is characterised by a significant presence of family-run farms and a reliance on low-margin crops. The region's agricultural sector is susceptible to fluctuations in market prices, which directly and significantly impact the financial well-being of rural households (Salvati et al., 2009). This, in turn, can lead to several challenges, including but not limited to debt accumulation and a general feeling of financial insecurity amongst smallholders.

Social aspect: The financial pressures experienced by farmers can significantly impact the stability of their family units, often resulting in generational disputes regarding the continuation of farming as a career path (Arnalte-Alegre & Ortiz-Miranda, 2013). This dynamic, in turn, has the effect of driving youth migration to urban areas, which in turn further depopulates rural regions.

Gender disparities

Economic aspect: Within southern Europe, women engaged in agricultural activities frequently encounter obstacles to accessing credit, technological resources, and land ownership. These constraints impede their ability to respond to market fluctuations, exacerbating their economic vulnerability effectively (Arnalte-Alegre & Ortiz-Miranda, 2013). The unequal distribution of resources is a key factor in restricting the overall economic efficiency of agricultural enterprises.

Social aspect: Women often face considerable challenges in achieving an equitable balance between agricultural pursuits and domestic responsibilities, particularly in contexts where caregiving obligations are also present (Salvati et al., 2009). The migration of male family members for employment further exacerbates gender inequities by imposing an increased burden of responsibility on female family members, who are often left with diminished resources to cope.

Vulnerabilities of seasonal and migrant workers

Economic aspect: Seasonal and migrant workers are integral to southern agriculture. However, they frequently encounter low wages and job insecurity, particularly during price declines. Farmers encountering challenges due to erratic revenue patterns reduce or defer remuneration, adversely impacting workers' economic stability (Salvati et al., 2009).

Social aspect: The poor living and working conditions experienced by migrant workers are demonstrated to perpetuate social inequalities, thereby engendering tensions within rural communities (Arnalte-Alegre & Ortiz-Miranda, 2013). This negatively affects the overall well-being and social integration of these communities.

Rural infrastructure and social services

Economic aspect: A decline in farm incomes results in diminished financial capacity within rural communities to invest in infrastructure and social services (Salvati et al., 2009). This contributes to the ongoing economic underdevelopment experienced by the southern region.

Social aspect: Inadequate access to healthcare, education, and digital connectivity in rural areas exacerbates social inequalities, engendering feelings of isolation amongst farmers and hindering their opportunities for advancement (Salvati et al., 2009).

Cultural erosion and social discontent

Economic aspect: Economic pressures are compelling farmers to transition from traditional, lower-yield crops to more lucrative, higher-yield alternatives. This transition has the unintended consequence of leading to the erosion of biodiversity and the decline of traditional agricultural practices that have been integral to rural communities for generations. As farmers prioritise economic viability, the landscape becomes increasingly dominated by monocultures, further exacerbating biodiversity loss and the cultural heritage tied to diverse farming methods (Arnalte-Alegre & Ortiz-Miranda, 2013).

Social aspect: The erosion of traditional farming practices can potentially jeopardise cultural heritage and community identity, fostering discontent and resistance to external interventions or regulatory changes. As these practices become less prevalent, local communities may perceive a loss of their history and way of life, potentially leading to increased opposition against policies that threaten their traditions and autonomy (Arnalte-Alegre & Ortiz-Miranda, 2013). This resistance has the potential to impede the implementation of agricultural reforms and sustainability initiatives, given the profound interconnection between the social structure of these communities and their agricultural foundations.

C. Broader social and economic impacts across regions

Food security

Economic aspect: Fluctuating prices directly impact consumers' expenditures on cereals, increasing the cost of staple foods and exacerbating inflationary pressures, which can compromise food security. From the perspective of agricultural producers, price instability disrupts supply chains, making it challenging to maintain a steady food supply (Arnalte-Alegre & Ortiz-Miranda, 2013). This volatility poses a significant threat not only to farmers' livelihoods but also to the availability of affordable and nutritious food for vulnerable populations, thereby compromising the overall food security of society.

Social aspect: The impact of elevated food costs on low-income households is of particular concern, as it is associated with increased food insecurity and the exacerbation of social inequality across the European Union. As the cost of staple foods rises, these households find it more challenging to afford essential nutrition, increasing their reliance on food assistance and deepening social disparities (Arnalte-Alegre & Ortiz-Miranda, 2013). This expanding socio-economic divide exerts mounting pressure on social welfare systems and hinders the efforts to ensure equitable access to food for all citizens.

Migration and urbanisation trends

Economic aspect: Economic instability in rural areas is a leading factor in migration to cities. This has resulted in a significant labour shortage for the agricultural sector while simultaneously placing pressure on urban infrastructure due to the inflow of rural migrants. As individuals migrate for improved economic opportunities, the agricultural workforce diminishes, limiting the sector's ability to maintain production levels (Arnalte-Alegre & Ortiz-Miranda, 2013). This decline in available labour undermines the sustainability of agricultural output, creating challenges for meeting demand and maintaining food security.

Social aspect: Migration from rural areas to urban centres raises several social and cultural issues. Among these are the creation of social and cultural discrepancies and increased pressure on urban services. Rural communities are losing social networks and cultural heritage, which weakens local identity (Arnalte-Alegre & Ortiz-Miranda, 2013). Concurrently, an increased demand for housing, healthcare and other essential services in urban areas exacerbates social instability.

Social inequalities

Economic aspect: The farms with abundant natural resources are better equipped to absorb market shocks. In contrast, smaller farms and those most marginalised farmers are shown to face a greater risk of bankruptcy and economic collapse. The disparity in resources between the two types of farms means that it is difficult for smaller operations to withstand price fluctuations or other economic pressures. This often results in financial instability and reduced viability in the agricultural sector (Salvati et al., 2009).

Social aspect: The disparities in access to resources and opportunities create tensions between large agribusinesses and smallholders. The unequal distribution of resources, including but not limited to funding, technology, and infrastructure, is a key factor contributing to this imbalance (Arnalte-Alegre & Ortiz-Miranda, 2013). This creates tensions as smaller farmers struggle to compete with larger entities over market power and policy influence.

3.2.1.2 GENDER DIMENSIONS AND VULNERABLE POPULATIONS

In the context of socio-economic challenges faced by the EU agricultural sector, understanding the gender dimensions and the impact on vulnerable populations is crucial to developing effective policies and strategies. Agriculture is a labour-intensive industry with deep ties to social norms and cultural practices, often resulting in differentiated roles for men and women and the exclusion or marginalization of specific groups within vulnerable populations.

The gender dimensions and vulnerable populations in EU agriculture highlight several key issues. Women migrant workers in agriculture face exploitation due to structural factors, necessitating a human rights and gender-based approach to address their vulnerability. The EU's commitment to gender mainstreaming in the Common Agricultural Policy has been criticized as ineffective, focusing on symptoms rather than causes of gender inequality. Vulnerable agricultural populations in Europe include foreign-born farmworkers, migrants, beginning farmers, farm families, and those with disabilities. Understanding gender differences is crucial for designing interventions that reduce vulnerability to climate change and promote gender equality in agriculture. Key activities to support gender-equitable climate-smart agriculture include collecting gender-disaggregated data and providing targeted climate services (Matthews, 2014; Boysen et al., 2015).

Gender disparities in agriculture

Gender plays a significant role in shaping the experiences of individuals within the agricultural sector, with women often facing more significant barriers than men. These barriers can manifest in unequal access to land, credit, technology, education, and training resources. Even though women make up a substantial proportion of the agricultural workforce, especially in rural areas, they are often underrepresented in decision-making processes, agricultural leadership, and policy formulation. Women in agriculture, particularly in southern Europe, face systemic barriers to access to finance, technology, land ownership and training. These inequalities limit their ability to adapt to price volatility and rising input costs. Furthermore, gendered labour divisions mean that women typically engage in lower-paid, less recognized, and more time-consuming tasks compared to men, limiting their economic opportunities and advancement.

Vulnerable populations in agriculture

Vulnerable populations in the agricultural sector include low-income farmers, migrant workers, youth, elderly individuals, and rural populations facing food insecurity. These groups are disproportionately impacted by fluctuating market prices, climate change, and shifting agricultural policies.

Migrant workers: Many developing countries supply the EU agricultural industry with seasonal workers, often working in vulnerable conditions with limited legal protection. These workers are vulnerable to exploitation, work in unsafe conditions and have limited access to social services.

Youth: In many rural areas, the younger generation is leaving agriculture for better opportunities in urban areas. This trend leaves older farmers, particularly in the EU, with succession challenges, limiting innovation and adaptation in the sector.

Elderly farmers: Older generations may not have the resources or knowledge to adopt modern agricultural practices or digital solutions. This can increase their vulnerability to market shocks or climate-related disruptions.

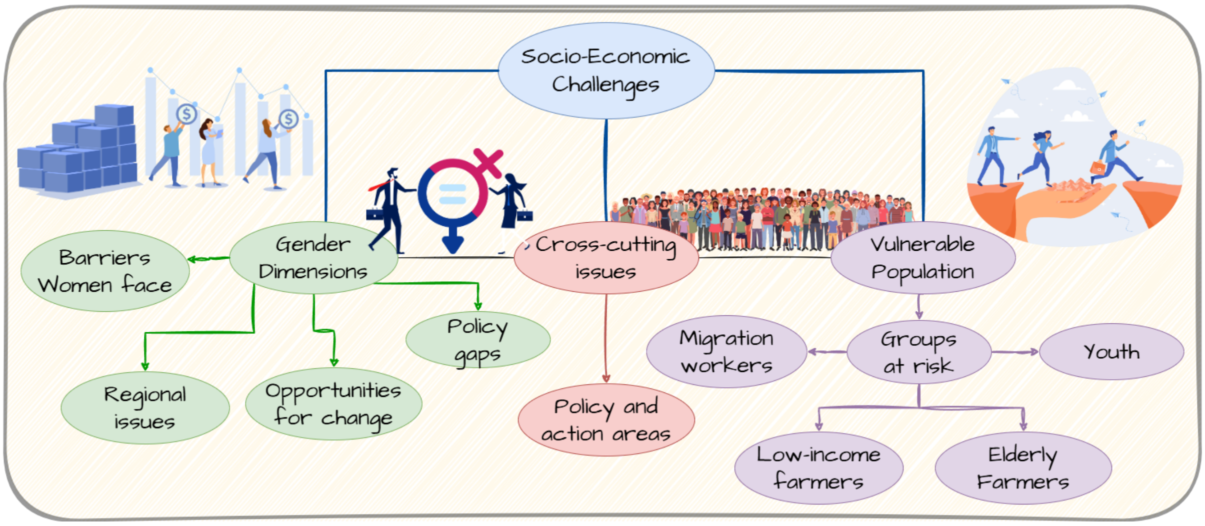

FIGURE 13: SYSTEMATIC INEQUALITIES IN AGRICULTURE

The above conceptual framework of Figure 13 illustrates systematic inequalities in agriculture. It shows the interconnected socio-economic challenges in EU agriculture. On top of this, socio-economic challenges influence various aspects like gender dimensions and vulnerable, showing how socio-economic issues influence women and marginalized groups in agriculture. On the one hand, gender dimensions are further linked to specific challenges, such as barriers women face, regional issues, and policy faps, which bind women's participation and opportunities in agriculture.

On the other hand, vulnerable groups, such as migrant workers, youth, elderly farmers, and low-income farmers, are part of the groups at risk and face overlapping issues like limited access to resources and opportunities. Cross-cutting issues like poverty and education further exacerbate these challenges, requiring comprehensive policies to address them. Finally, policy and action areas highlight where reforms can significantly impact, with opportunities for change focused on improving gender equality (Sutherland et al. 2021), addressing regional disparities, and bridging policy gaps to support these at-risk groups.

3.2.1.3 DIGITAL INCLUSION IN RURAL AREAS

Digital transformation is an important opportunity for EU agriculture but also reveals an important gap. Economically, small and medium-sized farmers cannot take advantage of digital solutions such as precision agriculture tools, data analytics and IoT devices due to the high cost of implementing these technologies. Regions with underdeveloped digital infrastructure, particularly in Southern and Eastern Europe, face additional barriers to entry.

From a social perspective, the digital literacy gap among older farmers and less educated communities limits the ability to adopt these innovations. Limited connectivity in remote areas exacerbates the problem, leaving many rural farmers excluded from the digital revolution. Efforts to bridge this gap include affordable digital tools, community-based training initiatives, and investment in rural broadband infrastructure (Perpiña et al., 2021).

3.2.1.4 IMPLICATIONS FOR DEVELOPING COUNTRIES DEPENDENT ON EU AGRICULTURE

The Common Agricultural Policy of the European Union has been the subject of considerable criticism for its potential negative impacts on the economies of developing countries. While certain developing nations may benefit from importing agricultural goods at reduced prices due to EU surpluses, others face challenges in competing with the subsidised exports of the agricultural products from the EU (Boysen et al., 2015). Recent CAP reforms have reduced its overall impact on global markets, though the effects remain significant for specific commodities and countries. Multiple levels characterise the policy-making process, including EU member states, the EU itself, and the international trading system. Eliminating EU agricultural support is difficult to envision in the global world where major actors in developed nations (USA, Australia, New Zealand and other OECD countries) all support their respective agricultures under the decreasing interest to farm. However, in theory, eliminating EU agricultural support could have small but positive effects on developing economies and poverty reduction. Nevertheless, the 2013 CAP reform did not fully realise the potential to reduce market distortions and enhance global food security, with rising concerns of EU farmers about food imports from third countries that have lower production costs due to lower sustainability standards. At the same time, developing countries are disappointed due to the failure to establish an end date for export subsidies.

The socio-economic challenges experienced by the EU agricultural sector have significant implications for developing countries dependent on EU agriculture. It affects a wide range of sectors, such as trade dynamics, food security, employment, and socio-economic stability

(Matthews, 2014; Boysen et al., 2015). Developing countries' reliance on EU imports for food and raw materials and on EU markets for exports highlights their vulnerability to market fluctuations and any policy changes in the EU. Consequently, disruptions in the EU agricultural sector can lead to economic and food security challenges in these dependent economies.

Economic implications

Impact on import-dependent economies

Price volatility: Developing countries reliant on the EU for cereals and other agricultural commodities are particularly vulnerable to price fluctuations. Such volatility in EU markets frequently increases commodity prices, which exerts upward pressure on the cost of staple foods in importing countries. These price surges have a cascading effect, contributing to inflation and disproportionately burdening low-income households. For low-income households, even minor fluctuations in food costs can substantially impact their capacity to access essential nutrition (Matthews, 2014; Boysen et al., 2015). Thereby exacerbating food insecurity and worsening socio-economic inequalities. This underscores the critical need to stabilise EU agricultural markets to mitigate the extensive impacts on dependent economies.

Trade imbalances: The higher costs for EU imports worsen trade deficits in developing economies. These countries are compelled to allocate a substantial proportion of their financial resources to secure essential food supplies (Matthews, 2014; Boysen et al., 2015). Increasing expenditure pressures national budgets in the long term, diverting funds from other vital sectors such as education, healthcare, and infrastructure. As a result, the economic pressure from rising import costs impacts food security and undermines broader development goals, further embedding economic vulnerabilities in these countries.

Disruptions in export-oriented agriculture

Export reliance on EU markets: Many developing countries depend on the EU as a key market for agricultural exports like tropical fruits, coffee, and cocoa. Economic instability within the EU can reduce demand for these products, resulting in significant income losses for farmers and industries in these developing nations (Matthews, 2014; Boysen et al., 2015). This decline in export revenues further exacerbates economic challenges, limiting the ability of these countries to invest in local development and meet their domestic needs.

Non-tariff barriers: The dynamic nature of EU policies can act as a barrier to agricultural exports from developing countries. These evolving policies often impose additional compliance costs, which can be challenging for farmers and exporters in developing nations to meet (Matthews, 2014; Boysen et al., 2015). The inability to consistently meet these standards can result in reduced market access, lower export volumes, and financial losses. This, in turn, can precipitate economic strain, thereby impeding agricultural growth and local industries' stability. This may result in a reduction of foreign exchange earnings.

Loss of market access

Competition with EU domestic production: Policies designed to enhance the autonomy of the EU about its agricultural sector may give precedence to the sourcing of goods and services within the bloc over the importation of such goods and services. This could result in a substantial reduction in market access for developing countries that have historically relied on the EU as a primary destination for their agricultural exports. By shifting focus towards increasing local production and self-sufficiency, these policies may impose trade barriers, such as tariffs or quotas, on goods imported from developing nations. This shift in policy could have far-reaching consequences for the export of essential commodities such as coffee, cocoa, tropical fruits, and other agricultural products, potentially undermining the economic stability of these developing economies. The reduced access to the EU market could result in a decline in revenues for farmers and agricultural industries in these countries and a decrease in foreign exchange earnings. Furthermore, there is a heightened risk of economic hardship, particularly in rural areas where agriculture is often the primary source of livelihood (Matthews, 2014; Boysen et al., 2015).

Social implications

Food security challenges

Dependence on EU imports: Developing countries reliant on EU agricultural imports are susceptible to food insecurity risks. Domestic challenges, including price fluctuations and supply chain disruptions, may precipitate a decline in EU exports. These issues can limit access to essential food supplies, exacerbating food insecurity in vulnerable nations. These countries depend on a steady supply of affordable food and raw materials from the EU. If EU exports decrease, they may face difficulties in securing essential goods. This could make it harder for them to maintain a stable food supply. Price volatility and supply chain disruptions have the potential to result in shortages, increased food costs, and constrained access to essential goods. This has the effect of exacerbating food insecurity and exerting additional pressure on vulnerable populations. This situation can also hinder the achievement of long-term food security and economic stability in these developing nations (Matthews, 2014; Boysen et al., 2015).

Malnutrition and inequality: Rising food costs in economies that rely heavily on imports disproportionately burden vulnerable populations. As food prices increase, low-income households, in particular, struggle to afford necessities, leading to higher rates of malnutrition and food insecurity (Matthews, 2014; Boysen et al., 2015). This economic pressure not only harms public health but also deepens social inequality, as the most marginalized groups are most affected by rising costs. In many cases, the inability to access nutritious food further exacerbates health disparities, limiting opportunities for education, employment, and overall social mobility. Consequently, the impacts of rising food costs create a cycle of poverty and inequality that becomes increasingly difficult to break.

Rural employment and livelihoods

Job losses linked to export declines: A decline in the demand for agricultural exports from the European Union can precipitate widespread job losses in developing countries, particularly in rural areas where agriculture constitutes the primary source of employment (Matthews, 2014; Boysen et al., 2015). As demand for key exports diminishes, farmers and workers in associated industries, such as processing and distribution, may encounter diminished income opportunities or unemployment. This phenomenon can precipitate an economic downturn in rural communities, where alternative employment opportunities are often constrained. This could compromise the livelihoods of individuals and communities, consequently exacerbating poverty and economic instability in these regions.

Gender disparities: Women constitute a considerable proportion of the agricultural workforce in developing nations. Consequently, they represent the primary demographic affected by the economic consequences of reduced exports. A decline in agriculture due to decreased demand has the effect of causing women to lose their jobs, to have lower incomes, and to experience greater economic insecurity (Matthews, 2014; Boysen et al., 2015). This has a disproportionately adverse effect on their capacity to provide for their families and communities, thereby compounding existing gender inequalities. These challenges impede women's access to resources, education, and decision-making power, perpetuating social and economic disparities.

<u>Disruption of local agricultural systems</u>

Dependency on EU-sourced agrochemicals and technology: Many developing countries are heavily dependent on EU imports of agrochemicals, seeds, and advanced farming technologies, which are essential for maintaining agricultural productivity. Fluctuations in EU prices or supply chain disruptions can significantly impact these crucial inputs' availability and cost. As a result, farmers in these regions are often forced to resort to less efficient and sustainable farming practices. Without access to high-quality seeds, chemicals, and technology, yields may decline, leading to reduced agricultural output. This, in turn, can cause long-term challenges such as lower food production, increased costs for farmers, and a greater vulnerability to environmental factors like pests, diseases, and climate change. Over time, these challenges undermine the overall sustainability of agricultural systems in developing countries, further deepening food security concerns (Matthews, 2014; Boysen et al., 2015).

Cultural shifts: The reliance on imported agricultural commodities and contemporary farming methodologies has the potential to progressively diminish traditional agricultural practices in developing countries, resulting in the erosion of cultural identity and agricultural resilience. As imported seeds, chemicals, and technologies become more prevalent, local farmers may be compelled to shift away from time-honoured, sustainable practices handed down through generations. This transition not only diminishes the cultural heritage associated with traditional farming but also undermines the resilience of agricultural systems. The sustainability and resilience of agricultural systems are diminished by the erosion of traditional farming methods, which have been adapted to local environments over time. As these methods become obsolete, farmers increasingly rely on external inputs, which can be costly and less suited to local conditions (Matthews, 2014; Boysen et al., 2015). This growing reliance undermines food sovereignty and community cohesion as local agricultural knowledge and practices are gradually replaced by external solutions. This transition can diminish rural communities' capacity to adapt to future challenges, threatening long-term food security and cultural continuity.

Broader implications for developing countries

Economic instability

Trade dependence: The economic stability of many developing countries is closely linked to their trade relationships with the EU, particularly in the agricultural sector. As these countries rely heavily on exports to the EU for crucial agricultural products, any disruptions to EU agriculture—such as price fluctuations, policy changes, or supply chain disturbances—can amplify the economic vulnerabilities within these nations. These disruptions affect the agricultural sector and trigger broader macroeconomic challenges, including reduced export revenues, inflation, and currency instability. Consequently, developing countries may face increased fiscal pressure, making maintaining essential public services and development programs harder. The ripple effects of such disturbances can undermine overall economic growth, deepen poverty, and increase social inequalities, further destabilising the economies of these nations (Matthews, 2014; Boysen et al., 2015).

Increased migration pressures

Rural exodus: Economic hardships caused by agricultural disruptions often push rural populations to migrate, either to urban centres within their own countries or abroad, including to the EU, in search of better opportunities. This migration, driven by the need for stable employment and improved living conditions, can lead to overcrowding, putting pressure on urban infrastructure and social services. The inflow of migrants also creates housing, healthcare, education, and employment challenges, straining already limited resources (Matthews, 2014; Boysen et al., 2015). Furthermore, migration can exacerbate social tensions and inequalities as new arrivals compete for jobs and services, leading to potential conflicts and further destabilising rural and urban communities.

Geopolitical and social tensions

Dependence on EU policies: The analysis demonstrates that developing countries' reliance on EU agricultural imports and markets renders them susceptible to the influence of EU agricultural and trade policies. Alterations or perceived inequities in these policies can engender substantial economic and social ramifications, as these nations may encounter challenges in adapting to novel regulatory frameworks or price volatilities. Such disparities can engender dissatisfaction and frustration, potentially fuelling geopolitical tensions between the EU and these countries (Matthews, 2014; Boysen et al., 2015). Furthermore, implementing inequitable policies can ignite social unrest within dependent regions, where farmers and local communities may perceive a sense of marginalisation or unfair treatment. This, in turn, can engender societal instability, erode diplomatic relations, and impede the facilitation of sustained development and cooperation.

3.3 OBSTACLES TO DIGITAL SOLUTION ADOPTION

3.3.1 LIMITED DIGITAL INFRASTRUCTURE IN RURAL AREAS

One of the primary challenges is the inadequate penetration of high-speed broadband in rural regions. The EU Digital Economy and Society Index (DESI) consistently highlights the urban-rural divide in internet access. While urban areas enjoy near-complete coverage of the fifth generation of cellular network technology (5G) networks, many rural regions lag significantly behind, with coverage rates deep below 60% in some member states (European Commission, 2023b). This infrastructure gap hinders the deployment of data-intensive technologies like IoT (Internet of Things) in agriculture and precision agriculture (Murugamani et al., 2022). For example, tools requiring real-time data collection and analysis are often impractical in areas with unstable internet connectivity.
Building digital infrastructure in sparsely populated rural areas is often considered economically non-beneficial. High deployment costs for fiber-optic networks or advanced 5G towers, combined with a limited user base, dissuade private investments. Public sector interventions, such as subsidies or EU-level programs like the Connecting Europe Facility (CEF), have attempted to mitigate this issue, but progress remains slow (Esteban-Navarro et al., 2020).
Additionally, fragmented policy approaches across EU member states further broaden the scope of the issue. While some countries have prioritized and advanced digital infrastructure development in rural areas, others remain behind due to inconsistent implementation of digital strategies. This lack of coordination between EU-level initiatives and national policies leads to inefficiencies and delays in achieving digital equity. Harmonized frameworks and targeted funding are essential to closing this gap and ensuring rural areas benefit from digital transformation in the likes of the urban environments (Feurich et al., 2024).

3.3.2 LACK OF STANDARDIZATION, INTEROPERABILITY, AND DIGITAL LITERACY AMONG FARMERS

Even in regions with improved infrastructure, digital literacy remains a critical barrier. Farmers often lack the technical expertise to implement and benefit from modern technologies like precision agriculture or digital supply chain tools. This digital divide is empowered by a lack of confidence in using these tools, creating a partial resistance to change. Rural educational programs and awareness initiatives, although present, are often insufficient in addressing the specific and diverse needs of agricultural stakeholders (Hackfort, 2021).

Moreover, studies reveal that digital literacy among rural populations is not only about operating devices but also understanding data privacy, cybersecurity, and how to integrate digital tools into traditional farming practices. The gap in digital literacy widens as technologies become more advanced, requiring a more complex strategies to effectively educate farmers and rural communities, preparing them for further emergence of digitalisation (Metta et al., 2023). The lack of standardization and interoperability in much of the digital tools further complicates the process of adoption of these new technologies. Farmers often face challenges in integrating various systems, such as farm management software, IoT devices, and precision agriculture tools, especially in case of various producers of such tools. These tools frequently operate on incompatible platforms, leading to inefficiencies and increased costs for farmers who attempt to reconcile different systems (Gómez-Carmona et al., 2023).

A potential solution to these challenges lies in data aggregation and the development of one-stop-shop platforms. These integrated digital ecosystems enable farmers to manage multiple agricultural technologies through a unified interface, reducing inefficiencies caused by fragmented systems. To fully leverage the potential of these platforms, developing standardized data-sharing frameworks and ensuring seamless interoperability between digital tools is essential. Establishing harmonized approaches across stakeholders can enable greater adoption of digital solutions and facilitate knowledge exchange, ultimately bridging the gap between fragmented systems.

Additionally, data sharing between systems is hindered by the absence of universal standards for structure and format. This adversely affects the desirable progression towards data aggregation and development of one-stop-shops. Without consistent frameworks, farmers are unable to fully utilize data collected from multiple sources, reducing the effectiveness of technologies such as big data analytics and artificial intelligence (Moreno et al., 2024). By fostering data aggregation, one-stop-shop platforms not only simplify farm management but also enable more effective utilization of big data analytics and AI-driven insights. These platforms serve as centralized hubs, allowing farmers to seamlessly integrate and analyse data from multiple digital tools. This integration is crucial for optimizing productivity, resource efficiency, and long-term sustainability in digital agriculture.

The development of open-source platforms and collaborative frameworks could mitigate these issues, but their adoption remains limited due to fragmented policymaking and resistance from proprietary technology providers. Economic constraints and lack of open developer communities further broadens these problems. Many farmers are reluctant to invest in technologies that they perceive as risky or incompatible with their existing systems. The high costs of adopting new technologies, combined with uncertainties about their return on investment, deter widespread and effective adoption (Ehlers et al., 2022).

3.3.3 HIGH COSTS OF IMPLEMENTATION AND DATA PRIVACY CONCERNS

The financial burden associated with adopting advanced digital tools is one of the primary barriers for farmers regardless of the scale of their operations. Implementing technologies such as precision agriculture, AI driven tools and IoT-based monitoring systems involves substantial initial investments in hardware, software, and training. These costs are particularly prohibitive for small and medium-sized farms, which constitute a part of the EU's agricultural sector (Guth et al., 2022).

Beyond upfront expenses, the ongoing costs of maintenance, software updates, and technical support further deter adoption. Even with subsidies, many farmers perceive these technologies as economically unsustainable, especially in regions with unstable agricultural incomes, despite their positive impacts on income (Liu & Zhou, 2023). Public-private partnerships and government grants have been introduced to mitigate these costs, but their reach remains limited, particularly in the periphery of rural areas.

As agriculture becomes increasingly data-driven, concerns about data ownership, privacy, and misuse are growing on par with the technologies. Farmers often lack clarity about who owns the data collected by digital tools, leading to fears of exploitation by technology providers or third parties. For example, data about crop yields, soil conditions, and market trends are valuable assets that, if misused, could disadvantage farmers in competitive markets (Gómez-Carmona et al., 2023). While integrated digital platforms present opportunities for streamlined farm management, concerns remain over data governance and control. Ensuring that farmers retain ownership of their data and can securely share information within trusted frameworks will be crucial for fostering adoption and confidence in these technologies.

In addition, the regulatory landscape surrounding data protection in agriculture is still evolving. While the EU's General Data Protection Regulation (GDPR) offers some safeguards, its application to agricultural data remains ambiguous. This uncertainty, coupled with farmers' limited knowledge of data rights and cybersecurity practices, can further poise the hesitation to adopt digital solutions (Linsner et al., 2021). To address the cyber security issues, clearer guidelines on data ownership and secure systems for data storage and sharing are urgently needed across the industry.

3.4 CASE STUDIES OF CURRENT CHALLENGES

3.4.1 CASE STUDY OF CZECHIA AND EASTERN EUROPE

Examples illustrating the socio-economic and digital barriers in the EU agricultural sector

The EU agricultural sector is undergoing a significant transition, driven by the adoption of digital and precision technologies aimed at improving productivity and sustainability. This transition, however, faces distinct challenges across regions. Digital Innovation Hubs (DIHs) play a key role in overcoming these barriers by providing support for farmers through technology trials, consulting, and specialized training. Socio-economic disparities, digital infrastructure gaps, and limited access to technology broaden these inequalities, presenting distinct challenges.

Challenge of farm size and farm structure

Eurostat (2024) categorizes farms in the EU into three distinct groups: (i) semi-subsistence farms, which primarily focus on producing food to feed the farmers and their families; (ii) small and medium-sized farms, typically family-run businesses; and (iii) large agricultural enterprises, which are more likely to operate as legal entities or cooperatives. Some countries have a prevalence of semi-subsistence and small and medium farms (Slovenia, Cyprus), few have a combination of the large and the small (Czech Republic). others Large agricultural enterprises hold the best position in the value chain and in policy-making. Contrariwise, semi-subsistence farms and small and medium farms are essential in maintaining land in disadvantaged rural areas with worsened climate and soil conditions.

The challenges to the adoption of digital technologies are to an extent common to all three categories. Although many farmers already use some kind of precision agriculture technologies, the use is mostly limited to simple straightforward solutions, which have clear potential to save costs or increase productivity and thus lower production costs. High-precision navigation systems, boom section control on sprayers and yield sensors can be currently considered the most common PA technologies.

Large enterprises, simply by upgrading their equipment on a regular basis, acquired the capability for variable-rate precision agriculture (Mrnustik and Sutherland, 2022). The large-scale farmers are educated professionals who keep up to date on agronomic developments. They are also able to employ new graduates who have the potential to be trained in recent technological developments, and who have wide knowledge networks.
In contrast, small and medium-sized farms, face specific challenges, such as disadvantages in the levels of human capital within households, specifically regarding members with advanced agricultural education; constraints on the financial viability of the innovation in the short term; and a strong motive to weigh the costs and benefits of the new technology and its alignment with existing practices.

For example, the adoption of variable application of fertilizers requires extra time for yield data or satellite data management and analysis, which cannot be usually accomplished with existing farm staff due to time reasons. In large farms, the increased workload is often covered with extra workforces, which are specialized in PA. This is not applicable in smaller farms, where data management and analysis are often conducted by specialised agricultural services.

Across all three size categories of farms, some progressive farmers already adopted variable application of fertilizers, variable rate seeding or even weeding robots for vegetable production. Some farmers also use drone imaging for mapping general crop status. Adoption of sophisticated technologies is, however, often connected with higher investment costs, labour costs, expertise, and insecure economic benefits.

Overall, expensive technology, unsecured profit and economic challenges can be considered among the most important reasons for the limited adoption of advanced PA technologies. An acceleration of PA adoption would require more intense intervention in terms of investment support or other agricultural policies.

Legal and policy barriers

In relation to supporting PA, there is a lack of targeted policy support across the majority of EU countries. For instance, the first version of the CAP Strategic Plan (2022) in the Czech Republic included an eco-scheme targeted to PA. This measure aimed to promote the adoption of variable-rate fertiliser use. However, this eco-scheme could not be ultimately implemented due to challenges in establishing controllable policy criteria. The policy requirement of controllable criteria turned out to be in conflict with the significant flexibility that PA adoption at the farm level requires. In the finalised version of the CAP Strategic Plan (Ministry of Agriculture, 2024), the policy support through eco-scheme targeted to PA was removed, while all other relevant policy measures such as technology investments, knowledge and information sharing, advisory services, and cooperation remain in place. In the EU, only Belgium-Flanders, Sweden and Italy introduced eco-scheme targeted to PA. It is probable that the challenge of controllable criteria for such type of an eco-scheme was common to more countries.

The introduction of digital agriculture presents several legal and regulatory challenges. There are several targeted databases based on data collection in agriculture (IACS, LPIS, FADN). From a technological standpoint, key issues include compatibility and interoperability problems that may hinder technological advancement, adoption rates of digital technology, and adequate data infrastructures on farms that are not equipped for data sharing. Additionally, there is significant brand protection by large companies, leading to vendor lock-in, along with poor compliance with standards for software development and data formats. Other challenges involve the sharing of data, the business models related to data management, and strategies for interconnectivity. Common standards, connectivity, and interoperability are critical issues in this field. Rural wireless and broadband coverage are often inconsistent, and the standards for sensor networks are still being developed, while specialised agricultural software is still evolving. Additionally, the large variety of rural environments and stakeholders complicates the situation.

Rural areas, particularly in marginalised uplands, generally lag behind urban areas in broadband deployment, which is essential for the effective use of digital data in farming (European Parliament, 2017). Interoperability at the country and EU level is currently facing significant challenges, including suboptimal functionalities and technical limitations. There are gaps in the EU's informational architecture, a complex legal and policy landscape, and a degree of fragmentation in EU data management. Furthermore, rural areas often struggle with poor broadband availability, making high-speed connectivity essential not only for farmers but for the entire rural economy (European Parliament, 2017).

Additionally, there are two critical legislative barriers that hinder the adoption of advanced agricultural technologies by farmers and land managers. The first challenge involves regulations governing the use of autonomous field robots. Current laws mandate that these robots operate within confined areas or under constant operator supervision, which limits their potential for widespread use (Hruška and Roubík, 2024). These requirements stem from unclear and inconsistent regulatory frameworks, creating uncertainty among farmers and stakeholders. As a result, autonomous field robots remain largely confined to research or demonstration environments rather than being integrated into mainstream agricultural practices where they could enhance productivity, efficiency, and sustainability. By limiting their operational autonomy, these regulations prevent farmers from fully benefiting from technological innovations that could address labour shortages and improve resource use.

The second issue arises from the prohibition of aerial pesticide applications, which blocks the use of drones as one of the core precision agriculture tools designed to optimize the use of pesticides in fields. The fully legitimate intent of this ban is to ensure environmental and public safety (Zwetsloot et al., 2018). However it inadvertently restricts access to technologies capable of reducing chemical use, minimizing waste, and improving crop management due to the low impact nature of the applications on crops. Together, these legislative challenges impede innovation and limit the farmers and land managers´ ability to be competitive globally in the agricultural sector. Addressing the regulatory obstacles through clearer, risk-based frameworks and supportive policies will be key to unlocking the full potential of the technologies, empowering the farmers' access to digital precision tools and enhancing the sustainability in the sector.

Challenges of small farm size

An example of digitalisation challenges in agriculture dominated by small family farms can be drawn from Polish situation. Farms of 50 ha or more account for only 2.5% of the total number of farms but cover about 31% of the agricultural land (Petrovic et al., 2024). This poses limitations in precision agriculture adoption. Installation of expensive technologies and provision of advanced data analysis is often conducted by specialised agricultural services.

Currently in Poland, Global Navigation Satellite Systems (GNSS) is the most used tool of PA, followed by auto section control of spreaders, sprayers, and planters on medium-size farms. Some companies have started to offer satellite image processing through website applications to estimate biomass production and yield potential and create maps, especially for variable-rate nitrogen application. Some companies provide services for mapping of soil electrical conductivity to sample soil by management zone, while the largest farms are using software based on GNSS technology to improve the working efficiency of tractors and machinery. In some universities and technical and agricultural secondary schools, there are improvements in teaching PA (Petrovic et al., 2024).

The challenge of the digital divide

A comparative study by Butu et al. (2024) highlights Romania as an illustrative case of socio-economic barriers in precision agriculture. Romanian farmers face significant hurdles, including limited access to financing for advanced technologies and a lack of targeted policy support. Compared to their Western European counterparts, Romanian farmers struggle with fragmented landholdings, which impede the efficient deployment of digital tools. Moreover, digital literacy programs are scarce, leaving many farmers unable to harness available technologies. These factors collectively slow Romania's agricultural modernization, highlighting the critical need for tailored financial and educational initiatives.

An educational challenge

Hungary's experience sheds light on the educational, economic and social hurdles faced by small-scale farmers. Balogh et al. (2021) identify comparatively farm sizes, fragmented land ownership, and limited access to credit as major obstacles to adopting precision agriculture tools in case of the small-scale farms. Furthermore, those farmers often lack digital literacy, reducing their capacity to implement sophisticated technologies. These challenges seem less apparent in case of most large-scale farmers who farm most of the arable land. The education capabilities as well as willingness to implement precision tools result in a situation where undertrained farmers with large farms remain the second most open group for technology implementation (Balogh et al., 2021). The resulting disparity highlights the specific context of former eastern bloc countries and the need for effective government actions mitigating this divide.

3.5 DIGITAL SOLUTIONS FOR AGRICULTURE

3.5.1 ROLE OF PRECISION AGRICULTURE, IOT, AND AI IN ENHANCING AGRICULTURAL EFFICIENCY

Precision agriculture uses technology to monitor, measure, and manage variability in fields, ensuring optimal use of resources such as water, fertilizers, and pesticides. By utilizing GPS-guided equipment, remote sensing, and soil sampling, PA allows for precise targeting of inputs, replacing the broad applications with more targeted ones, and reducing the size of known elements on the field. For example, variable rate technology (VRT) adjusts fertilizer application rates based on real-time data, reducing waste and enhancing crop yields (Pawase et al., 2023). Furthermore, PA minimizes environmental impact by optimizing resource use and non-target application overlap. Studies in the EU have demonstrated that precision techniques can significantly reduce greenhouse gas emissions and improve soil health. Farmers adopting PA technologies achieve significant reductions in both input costs and an increase in overall productivity, showcasing its potential to revolutionize efficiency and bolster sustainability (Balafoutis et al., 2017).

IoT has emerged as one of the core tools of modern agriculture, enabling real-time monitoring and automation. Smart sensors embedded in fields collect data on soil moisture, temperature, and weather conditions, which are transmitted to central systems for analysis. This information enables timely irrigation, pest control, and harvest planning, reducing manual labour and increasing operational efficiency (Farooq et al., 2020). IoT devices can also play a vital role in the predictive maintenance of equipment. For instance, smart tractors equipped with IoT sensors can detect potential mechanical issues before they lead to costly downtime. Additionally, connected supply chains powered by IoT provide a broad source of data for optimization of production processes and reduction of post-harvest losses (Awan et al., 2021).

AI enhances decision-making by analysing vast amounts of agricultural data and providing actionable insights. Machine learning algorithms predict crop diseases, optimize planting schedules, and assess market trends, allowing farmers to make informed choices. For instance, AI-driven image recognition identifies pest and weed infestations early, reducing the need for broad-spectrum pesticide applications and improving crop health (Muppala & Guruviah, 2020). AI can also be further integrated with IoT tools to enhance automation (De Abreu & van Deventer, 2022).

Autonomous drones and robots equipped with AI capabilities can potentially perform tasks such as planting, spraying, and harvesting with precision, reducing labour costs and avoiding human error (Martin et al., 2022). This capability would need to be reconciled with environmental risks in spraying with agrochemicals. In addition, AI systems can enable precision livestock farming by monitoring animal health and optimizing feeding strategies, further improving efficiency and sustainability (Brandon & Bommu, 2022).

Despite its potential, the adoption of these technologies depends on data harmonization and aggregation, the development of one-stop-shop, and overcoming key challenges such as high initial costs, lack of digital literacy among farmers, legal constraints, and issues of interoperability. However, EU initiatives like the European Green Deal and Horizon Europe promote the transition toward the integration of digital solutions in agriculture. Looking ahead, the convergence of precision agriculture, IoT, and AI is set to redefine agricultural practices. Collaborative efforts between policymakers, tech developers, and farmers are critical to realizing the full potential of these technologies in building a resilient and efficient agricultural sector.

3.5.2 ANALYSIS OF SUCCESSFUL CASE STUDIES IN DIGITAL ADOPTION

Digital technologies have transformed agricultural practices worldwide, offering valuable insights for the European Union. This section thoroughly examines successful case studies from individual countries, focusing on their strategies and lessons for fostering digital adoption in agriculture.

3.5.2.1 NETHERLANDS: PRECISION AGRICULTURE

The Netherlands has emerged as a leader in precision agriculture, leveraging advanced technologies such as GPS-guided equipment, drones, and soil sensors to optimise agricultural inputs and outputs. These technologies have resulted in a 20-30% decrease in fertiliser and pesticide usage, concurrently enhancing crop yields through precise field management. Farmers stand to benefit from real-time data analysis of soil conditions and weather patterns, facilitating sustainable resource allocation. The Dutch experience underscores the importance of investing in advanced technologies and offering training programs to equip farmers with the necessary skills to operate them effectively.

3.5.2.2 DENMARK: IOT AND SMART FARMING

Denmark has effectively incorporated IoT technologies into its dairy and crop sectors. Smart sensors have been employed to monitor soil moisture, resulting in a 50% reduction in water usage for irrigation. Additionally, real-time livestock monitoring has improved animal health and productivity. The success of this initiative can be attributed, in no small part, to the robust public-private partnerships that have facilitated funding and the scaling of IoT adoption, ensuring its accessibility even to smaller farms. Denmark's success underscores the necessity for developing collaborative frameworks to disseminate digital farming practices throughout rural regions within the European Union.

3.5.2.3 ITALY: AI IN VINEYARD MANAGEMENT

Italian vineyards have adopted AI-driven platforms for the management of pests and the optimisation of harvests. Machine learning models analyse climate data and pest patterns, reducing chemical use by up to 40% while improving grape quality and yield consistency. Initial resistance to adopting AI was addressed through government-subsidised training programs, which equipped farmers with the skills and confidence to utilise the new technology. Italy's experience demonstrates that targeted educational support can facilitate the integration of advanced technologies into traditional agricultural systems.

3.5.2.4 INDIA: DIGITAL COOPERATIVES FOR SMALLHOLDERS

Despite its geographical location outside the European Union, India's success in establishing digital cooperatives among smallholder farmers offers a valuable model for consideration. Mobile platforms have played a pivotal role in enabling farmers to access vital information, including market data, weather forecasts, and collective purchasing systems. This has led to a significant reduction in input costs and an enhancement in market access for farmers. It further impacted farmers' incomes, which resulted in a substantial enhancement in their economic well-being. The potential benefits of such cooperative approaches extend to smallholder farmers in southern Europe, where challenges such as resource constraints and fragmented land ownership are prevalent.

3.5.2.5 SPAIN: BLOCKCHAIN FOR SUPPLY CHAIN TRANSPARENCY

Spain has effectively integrated blockchain technology into its olive oil supply chain, enhancing traceability and ensuring adherence to sustainability standards. This technological integration has yielded several notable benefits, including fostering consumer trust through transparent labelling and streamlining administrative processes. The system's interoperability in Spain has been enhanced by the standardisation of blockchain protocols, facilitating widespread adoption. The success of this initiative underscores the importance of adopting harmonised digital standards across the European Union to ensure the seamless integration of such technologies.

4 SCIENTIFIC AND STRATEGIC PERSPECTIVES

4.1 INSIGHTS ON FOOD SECURITY AND AGROCHAMICAL INDEPENDENCE

4.1.1 RESEARCH ON SUSTAINABLE ALTERNATIVES: ORGANIC FERTILIZERS

Ensuring food security within the EU requires a resilient agricultural system that can sustainably produce sufficient food while minimizing external dependencies. The shift toward organic fertilizers directly supports this goal by reducing reliance on imported synthetic fertilizers, which are vulnerable to supply chain disruptions and price volatility. By enhancing soil fertility, organic fertilizers contribute to stable crop yields, ensuring long-term agricultural productivity in the EU. The European Union actively researches and promotes organic fertilizers derived from various biomass sources as part of its sustainable agriculture policy. Organic fertilizers, such as those produced from animal manure, sewage sludge, municipal solid waste, food waste, and insect frass, offer viable alternatives to traditional synthetic fertilizers, often associated with negative environmental impacts, including high carbon emissions and soil degradation.

The EU has placed significant emphasis on transitioning to more sustainable agricultural practices, which include reducing reliance on synthetic fertilizers and improving soil health. These organic fertilizers improve soil structure, enhance microbial activity and improve crop nutrient availability. They are integral to regenerative farming techniques that restore soil fertility and increase agricultural biodiversity. By improving soil health, organic fertilizers also contribute to carbon sequestration, an essential component of the EU's efforts to combat climate change. The EU's Green Deal and Farm to Fork Strategy highlight the importance of reducing greenhouse gas emissions and promoting practices that support the environment, further accelerating the adoption of organic fertilizers.

Innovative amendments such as biochar, fermented grass, and manure are also gaining traction in Europe, particularly in regions focused on agroecological approaches. Combined with cover crops and diversified crop rotations, these practices can help reduce soil erosion, improve nutrient cycling, and increase yields. Biochar, derived from plant biomass through pyrolysis, is particularly noteworthy as it improves soil structure, increases water retention, and sequesters carbon for long periods, providing additional benefits to European farmers. Insect frass, a relatively new organic fertilizer, is also attracting interest in the EU. A by-product of breeding insects for food and feed production, insect frass is rich in nutrients and can be easily absorbed by plants. Its use reduces waste and improves plant growth, pest resistance and tolerance to environmental stresses, which aligns with the EU's vision for more circular and sustainable food systems.

These innovations contribute to the EU's broader agricultural goals, including improving food security, reducing agriculture's environmental footprint, and supporting a circular economy. The move towards organic fertilizers is in line with EU regulations that encourage sustainable agriculture and the reduction of chemical inputs. As part of its Green Deal and Common Agricultural Policy, the

EU invests in research and development of these sustainable technologies and practices to ensure that European agriculture becomes more resilient, sustainable and in line with global climate goals. The EU is positioning itself as a leader in sustainable agricultural practices by promoting organic fertilizers and other innovative changes. This shift supports the development of a circular economy in agriculture, reduces dependence on fossil fuel-based synthetic fertilizers, contributes to climate change mitigation, and ultimately fosters a more resilient and environmentally friendly agricultural system across the continent.

Organic fertilisers in sustainable agriculture

Organic fertilisers, derived from various natural sources such as plant residues, animal manure, compost, and green manures, represent a critical tool in sustainable agriculture. These fertilisers are ecologically sound alternatives to synthetic fertilisers, often contributing to environmental degradation, such as nutrient leaching into groundwater, soil erosion, and reduced soil fertility. On the other hand, organic fertilisers positively impact soil health by improving soil structure, boosting microbial activity, and increasing water retention. They also provide essential nutrients more gradually and sustainably, ensuring long-term fertility. Liquid organic manures (LOM) such as dairy, pig, and biogas slurries are produced in particular in intensive livestock farming and fermentation in biogas plants. Nutrient levels in liquid organic manures vary greatly, so it is important to use advanced technologies to determine the concentrations before field application in order to ensure that fertilisation is tailored to the crop requirements (Höpker et al. 2025). Precise knowledge of the nutrient content in LOMs is a basic prerequisite for the optimum supply of these nutrients to crops and for avoiding environmental problems caused by over-fertilisation.

The constituents of LOMs can be determined on site using near infrared spectroscopy (NIRS). NIRS sensor mounted directly on application tank allows the application rate to be adjusted on the go according to the measured nutrient concentrations in the LOM and the amount of nutrients applied is also automatically documented. Based on previously created application maps, variable nutrient application within a field is also possible (Stenberg and Gustafsson 2013, Höpker et al., 2025). Digital innovations are increasingly being integrated into sustainable farming practices to optimize the efficiency of organic fertilizers. Precision agriculture technologies, including remote sensing, GPS-guided Variable Rate Application (VRA), and artificial intelligence-driven soil analysis, allow farmers to apply organic fertilizers in a more targeted manner. These technologies ensure that crops receive the right amount of nutrients at the right time, reducing waste and improving overall soil health. Smart farm management systems, which integrate weather forecasts, soil moisture sensors, and satellite imagery, also help farmers make data-driven decisions to maximize fertilizer efficiency while minimizing environmental impact.

Unlike their synthetic counterparts, organic fertilisers are not only beneficial to plants but also to the broader ecosystem. When applied to the soil, they enhance its biological activity, enriching it with beneficial microorganisms that help decompose organic matter and release nutrients. This improved soil biodiversity is key to making the soil more resilient, reducing the risk of soil-borne diseases, and improving crop productivity.

The uptake of organic farming was more pronounced in some EU countries than in others (see figure below). The highest proportion of fully organic holdings was found in Austria (21.8%), followed by Estonia (16.4%) and the Czech Republic (15.4%). In Hungary, Poland, and Malta, less than 0.5% of all agricultural holdings are fully organic.

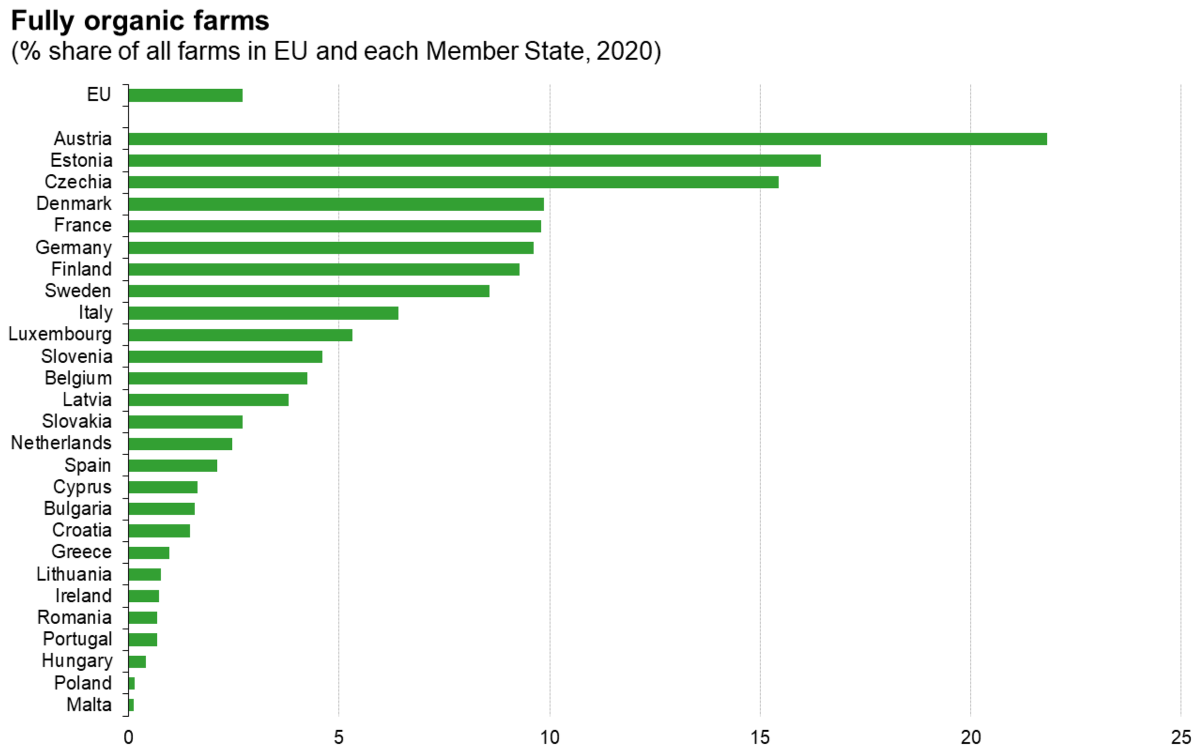

FIGURE 14: FULLY ORGANIC FARMS . SOURCE: EUROSTAT

Current research in the field of organic fertilisers is focused on several critical areas to optimise their effectiveness and scalability in agricultural systems, particularly within the EU context:

Optimisation of raw materials

Researchers are working on refining the nutrient content and consistency of organic fertilisers. One of the key challenges is ensuring that organic fertilisers provide a balanced nutrient profile and a consistent release of nutrients over time. Scientists are investigating novel ways to improve the nutrient release rates of organic fertilisers, making them more efficient and effective for crop growth. This includes enhancing the ability of organic fertilisers to release nitrogen, phosphorus, and potassium at the appropriate times to meet plant demands. There is also a focus on minimising the potential for contamination with harmful substances, such as heavy metals and ensuring the overall safety and sustainability of organic fertilisers. In addition, improvements in the production processes of these fertilisers, including the development of more energy-efficient and cost-effective methods, are critical for ensuring their viability in large-scale agricultural practices.

Integration with other sustainable practices

Organic fertilisers are most effective when integrated into a broader suite of sustainable farming practices. These include crop rotation, reduced tillage, and cover cropping, all working together to improve soil fertility and maintain ecological balance. Crop rotation, for example, helps prevent soil depletion by varying the nutrient demands of different crops, while cover cropping protects the soil from erosion and improves its structure. Reduced tillage minimises soil disturbance and enhances the soil's organic matter content and water retention. By combining organic fertilisers with these practices, farmers can create farming systems that increase crop yields, promote biodiversity, prevent pest outbreaks, and improve resilience to climate change.

In the EU, where sustainable agriculture is a significant priority, these integrative approaches align with EU policies such as the Green Deal, which aims to reduce pesticide use and enhance biodiversity. The synergy between organic fertilisers and sustainable farming practices is essential for achieving the EU's environmental goals, including soil health preservation and reducing greenhouse gas emissions from agriculture.

Economic feasibility and scalability

Despite the significant ecological benefits of organic fertilisers, their economic feasibility and scalability challenges remain. The production of organic fertilisers can be more costly than synthetic fertilisers, mainly due to the labour-intensive nature of sourcing and processing raw materials. Additionally, large-scale logistics, such as transporting organic materials to farms and managing large quantities of waste, pose further barriers to widespread adoption. As a result, there is a need for cost-effective solutions to make organic fertilisers more accessible to farmers, particularly small and medium-sized enterprises across the EU.

Developing local production systems for organic fertilisers is critical to address these challenges. By utilising local agricultural waste and organic matter, farmers can reduce transportation costs and improve the sustainability of their farming systems. Furthermore, innovations in technology, such as automated composting or bioconversion processes, could help streamline the production of organic fertilisers, making them more affordable and scalable. Efforts to subsidise organic fertilisers or provide financial incentives for farmers to transition to sustainable farming practices are also being considered at the EU level.

The EU's Common Agricultural Policy supports the transition to organic farming. Through CAP, the EU provides funding for research and development and subsidies for farmers adopting sustainable practices, including using organic fertilisers. However, for the widespread adoption of organic fertilisers to become more feasible, further investments are required in infrastructure, research, and training to ensure that farmers can successfully integrate these fertilisers into their operations. A more widespread adoption of organic fertilizers will strengthen the EU's food security by reducing reliance on external agricultural inputs and promoting self-sufficient farming systems. By leveraging locally available organic waste to produce fertilizers, EU agriculture can mitigate risks associated with geopolitical tensions, trade restrictions, and supply chain disruptions, ensuring that food production remains stable and resilient.

The role of organic fertilizers in circular agriculture

The use of organic fertilisers aligns with the concept of circular agriculture, a key principle of the EU's agricultural strategy. Circular agriculture focuses on creating closed-loop systems where waste products are recycled and reused, reducing the need for external inputs and minimising environmental impact. Organic fertilisers, such as food waste, livestock manure, or agricultural byproducts, can be produced and used locally, reducing the need for synthetic fertilisers and fossil fuel-based inputs. This circular model not only supports the sustainability of farming systems but also contributes to waste reduction, energy savings, and the conservation of resources.

In conclusion, while organic fertilisers offer significant ecological and agricultural benefits, further research, policy support, and infrastructural development are essential to overcoming the challenges that currently limit their widespread adoption, especially in the EU. The EU can continue fostering more sustainable and resilient agricultural systems by optimising raw materials, integrating organic fertilisers with other sustainable farming practices, and addressing economic and logistical challenges. The transition to organic fertilisers will play a critical role in achieving the EU's broader sustainability goals, ensuring food security, and mitigating the environmental impact of agriculture.

4.1.2 RESEARCH ON SUSTAINABLE ALTERNATIVES: BIOFERTILIZERS

Biofertilizers are increasingly considered sustainable alternatives to chemical fertilizers, especially in European agriculture. They provide a promising approach to improving soil fertility, enhancing plant growth, and boosting crop productivity while being environmentally friendly and cost-effective (Bhardwaj et al., 2014; Nosheen et al., 2021). In Europe, where agricultural practices are moving toward sustainability, the use of biofertilizers aligns with EU policies aimed at reducing chemical fertilizer dependence, minimizing environmental pollution, and fostering organic farming systems.

Research on biofertilizers has evolved significantly in recent years. Initially, much of the focus was on nitrogen fixation, crucial in enriching soil nitrogen content (Zhao et al., 2023). However, the scope of research has expanded to explore additional mechanisms through which biofertilizers can enhance plant yield, improve soil health, and even mitigate the negative impacts of climate change, a pressing issue for European agriculture. As Europe faces increasing challenges from climate variability, such as droughts and temperature fluctuations, biofertilizers' ability to enhance plant tolerance to abiotic stress has become particularly relevant.

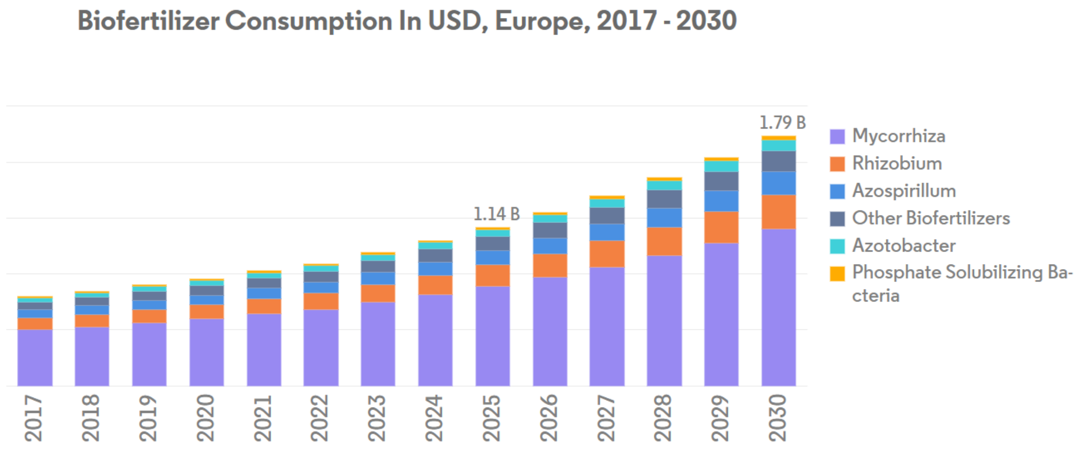

FIGURE 15: BIOFERTILIZERS CONSUMPTION IN EUROPE. SOURCE: MORDOR INTELLIGENCE

The most commonly used microorganisms as biofertilizers in agriculture include mycorrhiza, azospirillum, azotobacter, rhizobium, and phosphate-solubilizing bacteria (Zhao et al., 2023).

Among these biofertilizers, mycorrhiza is the most widely used in Europe, accounting for a market share of 62.8% in 2022, valued at USD 549.5 million. Mycorrhiza is a fungus that forms a symbiotic relationship with a plant's root system. It increases the root surface area of plants, thereby improving their nutrient uptake.

Rhizobium is the most critical nitrogen-fixing bacterium that forms a symbiotic relationship with plants and lives in the root nodules of leguminous plants. Rhizobium is the second most consumed biofertilizer in the region, with a share of 13.2% in 2022.

The European Union plans to shift to sustainable vegetable protein production by expanding the area under legumes.

Azospirillum and Azotobacter are free-living nitrogen-fixing bacteria that can fix atmospheric nitrogen and make it available to plants non-symbiotically. Biological nitrogen fixation contributes to soil fertility and plant productivity. The use of Azotobacter is expected to grow in Europe due to the increasing demand for food production (Mahmud et al., 2021).

In this way, biofertilizers contribute to yield improvement and reducing pesticide use, aligning with the EU's Green Deal objectives.

Biofertilizers function through both direct and indirect mechanisms. Directly, they can produce phytohormones, which stimulate plant growth and solubilize essential nutrients, making them more available to plants. Indirectly, they promote disease resistance by outcompeting harmful pathogens and activating plant defence mechanisms (Mahmud et al., 2021). However, their effectiveness depends on various factors, including the type of crop, the specific inoculants used, and the environmental conditions in which they are applied (Mahmud et al., 2021). This is important in Europe, where diverse climates and crop systems exist, requiring tailored biofertilizer solutions.

For the EU, the widespread adoption of biofertilizers offers a sustainable route to achieving food security and increasing the resilience of agricultural systems. With the EU's emphasis on reducing synthetic chemical inputs and transitioning to more organic and regenerative farming methods, biofertilizers can play a key role in meeting these goals. Moreover, their potential to sustainably increase agricultural productivity is critical for ensuring the region can feed its growing population while minimizing negative environmental impacts (Nosheen et al., 2021). Given the EU's regulatory framework, which encourages innovation and environmentally friendly practices, biofertilizers are poised to become a cornerstone of the future of European agriculture.

4.1.3 RESEARCH ON SUSTAINABLE ALTERNATIVES: NUTRIENT CYCLING

A sustainable nutrient cycle is critical for achieving environmental targets, as is evident in the recent global sustainable development goals or in the EU's green and circular economy strategies. Promoters of better nutrient management are agroforestry, diversified cropping systems, cover crops, crop rotation, organic amendments, livestock integration, and nutrient recovery from urban and peri-urban waste. Digital solutions enable these practices by providing real-time monitoring and data-driven decision-making solutions. For instance, Soils with accurate data about soil health and macro and micronutrient contents are being supported and monitored by satellite imagery, drone and IoT sensors that optimize the agroforestry systems and crop rotations. In organic agriculture, digital tools like nutrient sensors and AI-based suggestions facilitate the precise application of organic inputs such as compost and manure.

In urban areas, digital technologies support nutrient recovery from waste by monitoring organic waste streams and providing insights into nutrient content. Precision farming technologies, including real-time soil nutrient monitoring and AI-driven systems, are instrumental in reducing nitrogen pollution and improving overall soil health. Such technology solutions can be helpful in areas with low connectivity where offline aggregation and data collection facilities ensure the farmers get the essential information required to use sustainable practices correctly. The table 8 highlights the role of digital solutions in enhancing sustainable nutrient cycling practices across EU agriculture. It outlines how various digital tools and technologies support the implementation and efficiency of key practices aimed at improving soil health, reducing nutrient loss, and promoting sustainable farming.

TABLE 7: DIGITAL SOLUTIONS SUPPORTING SUSTAINABLE NUTRIENT CYCLING PRACTICES IN EU AGRICULTURE

Sustainable practice	Digital solutions	Role of digital solutions
Agroforestry and crop diversification	Satellite imagery, Drones, IoT sensors	Monitor and manage landscape features, optimize nutrient cycling and soil health with real-time data, and support offline data processing in regions with limited connectivity.
Cover crops and crop rotation	Soil moisture sensors, Remote sensing technologies, AI analytics	Provide real-time insights into soil conditions, optimize crop rotation schedules, and manage cover crops, even in low-connectivity areas through data aggregation and offline storage.
Organic amendments and livestock integration	IoT sensors, AI-based recommendation systems, Digital nutrient tracking tools	Monitor nutrient content in organic fertilizers, suggest optimal application methods, and track nutrient cycles, even in areas with limited infrastructure.
Urban and peri-urban nutrient recovery	AI analytics, IoT sensors, Data aggregation platforms	Optimize nutrient recovery from waste streams, monitor real-time data for nutrient recovery processes, and ensure efficiency in areas with limited digital infrastructure.
Composting and biochar integration	Real-time composting condition sensors, AI-driven monitoring systems	Monitor nitrogen levels and composting conditions, suggest optimal environments for composting and biochar, ensuring efficiency and sustainable soil management.
Nitrogen management and EU Directives	Precision farming tools, Real-time soil monitoring, Nitrogen-fixing bacteria applications, Data aggregation systems	Support precision nitrogen application, optimize nutrient use for crop yield, and provide real-time monitoring, including in areas with limited connectivity.

4.2 IMPACTS OF AGROCHEMICAL REDUCTION ON CROP YIELDS

Reducing the use of agrochemicals, a key aspect of achieving agricultural self-sufficiency and sustainability in the EU profoundly impacts crop yields and soil health. Agrochemicals, such as synthetic fertilizers, pesticides and herbicides, have historically played a key role in increasing agricultural productivity. However, their overuse has led to environmental degradation, depletion of soil nutrients, and loss of biodiversity, prompting a shift toward more sustainable practices. Below is a detailed analysis of the impacts.

Short-term effects

In the short term, the reduction of synthetic fertilizers and pesticides can result in a decline in crop yields. These inputs are crucial for optimal plant growth and protection against pests, diseases, and weeds. Fertilizers provide essential nutrients, while pesticides safeguard crops from potential damage. Without these inputs, crops may experience stunted growth, nutrient deficiencies, and increased susceptibility to pests and environmental stress, ultimately leading to lower productivity. Although alternative pest management strategies and sustainable practices may help alleviate some of these issues, the immediate impact on yields can be substantial, especially in regions that rely heavily on high-output farming (Zhang et al., 2015). Moreover, the absence of synthetic fertilizers can lead to nutrient imbalances, with crops depending on them for macronutrients like nitrogen, phosphorus, and potassium, resulting in poor growth and diminished productivity.

Long-term effects

On the other hand, long-term effects of reducing agrochemical inputs can yield more positive outcomes, though the transition can be challenging. As soils adapt to reduced chemical inputs, crop yields may stabilize or even improve, especially when practices such as organic farming and improved nutrient management are adopted. These practices promote soil health, enhance biodiversity, and improve nutrient cycling, supporting long-term productivity (Zhang et al., 2015). However, the transition period can be challenging, requiring significant investments in new knowledge, technology, and skills, which could cause temporary fluctuations in crop yields (Altieri & Nicholls, 2013). Over time, this shift is expected to yield more stable and sustainable systems.

Moreover, diversified farming systems and integrated pest management can contribute to increased resilience against climate variability. These systems promote biodiversity and strengthen natural pest control, reducing dependency on agrochemicals. Over the long term, the benefits include enhanced soil health, better pest management, and a lower risk of crop failure due to environmental stresses (Seufert & Ramakutty, 2017). By integrating diverse crops and natural pest management strategies, farmers are better equipped to adapt to changing climate conditions while maintaining productivity.

4.3 INTERNATIONAL STRATEGY PLANS: INSIGHTS FROM GLOBAL PRACTICES

4.3.1 KEY GLOBAL STRATEGIES FOR SUSTAINABLE AND RESILIENT AGRICULTURE

There has been a mounting imperative to reevaluate agricultural policies in contemporary global events. A prevailing discourse has centred on intensification rather than sustainability (Timpanaro et al., 2023). However, evidence suggests that sustainable and competitive agriculture are not mutually exclusive, provided that sound agronomic practices and territorial strategies are implemented (Timpanaro et al., 2023). To address emerging challenges, precision conservation agriculture, digital agriculture, and resilient farming methods have been identified as crucial for maintaining agricultural productivity (Ali & Dahlhaus, 2022). Sustainability remains central to enhancing the resilience of farming systems, emphasizing improved resource use efficiency, landscape-scale resilience approaches, and integrated crop-livestock systems (Popescu et al., 2023). Achieving sustainable and resilient agriculture is a shared global goal, and numerous countries and organizations have implemented innovative strategies to tackle agricultural challenges while promoting sustainability and food security (Webb et al., 2017). This section outlines key international strategy plans and best practices that can inform EU efforts to enhance farm independence and resilience.

Adopting Climate-Smart Agriculture (CSA)

The United Nations Food and Agriculture Organization has advanced the concept of climate-smart agriculture, an integrated approach that aims to enhance productivity, adapt to climate change, and reduce greenhouse gas emissions. The following strategies are key components of this approach:

- **Precision agriculture**: The utilization of advanced technologies, including remote sensing, GPS mapping, and the Internet of Things (IoT), facilitates the optimization of resource utilization and the enhancement of agricultural yields.
- **Agroforestry**: Integrating agricultural and forestry practices is a strategy to enhance soil fertility, mitigate erosion, and augment carbon sequestration.
- **Climate-resilient crops**: Developing and deploying crop varieties with enhanced tolerance to drought, pests, and extreme weather conditions.

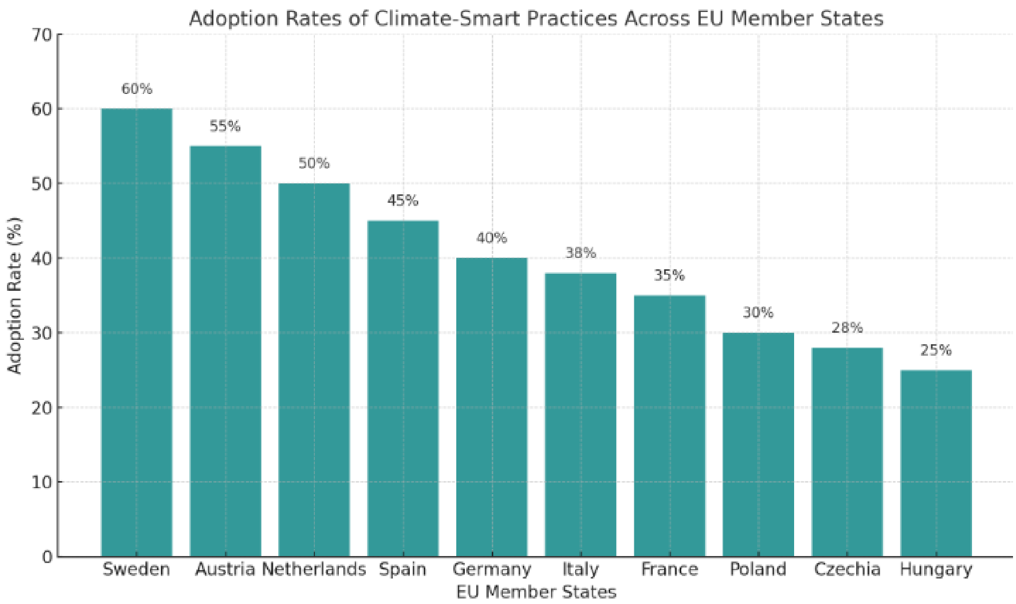

FIGURE 16: ADOPTION OF CSA ACROSS THE EU MEMBER STATES. SOURCES: EUROSTAT

Figure 16 illustrates the adoption rates of climate-smart agricultural practices across selected EU member states, ranked from highest to lowest. Sweden leads with a 60% adoption rate, reflecting the significant integration of sustainable methods like agroforestry and carbon farming. Austria and the Netherlands follow closely, indicating proactive efforts toward environmental sustainability. Conversely, Hungary and Czechia show lower adoption rates, suggesting potential barriers such as limited resources or differing policy priorities.

Nutrient management plans and soil health initiatives

Nutrient management focuses on reducing dependence on chemical fertilizers while promoting soil health. One example is India's Soil Health Card Scheme, which provides farmers with tailored advice on fertilizer use, helping them optimize nutrient application and restore soil vitality. Additionally, using organic fertilizers, composting, and crop rotation is crucial in enhancing soil quality and maintaining long-term soil fertility. Furthermore, cover cropping and no-till farming are encouraged to reduce soil erosion, improve soil structure, and enhance biodiversity, all of which contribute to a more sustainable and resilient agricultural system.

Integrated water resource management

Water scarcity poses a significant challenge to global agriculture, and countries like Israel have developed innovative water management strategies that can serve as models for others. One key method is drip irrigation, a precision technique that maximizes water efficiency by delivering water directly to the roots of plants. Additionally, Israel has implemented desalination technologies to transform seawater into usable irrigation water, addressing water shortages in arid regions. Another important practice is using recycled wastewater, which involves treating and reusing wastewater for agricultural purposes, reducing the demand for freshwater and promoting sustainable water usage in farming.

Digital transformation in agriculture

Digital tools have profoundly transformed agricultural practices on a global scale, with notable examples including:

- **India's e-Choupal Initiative**: This digital platform offers rural farmers essential information, including market trends, weather forecasts, and optimal agricultural practices.
- **The Netherlands' AgTech Innovations**: The country has extensively used greenhouse automation, artificial intelligence (AI) based yield forecasting, and vertical farming.
- **Data-Driven platforms**: Initiatives like Kenya's M-Farm connect smallholders to markets and provide real-time pricing information.

Promoting organic and regenerative farming

Several countries have adopted national programs to promote organic and regenerative agriculture, which emphasize biodiversity and long-term soil health:

- **Denmark**: With its ambitious organic farming targets, Denmark supports conversion subsidies and extensive research on organic methods.
- **Costa Rica**: Known for its regenerative practices, Costa Rica integrates agroecological principles to balance productivity and environmental health.

Global policies to safeguard food security

- **The African Union's Malabo Declaration**: The primary focus of this initiative is to promote agricultural growth and ensure food security through investments in sustainable farming practices and value-chain development.
- **US Farm Bill**: The organization supports research in sustainable practices and provides subsidies to incentivize environmentally friendly farming.
- **EU's Green Deal and Farm-to-Fork Strategy**: Despite their internal nature within the European Union, these initiatives establish a framework for global collaboration on sustainable food systems.

4.3.2 LESSONS FOR EU AGRICULTURAL INDEPENDENCE

Achieving agricultural independence within the European Union necessitates a comprehensive understanding of the internal and external factors influencing food security and resilience. The EU benefits from insights from ongoing and planned international strategy plans. These insights can serve as a compass, guiding the EU in addressing its reliance on imports, ensuring the stability of its agricultural sector, and fostering sustainable practices. The ensuing sections outline key domains that offer insights into the advancement of EU agricultural autonomy.

Diversification of input sources

The EU's reliance on imported agrochemicals, seeds, and other farming inputs is a substantial hurdle to achieving agricultural autonomy. International strategies underscore the significance of diversifying input sources to mitigate risks associated with supply chain disruptions. For instance:

- **Reducing dependency**: Promote domestic production of fertilisers and agrochemicals by supporting local industries and research.
- **Strategic reserves**: Establishing reserves for essential agricultural inputs protects against global supply shocks.
- **Global partnerships**: To ensure that alternative suppliers are secured, collaboration with non-EU countries is imperative. Moreover, cooperation with non-EU countries is essential to ensure that trade agreements align with EU sustainability and food security goals.

Strengthening internal food systems

International strategies underscore the imperative for resilient food systems capable of withstanding external shocks such as fluctuating global prices or geopolitical turbulence. The European Union (EU) stands to benefit from several key insights from these international strategies.

- **Local production enhancement**: The promotion of local food production should be pursued through the incentivisation of regional farming and the reduction of barriers faced by smallholders.
- **Circular economy in agriculture**: Adopting circular models prioritising resource utilisation, such as the recycling of nutrients and the reduction of waste, is imperative.
- **Market stability mechanisms**: Implementing safety nets, including price stabilisation funds and insurance programs, is crucial for safeguarding farmers against the adverse effects of market volatility.

Integration of digital solutions

A review of global examples demonstrates the transformative potential of digital solutions in agriculture. Nevertheless, the European Union faces substantial barriers to capitalising on these technologies.

- **Investment in infrastructure**: Expanding rural connectivity to ensure equal access to digital tools across all member states is crucial.
- **Capacity building**: Implementing training programs designed to enhance farmers' digital literacy is imperative, facilitating their capacity to utilise precision farming technologies.
- **Data governance**: The development of comprehensive policies about data privacy, standardisation, and interoperability is imperative to address farmers' concerns and establish confidence in utilising digital solutions.

Leveraging international trade policies

In pursuing agricultural independence, international trade policies play a pivotal role. The European Union may get benefits from the adoption of global best practices such as:

- **Protecting domestic agriculture**: Explore mechanisms to protect domestic producers from unfair competition.
- **Export growth**: Reinforce EU farmers' ability to access global markets for niche products to reduce reliance on imports.
- **Sustainable trade agreements**: Negotiate environmental and social standards agreements, balancing trade with sustainability goals.

Addressing socio-economic challenges

EU agriculture's socio-economic challenges, including price volatility and rising input costs, must be tackled to achieve independence. It can be achieved by:

- **Income diversification**: Support programs that help farmers diversify income sources via agro-tourism, renewable energy projects, or secondary crop cultivation.
- **Community-based resilience**: Promote cooperative farming models and community-driven solutions to enhance resilience at the local level.
- **Equity and inclusion**: Ensure policies address discrepancies among smallholders and large agribusinesses, facilitating a more equitable agricultural landscape.

Scaling leadership in sustainability and climate resilience

The European Union (EU) has established itself as a global leader in implementing sustainable agricultural practices. The EU's ambitious policies, including the European Green Deal, the Farm to Fork strategy, and the Climate Adaptation frameworks, have set a benchmark for other regions and organisations to emulate. The EU should prioritise expanding and refining these initiatives to strengthen its leadership further and ensure agricultural autonomy.

- **Expanding climate-smart practices**: The EU should continue promoting and funding climate-smart agriculture to strengthen its efforts further. This encompasses the promotion of innovations in crop varieties demonstrating resilience to climate extremes, the cultivation of agroforestry systems, and the expansion of carbon farming initiatives that provide incentives for farmers to sequester carbon in soils.
- **Enhancing soil health initiatives**: Programs like the EU Soil Mission should expand their reach, encouraging widespread adoption of cover cropping, no-till farming, and organic amendments to restore degraded soils.
- **Pioneering water-efficient agriculture**: With growing concerns over water scarcity, the EU should leverage its advanced technologies in precision irrigation and water management systems. This includes deploying real-time water monitoring tools and incentivising investments in water-saving infrastructure across member states.
- **Driving global collaboration**: As a leader, the EU can further influence global agricultural sustainability by sharing best practices and technologies with other regions. Strengthening partnerships with developing countries will enhance global resilience and support mutual goals of sustainable development.

4.3.3 NATIONAL STRATEGIES FOR NOSTRADAMUS PILOT SITES

4.3.3.1 GERMANY

Germany's agricultural policies prioritize technological innovation and sustainability to ensure food security and reduce dependence on external resources. A foundational element of these initiatives is the Digital Agenda for Agriculture, which aims to promote the adoption of precision farming through investments in the Internet of Things (IoT) technologies, smart sensors, and data-driven decision-making systems. However, the adoption of these technologies by smaller farms is hindered by the substantial costs of implementation and the paucity of technical expertise. Germany's strategy entails a commitment to curtailing its reliance on agrochemicals, as evidenced by the National Action Plan on the Sustainable Use of Plant Protection Products, which aims to reduce pesticide utilization by half by 2030. To further enhance sustainability, the Federal Organic Farming Program offers incentives for organic farming to achieve 30% of agricultural land under organic cultivation by 2030. Despite these advancements, price volatility in the global cereal market persists, inciting endeavours to diversify production and fortify domestic grain storage capacities (Federal Ministry of Food and Agriculture, n.d; Ahmed and Shakoor, 2025).

4.3.3.2 SERBIA

Notwithstanding its non-EU status, Serbia has been aligning its agricultural policies with EU standards to enhance trade opportunities and ensure food security. The National Agriculture and Rural Development Strategy for 2024 underscores the harmonization of Serbian agricultural exports with EU safety and sustainability standards facilitated by certification programs to enhance export readiness. Furthermore, Serbia has initiated programs such as the Digital Village Initiative, which aims to improve rural connectivity and introduce digital farming technologies. However, low digital literacy among farmers is a significant impediment. Serbia prioritizes expanding domestic cereal and oilseed production through state-guaranteed pricing and subsidies for modern irrigation systems and anti-hail nets to ensure food security and resilience to drought. However, the country's heavy reliance on EU imports of fertilizers and machinery renders it vulnerable to supply chain disruptions, underscoring the need for diversification in agricultural inputs (Government of Serbia, n.d).

4.3.3.3 SWITZERLAND

Switzerland's agricultural strategy is characterized by a commitment to self-sufficiency and sustainability, complemented by its reputation for technological leadership. The nation's strategic framework, delineated in the Agricultural Policy 2022+, prioritizes promoting local food production, organic farming practices, and initiatives to enhance soil health. The practice of crop rotation and the employment of compost-based fertilisation techniques further reinforces these initiatives. Notably, Switzerland's leadership in Agriculture 4.0, which integrates robotics, satellite imaging, and artificial intelligence into farming practices through public-private partnerships, is noteworthy.

These innovations are designed to enhance resource utilization and boost agricultural efficiency. However, Switzerland is confronted with escalating costs for imported agrarian inputs, including fertilizers and seeds, which can adversely impact production efficiency. Switzerland has diversified its trade agreements to reduce its reliance on the EU while maintaining stringent sustainability standards in its domestic policies (Federal Department of Economic Affairs, Education and Research (EAER). (n.d.).

4.3.3.4 SLOVENIA

Slovenia is committed to modernizing its agricultural sector while preserving rural traditions and enhancing sustainability. The Slovenian Rural Development Program (2014–2020) has been pivotal in promoting organic farming, with 10% of agricultural land now dedicated to organic cultivation. Investments in soil health, erosion control, and crop diversification are central to Slovenia's strategy for agricultural resilience. The government has also supported precision farming by allocating innovative equipment and technology subsidies. However, connectivity issues in rural areas continue to impede the adoption of these technologies on a wide scale. The government's strategic emphasis on enhancing domestic cereal production entails the modernization of storage facilities and the promotion of crop rotation to reduce dependency on EU imports. However, challenges such as a diminishing rural workforce and an ageing farming population impede the pace of agricultural innovation and modernization (Ministry of Agriculture, Forestry and Food of the Republic of Slovenia, 2021; European Commission. (n.d)) .

4.3.3.5 CYPRUS

The island nation of Cyprus faces distinctive challenges due to its Mediterranean climate, characterized by water scarcity and a significant reliance on agricultural imports. The National Rural Development Program (NRDP) has identified the promotion of water-efficient farming practices as a priority, focusing on the implementation of precision irrigation systems, desalination projects, and cultivating drought-resistant crop varieties. These measures are designed to adapt agricultural practices to the challenges posed by climate change. Furthermore, Cyprus is undertaking initiatives to expand its organic farming sector to reduce its reliance on imported agrochemicals. This initiative is supported by programs designed to promote local seed production and bio-fertilizers. However, the integration of digital farming technologies in Cyprus remains in its nascent stages, with efforts concentrated on enhancing rural broadband connectivity and providing training opportunities for farmers to adopt innovative technologies. The limited infrastructure and the high costs of digital tools persist as significant barriers. As an island nation with a high dependence on EU imports, Cyprus faces significant vulnerabilities due to price fluctuations and disruptions in its supply chain, underscoring the critical importance of ensuring food security (European Commission, 2023c).

5 PRIORITIES DERIVED FROM CURRENT RESEARCH

The evolution of technology and data systems presents exceptional opportunities to transform European agriculture. It ensures sustainability, resilience, and competitiveness in the sector. However, a comprehensive and interoperability approach is essential to unlock the full potential of digitalisation.

This section outlines the most important priorities derived from current research. It focuses on critical areas such as data and technology resource independence, system compatibility, sustainability at the farm level, and socioeconomic challenges in small farms.

Data and technology resource independence at EU level

- Encouraging collaborative efforts among public sector actors, the private sector, civil society, and stakeholders throughout the agriculture value chain to foster the One Health transition and development and adoption of digital technologies.
- Expanding ICT infrastructure to improve rural connectivity through mobile networks, electricity, and cloud computing.
- Further development of Galileo framework of Earth Observation (Sentinel I and Sentinel II) to foster data provision and development of digital agriculture in Europe
- Implementing AI Act[26] in the agricultural sector in view of the complex measures outlined by the Act and linked to different layers of risks

Compatibility and interoperability of various data collection systems, digital tools, and databases

- Supporting the integration of various data collection systems linked to agriculture (IACS, LPIS, FADN), enabling data interoperability
- Setting up common data standards which ensure open access for farmers, land managers and stakeholders
- Developing open technologies hindering the vendor lock-in
- Farm data enhancement to ensure integration of various data at the farm level, leading possibly to data harmonization and aggregation

Sustainability priority at farm level and issues in return on investment

- Strengthening efficiency and effectiveness of implementing agricultural policy support measures
- Increasing the targeted support to technology investments for farmers and land managers
- Stimulating a task-force group at EU level to clarify the various criteria for defining the eco-scheme targeted to precision agriculture, appropriate to different regions, in a way that complies with the policy requirement of controllable criteria

[26] https://digital-strategy.ec.europa.eu/en/policies/regulatory-framework-ai

- Exploring the use of market-based instruments instead of policy supports targeted to sustainability
- Developing digital supply chains that enhance the understanding of sustainability by interconnecting suppliers and consumers of agricultural products

Socioeconomic priorities impacting digitalisation in small farms

- Developing digital skills among the rural population and agricultural stakeholders
- Supporting generational renewal in agriculture
- Supporting training, information, education, and knowledge-transfer

Expanding policies to support demonstration farms to help inform small-scale farmers and increase cooperation and promote trust to cooperate between farmers and agricultural stakeholders.

6 CONCLUDING REMARKS/SYNTHESIS

To drive the research under the Nostradamus project, capacity building is needed to integrate common knowledge about technology evolution with scientific knowledge in the areas of sustainability, agricultural resilience and food security. The domains of research to be boosted are agronomy, agricultural technology and political science. It is reasonable to expect that digitalisation is going to be the cornerstone of agriculture and its transformation in the near future, imbricated with climate and food agendas. Therefore, this evolution needs to proceed in synergistic and coordinated ways.

This report has highlighted the complex policy landscape surrounding Europe's agriculture. While the policies, strategies, and interventions aim to enhance sustainability, agricultural resilience, and food security, the Nostradamus project will be closely involved in navigating the complexities of how these policies and strategies are implemented and their potential effectiveness in practice.

Assessing whether these policies and strategies fulfil their objectives will require examining specific indicators, such as reductions in agrochemical use, improvements in soil health, increased adoption of sustainable practices by farmers, and overall contributions to food security. These metrics are particularly relevant given the concerns expressed by farmers and land managers regarding agrochemical dependency and food security.

Attention should be focused on the developments related to the CAP, the European Green Deal, the Farm-to-Fork Strategy, the REPower Initiative and the One Health initiative, which encompasses four pillars of resilience, and the EU Digital Strategy, among others.

In addition to knowing where the key policies, strategies and interventions are, it is also important to note that digitalisation is likely to intervene and magnify the shift in agriculture. The main priorities derived from the research presented in this report are:

- data and technology independence at EU level;

- compatibility and interoperability of various data collection systems, digital tools and databases;
- improved criteria defining the precision agriculture eco-scheme
- the sustainability priority at the farm level; and
- socioeconomic priorities impacting digitalisation on small-scale farms.

The outcomes of the Nostradamus project will help address these priorities by enhancing digital literacy and supporting the development of scalable and accessible solutions, particularly for small-scale farms. To sum up, increased awareness is needed alongside increased institutional capacities to prepare solutions to extend digital literacy among rural populations beyond merely operating devices. Such measures for increasing awareness and institutional capacities should encompass a comprehensive understanding of data privacy, cybersecurity, and the integration of digital tools into traditional farming practices. Additionally, we may need to define simple and clear goals for more complex strategies to effectively educate farmers and rural communities. This capacity building is essential for navigating the increasing emergence of digitalization.

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