Assess NBS innovations using AKIS and value chain frames

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Executive summary

This report investigates how Agricultural Knowledge and Innovation Systems (AKIS) shape the emergence, functioning and scaling of innovations for more sustainable and circular nutrient management in Europe. While AKIS research has so far focused mainly on national-level system descriptions, mission-oriented innovation agendas and farm-level adoption behaviour, considerably less is known about how specific innovations are embedded in, and conditioned by, concrete AKIS configurations in particular regional and sectoral contexts. To address this gap, we apply an innovation-centred AKIS diagnosis to four nutrient-related innovation cases in Europe, and subsequently conduct a comparative cross-case analysis.

The report has three main objectives: (1) to illustrate the diversity of sustainable nutrient-management-related innovations across selected European countries; (2) to identify key AKIS features that support the functioning and performance of these innovations; and (3) to examine how these innovations contribute to broader transformation pathways towards sustainable and circular nutrient use. Four cases are used int his report which encompass different types of innovation and contexts: a grass–biorefinery nature-based solution (NBS) in the Limfjord catchment (Denmark), NBS for nutrient retention and water-quality protection in the Szigetköz region (Hungary), the 'Planty Organic' plant-based organic arable system in the Northern Netherlands, and the Thallo fertiliser derived from abattoir waste in England (United Kingdom). All innovations operate at the intersection of environmental regulation, agricultural production and evolving circularity or bioeconomy agendas.

For each case, we carried out a structured AKIS diagnosis. This involved mapping the diversity of actors (farmers, research and education institutions, advisory services, public authorities, private value-chain actors, NGOs and intermediaries), characterising knowledge and financial infrastructures (research capacities, advisory and education systems, funding schemes, market arrangements), and analysing coordination mechanisms (vertical links between research–advisory–farmers and policy levels, horizontal links across sectors and regions, and the role of intermediaries). On this basis, we performed a cross-case comparison that identifies common patterns and differences in those three dimensions: actor diversity, the robustness and diversification of knowledge and funding infrastructures.

The findings indicate that innovations in nutrient management are not primarily driven by singular technological breakthroughs, but shaped by how actors, infrastructures and coordination arrangements interact around concrete innovations. Across Denmark, Hungary, the Netherlands and the UK, innovations tend to gain robustness and scaling potential where (i) actor constellations are broad and relatively balanced—meaning that farmers, research, advisory services, public authorities, value-chain firms and civil-society actors are meaningfully involved; (ii) knowledge and financial infrastructures are institutionally embedded, diversified and able to support sustained experimentation and iteration; and (iii) coordination mechanisms provide both strong vertical connections (linking research, advisory services, practice and policy) and horizontal connections (linking agriculture with water management, bioeconomy actors and environmental NGOs). Under such conditions, local niche initiatives can more easily inform policy refinement, market development and wider discourses on circular nutrient use.

Conversely, where key actor groups are weakly involved or missing (e.g. advisory services, value-chain firms, NGOs, implementing authorities), where knowledge exchange relies primarily on informal networks and short-term projects, and where coordination is narrow or fragmented (e.g. confined to a product niche or a single policy silo), innovations generate substantial local learning and environmental benefits but tend to remain fragile and localised. Their contribution to system-wide change is then contingent on a few individuals, firms or projects and vulnerable to funding volatility and regulatory uncertainty.

Methodologically, this report demonstrates the added value of using AKIS diagnosis and cross-case comparison in an innovation-centred way. AKIS frameworks have so far been employed mainly to characterise and compare national systems; our approach shows how they can be repurposed to analyse specific innovation constellations in Denmark, Hungary, the Netherlands and the UK, identify context-specific bottlenecks and enabling conditions, and derive implications for the design of transformation-oriented support measures. In doing so, the study contributes both to a more fine-grained understanding of how nutrient-management innovations are embedded in their institutional environments and to the further development of AKIS analysis as a tool for supporting sustainability-oriented, locally grounded but system-relevant innovation processes.

Table of Contents

List of figures

List of tables

List of Abbreviations

AKIS	Agricultural knowledge and innovation system
CAP	Common Agricultural Policy
EU	European Union
FAS	Farm advisory system
N	Nitrogen
NAK	Hungarian Chamber of Agriculture
NBS	Nature-based solutions
WFD	EU Water Framework Directive

1. Introduction

Knowledge and innovation are widely recognised as critical resources for enabling European agriculture to address challenges such as global competition, food safety, public health, and environmental and climate pressures. Reflecting this, the reform of the European Union's (EU) Common Agricultural Policy (CAP) places strong emphasis on strengthening Member States' Agricultural Knowledge and Innovation Systems (AKIS) and on fostering knowledge exchange and innovation in agriculture and rural areas (EU 2021/2115).

Despite this increased policy focus, AKIS analyses have so far concentrated mainly on national-level system descriptions, mission-oriented innovation approaches, or farm-level decision-making and innovation adoption (Klerkx and Begemann, 2020; Sutherland and Labarthe, 2022; Birke et al., 2025). While informative, these perspectives provide limited insight into how AKIS configurations support specific innovations and how such innovations contribute to broader sustainability and nutrient-management transformations. In particular, there is little evidence on how knowledge, advisory services, governance arrangements, and institutional infrastructures interact around concrete innovation cases in different regional and sectoral contexts.

An innovation-centred AKIS diagnosis addresses this gap by examining how actors, networks, and institutions coalesce around particular innovations. This approach moves beyond viewing AKIS as a static national structure and instead captures its context-specific nature. It is especially relevant for nature-based solutions (NBS) and nutrient-management innovations, which depend on coordinated action across research, advisory services, practice, and governance levels. By mapping actors, linkages, and institutional settings, an AKIS diagnosis helps identify bottlenecks, enabling conditions, and leverage points that shape innovation performance and uptake.

The AKIS diagnoses presented in this report provide an overview of AKIS infrastructures and innovation support arrangements linked to selected NBS innovations at site, regional, and—where relevant—national levels. They offer insight into the institutional environments in which actors in the nutrient-management domains operate and provide an evidence base for strengthening cooperation among AKIS actors and aligning innovation support with transformation objectives.

Against this background, the trans4num project analyses its innovation cases from an explicit AKIS perspective. The report aims to:

(1) illustrate the diversity of sustainable nutrient management-related innovations across selected European countries;

(2) identify key AKIS features across cases that support the innovations functioning and performance; and

(3) examine how these innovations contribute to broader nutrient-management transformation pathways.

The report is structured as follows. Section 2 introduces the AKIS concept and its main components. Section 3 describes the methodology. Section 4 presents the cross-country analysis of AKIS features, with particular attention to advisory organisations and services.

Section 5 summarises the main findings and draws conclusions and recommendations for future AKIS research and policy development.

The country-specific case study chapters were drafted by the respective co-authors: the Danish case by Morten Graversgaard and August Kau Lægsgaard Tidemand, the Hungarian case by Andras Vér and Viktoria Vona, the Dutch case by Friederike Selensky, and the UK case by Maxwell Dzudzor. These chapters were only subject to minor editorial adaptations by the lead author to ensure coherence across the report, while preserving the original empirical focus and interpretations developed by the respective country teams.

2. Key conceptual elements

2.1 Agricultural Knowledge and Innovation Systems (AKIS) as a theoretical framework

The Agricultural Knowledge and Innovation Systems (AKIS) concept has its roots in agricultural extension research (Röling, 1988; Blum, 1991) and has since evolved into a widely used framework in agricultural research and policy (EU-SCAR, 2012; Knierim et al., 2015; EU, 2020/COM381). Here we understand AKIS as a concept for identifying links between people and institutions purposefully involved in generating, sharing, and using agricultural knowledge, information, and technologies (World Bank 2012; Knierim et al., 2015). It involves farmers, researchers, advisors, educators, and other actors to promote mutual learning and support innovation for agricultural development and societal benefit, within the agricultural sector or along the value chain.

AKIS can be analysed from different, complementary perspectives, including process-oriented, function-oriented, and infrastructural approaches (Knierim and Birke, 2023). In the context of this report, which aims to provide a comprehensive diagnosis of the institutional environment supporting agricultural innovation, an infrastructural perspective is adopted. This perspective provides a clear analytical focus and supports systematic assessment of how innovation support is organised and governed.

The infrastructural perspective concentrates on the presence and interaction of organised actors, such as research institutions, advisory organisations, and financing bodies, as well as on the infrastructures that shape innovation processes, including rules and regulations and physical and organisational infrastructures (Klerkx et al., 2012; Knierim et al., 2017). It can be applied across spatial scales (local, regional, national), within specific agricultural sectors or agricultural value chains (EU SCAR, 2012 and 2013). Actor roles and interactions are strongly influenced by infrastructures that require substantial collective investment and cannot be established by individual actors alone (Hermans et al., 2015). From this perspective, the central analytical question is whether existing AKIS infrastructures support agricultural knowledge exchange and innovation, or whether they limit or constrain innovation processes within a given context.

2.2 Innovation systems and value chains

The innovation systems' perspective builds on core elements of an AKIS – such as effective information channels for farmers and strong, up-to-date research and training institutions – but extends them to a wider set of actors and relationships (Hall et al., 2006; EU SCAR, 2013). It explicitly includes the many public and private actors operating along agricultural value chains and highlights that an enabling environment for using knowledge (e.g. incentives, rules,

networks, financing) is as important as knowledge generation and dissemination itself (Hall et al., 2006). In this sense, value chains can be seen as one important arena within an innovation system, where actors jointly reorganise production, processing, marketing, and consumption to enhance competitiveness and sustainability, understood here as "the set of interconnected, value-creating activities undertaken by an enterprise or group of enterprises to develop, produce, deliver, and maintain a product or service" (Hall et al., 2006:24). In trans4num, this value chain dimension is particularly relevant in two cases: in Denmark, where a new value chain is being developed to support the broader uptake of an innovation, and in the UK, where the innovation results from the optimisation of an existing value chain, whereas in the Dutch and Hungarian cases, value chain aspects are currently less central, as both innovations are still in an early phase of testing and of developing their agricultural application and practical integration. The AKIS concept provides the overarching framework for the AKIS diagnosis in all cases by focusing on the interactions, capacities, and coordination mechanisms among actors (EU SCAR, 2013). Where value chain aspects are present (as in the Danish and UK cases), they are interpreted as specific configurations of actors and linkages within the wider AKIS, illustrating how AKIS functions can support or constrain innovation processes embedded in agricultural value chains (EU SCAR, 2013).

2.3 AKIS across contexts

The infrastructural perspective views AKIS as context-specific configurations shaped by institutions (national or regional), legal frameworks, and socio-cultural conditions. As AKIS evolve historically, direct case-to-case comparison across regions or countries is not meaningful; instead, comparative analysis focuses on identifying typical structural features and patterns across contexts (Knierim and Prager, 2015). The cross-comparison concentrates on three core dimensions (Birke et al., 2025):

First, corporate **actor diversity and pluralism** captures the range of organised actors involved in knowledge exchange and innovation, including public authorities, research and education organisations, private advisory services, farmer-based organisations, non-governmental actors (Birner et al., 2009; Knierim et al., 2015) as part of the value chain actors (OECD/EU SCAR, 2012). Actor diversity can enhance innovation through multiple knowledge sources and interaction, while also creating governance challenges (Garforth et al., 2003; Knierim et al., 2017).

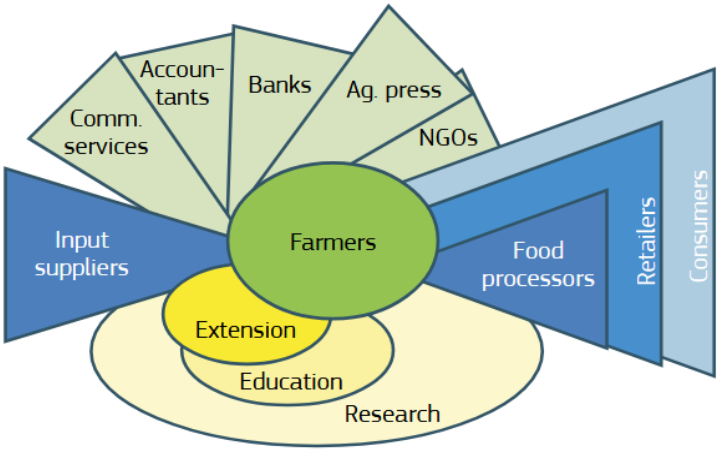

Figure 1: Possible value chain actors to be considered (OECD/EU SCAR, 2012).

Second, **knowledge and financial infrastructures** enable innovation processes. Knowledge infrastructures include research facilities, advisory services, data resources, and digital systems supporting knowledge generation and dissemination (Smith, 1997; EU-SCAR AKIS, 2019). Financial infrastructures refer to funding instruments, subsidies, and incentives that provide the resources required for innovation activities (O'Sullivan, 2005; Wieczorek and Hekkert, 2012).

Third, **coordination mechanisms** link actors and infrastructures within a pluralistic AKIS. These mechanisms may be vertical (across governance levels) or horizontal (among actors at the same level), and may operate through formal structures or informal networks and interactions (Martinez and Jarillo, 1989; Moreno-Miranda and Dries, 2002; Röling, 1992; Klerkx et al., 2012).

Together, these three dimensions form an analytical grid for examining and comparing AKIS across contexts, supporting conclusions across cases within their contexts clarifying similarities and differences (Esser and Vliegenthart, 2017).

3. Methods

3.1 Innovation cases

Within trans4num, four innovation cases were chosen to explore their AKIS. The decisions were based on boundary objects meaning some innovations are linked to a very broad group of actors such as regenerative farming which makes it challenging to draw the boundary and reduces the likelihood of reaching key actors. All cases are dealing with the topic of sustainable nutrient management responding to context specific needs (Table 1). More context details are given in section 4 in every respective section for each case.

Table 1: trans4num innovation cases investigated in this deliverable.

Country	Innovation's name	Innovation' description	Number of actors interviewed
Denmark	GBR	Green Biorefining with accompanied nutrient flow optimisation	21
Hungary	Szigetköz innovation	Combined measures: crop rotation, biofertilsers and biostimulants, and reduced tillage	4
Netherlands	Planty organic	Plant based crop rotation	7
UK	Thallo	Phosphor fertiliser from abattoir waster	3

3.2 AKIS diagnosis

The AKIS diagnosis builds on insights from earlier stakeholder-engagement (see deliverable 2.2 "1st report on NBS cases' implementation and transdisciplinary evaluation in

Hungary/Denmark/ Netherlands/ UK" and deliverable 2.3 "2nd Report on NBS cases´ implementation and transdisciplinary evaluation in Hungary, Denmark, Netherlands, and UK) activities to ensure continuity and avoid redundant data collection. In turn, the resulting AKIS maps and analyses also provide inputs for subsequent project tasks, including higher-level stakeholder workshops and modelling activities.

For conducting the infrastructural AKIS diagnosis we followed the guideline developed in the frame of the i2connect project (Knierim and Birke, 2024) and adapted it to the trans4num setting. It follows a structured, multi-phase process combining document review, visual mapping, expert consultation, and synthesis. Its purpose is to analyse the AKIS surrounding selected NBS innovations and to identify key actors, infrastructures, and coordination patterns relevant for nutrient-management innovation. The four phases of the methodological procedure were the following:

1. **Review phase**

The review phase established the contextual and institutional background for the AKIS analysis. Case partners compiled and synthesised relevant information existing on the national or regional agricultural and nutrient-management context, drawing on policy documents, strategic plans, previous AKIS reports, and relevant research and administrative sources. This includes a concise overview of the structural characteristics of the agricultural sector and the relevance of nutrient management and NBS within the respective context.

In parallel, partners identified organisations and stakeholders relevant to the development, dissemination, and support of the innovation. Based on this information and partners' prior expertise, a first narrative summary and a preliminary list of AKIS actors were produced.

2. **Context analysis of the NBS innovation**

To situate the innovation, a brief contextual analysis of the NBS setting was carried out. This included socio-economic, agricultural, and environmental characteristics of the region or country, with particular attention to the innovation's nutrient-management challenges and the role of agriculture. Relevant data were selected based on their significance for the innovation and summarised. The analysis also identifies relevant public policies, funding schemes, advisory services, and innovation-support instruments shaping the innovation environment.

3. **AKIS mapping**

Building on the review, an initial AKIS map was developed to visualise the organisations involved in the innovation and their knowledge-related interactions. Actors were classified into five categories (public sector, research and education, private sector, farmer-based organisations, and civil society), and linkages were represented according to their strength and direction of knowledge flow (Knierim and Birke, 2024). The innovation itself was placed at the centre of the map to emphasise its role within the AKIS.

This draft map served as a discussion tool in expert interviews with key AKIS stakeholders and value chain actors. Interviewees validated, refined, and complemented the map by commenting on actor roles, relationships, and missing or contested elements. Their inputs were used to revise the map and to document converging and diverging perspectives. The number of interviews differs from case to case depending on the complexity as some cases

have been operating more in silos such as the UK case or a smaller diversity of actors has been linked to the innovation as in Hungary. and others reaching more out beyond the innovators group.

4. Integration and reporting

In the final phase, findings from the review and interviews were integrated into a consolidated AKIS map. The results capture both shared assessments and differing viewpoints on AKIS functioning and innovation support. Outcomes were discussed with partners and stakeholders to support shared understanding and reflection on system performance, future development needs, and potential interventions.

3.3 Data analysis for cross comparison

The cross-comparative analysis broadly followed the approach outlined by Birke et al. (2025). Project partners provided structured information in line with the theoretical framework described in Section 2.2, with a focus on actor diversity, knowledge and organisational infrastructures, financial resources, and institutional and coordination arrangements supporting the innovation cases.

Actors were classified using the AKIS categories applied in the diagnosis (Knierim et al., 2015), and knowledge infrastructures were analysed following Smith's (1997) framework. Coordination mechanisms were identified and categorised inductively based on the empirical material provided by project partners.

A qualitative content analysis was then conducted to compare the four innovation cases. Where feasible, occurrences were quantified (e.g. types and numbers of actors or infrastructures) to support systematic comparison. Similarities, differences, and emerging patterns across cases were analysed. Ambiguities in interpretation were addressed through iterative discussions and feedback with innovation partners, although some degree of interpretative bias cannot be fully excluded.

4. Results

4.1 Denmark – Green Biorefinery

4.1.1 Main structural characteristics of the innovation's context

Denmark is characterised by an intensive and highly productive agricultural sector, with approximately 61% of the national land area under agricultural use. The Danish agricultural sector is a structurally concentrated sector with relatively large farms and strong livestock orientation. Livestock production, particularly pigs and dairy cattle combined with large areas of arable cropping, results in high nutrient flows within agricultural systems. Although nitrogen (N) losses from agriculture have been significantly reduced since the 1990s (Dalgaard et al., 2014), nutrient leaching remains one of the main environmental pressures on Danish aquatic ecosystems, especially coastal waters (Miljøstyrelsen, 2020). Nitrogen losses from agriculture continue to be the primary cause of non-compliance with the EU Water Framework Directive (WFD) in several Danish catchments.

General characteristics of the Limfjord region

The Limfjord catchment in northern and western Jutland is one of Denmark's most environmentally sensitive regions, and among those most affected by N loading (MST, 2025).

The catchment covers approximately 7,500 km² and includes intensive agricultural landscapes, river systems, and the shallow Limfjord coastal water body. The Limfjord has repeatedly failed to meet the environmental objectives of the EU Water Framework Directive due to high nutrient loads, resulting in:

- Periodic algal blooms
- Oxygen depletion
- Biodiversity loss

Agriculture is the dominant land use in the catchment and contributes substantially to regional employment and value creation. At the same time, the combination of sandy soils, intensive livestock production, slurry application and artificial drainage systems increases the risk of nitrate leaching to groundwater and coastal waters. The region is therefore a priority area for targeted N reduction measures at both national and regional levels. Several municipalities (e.g., Viborg, Skive, Morsø, Holstebro, Vesthimmerland) operate under national River Basin Management plans to reduce nitrate leaching and ammonia emissions. Measures include catch crops, wetlands, manure regulation and increasingly land-use-based solutions such as perennial cropping systems. Regional governance in municipalities is currently dominated by Green Tripartite and WFD River Basin Management Plans that mandate aggressive N-reduction, necessitating a shift from passive mitigation toward systemic land-use solutions.

Agricultural sector characteristics relevant to the NBS site

Denmark has approximately 12.3 million pigs and 1.5 million cattle, reinforcing its strong livestock orientation. The Limfjord catchment mirrors this production structure through cereal and forage-dominated rotations, including winter wheat, barley, rapeseed, grass-clover for silage, and maize whole-crop, high livestock density (especially pigs and dairy cattle), and extensive slurry and fertiliser use. These structural characteristics make the catchment particularly vulnerable to N leaching because sandy soils dominate many areas, and annual crops leave soil uncovered during autumn and winter, manure availability is high, and drainage systems transport nitrate rapidly to fjords, leading to high nutrient runoff.

The NBS solution — perennial grasses coupled with green biorefining — directly addresses these structural drivers by ensuring year-round soil cover and deep root networks, which significantly outperform annual cereals in nitrogen uptake efficiency.

Environmental and nutrient management challenges in the Limfjord catchment

Despite national improvements since 1990 (37% reduction in N leaching and 43% reduction in ammonia emissions), N losses from agriculture remain the primary reason for poor ecological status in the Limfjord.

Key challenges include:

- Nitrate leaching from annual cropping systems
- Manure management in livestock-intensive areas
- Climate commitments requiring agricultural GHG reductions
- Soil carbon depletion in arable systems

- Continued pressure from EU WFD and national River Basin Plans

The challenge is not only to reduce N losses further, but to do so while maintaining farm viability and supporting rural development. In this context, land-use-based and systemic solutions have gained increased attention. Systemic solutions that provide "public goods" (water quality) while generating "private value" (bio-products) are increasingly viewed as the only viable path forward for regional development.

Long-standing Danish experience with permanent grass as an environmental measure

Denmark has more than 35 years of experience using permanent grass as a land-use-based N mitigation measure. One of the earliest examples is the Tunø groundwater protection case, initiated in 1986–1987, the first area in Denmark where permanent grass was systematically used as a measure to reduce nitrate pollution (Graversgaard et al., 2020; Graversgaard et al. 2026). At that time, nitrate concentrations in drinking water wells exceeded 150 mg NO_3/l. Arable land within protection zones was converted to permanent grass, combined with advisory support and continuous monitoring, and nitrate concentrations declined to approximately 25 mg NO_3/l.

Two decisive success factors were later identified: Continuous demonstration of environmental effects through monitoring, and lower costs compared to technical water-treatment alternatives. Although Tunø lies outside the Limfjord catchment, the case illustrates that Danish farmers and advisory systems have long-standing experience with perennial systems as environmental measures. The current NBS innovation therefore does not introduce perennial grass as a new agronomic concept; rather, it reconfigures existing knowledge within new value chains and governance settings.

From environmental protection to nature-based solution

The Limfjord NBS builds on this historical experience but extends it beyond environmental protection.

By linking perennial grass systems to green biorefining and circular bioeconomy concepts, grass is reframed as a productive crop integrated into new value chains. The Danish NBS emphasise the multiple benefits of perennial crops, including continuous green cover, reduced leaching, high biomass and protein yield, and increased soil carbon storage.

Research have demonstrated the multiple benefits of perennial crops and grass–legume systems (Table 2):

- 40–60% reduction in nitrate leaching compared to cereals (Manevski et al., 2018; Pugesgaard et al., 2015)
- High biomass and protein yields enabling substitution of imported soy (Solati et al., 2017; 2018)
- Increased soil carbon sequestration (Shang et al., 2024)
- Stabilised nitrogen budgets and reduced environmental losses

The transition from simple environmental protection to a systemic Nature-Based Solution (NBS) in the Limfjord catchment represents a paradigm shift in Danish land-use policy. While traditional measures focused on "end-of-pipe" solutions or passive land retirement, the integration of perennial grass–legume systems with green biorefining addresses the root

cause of nitrate leaching while maintaining agricultural productivity. Perennial systems provide near-continuous soil cover and extensive root networks that significantly outperform annual cereals in nitrogen uptake efficiency. Research indicates that these systems can reduce nitrate leaching by 40-60% (Pugesgaard et al., 2015). However, the "Nature-Based" element extends beyond the field: by cascading this biomass through a green biorefinery, we achieve a circular nitrogen loop.

Green biorefining adds a circular-economy dimension through protein extraction for food and feed, fibre for biomaterials, residues for biogas, and the potential for additional high-value bio-based products. In this way, the innovation links agriculture, biogas plants, feed industries, material science and regional green-growth strategies. The transition from annual cereal systems to perennial biorefinery cascades represents a shift from efficiency-based mitigation to a more systemic resilience approach, in which environmental protection and economic valorisation are pursued simultaneously.

The Limfjord catchment represents a "wicked problem"—a systemic deadlock where EU-mandated nitrogen reduction targets (WFD) collide with path-dependent farming traditions (Dietz et al., 2024). Traditional mitigation is insufficient; the region requires a socio-technical transition that decouples agricultural productivity from nitrogen loss. The current innovation—perennial grass coupled with green biorefining—is framed as a "Cascade use of biomass" model (Klerkx & Begemann, 2020), where biomass is fractionated to extract high-value protein before residues are returned as circular bio-fertilizers.

Table 2: Indicative comparison of annual cereal systems and perennial grass-based biorefinery systems

Cropping system	N-leaching (kg N/ha/yr)	Biomass yield (t DM/ha)	Protein potential
Annual cereals (wheat/barley)	50–70	7–10	Low (grain only)
Perennial grass-clover	15–25	10–15	High (green protein)
NBS: grass + biorefinery	<20	12–18	High-value isolate
Reduction / improvement	60–70% decrease	40–50% increase	Value-added

Note: values are indicative and intended to illustrate the relative performance logic of the innovation based on the reviewed literature and project materials.

Public policy, funding schemes and frameworks relevant for the NBS

Key policy drivers include the EU Water Framework Directive and Nitrates Directive, Danish national River Basin Management Plans, the Green Tripartite Agreement (2024), the Danish Climate Act (agricultural emission reductions, carbon sequestration), the CAP Strategic Plan (eco-schemes, agri-environmental measures), and regional bioeconomy and green-growth strategies. Together, these create strong pressure and increasing opportunity for land-use solutions that reduce nitrogen losses while contributing to climate and bioeconomy goals. The GTA is particularly transformative, providing the political legitimacy to treat nitrogen

mitigation not as a "compliance cost," but as a strategic objective for national climate and bioeconomy policy.

Advisory and AKIS-related funding structures

Denmark's advisory system is predominantly user-financed, but the NBS is supported indirectly through sector levies (production levy funds) financing innovation and trials, the pesticide tax reimbursement fund (supporting environmental projects), EU and national research and innovation programmes, municipal and regional water-quality projects, and biogas subsidies and green-industry related support schemes and funds. The Danish advisory services are largely market-based, while sector funds and project-based financing remain important for innovation and development (Klitgaard, 2019).

Together, these mechanisms and structural, environmental and policy conditions make the Limfjord catchment a highly relevant setting for analysing how AKIS actors support the development and scaling of perennial grass-based biorefinery systems.

A defining feature of the Danish case is the 'Cascade Use of Biomass' within a circular bioeconomy. The economic viability of the biorefineries (e.g., Ausumgaard) depends on their industrial symbiosis with biogas plants. This integration allows for the immediate processing of side-streams (press-cake and brown juice) into energy and liquid fertilizer, minimizing the high transport costs associated with fresh, high-water-content grass biomass. This symbiotic model is essential for moving green protein from a niche pilot to a competitive commodity.

4.1.2 Characteristics of the NBS innovation embedding AKIS

Following the infrastructural understanding of Agricultural Knowledge and Innovation Systems (AKIS), this chapter describes the organisations, coordination mechanisms and knowledge linkages that constitute the innovation support environment for the grass-based biorefinery Nature-Based Solution (NBS) in the Limfjord catchment. Unlike traditional agricultural innovations focused on incremental productivity gains, the Limfjord Nature-Based Solution (NBS) represents a systemic bioeconomy transition, requiring the orchestration of cross-sectoral knowledge flows that extend far beyond the farm gate.

Overall AKIS structure

The Danish AKIS is generally characterised by relatively strong coordination mechanisms between research institutions, advisory services, farmers and public authorities. Compared with many other European countries, the Danish AKIS is highly institutionalised and relies on close interaction between publicly funded research and a largely farmer-financed advisory system. Advisory services are predominantly farmer-owned and user-financed and organised through a two-layer structure consisting of a national knowledge centre, called SEGES Innovation, and a network of local advisory centres forming the Danish Agricultural Advisory Service (DAAS). SEGES Innovation functions as a central hub for applied research, knowledge development and advisory tools, while the local advisory centres translate this knowledge into farm-level decision-making.

In traditional AKIS settings, innovation often concerns improvements in farming practices, such as crop management, fertilisation strategies or animal husbandry. In such cases, advisory services usually play a central role in transferring knowledge from research institutions to

farmers. In contrast, the innovation analysed in this case differs from many conventional agricultural innovations typically studied in AKIS analyses.

In the Limfjord case, the innovation is fundamentally a value-chain bioeconomy innovation. The core idea is to replace imported protein feed, particularly soybean meal, with locally produced protein extracted from perennial grass and clover through green biorefining technologies. This transformation connects agricultural production with industrial processing technologies and new bio-based value chains. As a result, the innovation involves not only farmers and advisory services but also research institutions, industrial actors, technology developers, energy producers, regional innovation organisations and policy actors. The key challenge is not primarily the agronomic feasibility of perennial grass systems—this knowledge is already well established—but rather how to organise value chains, scale up processing capacity and reduce production costs so that green protein becomes economically competitive with imported protein sources. Consequently, the innovation system surrounding the Limfjord NBS can be described as a cross-sectoral and multi-actor AKIS, where research, industry, policy and regional development actors play particularly important roles alongside the traditional agricultural knowledge actors.

Key AKIS actors relevant for the NBS

Public authorities

Public authorities play a key role in shaping the regulatory and policy environment in which the innovation develops. At national level, Ministry of Food, Agriculture and Fisheries (Ministeriet for Fødevarer, Landbrug og Fiskeri) and and Ministry of Environment (Miljøministeriet) and the Agency for Green Transition and Aquatic Environment (Styrelsen for Grøn Arealudvikling og Vandmiljø), are responsible for implementing EU agricultural and environmental policies, including the Common Agricultural Policy (CAP), the Water Framework Directive (WFD) and the Nitrates Directive. These institutions define nutrient regulations, environmental schemes and agricultural support instruments that directly influence farm management and land-use decisions. In particular, water-quality regulation related to the Limfjord catchment creates strong incentives for land-use solutions that reduce nitrogen losses. Perennial cropping systems and land-use changes are therefore increasingly considered in policy discussions as potential measures contributing to water-quality improvements. At regional and local levels, municipalities within the Limfjord catchment play an important role in implementing River Basin Management Plans and national water plans. Municipalities are responsible for planning and implementing measures aimed at reducing nitrogen losses, including wetlands, buffer zones, catch crops and other land-use measures. They therefore function as key intermediaries between national policy frameworks and local implementation. Municipalities are also increasingly involved in collaborative initiatives with farmers, advisory services and research institutions to explore innovative solutions for improving water quality and climate mitigation in the region.

Research and education

Research institutions are central actors in the innovation system and play a major role in developing the knowledge base for perennial cropping systems and green biorefining technologies.

Aarhus University (AU), particularly through its campus in Viborg (Foulum) and the Danish Centre for Food and Agriculture (DCA), plays a leading role in research on agroecology, nutrient cycling, perennial cropping systems and green biorefining technologies. Researchers at AU have been central in developing and demonstrating the concept of green biorefining of grass and clover, where green biomass can be fractionated into high-value protein concentrate, fibre fractions and residual streams for energy production. Through research-based policy advice and participation in national and European research projects, Aarhus University also contributes directly to policy development and innovation strategies related to bioeconomy, climate mitigation and sustainable land use. The University of Copenhagen (UCPH) contributes to the knowledge base through research on soil science, nitrogen cycling, environmental modelling and ecosystem impacts of agricultural land-use systems. In addition, agricultural colleges and vocational education institutions in northern and western Jutland play an important role in knowledge dissemination and capacity building by providing training and education for farmers, advisers and technicians. These institutions contribute to the diffusion of new knowledge and practices related to perennial crops and sustainable land management.

Advisory services and farmer-based organisations

Advisory services constitute a central pillar of the Danish AKIS and function as the main interface between research institutions and farmers. SEGES Innovation operates as the national agricultural knowledge centre and is responsible for developing advisory tools, conducting applied research and coordinating innovation activities within the agricultural sector. In relation to the NBS innovation, SEGES contributes through field trials, demonstration projects, life-cycle assessments and the development of advisory tools related to nutrient management and biomass production.

At regional level, knowledge is transferred to farmers through the local advisory centres that form the Danish Agricultural Advisory Service (DAAS). Key advisory centres operating in the Limfjord region include organisations such as Velas, Agilix, SAGRO, and Fjordland. These centres maintain close relationships with farmers and provide individualised advisory services that translate research results and regulatory requirements into practical farm management decisions. Besides this, these centres support farmers with a wide range of advisory services related to crop management and environmental compliance.

Key advisory centres operating in the Limfjord region include organisations such as Velas, LandboNord and AgriNord. These centres support farmers with a wide range of advisory services related to crop management and environmental compliance.

Typical advisory activities include:

planning crop rotations and perennial grass establishment

advising on harvesting strategies and logistics

calculating nutrient balances and regulatory compliance

supporting economic assessments and investment decisions

analysing the financial and operational implications of producing green biomass for biorefineries.

However, in this particular innovation the role of advisory services differs somewhat from their role in conventional agricultural innovations. Because the agronomic knowledge of perennial grass systems is already well established in Denmark, the key uncertainties relate less to crop management and more to market development, processing infrastructure and value-chain organisation. Advisory services therefore play a supportive role, assisting farmers with implementation, while the main drivers of innovation lie in research, policy frameworks and emerging bioeconomy industries. The Danish Agriculture & Food Council (Landbrug & Fødevarer – L&F) acts as a national interest organisation representing the agricultural sector and plays an important role in agenda setting, policy dialogue and strategic development of innovation initiatives related to sustainable agriculture and bioeconomy.

Farmers and farmer organisations

Farmers represent the central actors in the innovation system, as they ultimately decide whether to adopt perennial cropping systems and supply biomass for biorefining.

In the Limfjord region, farmers participate in experimentation with perennial grass systems, assess their economic viability and provide practical feedback on the feasibility of integrating such systems into existing farm structures. Participation in demonstration projects and field trials allows farmers to test the agronomic performance of perennial crops under local conditions.

Regional farmer networks and informal producer communities are particularly important for peer learning and exchange of practical experiences. Such networks can accelerate innovation diffusion by enabling farmers to learn from early adopters and demonstration farms.

Farmer organisations (e.g. Velas, Agilix, SAGRO, etc) also play an important role in representing farmers' interests in policy discussions and innovation initiatives.

Private sector and bioeconomy actors

Private-sector actors play a crucial role in developing the value chains required to make perennial biomass economically viable. A key regional actor in the Limfjord innovation ecosystem is Klimafonden Skive, a foundation dedicated to promoting sustainable business development and green technology solutions. The foundation works to create favourable conditions for companies operating within bioeconomy, renewable energy and sustainable land-use sectors.

Klimafonden Skive functions as a regional innovation intermediary, facilitating collaboration between agriculture, aquaculture, processing industries, research institutions and public authorities. Through activities such as system-based innovation projects, conceptualisation of bioeconomy solutions and the development of living laboratories, the foundation contributes to strengthening cross-sectoral cooperation and regional innovation capacity.

Other important private-sector actors include:

- Biogas plants, which can utilise residual biomass streams from biorefining processes (such as press cake and fibre fractions) and convert them into renewable energy while returning digestate nutrients to agricultural soils.
- Emerging green biorefineries, which process grass and clover biomass into protein concentrates, fibre fractions and other bio-based products. Although still in early

commercial stages, these facilities represent a key technological component of the NBS innovation.
- Feed and food companies, which are increasingly interested in green protein as a potential substitute for imported soybean protein in livestock feed.
- Machinery and technology providers, which develop specialised equipment for harvesting, transporting and processing green biomass.

Together, these actors contribute to the development of a new bioeconomic value chain, transforming perennial biomass from an environmental mitigation measure into a productive agricultural resource.

NGOs and civil society

Civil society organisations and environmental NGOs also influence the innovation system, primarily through agenda setting, public debate and participation in stakeholder processes related to water quality and sustainable land use. Environmental NGOs are active in discussions concerning nutrient pollution, biodiversity protection and sustainable agriculture. Through participation in policy consultations, collaborative projects and public debate, these organisations influence the broader governance context within which agricultural innovations develop. Local stakeholder platforms and catchment-based collaboration initiatives also play an important role in facilitating dialogue between farmers, municipalities, environmental organisations and other stakeholders concerned with water quality in the Limfjord. Such collaborative initiatives can help build trust between actors and support the development of collective approaches to addressing complex environmental challenges.

Knowledge flows among AKIS actors

The Danish AKIS for this NBS operates across three distinct interaction planes:

1. The System Plane: Focused on technical infrastructure, including farmers as biomass suppliers and biorefineries (e.g., Biorefine, BiomassProtein) as processors.
2. The Knowledge Plane: Exhibits strong vertical coordination between Aarhus University (AU-Foulum), SEGES Innovation, and the local advisory hubs. While agronomic knowledge is mature, there is a recognized gap in 'value-chain' knowledge regarding market off-take.
3. The Acceleration/Inhibition Plane: This layer includes the regulatory framework, notably the 2024 Green Tripartite Agreement. This is the most critical layer for scaling, as it currently hosts the primary barriers related to 'Novel Food' approvals for human protein and the stability of long-term economic incentives.

The AKIS map (**Fehler! Verweisquelle konnte nicht gefunden werden.**) suggests that the strongest knowledge flows are located between research, advisory services and farmers. Aarhus University contributes scientific knowledge on perennial systems, biorefining technologies and environmental effects, while CFS and local DAAS centres play a key bridging role in translating this knowledge into farm-level decisions. Farmers contribute practical feedback on feasibility, management and economic implications, thereby forming two-way learning loops.

Public authorities mainly influence the innovation environment through regulation, strategic targets and funding frameworks, especially in relation to the CAP, Green Tripartite, the Water Framework Directive, climate policy and rural development. Their linkages to farmers are

therefore more indirect and often mediated through advisory structures and local implementation processes.

Private-sector actors, including biorefineries, biogas plants and feed/protein processors, are increasingly relevant because they create market demand and value-chain incentives for perennial biomass. However, compared with the research–advisory–farmer triangle, these linkages are still less institutionalised and remain an important area for further validation during interviews.

NGOs and stakeholder groups influence the AKIS more indirectly through agenda setting, legitimacy building and participation in broader environmental and regional development debates.

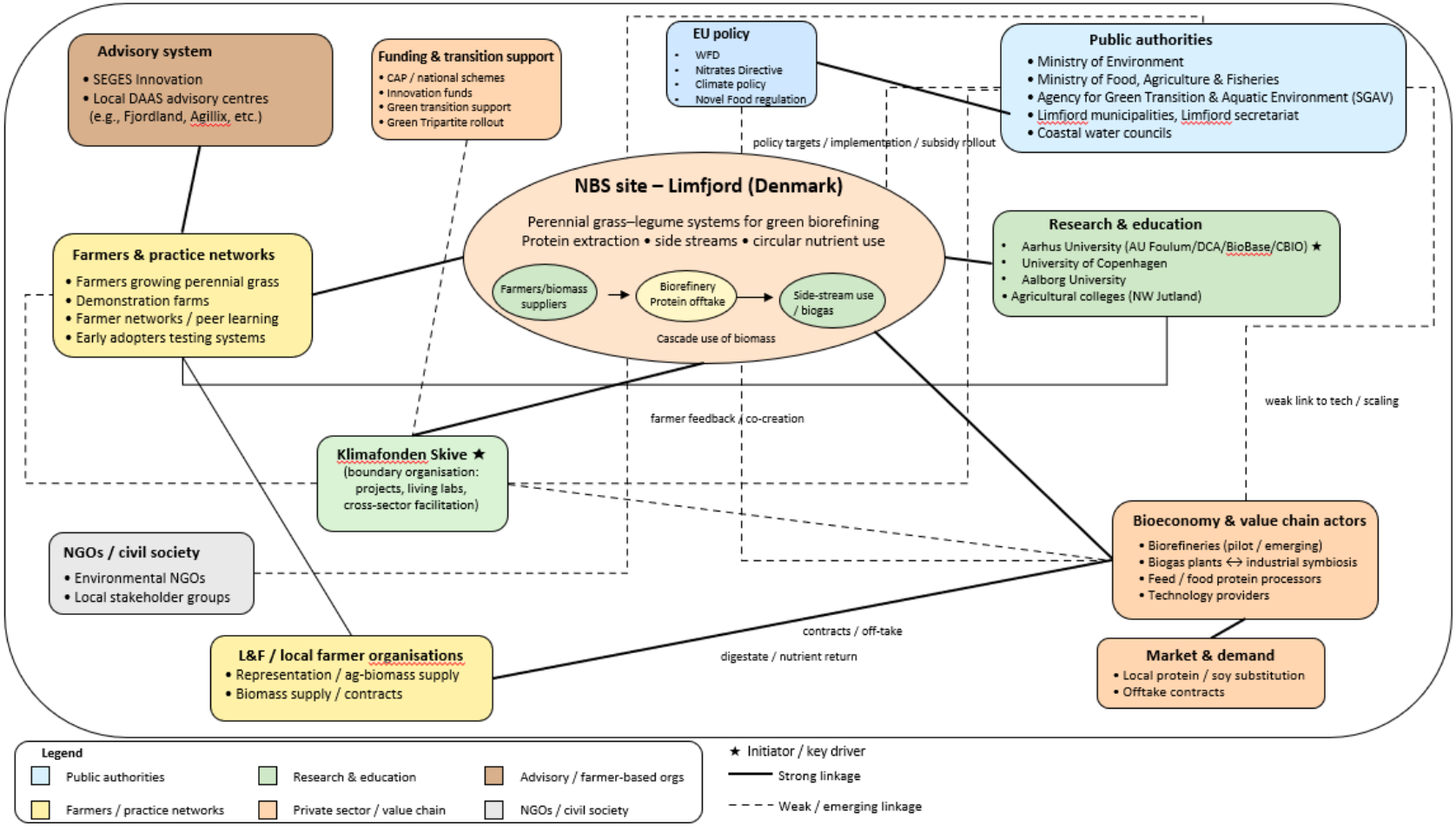

Figure 2: Preliminary AKIS map of the grass-based biorefinery NBS in the Limfjord catchment (Denmark).

The figure presents a review-phase snapshot of the main actors and selected linkages surrounding perennial grass–legume systems for green biorefining in the Limfjord case. It highlights the interaction between the regional farming and value-chain core and the national policy, research, and funding environment, including key coordination challenges related to market formation, side-stream valorisation, and transition support. The map is a draft analytical version developed for discussion, validation, and refinement in the subsequent interview phase.

4.1.3 Relevant innovation support for the NBS

To move from pilot-scale research to a robust regional NBS, the focus of innovation support measures must evolve from simple technical advice to a comprehensive risk-management approach.

Advisory services and Knowledge Transfer

Advisory support in Denmark is characterized by a strong, user-financed, farmer-owned structure. Local DAAS (Danish Agricultural Advisory Service) centres serve as the primary interface, supported by the national expertise of SEGES Innovation. Their role has expanded beyond basic agronomy; they now facilitate nutrient planning, economic viability assessments for bio-refining, and navigating the complex regulatory compliance required for Water Framework Directive (WFD) targets.

Funding Schemes and Policy Integration

The Limfjord NBS leverages a hybrid funding model. While advisory services are private, the innovation benefits from a strategic mix of public and sector-based funding, including:

- **Sectoral Support:** Levies and research programs focused on green transition.
- **EU & National Policy:** CAP eco-schemes and national Climate Act funding.
- **Regional Initiatives:** Municipal water-protection funds that incentivize landscape-scale nitrate mitigation.
- **Research-Policy Interface:** Funding from the Ministry and dedicated bioeconomy agendas ensures that research-based policy advice remains aligned with market scaling.

In addition, green biorefining has benefited from ministry-linked research support, research-based policy advice structures, and broader innovation funding linked to climate and circular bioeconomy agendas.

Innovation diffusion mechanisms

Innovation diffusion relies on on-farm trials, demonstration fields, advisory tools, workshops and collaboration with biogas plants and biorefineries. Communication efforts such as newsletters, open houses and stakeholder meetings have also played an important role, especially in the transition from research platform to emerging innovation system. These approaches support peer learning, improve legitimacy and reduce adoption barriers. Diffusion is achieved through a multi-modal approach:

- **Demonstration:** On-farm trials and open-house events bridge the gap between "academic success" and "field reality."
- **Collaborative Ecosystems:** Strengthening links between farmers, biogas plants, and biorefineries creates a tangible value chain.
- **Stakeholder Dialogues:** Regular meetings foster peer-to-peer learning and improve the social legitimacy of the project.

De-risking the transition for Limfjord farmers

A significant barrier to wider adopting perennial grass systems as an NBS is that the innovation depends on emerging value chains rather than well-established commodity markets, which is a "lock-in" risk inherent in new value chains. Unlike established grain markets with daily commodity pricing, green biorefining relies on long-term contracts between farmers, logistics providers, and emerging processing facilities. Shifting from annual cropping to perennial biomass systems may involve machinery investments, contract uncertainty and changes in land-use planning. This means that innovation support must go beyond agronomic advice.

The transition from annual cereal crops to perennial biomass systems represents a structural change for farmers. The Climate Foundation Skive (CFS) plays a critical role as a missions-driven boundary organization. Rather than acting as a traditional advisor, CFS functions as an 'institutional entrepreneur' that 'greases' the interactions between the three planes of the AKIS system. CFS facilitates the transition by acting as an intermediary between local municipalities (environmental regulators) and private technology providers, effectively bridging the horizontal coordination gap that often stalls bioeconomy innovations.

For a Limfjord farmer, transitioning from annual cereal production to perennial systems involves significant capital investment in specific harvesting equipment and a change in land-use status. To mitigate these risks and ensure the transition is socially and economically sustainable, the AKIS-related infrastructures must facilitate three key de-risking mechanisms:

Regulatory sandbox:

- **Contractual security:** The development of standardized, multi-year biomass supply agreements that guarantee off-take, protecting the farmer against the volatility of early-stage biorefinery operators.
- **Advisory-led financial modelling:** DAAS advisory centres must shift from traditional crop-budgeting to "whole-farm bioeconomic assessment," helping farmers calculate the total value of the system—including environmental payments, nutrient-reduction credits, and income from high-value protein streams.
- **Governance backstops:** Local authorities and national policy frameworks—aligned with the Green Tripartite Agreement—need to provide a "safety net" or transitional subsidies. This bridges the gap for farmers during the initial years of establishment, ensuring that environmental protection (N-reduction) is not solely funded by the farmer's pocket, but supported by the societal value of improved water quality in the Limfjord.

By framing this as a shared responsibility between the supply chain, the state, and the producer, the AKIS diagnosis identifies its functioning and supports as a risk-identification instrument, when turning a technical challenge into a viable regional development strategy. This makes a well-functioning AKIS not only a knowledge system, but also a risk-identification and coordination system for regional transformation.

4.1.4 Summary and conclusion

The Limfjord grass–biorefinery Nature-Based Solution (NBS) represents a significant paradigm shift in Danish agricultural policy: the transition from treating perennial grass as a static environmental compliance measure to leveraging it as a dynamic, circular bioeconomic asset.

Synthesis of Findings

Our AKIS diagnosis confirms that the Limfjord catchment possesses the requisite institutional density—spanning research, advisory networks, and policy frameworks—to support a transition toward systemic circularity. The strengths of the Danish system are evident in:

- Historical path-dependency: The successful re-purposing of over 35 years of perennial grass management knowledge (the "Tunø Legacy") provides a robust, low-risk foundation for farmer adoption.
- Institutional intermediation: The role of the Climate Foundation Skive (CFS) as an "Institutional Entrepreneur" is pivotal in overcoming the structural "lock-in" of cereal-dominated production by facilitating regulatory sandboxes and cross-sectoral coordination.
- The cascade nexus: The innovation effectively bridges the Food-Nutrient-Energy nexus. By applying the "Cascade Use of Biomass" principle, the system successfully decouples regional ecological status from agricultural economic risk.

Remaining Systemic Uncertainties

Despite these strengths, the transition remains vulnerable to three systemic bottlenecks:

1. Market formation: The lack of standardized, long-term biomass off-take agreements continues to create price volatility for early-adopter farmers.
2. Economic incentives: Current policy instruments are still primarily designed for "mitigation-as-cost" rather than "circular-value-creation."
3. Institutional coordination: While vertical links (Research-to-Farmer) are strong, "horizontal" integration (Municipality-to-Private-Technology-Provider) remains the most significant hurdle for catchment-wide scaling, revealing a clear bottleneck in the way these actors are embedded and coordinated within the AKIS.

4.2 Netherlands – Planty organic innovation

Planty Organic is a long-term farming experiment initiated in 2012 at the SPNA experimental farm in Kollumerwaard, in the north of the Netherlands. The innovation focuses on organic arable crop production using exclusively plant-based nutrient sources, excluding animal manure, animal by-products, and synthetic fertilisers. Nutrient supply is based on legumes, cover crops, green manures, compost, bokashi, and cut-and-carry plant biomass, particularly grass–clover.

The innovation emerged from a practical need identified by organic arable farmers to improve nitrogen efficiency while reducing dependency on livestock-based inputs. Planty Organic aims to enhance soil fertility, support soil life and biodiversity, and reduce nutrient losses through slower and more controlled nutrient release.

Long-term experimentation has shown that fully plant-based nutrient systems are feasible but face structural challenges, particularly the mismatch between nitrogen availability and crop demand over time, which can affect yields. Addressing these challenges requires improved knowledge on nutrient dynamics, fertilisation timing, and soil microbiological processes. Knowledge generated through Planty Organic is shared through research, advisory activities, and on-farm implementation with arable farmers.

4.2.1. Main characteristics of the innovation's context

The Netherlands has a highly intensive and technologically advanced agricultural sector. Despite its small geographical size and high land and labour costs, the country is one of the world's largest exporters of agricultural products (Government of the Netherlands, 2026). High productivity per hectare, strong logistics infrastructure, and a favourable geographic position contribute to this export orientation. Agricultural land use remains substantial, although the total number of farms has reduced over time, while the average farm size has increased significantly (Agro & food portal, 2024). This structural development reflects ongoing concentration, intensification, and rising capital requirements.

Agriculture contributes approximately 7% to national GDP and around 8.5% to employment when including primary production and supply chains (Verhoog, 2020). Most agricultural labour is provided by entrepreneurs and family members working full-time on farms (Wielinga, 2021). The sector faces several structural challenges, including high land prices, difficulties in farm succession, changing consumer demands, climate objectives, and increasing regulatory pressure (Paree et al., 2024).

Nutrient management and environmental sustainability are central issues in Dutch agriculture. Historically high nitrogen and phosphorus surpluses, linked to intensive livestock production and fertiliser use, have led to environmental concerns and stricter regulations. These pressures have stimulated policy attention towards circular agriculture, reduced emissions, and more sustainable production systems (Paree et al., 2024).

The Provinces of Friesland and Groningen are mostly rural, and are characterised by farming also as employment sector. In both provinces salaries are the lowest in the Netherlands while life satisfaction is among the top three regions (OECD regional Well-Being, 2025). The soils are characterised as light clay in the west of Groningen and heavy clay in the east and therefore used for arable farming. This is linked to the north of the Netherlands being short on organic manure, though there are manure transportation options from animal intensive regions to arable regions.

The Dutch AKIS

The Dutch AKIS is internationally recognised for its strong research, education, and innovation capacity, but it is also characterised by fragmentation (Paree et al., 2024). Following the privatisation of the public extension service in the 1990s, advisory services evolved into a pluralistic system consisting of independent advisors, product-related advisors, farmer organisations, research institutes, and educational bodies. While this diversity supports innovation, it has also resulted in a lack of cohesion and a shared long-term vision.

To address fragmentation and steer the transition towards circular agriculture, the Dutch government has introduced coordination and support instruments, most notably a subsidised voucher system that allows farmers to access independent advisory services and training. Education and research play a central role in the AKIS, with a well-developed system ranging from vocational education to university-level research, including Wageningen University & Research as a key actor. Advisory services, research institutions, farmer organisations, and public authorities interact through various project-based and policy-driven mechanisms to support innovation and knowledge exchange.

4.2.2. Characteristics of the Planty Organic's AKIS

AKIS actors and their linkages

A broad range of AKIS actors has shaped the development of Planty Organic. A key initial driver was an informal study group of motivated farmers who, in close interaction with researchers, jointly developed and refined the core idea of plant-based nutrient management. This loose network, centred around individuals from Biowad, the Louis Bolk Institute and SPNA, provided the social capital, practical experience and feedback needed to initiate the innovation, which was then tested on SPNA's trial site. As experimental results accumulated and visibility increased, these informal arrangements gradually evolved into a more formal, institutionally supported innovation pathway embedded in the AKIS, while the relative importance of purely informal exchanges decreased. The following section describes the main actors involved and their respective roles in knowledge flows and innovation support:

Farmer/famer-based organisations:

- **Biowad**: is a regional association of organic farmers in the Wadden Sea area. They initiated Planty Organic, with close connection to SPNA and the Louis Bolk Institute, organised the initial funding, hosted farmer study groups and meetings, and acted as a central intermediary for knowledge co-creation, dissemination and political advocacy for organic and plant-based nutrient management.
- **Farmers associations:** Other farmer associations and bio-cyclical networks, including those in Germany, exchanged ideas and trial results across borders, offered conceptual inspiration on similar farming approaches, and encouraged their members to experiment with and adapt elements of plant-based nutrient management on their own farms.
- **Individual farmers/entrepreneurs:** they act as early adopters by already testing plant-based nutrient management on their farms, contributing concrete practical experience, providing trial fields, offering critical feedback, and serving as visible demonstration cases for their peers.
- **BoerenNatuur:** it is the national umbrella organisation for 40 farmer collectives (around 11,000 farmers managing about 100,000 hectares) that implement agri-environmental schemes at landscape scale, and it acts as a bridge between farmers, biodiversity and environmental policy, and NGOs, thereby helping align innovations like Planty Organic with agri-environmental instruments and landscape-level nature objectives.
- **Farmer study groups and regional farming and practice communities:** They organise regular meetings and field visits in which farmers collectively interpret trial results, exchange experiences and adapt concepts to their local conditions, thus functioning as key practice-based learning hubs and multipliers within the AKIS. Strong connection and feedback by peers is also supported through social media groups formed on specific topics.

Private sector:

The private sector overall has only played a limited direct role in Planty Organic, because plant-based nutrient management is not closely aligned with conventional input-market

interests, although some advisory and financial actors still contribute to knowledge transfer, risk-sharing and investment support.

- **Advisory Services:** such as Delphy, Agrifirm, WPA Robertus, Van Iperen and Profyto-DSD translate research results into practical recommendations, support farmers in implementing innovative nutrient strategies on their farms, and disseminate knowledge through their advisory networks, thereby linking experimental findings with a broader circle of practitioners.
- **LTO-related funds:** They provide financial instruments that co-finance sustainable and circular innovations, including pilot and demonstration projects, and they reduce financial barriers to adoption by connecting farmers, start-ups and advisory services and sharing some of the initial investment risks.
- **Rabobank:** It is a cooperative bank with a strong focus on the food and agriculture sector. They support sustainable and circular farming systems by offering tailored financial products, sharing sectoral knowledge and mobilising its networks, thereby enabling farms to invest in transitions towards systems such as Planty Organic when these fit the sustainability strategy.

Research and education

- **Louis-Bolk Institute**: is the main scientific partner in Planty Organic, and it co-designed the experimental set-up, carried out monitoring and data analysis, reported and published results, and maintained intensive interactions with farmers and other researchers (also via personal links to Biowad), ensuring both scientific robustness and effective knowledge circulation.
- **Wageningen University & Research (WUR):** The University was initially involved through informal exchanges with researchers from the Louis Bolk Institute. Later it became a research partner that integrated Planty Organic concepts into broader research projects such as “Farm of the Future”, contributed systems analysis and modelling, and embedded the innovation within wider agendas on circular and climate-smart agriculture.
- **Other research institutions:** They include Universities of Applied Sciences such as Van Hall Larenstein and Aeres and research farms like Proefboerderij Rusthoeve. They conducted additional practice-oriented experiments, used Planty Organic as a case in education and student projects, and integrated Planty Organic results into their trial fields, thereby broadening the innovation’s relevance and outreach.

Third sector:

- **SPNA**: It is an applied research foundation with pilot farms in the northern Netherlands that hosts the long-term Planty Organic field trials on its research site, collaborates closely with Biowad and regional farmers, and has taken over responsibility for the continuation and financing of the experiments (mainly via EU projects), thus securing long-term data series and maintaining a strong link to practical farming questions.
- **Bionext:** It is the national platform for the organic value chain in the Netherlands, supported by the associations Biohuis, BioNederland and Biowinkelvereniging. They

connect organic actors from farmers to retailers, promote quantitative and qualitative growth of the organic sector and its core values (health, ecology, fairness, care), and help position innovations like Planty Organic within the wider organic market and chain cooperation.

Public Sector:

- **Provincial authorities:** They design and implement regional policies on nitrogen, manure, water quality and nature restoration, manage regional agricultural and environmental subsidy schemes, and collaborate with farmer collectives, water boards and knowledge institutions, thereby providing an important policy and funding framework for experimentation with and scaling of practices developed in Planty Organic. They provided primarily financial support and are engaged in knowledge exchange through visiting the sites.
- **Ministry of Agriculture:** is the main national authority for agricultural, manure and nitrogen policy, and it finances innovation and transition programmes (such as CAP measures, EIP-Agri and circular agriculture schemes), sets the overall regulatory conditions for nutrient management, and thereby creates national-level enabling frameworks through which innovations like Planty Organic are supported financially and mainstreamed.
- **Water boards**: They are regional authorities responsible for water quantity and quality and for implementing the EU Water Framework Directive and the Nitrates Directive. They work closely with farmers, LTO and advisory services to reduce nutrient emissions, making them key partners where innovations in nutrient management directly contribute to achieving water quality objectives. Results and knowledge resulting from Planty Organic are incorporated into their own projects.
- **The Netherlands Enterprise Agency (RVO)**: It implements national and EU subsidy and innovation schemes, including CAP measures and programmes for nitrogen reduction and sustainable agriculture, and it interacts directly with farmers, advisors and research institutions, thereby linking innovative practices such as Planty Organic to relevant funding and support instruments and facilitating their broader uptake.

Knowledge flows and innovation support among AKIS actors

As outlined in Section 4.2.1, the Dutch AKIS is characterised by a relatively strong role of private advisory services, which can lead to fragmentation of knowledge provision at national level. In the case of Planty Organic, however, we found that a well-established and effective informal knowledge exchange existed within the innovation's region, through which a diverse set of actors contributed to the development of the concept (Figure 3). The innovation was initially shaped in this informal space of exchange between motivated farmers and researchers, and formal innovation support was only mobilised once the concept had been sufficiently developed and more long-term support was secured when first trial results were available. We summarise a few observations below:

- **Practice-driven, trust-based practitioner–research networks**: A diverse and trust-based informal network between practitioners and researchers is well established in the region, enabling strong practice-oriented knowledge exchange in which concrete gaps in farming practice (e.g. nutrient management) are jointly

identified and translated into focused research questions and experimental designs, with ideas co-developed and continuously adjusted in response to new insights. The use of SPNA's trial site, combined with close interaction with farmers through Biowad, created this effective feedback loop.

- **High dependence on a few key individuals in early phases (person-level vulnerability)**: The early development of Planty Organic relied heavily on a small number of particularly active individuals from Biowad, the Louis Bolk Institute and SPNA, with continuity depending on their ongoing personal engagement and initiative, including in mobilising financial resources, as broader formal support structures remained limited until several years of testing had been completed. They also served as key boundary/bridging organisations that connected otherwise separate spheres (farmers, science, policy, funding).
- **Topic-driven networks focused on nutrient management and circularity**: The innovation emerged within a thematically focused network centred on plant-based nutrient management and circular-, crop-based or organic systems, with this clear topic focus helping to concentrate attention and resources, sharpen problem framing (e.g. reducing external inputs while maintaining yields) and facilitate targeted exchanges among farmers, researchers and NGOs around this specific set of challenges on between regional to international level.
- **Stepwise move from local innovation to broader research agendas**: Knowledge flows evolved from a local initiative into broader research and policy debates. Initially, exchange was mainly within the regional network; later, concepts and results were taken up in national research programmes (e.g. "Farm of the Future") and though limited also in societal discussions on circular agriculture and provincial funding agendas, indicating initial vertical diffusion of knowledge.
- **Limited involvement of private sector advisors**: Private upstream/downstream actors (e.g. fertiliser companies, processors, retailers) were only weakly integrated into the knowledge flows around Planty Organic. s advisors in the Netherlands are predominantly from the private sector, and Planty Organic's focus on reduced external inputs makes it relatively unattractive from a marketing and sales perspective, their interest in the concept – and thus the intensity of exchange and knowledge transfer – has remained limited.
- **Long-term experimentation as a learning and credibility mechanism**: Following the initial years of testing, the decision to continue Planty Organic as a long-term organic trial provided a process framework that generated robust time-series data on yields, soil fertility and nutrient balances, strengthened credibility among farmers and policymakers, enabled iterative learning and adaptive management over multiple years, and inspired additional trials by actors beyond the original core group. SPNA as a trialling intermediary to test practical relevant questions of farmers ensured it's continuity without taking farmers financial situation at risk.
- **Fragmented financial resources**: There are different options for innovators to apply for financial resources but they are scattered across institutions and authorities with their own agendas. Intermediary advisers (need to be paid) can support this process. In the case of Planty Organic individuals within Biowad and SPNA were experienced

and connected through their occupations to a number of financiers to develop a strategy.

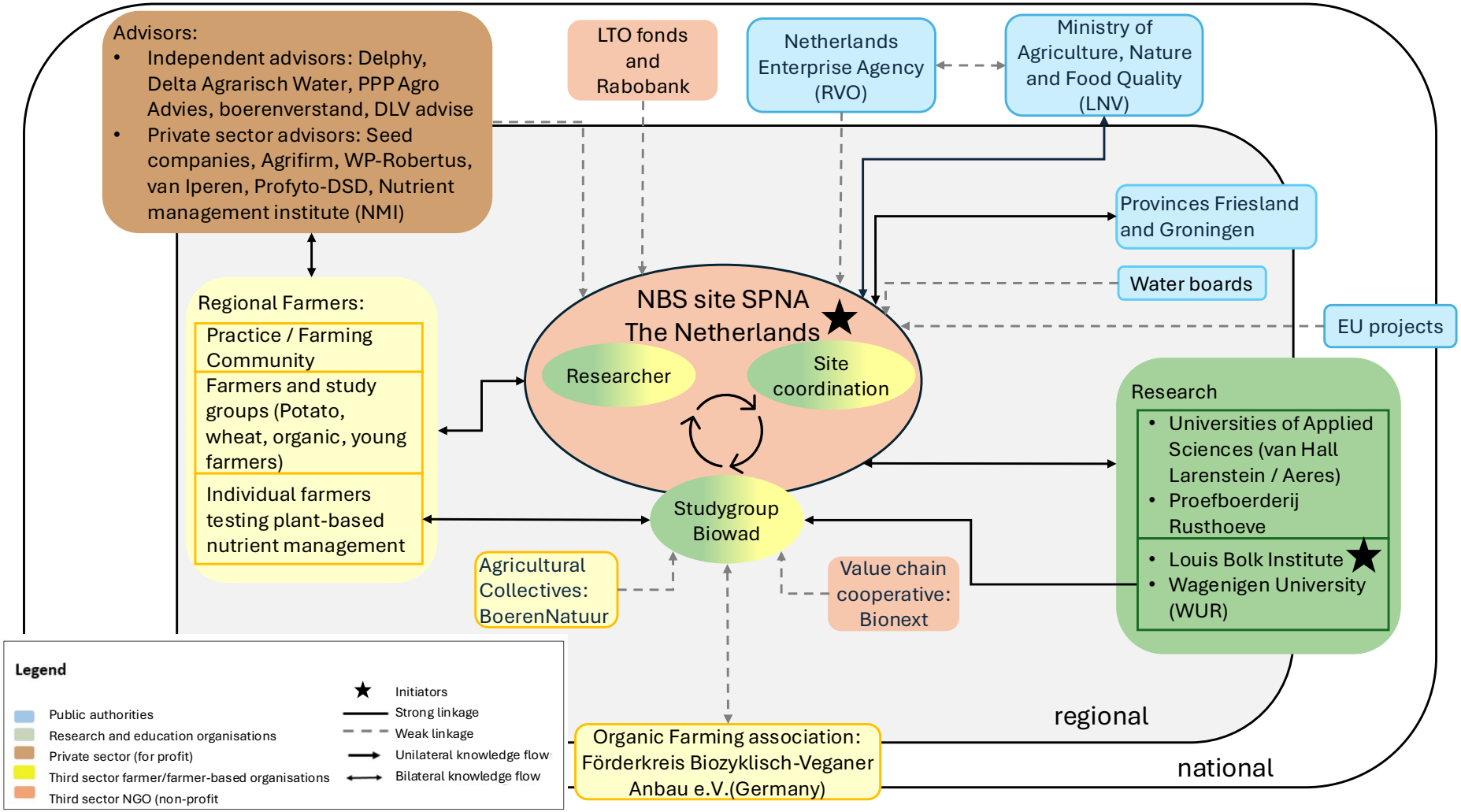

Figure 3: Represented AKIS of the "Planty Organic" Innovation in the Netherlands.

4.2.3. Summary and conclusion

Overall, the Planty Organic case illustrates how strong individuals, networks and a few bridging organisations can partially compensate for a fragmented, privately dominated AKIS and support the bottom-up emergence of a complex innovation. Knowledge exchange was driven mainly by researchers and farmer-based organisations, resulting in reciprocal learning processes. In contrast, the privatised advisory system has shown limited interest in low-input, plant-based circular systems, leading to weak connections with influential private sector actors and slowing wider uptake.

At the same time, the case highlights persistent coordination gaps that hinder broader diffusion and mainstreaming of plant-based nutrient management. Although nutrient circularity is part of the national policy agenda, Planty Organic was shaped more by provincial priorities and funding, with SPNA providing empirical evidence that informed regional agenda-setting. Relevant value-chain actors (e.g. potential processors of plant-based fertiliser products and other private companies) have so far remained largely absent from the AKIS around Planty Organic; only Bionext, an organic value-chain cooperative, has had more sustained interaction. Finally, formal education and training structures have not yet integrated the case systematically, limiting its role as a reference point for future farmers, advisers and policymakers. Therefore, Planty Organic was very successful in developing and testing a plant-based system but the wider reach of this innovation is still limited, as one interviewee stated.

4.3 Hungary – The Szigetköz innovation case

The Szigetköz region, located in Northwestern Hungary along the Danube, is one of the most fertile agricultural landscapes of the country, while also being an ecologically sensitive floodplain area. Its soils, shaped by centuries of river sedimentation, are well-suited for intensive crop and livestock production. At the same time, groundwater levels, nitrate sensitivity, and the coexistence of protected natural habitats make the region highly relevant for nutrient management innovations.

The innovation addressed here is the testing and demonstration of NBS in agriculture, focusing on sustainable nutrient management and ecosystem services. These solutions aim to balance agricultural productivity with environmental protection. In Szigetköz, this involves practices such as:

- improving soil fertility through organic amendments and cover crops,
- reducing nutrient losses by buffer zones and wetlands,
- promoting precision fertilization to minimize leaching,
- and integrating ecological water retention with farming activities, thereby aligning agricultural practices with broader European sustainability goals.

4.3.1 Main characteristics of the innovation's context

Hungary has a long tradition of intensive agricultural production, with approximately 5.1 million hectares of land under agricultural use, representing more than half of the country's total territory. About 82% of this area is arable land, dominated by cereals (maize, wheat, barley), oilseeds (sunflower, rapeseed, soybean), and increasingly maize silage and other feed

crops. Livestock production remains important, with cattle, pigs, and poultry concentrated in specific regions. This structural setup makes nutrient management a key issue for both productivity and environmental sustainability.

Building on these structural characteristics, several national and EU policy frameworks directly shape the regulatory, economic, and institutional context for nutrient management innovations in Hungary:

- Hungary's nutrient management strategies are closely aligned with the EU's Common Agricultural Policy (CAP), particularly through the Rural Development Programme (RDP). Farmers have access to support schemes under the CAP's cross-compliance and conditionality requirements, including nutrient management plans, soil protection measures, and restrictions in nitrate-vulnerable zones.
- Nitrates Directive (91/676/EEC): Hungary has designated nitrate-vulnerable zones (NVZs), where strict limits on manure application and storage are enforced. Farmers operating in these zones are obliged to prepare nutrient management plans and follow crop rotation restrictions to reduce nitrate leaching into groundwater.
- National River Basin Management Plan (RBMP): Within the framework of the EU Water Framework Directive, Hungary has adopted measures to reduce nutrient pollution, particularly targeting phosphorus and nitrogen loads in surface and groundwater bodies. This includes restrictions on fertiliser application periods and mandatory buffer zones along watercourses.
- National Rural Development Programme (2014–2020, extended to 2022, and integrated into CAP Strategic Plan 2023–2027): Provided financial support for sustainable nutrient management practices, precision farming technologies, manure management systems, and advisory services on fertilisation.
- CAP Strategic Plan 2023–2027: Hungary's current strategy emphasises climate-smart agriculture and precision nutrient management as key areas of intervention, aiming to improve fertiliser efficiency, reduce greenhouse gas emissions, and prevent soil degradation.

Despite providing an important overarching framework and financial incentives, these policy instruments often remain rather abstract at farm level and do not automatically translate into coherent, practice-oriented nutrient management on the ground. As a result, significant gaps persist between regulatory intentions and day-to-day decision-making by farmers and advisors. In this context, several key, practice-relevant challenges for nutrient management in Hungary can be identified:

- Nutrient Imbalances: While nitrogen surpluses and risks of leaching exist in intensive livestock areas, phosphorus depletion is observed in arable soils due to insufficient application.
- Water Quality Risks: Nitrate pollution of groundwater remains a concern, particularly in NVZs along the Danube and Tisza river basins.
- Climate Adaptation: Increasing frequency of droughts and extreme weather complicates nutrient use efficiency and requires site-specific fertilisation strategies.
- Knowledge Gaps: Despite available advisory services, adoption of precision nutrient management technologies is uneven, with small and older farmers less likely to adopt innovations.

- Institutional Fragmentation: The AKIS system in Hungary is well developed but fragmented. Advisory services are provided by the Hungarian Chamber of Agriculture, private consultants, cooperatives, and input suppliers, but coordination and knowledge exchange remain limited.

The Szigetköz region exemplifies many of these national-level challenges in a particularly condensed form. With around 110,000 inhabitants and roughly 60% of the land under agriculture—dominated by maize, wheat, sunflower, rapeseed, and intensive cattle and pig production—the area combines export-oriented farming with a mixed structure of family farms and large cooperatives. At the same time, nitrate-polluted groundwater, manure surpluses, and climate-related risks such as droughts and floods intersect with a dense regulatory setting shaped by the EU Nitrates Directive, the CAP Strategic Plan 2023–2027, national eco-schemes for precision farming, and Natura 2000 restrictions in water-sensitive zones. The coexistence of intensive production systems and the Szigetköz Biosphere Reserve generates particularly strong pressure to reconcile productivity with water and soil protection. This tension is embedded in a relatively well-developed regional AKIS: applied research and higher education in Mosonmagyaróvár (Széchenyi István University), the advisory role of the National Chamber of Agriculture and cooperatives, services from private consultancies and agri-tech providers, as well as the engagement of NGOs and conservation groups. In this context, NBS testing and demonstration becomes highly relevant as it aligns local agricultural practices with environmental objectives and EU sustainability priorities.

The Hungarian AKIS

Hungary's AKIS is characterised by a heterogeneous and multi actor structure, integrating research and education institutions, advisory services, farmer organisations, the commercial sector, and regulatory bodies. At its core, AKIS is defined as the network of people and institutions involved in the creation, sharing and use of agricultural knowledge, and in innovation processes in the agricultural sector. While Hungary's AKIS appears well-developed in terms of institutional actors, interview results reveal a more nuanced picture of how knowledge exchange functions in practice. Knowledge flows are predominantly practice-driven, with farmers, advisors, and input suppliers forming the core of operational knowledge exchange. Peer-to-peer learning and personal advisory interactions are consistently identified as the most effective mechanisms for innovation uptake, while formal research outputs often reach farmers only indirectly or with delay.

The principal actors include the Ministry of Agriculture, the Hungarian Chamber of Agriculture (NAK) which plays a key role in advocacy and coordination, the Research Institute of Agricultural Economics (AKI), universities and research institutes, private and commercial advisory firms, and agricultural producers (Table 1). The landscape also includes NGOs, input supplier companies, farmer cooperatives and other associations.

The advisory system in Hungary has evolved significantly. The national Farm Advisory System (FAS) is one framework through which advisory services are organised and regulated. NAK and its subsidiary advisory arms register, coordinate and monitor advisory providers under the FAS system, ensuring that farmers receive guidance especially in relation to EU conditionality, environmental and nutrient management requirements.

Hungary's AKIS exhibits both strengths and constraints in terms of knowledge flows. The system includes a diverse range of actors, such as research institutions, advisory services,

farmers, and commercial stakeholders, which enables multiple channels for knowledge exchange. However, the interaction between these actors is not always fully coordinated, and knowledge transfer processes can be fragmented.

Interview findings suggest that the dominant knowledge pathway follows a "research–advisor–farmer" logic rather than a direct "research–farmer" model. Although universities and research institutions are present and active, their direct influence on farm-level decision-making remains limited. Advisors, farmer networks, and input suppliers act as key intermediaries, translating knowledge into applicable solutions.

Knowledge exchange is often facilitated through advisory services and informal networks, which play an important role in translating scientific knowledge into practical applications. At the same time, challenges remain in ensuring that innovations are effectively disseminated and adopted across different types of farms.

A key structural weakness of the Hungarian AKIS is the limited integration between institutional actors. Interviewees consistently highlighted weak linkages between research institutions and farmers, as well as an almost complete absence of direct interaction between policymakers and farm-level actors. These gaps reduce the efficiency of knowledge transfer and slow down the adoption of more complex innovations such as NBS.

Innovation uptake in Hungary is strongly driven by financial incentives rather than intrinsic motivation or market demand. Interview evidence suggests that a significant proportion of farmers' decisions related to innovation adoption are influenced by available subsidies and funding schemes. This indicates a high dependency on policy-driven incentives, which may limit the long-term sustainability of innovation processes.

In addition to structural factors, behavioural aspects also play a significant role. Several interviewees pointed out that a lack of openness and motivation among farmers can hinder the adoption of new practices. Routine-based decision-making and risk aversion further limit experimentation with NBS, particularly among smaller and older farm operators. On the strength side, there is a broad institutional base with strong links to research and education. On the constraint side, the system is described as fragmented: advisory service provision is heterogeneous in quality and coverage, and smaller farms (especially those with older operators) are less well served. Coordination between research, advisory and practice (farmers) is variable; there are delays in transferring research-based innovations into farm level application, particularly for new nutrient management or precision agriculture technologies.

Advisory services are the key interface between research and practice. Given the challenges of nutrient imbalances (e.g., phosphorus deficiency in certain soils) and regulatory pressure (e.g., nitrate vulnerable zones), advisors translate nutrient management plans, monitoring data, and technological options into farm level decisions. However, uptake of advanced nutrient management innovations tends to be slower among less resourced farms, partly due to limited advisory outreach and the ageing profile of farm operators. However, the bridging function of these actors is not fully institutionalised and often depends on individual relationships or project-based cooperation. This creates inconsistencies in knowledge dissemination and limits the continuity of innovation support.

Going forward, Hungary's AKIS faces three development priorities: enhancing the digitalisation of advisory and knowledge exchange services; improving the coverage and quality of advisory services across farm sizes and regions; and strengthening interactive innovation processes that link farmers, advisors, researchers and commercial actors in co creation and experimentation.

Table 3: Key AKIS actors in Hungary

Category	Example Organisations	Role
Public authorities	Ministry of Agriculture; Regional authorities	Policy, regulation, funding schemes
Research & Education	AKI; Universities; Institute for Soil Sciences	Research, training, knowledge production
Private sector	Independent advisors; input suppliers	Commercial advisory services, innovation transfer
Farmer-based organisations	NAK; Cooperatives; Chambers of Agriculture	Representation, advisory coordination
NGOs	ÖMKi; environmental NGOs	Non-profit support, sustainability initiatives

Interviews also revealed missing or underrepresented actors in the Hungarian AKIS, particularly from the processing industry and the financial sector. Their limited involvement reduces the potential for scaling innovations and integrating NBS into broader value chains.

4.3.2 Characteristics of the Szigetköz NBS innovations AKIS

AKIS actors and their linkages

The development and uptake of NBS for nutrient management in Szigetköz take place within a dense AKIS. Around the core innovation, multiple actors interact through formal advisory structures, research–practice collaborations, market-based services, and advocacy networks. Knowledge flows are shaped by CAP implementation, regional research capacities, farmer-based organisations, and emerging environmental coalitions. The following overview summarises the main AKIS actors involved and their typical roles in supporting (or indirectly influencing) the NBS-related innovation and learning:

- **Public authorities**
  Ministry of Agriculture, Department for Rural Development; Győr-Moson-Sopron County Government (Agricultural and Environmental Units): Provide policy and subsidies, with a strong linkage to farmers through CAP support.
- **Research & education**
  Széchenyi István University, Mosonmagyaróvár Campus (Faculty of Agricultural and Food Sciences); Hungarian Research Institute of Soil Science and Agricultural

Chemistry (ATK TAKI): Maintain a two-way exchange with farmers via trials and training.

- **Farmer-based organisations**
  National Chamber of Agriculture (NAK), regional office in Mosonmagyaróvár; local cooperatives: Have strong links to farmers and facilitate peer-to-peer knowledge flow.
- **Private sector**
  Independent agronomic advisors (fertilization planning, precision farming); agri-tech companies (soil scanners, precision equipment providers): Provide a mainly one-way flow of services and technologies to farmers.
- **NGOs / civil society**
  Szigetköz Nature Conservation Foundation; local water protection associations; environmental NGOs involved in sustainable farming advocacy: Exercise a weak but growing influence on policy and awareness.

Knowledge flows and innovation support among AKIS actors

The main knowledge flow for the innovation follows a predominantly linear path from research to practice. Applied research institutions and universities generate knowledge, which is channelled through advisory actors—such as independent agronomic advisors, the National Chamber of Agriculture, and local cooperatives—before reaching farmers as recommendations, training, and technical services (Research → Advisory → Farmers). This is complemented by strong peer-to-peer exchange within and between cooperatives and farmers, where practical experience and local adaptations are shared directly (Cooperatives ↔ Farmers). In parallel, NGOs and civil society organisations, including nature conservation and water protection groups, primarily direct their knowledge and positions towards policymakers (NGOs → Policymakers), aiming to influence regulatory frameworks and public support for more sustainable nutrient management.

The innovation is supported by a combination of policy instruments, advisory services, and research activities. At policy level, the CAP Strategic Plan 2023–2027 provides financial incentives for precision farming, nutrient management planning, and environmentally friendly practices, including elements relevant to NBSs. In addition, regulatory frameworks such as the Nitrates Directive and the River Basin Management Plan create a compliance-driven environment that encourages more sustainable nutrient use.

At the operational level, advisory services play a central role in translating these policy requirements and technological options into farm-level decisions. The National Chamber of Agriculture (NAK), private advisors, and input suppliers act as key intermediaries, providing tailored recommendations and technical support. Research and higher education institutions, such as Széchenyi István University, contribute through applied research, field trials, and knowledge dissemination.

However, the effectiveness of innovation support is constrained by fragmentation and uneven access to advisory services. Smaller farms and less connected actors may face difficulties in accessing high-quality advice and innovation opportunities. Strengthening coordination between policy, research, and advisory actors, as well as improving accessibility of support services, will be essential to enhance the uptake and scaling of NBS in the region.

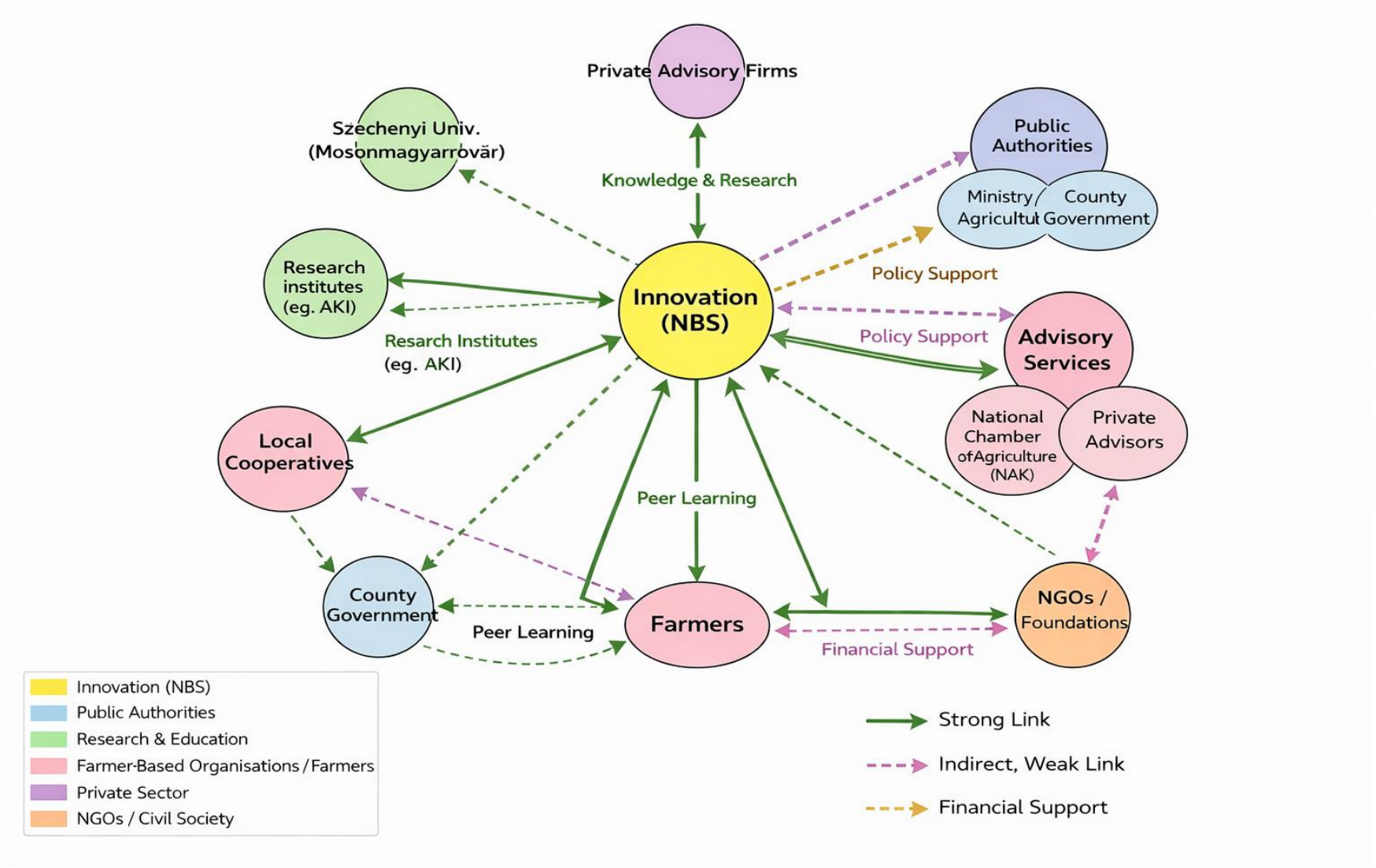

Figure 4: AKIS map of the Szigetköz NBS innovation in Hungary.

4.3.3 Summary and conclusion

The Hungarian case demonstrates that NBS for nutrient management are highly relevant in regions such as Szigetköz, where intensive agriculture coexists with sensitive ecosystems. AKIS provides a solid institutional foundation, with a broad range of actors involved in knowledge generation and dissemination. At the same time, the analysis highlights several structural challenges. Knowledge exchange is largely practice-driven, with advisory services playing a central role, while direct links between research and farmers remain limited. The system is fragmented, and coordination between actors is often weak. In addition, innovation uptake is strongly influenced by financial incentives, and behavioural factors such as risk aversion further affect adoption. Overall, the successful implementation and scaling of NBS in Hungary will depend on strengthening the integration of AKIS actors, improving knowledge flows between research and practice, and enhancing the accessibility and effectiveness of advisory services. Greater emphasis on interactive, co-creation-based innovation processes could further support the transition towards more sustainable nutrient management systems.

4.4 UK – Thallo innovation

Thallo is a multi-nutrient fertiliser innovation developed in Devon, UK, by Elemental Digest Systems Ltd (EDS). Grounded in the principles of nutrient circularity, the process converts abattoir waste, specifically animal bone and blood by-products, into a stabilised fertiliser pellet. This innovation emerged to address escalating waste disposal costs and the UK's heavy reliance on imported phosphate rock.

By recovering phosphorus from domestic waste streams, Thallo enhances resource security. Despite achieving "Proof of Concept" (POC) and successful validation through long-term trials at Rothamsted Research showing yields comparable to conventional mineral fertilisers, the innovation faced significant structural hurdles. High operating costs and a lack of early commercial revenue led to the original company's bankruptcy before it reached industrial scale. However, the intellectual capital and networks persist, with renewed interest in reviving the technology as of 2025.

4.4.1 Main structural characteristics of the innovation's context

The UK agricultural sector is characterised by intensive arable farming in the east and livestock-dominant systems in the west. This diversity makes nutrient management a central issue for productivity, environmental sustainability, and regulatory compliance. Despite its status as a major global economy, the UK food system is marked by a significant "civil food resilience gap," as the nation relies heavily on imports for its nutritional and caloric needs (Macdiarmid et al., 2018). Total agricultural land use covers a substantial portion of the country, managed by approximately 104,500 farm holdings, though the sector has seen a long-term trend of farm consolidation and increasing capital intensity.

Agriculture and the wider food system contribute approximately 9% to Gross Value Added and support over 4 million jobs. However, the sector remains highly dependent on external inputs, particularly mineral phosphorus, which is almost entirely imported from Morocco, Russia, and China. This dependence creates vulnerability to global price volatility and geopolitical risks associated with the concentration of phosphate reserves.

Following the policy shift post-Brexit, the UK has transitioned from the EU's Common Agricultural Policy to the Environmental Land Management (ELM) framework. This model operates on the "public money for public goods" principle, prioritising soil health, precision nutrient management and carbon sequestration (Cardwell, 2024).

This transition is reinforced by regulatory instruments, including the Farming Rules for Water and Nitrate Vulnerable Zones, which impose stricter controls on nutrient application and storage. Historically, abattoir outputs were treated as high-liability waste due to biosecurity concerns under Regulation EC No 1069/2009 (Carlini et al., 2013). However, contemporary standards now facilitate the reuse of organic waste, repositioning meat-processing byproducts as a recoverable resource (Marshall et al., 2019). This shift redefines abattoir waste as a potential resource within a circular bioeconomy rather than solely a disposal liability.

These structural supply risks and environmental pressures have accelerated demand for circular nutrient solutions that strengthen domestic resource security. By converting perishable abattoir byproducts into a stabilised, regulation-compliant fertiliser with controlled release characteristics, Thallo alleviates disposal bottlenecks while partially substituting for mineral phosphorus imports. This transition transforms a high liability waste stream into a reliable domestic nutrient source, enhancing both environmental compliance and input security in UK agriculture.

4.4.2 Characteristics of the innovations AKIS

AKIS actors and their linkages

A diverse set of AKIS actors has influenced the evolution of the Thallo nutrient-recovery innovation. Its development has been propelled mainly by entrepreneurial drive and strong scientific collaboration. The network brings together private-sector partners, research institutions, international collaborators, financial stakeholders, and regulatory authorities, all contributing to the innovation's trajectory.

Private sector

Elemental Digest Systems served as the central organisational actor, responsible for concept development, patenting, research coordination, and commercialisation efforts. The innovation originated from the founder's recognition of abattoir waste as a potential source of phosphorus. This idea was operationalised through in-house technical expertise, particularly the work of a chemist who developed the conversion process. Agronomists and business development staff supported product testing and market positioning. Upstream actors, including abattoirs, supplied the raw material, linking the livestock and fertiliser sectors.

Research and education

Rothamsted Research served as the primary scientific partner, conducting greenhouse and long-term field trials that validated agronomic performance. The research network expanded internationally through collaboration with the University of Cape Coast (supported by a Royal Society fellowship), enabling testing under tropical conditions. The University of Hohenheim further embedded the innovation within European research on nutrient management and sustainability.

Public sector and regulations

Regulatory authorities, particularly the Environment Agency and the Animal and Plant Health Agency (APHA), played a decisive gatekeeping role. Strict biosecurity and waste management regulations created uncertainty because the innovation did not clearly fit within existing categories. Policy frameworks shaped by the Department for Environment, Food & Rural Affairs (DEFRA) and, earlier, EU regulations further influenced the approval pathway.

Farmers and farmer organisations

Farmers were largely absent from the development phase and positioned mainly as potential end users. Their limited involvement reflects the early-stage nature of the innovation and contributed to a weak feedback loop between research and practice.

Financial and third sector actors

Financial and third sector actors played a supportive but limited role in innovation support. Private investors and venture capital actors were engaged as potential enablers of scale-up and commercialisation, although their involvement remained at an exploratory stage. Consultants and knowledge brokers provided specialised expertise in areas such as agronomy, chemistry, and regulatory compliance, supporting technical development and navigating the institutional environment. Additional laboratories and scientific institutions complement the work of the core research and educational institutions in the AKIS, providing specialised analyses, including soil and nutrient leaching assessments.

International policy and global fertiliser market actors

International actors linked to phosphate supply and global fertiliser markets posed as external pressures that shaped the innovation. Before Brexit, the European Union's focus on nutrient security and its reliance on Moroccan phosphate reserves highlighted structural vulnerabilities in conventional systems.

Knowledge flows and innovation support among AKIS actors

The AKIS surrounding the Thallo innovation, summarised in (Figure 5), is characterised by a high degree of technical centralisation and asymmetrical knowledge exchange. Knowledge flows followed a predominantly research-driven, entrepreneur-initiated trajectory, unlike traditional demand-pull agricultural development models. The following observations summarise the key dynamics:

- **Entrepreneurial-scientific networks with concentrated expertise**: The innovation was shaped within a closely connected, trust-based network of private sector actors and researchers, characterised by intensive two-way knowledge exchange between key individuals and the organisation, as well as with Rothamsted Research, particularly in the early stages. This core network enabled rapid experimentation and iterative refinement of the fertiliser concept through continuous interaction between chemical development and agronomic validation. However, while this structure facilitated agility and continuity, it also created a structural vulnerability, as critical knowledge remained largely tacit and concentrated in a few individuals rather than being institutionalised within broader support systems.
- **Research-led validation**: Formal research actors played a critical role in providing scientific legitimacy and experimental infrastructure, enabling the generation of robust,

longitudinal data. The collaboration between private-sector innovators and research institutions created strong feedback loops in which experimental results directly informed ongoing product development.

- **Specialised research networks as distributed knowledge contributors**: Beyond the core partnership, additional laboratories and scientific actors acted as distributed knowledge contributors, providing targeted expertise in areas such as soil analysis and environmental assessment. While these specialised knowledge flows significantly strengthened the scientific evidence base, they remained functionally isolated. These distributed networks strengthened the scientific evidence base but remained functionally specialised and only partially integrated into the overall coordination of the innovation system.
- **International scientific collaboration**: Knowledge exchange extended beyond the national level through collaborations with international research institutions. These interactions facilitated bidirectional learning across agro-ecological contexts, particularly between temperate and tropical systems, thereby enhancing the innovation's adaptability and external validation.
- **Limited integration of farmers in early innovation phases**: Farmers and farmer-based organisations were weakly embedded in the knowledge exchange system, particularly during the development and validation stages. Their role was largely confined to downstream dissemination, with limited opportunities for co-creation or feedback, resulting in a gap between scientific development and practice-based knowledge.
- **Weak engagement with financial commercial actors**: Private investors and other financial actors were only marginally involved in the innovation process, limiting the mobilisation of resources required for scale-up. The absence of strong linkages to commercial value chains further constrained the translation of scientific validation into market adoption.
- **Regulatory environment as a weakly aligned system component**: Interactions with public authorities were characterised by limited and predominantly compliance-driven engagement. Regulatory uncertainty, particularly regarding classification and biosecurity requirements, constrained knowledge exchange and slowed the transition from experimental development to commercial deployment.
- **Knowledge dissemination driven by scientific channels**: Dissemination occurred primarily through academic publications, professional networks, and international collaborations, including targeted presentations by Rothamsted Research to international fertiliser organisations. These activities contributed to awareness and legitimacy within global industry networks. However, these flows were largely unidirectional, with limited structured mechanisms for feedback into the innovation process or for wider practitioner uptake.

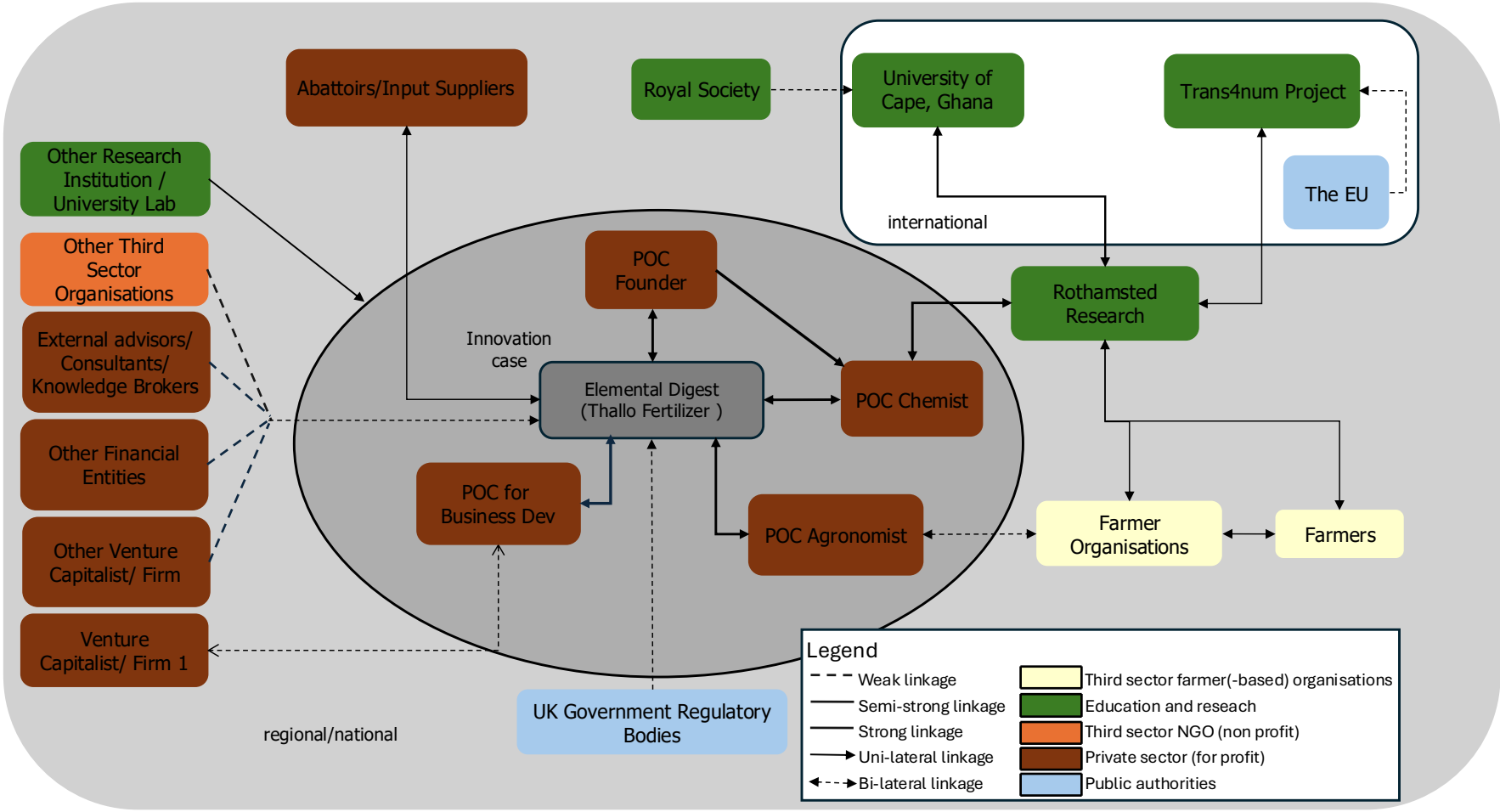

Figure 5: AKIS map of the Thallo® innovation in the UK.

4.4.3 Challenges and relevant innovation support for the NBS

To bridge the gap between scientific validation and commercial adoption, the Thallo innovation requires a more integrated support structure. Based on the UK's shifting policy landscape, the following support mechanisms are critical.

First, regulatory conditions hindered progression beyond the experimental and proof-of-concept stages. Addressing this requires collaboration with the Environment Agency and APHA to establish a fast-track approval pathway for animal by-product-derived fertilisers that meet defined safety standards, so as to reduce the regulatory friction that previously constrained scale-up.

As outlined earlier, the innovation failed to progress from proof of concept to industrial-scale production in part due to the absence of early commercial revenue. Addressing this gap requires targeted investment to support scale-up, including access to substantial capital from institutions such as the UK Infrastructure Bank or dedicated circular-economy funds to finance commercial-scale production.

Similarly, interview evidence indicated that the product would likely enter the market at a significantly higher price point than conventional mineral phosphate fertilisers, at around twice the price. Without a policy mechanism to recognise the environmental value of recycled phosphorus, this price differential would have constrained early adoption despite strong technical validation. This barrier could be mitigated by formally recognising recycled phosphorus fertilisers within the Sustainable Farming Incentive (SFI) and the higher tiers of the ELM. Aligning environmental payments with nutrient-recycling outcomes would then enable farmers to receive public support for adopting these lower-carbon inputs, effectively narrowing the price gap and creating more favourable conditions for market entry.

Lastly, engagement with farmers and farmer organisations was notably limited throughout the development process. This lack of integration reduced opportunities for these stakeholders to act as co-developers, participate in on-farm testing, or gain the early familiarity with the product necessary for future market confidence. Complementary support from Rothamsted Research or other third-party institutions could address this gap by involving stakeholders early in the innovation process and partnering with them for on-farm trials in the UK and Europe, similar to the field trials conducted in Ghana. This approach would build trust, encourage early adoption, and help the innovation move effectively from scientific validation to practical implementation.

4.4.4 Summary and conclusion

Overall, the Thallo case shows how a high-potential nature-based innovation can achieve strong scientific validation through a close entrepreneurial–research partnership, yet still struggles to progress from proof-of-concept to commercial deployment. The innovation effectively leveraged research partnerships, including Rothamsted Research, to demonstrate agronomic performance and address the UK's reliance on imported mineral phosphorus. However, challenges which hindered the early commercialisation of the innovation, specifically regulatory misalignment, limited access to circular-economy investment, and insufficient early-stage engagement with farmers, contributed to the initial collapse of the business.

The persistence of Thallo's intellectual capital into 2025 indicates that, although the original business structure failed, the underlying knowledge remains a critical asset for the UK's "public money for public goods" transition. To move from knowledge recovery to mainstream implementation, the innovation requires a shift from a research-led model to a more integrated AKIS. This involves aligning regulatory fast-tracks with environmental policy incentives, such as the SFI, and fostering participatory on-farm trials. Only by bridging these gaps can such NBS circular nutrient innovations become reliable components of a resilient domestic food system.

5. Cross country findings

5.1 AKIS actors and infrastructures of innovations

Our cross-country comparisons build on the analytical framework proposed by Birke et al. (2025), which is grounded in concepts from organizational sociology and institutional economics. In line with this approach, we analyse and compare the innovation-centred AKIS diagnoses by examining (i) the diversity of organizational actors, (ii) the availability of knowledge and financial infrastructures, and (iii) the coordination mechanisms in place. As AKIS entities are historically embedded in country-specific institutions, legal frameworks and cultural contexts, direct one-to-one comparison between national systems is not feasible (Knierim and Prager 2015). However, by applying this framework, we can identify typical features as well as broader patterns and trends across innovation cases.

5.1.1 Diversity of actors' categories represented in innovations AKIS

Across the four innovation cases, a broad spectrum of AKIS actors is involved, but their composition and relative weight differ markedly, with clear implications for how innovations emerge and scale (Table 4).

- In all cases, multiple actor types are present (public authorities, research and education, advisory services, farmers and farmer-based organisations, private companies, NGOs). Roles are often overlapping: research organisations are also active in advisory work, grant acquisition and knowledge brokerage; farmer-based organisations combine interest representation, active engagement in experimentation and informal advice.
- A common pattern is that where sectors are underrepresented, innovation pathways face bottlenecks. In the Netherlands, the weak involvement of private value-chain actors and commercial advisers may slow down or constrain the further scaling of Planty Organic. In the UK, the dominance of a relatively narrow group of private and research actors around Thallo, combined with limited engagement of public authorities, farmers and NGOs, may similarly restrict wider outreach and create potential vulnerability to regulatory changes.
- Although we observe actor type diversity in all four cases, the diversity within the types and the number of engaged actors varies clearly. Denmark and Hungary both exhibit a comparatively broad and dense actor landscape, but with different emphases. In Denmark, a strong research–advisory–farmer triangle is complemented by emerging value-chain actors (biorefineries, biogas plants, feed companies) and local stakeholder platforms, while public authorities are present across levels mostly as framework setters and funders instead of day-to-day drivers. In Hungary, numbers

and diversity of involved actors is the lowest among the cases although the regional AKIS is characterised as relatively dense. Thus, public authorities and private advisory/technology providers, although particularly influential, have not yet fully engaged with the NBS innovation, farmer-based organisations as key intermediaries and NGOs/civil society actors are still relatively weak in their contribution to the innovation's diffusion, and the level of integration of the innovation into, and outreach within, the wider AKIS remains limited so far.

- The Planty Organic case (Netherlands) stands out for its relatively high number of involved actors, with a strong reliance on farmer-based organisations and research actors, combined with a low representation of private sector companies and formal advisory services. Key individuals from farmer groups and research institutes acted as bridging actors between practice, science and finance, while most informal actors operated at regional level and formal actors (research, some public authorities) connected to the national level.
- The UK Thallo case is characterised by a relatively narrow actor constellation centred on private sector and research actors directly involved in the technical innovation. Other sectors (public authorities, farmers, NGOs) were only loosely connected, mainly through limited or informal linkages, resulting in a small core network with few formalised, wider supporting structures.

Taken together, the cases show that diversity of actors per se is not enough; what matters is how specific actor constellations interact around applied research and practice. Across all four cases, a strong and iterative role of applied research – in combination with on-farm trials, experimentation and joint learning processes – emerges as a core driver of innovation. A closely connected second factor is the quality of direct linkages with farming practice: where researchers work in tight interaction with farmers (NL, DK), innovations are perceived as relevant, are tested and adapted under real conditions, and thus gain in attractiveness and robustness. Where this researcher–farmer connection is weak or intermittent (UK, HU), the original appeal and practical fit of the innovation remains more limited.

The cases further suggest that the configuration of "triangles" between research and key intermediary actors influences how innovations are adapted in practice. In Denmark, a strong research–advisory–farmer triangle, and in the Netherlands a research–NGO–farmer triangle, provide continuous feedback and support context-specific adaptation of the innovations to farming practice. At the same time, the Danish case illustrates that a comparatively broad constellation of actors – including research, advisory services, farmers, value-chain actors and public authorities – is already engaged around the innovation. By contrast, in the Netherlands, Hungary and the UK, the involvement of private value-chain actors, advisory services, NGOs and farmer-based organisations around the focal innovations is more limited. In these cases, the role of such actors in framing, supporting and embedding the innovations (e.g. through market arrangements, advisory programmes or collective initiatives) is, so far, less visible in the empirical material.

Table 4: Cross analysis of trans4num AKIS innovation case studies on diversity of actors

Innovation case	Diversity of actors
Denmark	- Broad range of actor types - Emerging value chain actors - Strong research-advisory-farmer triangle - Local stakeholder platforms - Public authorities across levels
Planty Organic	- Initiation characterised by key individuals from farmer-based organisations and research - Representation of private sector low - Informal actors are mainly regional, formal actors act also on national level - Key actors mainly consist of practice and research and some governmental actors - High diversity among farmer-based organisations public authorities
Hungary	- Broad and dense AKIS (range of actor types) - Strong role of public authorities - Active research and education actors - Farmer-based organisations as key intermediaries - Dominant private advisory and technology providers - Emerging but weaker NGO and civil society influence
UK	- Actors concentrated around technical Thallo innovation from private sector and research - Actors of other sectors also had linkages to the innovation but limited (authorities, farmers, NGOs) - Core actors linked through informal connections; more formal and wider actors are limited

5.1.2 Knowledge and financial infrastructures

Across the four cases, all innovations draw on both knowledge and financial infrastructures, but they differ in how formalised, diversified and reliable these are (Table 5). These differences are central for understanding why some NBS pathways scale more easily than others.

- A key parallel is that in every case knowledge generation involves more than one actor type: research institutions, advisory services, farmers and private companies all contribute, often with overlapping roles (e.g. researchers advising, advisers involved in trials, farmers co-generating practice-based knowledge). Likewise, all cases combine several funding sources rather than relying on a single stream.
- The sharpest contrast lies between highly institutionalised knowledge infrastructures (especially Denmark, partly Hungary) and more informal, person- and project-driven ones (Netherlands, UK). Denmark exemplifies a mature, formalised knowledge

infrastructure (SEGES, DAAS, colleges, long "Tunø Legacy") coupled with a structured, hybrid funding mix (sector levies, CAP eco-schemes, climate funds, municipal water funds, research/bioeconomy funding). Hungary similarly channels knowledge and finance through established public and advisory structures (CAP implementation, subsidies, regulation), but with more top-down flows and notable access gaps. By contrast, Planty Organic (Netherlands) and Thallo (UK) rely far more on informal or narrowly configured infrastructures. In the Netherlands, knowledge exchange is anchored in regional, topic-driven farmer groups and researchers, with SPNA offering only a light formal backbone; funding is patchy, assembled via banks, regional authorities and later project funds, largely mobilised through personal networks. In the UK, the knowledge base is concentrated in a small set of private value-chain linkages and a few external researchers, with Rothamsted as a key bridge; funding is dominated by private sector contributions and is constrained by high capital needs.

- A further cross-cutting pattern is that where formal, multi-channel diffusion means are strong (e.g., trials, demos, advisory tools, events, stakeholder platforms), as in Denmark, innovations can move smoothly from research pilot to regional scaling. Where diffusion relies mainly on informal networks and a few core actors (Netherlands, UK), knowledge circulation is effective within the core but more fragile and harder to expand.
- Finally, while financial incentives play a role everywhere, their function differs: in Hungary they act primarily as top-down drivers for compliance and uptake, in Denmark they are part of a broader innovation- and transition-oriented funding architecture, and in the Netherlands/UK they remain fragmented or commercially constrained, making long-term NBS development dependent from funding volatility.

Overall, the comparison shows clear differences in how knowledge and financial infrastructures support the four NBS pathways. In Denmark, a dense and institutionalised system of advisory, research and funding bodies is complemented by rich informal networks, creating comparatively favourable conditions for both experimentation and scaling. In Hungary, formal public and advisory structures provide substantial knowledge and funding channels, but these are more hierarchical, with limited bottom-up experimentation and only partial integration of the NBS into the wider AKIS. In the Netherlands, active and innovative farmer–research networks are only lightly supported by formal institutions and depend on fragmented, project-based funding and personal ties, which sustains experimentation but makes long-term development and broader diffusion more fragile. In the UK, a narrow, firm-centred infrastructure concentrates knowledge and private capital within a small core of actors, enabling rapid technical progress but offering only a thin basis for wider outreach and scaling beyond this core.

Table 5: Cross analysis of trans4num AKIS innovation case studies on knowledge and financial infrastructures

Innovation case	Knowledge and financial infrastructures
Denmark	- Mature knowledge infrastructure: SEGES and DAAS centres, agricultural colleges, and long-standing agronomic experience with perennial grass ("Tunø Legacy") - Multiple diffusion channels: trials, demonstration fields, advisory tools, events, newsletters and stakeholder meetings. - Hybrid funding mix: sector levies, CAP eco-schemes, Climate Act funds, municipal water-protection funds, and ministry/bioeconomy research funding
Planty Organic	- Knowledge infrastructure mainly informal through topic driven farmers-based organisations/ study groups and researchers - High number of research actors and farmer-based organisations involved - Knowledge and financial infrastructure stabilised through bridging trial organisation (SPNA foundation) - Initial financial infrastructure supported through informal linkages - Initial financing more regional (through provincial authorities, SPNA) and through bank, in the later development through national/EU financing
Hungary	- Knowledge moves from research and policy to farmers via advisory actors, complemented by strong farmer–farmer exchange, but with relatively few direct research–farmer links - National and county-level authorities (Ministry of Agriculture, county government) are central through CAP implementation, subsidies and regulatory frameworks, and maintain strong direct links to farmers - Innovation uptake is strongly influenced by financial incentives and constrained by fragmented access to advisory support
UK	- Knowledge infrastructure is based on informal private sector and value chain linkages from abattoir waste as well as some external researchers on chemistry and agronomy. - A bridging actor for fertilising knowledge and trials is Rothamsted Research - The financial infrastructure was scattered and restricting as the innovations development is financially intensive - Financial support mostly through private sector

5.1.3 AKIS coordination mechanisms

Across the four cases, coordination depends not only on the number of actors, but on how their interactions are organised and how far these interactions extend into the surrounding

AKIS (Table 6). All cases show some form of coordination around the focal innovation, yet differ strongly in how formalised, inclusive and multi-level these mechanisms are, and in the extent to which they connect the innovation niche with the wider AKIS.

A core parallel is the importance of farmer-centred networks and advisory actors for day-to-day coordination. In Denmark and Hungary in particular, advisory services and farmer-based organisations translate policy and research into farm decisions and facilitate peer learning, creating relatively strong vertical (research–advisory–farmer) and horizontal (farmer–farmer) linkages that reach into the wider AKIS. In the Netherlands, a dense research–farmer network and strong farmer-to-farmer exchange similarly underpin coordination around Planty Organic, but this is more strongly anchored in informal, regionally bounded networks and less in nationwide advisory structures. Peer-to-peer exchange among farmers and cooperatives is a recurring feature across all cases, even where more formal mechanisms are weaker.

Bridging or intermediary organisations act as key coordination hubs, but with different mandates, scales and degrees of AKIS integration. In Denmark, SEGES/DAAS and Klimafonden Skive provide institutionalised, cross-sectoral coordination: they link research, farmers, public authorities and emerging value-chain actors, and connect local initiatives to national policy debates (e.g. water quality, climate), thereby clearly situating the innovation within the broader AKIS. In Hungary, public advisory services and some private technology providers function as important intermediaries between policy, research and farmers, but their engagement with the NBS case is still emerging; in addition, a farm demonstration network exists that could, in principle, support wider diffusion, yet its concrete role for this NBS remains unclear in the current material. In the Netherlands, SPNA plays a bridging role mainly at regional level by coordinating practice–research interactions via trials, study groups and events. While this creates strong local coordination, SPNA's potential to channel experiences from Planty Organic more systematically into national advisory and policy arenas is only partially used so far. In the UK, Rothamsted Research constitutes a potential bridge between the firm-centred Thallo network and the wider AKIS; however, at present coordination is largely confined to a small group of private actors and collaborating researchers, with relatively loose links to broader advisory structures, farmer communities and public authorities.

Policy frameworks and domestic initiatives shape how strongly innovation cases are connected to the wider AKIS. In Denmark, coordination around the NBS is closely tied into ongoing policy processes (e.g. water quality and climate targets), with established feedback loops between practice, research and policymaking; this anchors the innovation firmly within national AKIS structures. In Hungary, coordination is more top-down: CAP implementation, regulatory requirements and advisory services structure interactions. While the regional AKIS is dense, we currently see only limited evidence that the NBS case is substantively integrated into CAP implementation or broader policy agendas; rather, potential entry points (e.g. demonstration farms, advisory programmes) are present but not yet clearly activated for this innovation. In the Netherlands, coordination around Planty Organic is loosely linked to national agendas on circularity and nitrate reduction, but remains primarily regionally driven and informally organised, with only selective connections to formal advisory and policy channels. In the UK, weak and evolving regulatory coordination around animal-by-product-derived fertilisers and market authorisation means that Thallo is mainly

coordinated within a private–research niche, with limited institutional embedding in national AKIS frameworks.

Taken together, the cases indicate that effective AKIS-related coordination emerges where (i) strong vertical research–advisory–farmer linkages are institutionally anchored and reach beyond the immediate pilot; (ii) dedicated intermediaries bridge sectors and governance levels and actively connect innovation niches with formal AKIS structures; and (iii) policy frameworks provide both strategic direction and feedback channels from practice. Denmark approximates this configuration most clearly. Hungary has many of the formal elements (public advisory system, demonstration network, CAP instruments), but their concrete mobilisation for the NBS case and integration into the wider AKIS remain limited so far. In the Netherlands, coordination is strong within the research–farmer network, but only lightly connected to formal advisory and policy infrastructures, leaving substantial untapped potential for organisations like SPNA to play a stronger AKIS-bridging role. In the UK, coordination is highly effective within a narrow, firm-centred network, yet weakly connected to wider advisory, farmer and policy arenas, which limits the innovation's current anchoring within the broader AKIS.

Table 6: Cross analysis of trans4num AKIS innovation case studies on AKIS coordination mechanisms

Innovation case	AKIS coordination mechanism
Denmark	- Strong vertical coordination: intensive research–advisory–farmer links, with SEGES/DAAS as key intermediaries. - Cross-sectoral intermediation: Klimafonden Skive coordinates agriculture, industry and public actors and supports regulatory sandboxes. - Participatory governance: catchment-based stakeholder platforms and dialogues; remaining gap in horizontal coordination between municipalities and private technology/value-chain actors.
Planty Organic	- Domestic policy on nitrate use reduction as frame - Regional authority coordination reflects domestic policy on circularity - Bridging actor (SPNA) coordinating knowledge exchange within specific topics (institutionalised practice-research interface) - Informal, horizontal coordination: research-research exchange, farmer-research study group, peer-to-peer exchange also through social media groups and exchange with similar networks
Hungary	- Advisory services central in coordinating policy requirements and technological options into farm-level decisions - Strong peer-to-peer exchange and learning within and between cooperatives and farmers - Larger or well-connected farms benefit from the dense advisory environment; smaller and less connected actors have more limited access to high-quality support

	- Fragmentation and weak coordination between policy, research and advisory actors
UK	- Coordination mostly centred around product innovation - Low regulatory coordination on animal by-product-derived fertilisers and market introduction

5.2 Implications for transformation pathways

The AKIS diagnoses across the four trans4num cases provide first indications of how transformation pathways towards more sustainable and circular nutrient management are shaped by context-specific actor constellations, knowledge and financial infrastructures, and coordination mechanisms. In line with the incremental, adaptive and iterative pathway concept introduced in deliverable 1.6 "Report on transformation pathways towards innovative NBS", the cases show how local innovations develop through sequences of small adaptations. They highlight how individuals and organisations engage in these developments that sometimes reach beyond their customary fields of responsibility.

Across cases, innovation development is closely linked to how actors enter, engage, connect and remain involved. New actors from different parts of society (farmer groups, research organisations, advisory bodies, NGOs, value-chain companies, public authorities) are gradually integrated. Horizontal linkages (e.g. farmer–farmer, farmer-based organisations–NGOs, informal producer networks) and vertical linkages (e.g. research–advisory–farmer, regional initiatives–national ministries) co-evolve, structuring learning processes and coordination arrangements. However, the composition and strength of these linkages differ markedly between cases and have direct implications for transformation trajectories.

A first cross-cutting pattern is that broad actor constellations from all sectors, as in Denmark and to some extent Hungary, are associated with more robust, potentially scalable pathways. In Denmark, a strong research–advisory–farmer triangle is embedded in a wider constellation of municipalities, bioeconomy value-chain actors, and stakeholder platforms. In Hungary, a wide range of actors is also present, but with a stronger emphasis on public authorities and private advisory/technology providers. By contrast, in the Netherlands (Planty Organic) and the UK (Thallo), actor configurations are narrower or more uneven: Planty Organic is driven mainly by farmers and researchers with weak private advisory and value-chain involvement, while Thallo is centred on a small private sector–research niche with limited engagement from farmers, NGOs or public implementers. These differences in actor diversity shape whether innovations remain fragile and localised, or gain support across multiple societal domains.

A second pattern concerns knowledge and financial infrastructures. All four cases rely on multiple knowledge sources and funding streams, but the degree of institutionalisation and diversification varies considerably. Denmark combines a mature, formalised advisory and education system (SEGES, DAAS, colleges, the "Tunø Legacy") with a hybrid, transition-oriented funding architecture (sector levies, CAP eco-schemes, climate funds, municipal water funds, research and bioeconomy programmes). Hungary also has strong formal structures, but knowledge flows are more top-down, and financial incentives are geared mainly towards compliance, with uneven access to high-quality advice. In the

Netherlands and the UK, by contrast, knowledge and finance are more informal, project- or niche-based: Planty Organic depends on regional farmer networks, a few research institutes and a patchwork of grants and loans, while Thallo relies heavily on private capital and specialised value-chain know-how. This means that, although all four cases can generate learning and experimentation, their capacity to sustain and scale innovations depends strongly on whether knowledge and funding are embedded in stable, system-level infrastructures or remain contingent on a few actors and projects.

Third, coordination mechanisms differ not only in strength but also in their orientation. Denmark again illustrates a comparatively integrated model, with strong vertical research–advisory–farmer linkages, cross-sectoral intermediation (e.g. Climate Foundation Skive) and participatory, catchment-based platforms that connect agriculture, industry, authorities and civil society. Hungary shows strong coordination around policy implementation (CAP, Nitrates Directive, River Basin Management) and advisory translation, yet suffers from fragmentation between policy, research and advisory, and from unequal access for smaller farms. In the Netherlands, coordination around Planty Organic is largely horizontal and informal—through ambitious study groups, regional farmer–research networks and SPNA's trial platform—with only weak anchoring in national policy or value chains. In the UK, coordination is mainly confined to the product innovation niche, with limited regulatory alignment on animal-by-product fertilisers and weak integration into the broader AKIS.

These differences in actor diversity, infrastructures and coordination have direct implications for transformation pathways. The Planty Organic case vividly illustrates an incremental, bottom-up pathway where a relatively stable farmer–research coalition, supported by a bridging trial organisation, iteratively refines a radical concept under conditions of limited formal support and weak value-chain engagement. Learning is rich, but scaling is slow and vulnerable to the absence of private advisory and processing actors. The UK Thallo case shows a similar vulnerability from another angle: a technically sophisticated, private-sector-driven innovation can advance quickly within a niche, but weak regulatory coordination and limited societal anchoring constrain its potential to reconfigure wider nutrient management practices.

By contrast, the Danish case demonstrates how a dense, well-coordinated AKIS with diversified funding can turn a niche (perennial grass–biorefinery systems) into a credible regional transition strategy, supported by policy feedback loops, de-risking instruments and emerging markets. Hungary occupies an intermediate position: financial incentives and advisory structures can steer practices towards more sustainable nutrient use, but fragmentation and access gaps limit the depth and inclusiveness of transformation, especially for smaller or less connected farms.

Across all four cases, the diagnoses thus reinforce the need for multi-level and multi-actor approaches. Local, incremental pathways can generate substantial learning and environmental benefits when driven by committed coalitions of farmers, researchers and, in some instances, civil society and regional authorities. Yet, where important AKIS components—such as advisory services, value-chain firms, NGOs or implementing authorities—are weakly involved or absent, these pathways tend to stall at niche or pilot scale. Strengthening vertical connections between local initiatives and higher-level policy

frameworks, and horizontal connections to value-chain, financial and civil-society actors, appears crucial for moving from isolated experiments towards system-wide transformation.

In this sense, the trans4num AKIS diagnoses do more than document case-level innovations. They indicate moments and stages of innovation processes when broadening and balancing actor diversity are advantageous, where knowledge and financial infrastructures should be stabilised and oriented towards transformation, and where coordination mechanisms should be reinforced or redesigned. Addressing these systemic gaps will be key to linking diverse, context-specific pathways into a more coherent, European-wide transition towards sustainable and circular nutrient management.

6. Conclusion

The four case studies illustrate that nutrient-related innovations take very different forms – from plant-based organic arable systems and grass biorefinery concepts to NBS for nutrient retention and novel fertiliser products – and are anchored in distinct environmental, economic and institutional contexts. Despite this diversity, all cases respond to similar underlying pressures: tightening environmental regulation, concerns about input dependence, and the search for more circular, resilient farming systems.

Across cases, the AKIS diagnoses highlight three interrelated features that shape innovation performance and the degree of connection to the wider AKIS: (1) actor constellations that combine farmers, research and advisory actors, and, where present, value-chain, policy and civil-society organisations; (2) knowledge and financial infrastructures that range from robust, institutionalised and multi-channel (as in Denmark, partly Hungary) to more informal, project- and person-driven arrangements (Netherlands, UK); and (3) coordination mechanisms – often mediated by intermediaries such as SEGES/DAAS, Klimafonden, advisory services, SPNA, Rothamsted or farm demonstration networks – that link horizontal networks (farmer–farmer, cross-sector platforms) with vertical structures (research–advisory–farmer chains, regional–national policy interfaces) and thereby connect local innovation niches with the surrounding AKIS.

The cases point to clear differences in how these elements come together. In Denmark, a dense constellation of research, advisory, farmer and value-chain actors is embedded in mature knowledge and funding infrastructures and supported by institutionalised coordination mechanisms that are closely tied into policy processes; this creates comparatively favourable conditions for both experimentation and scaling. In Hungary, formal public and advisory structures and a farm demonstration network offer potential entry points for wider coordination, but engagement with the NBS case and integration into CAP implementation and broader AKIS arenas remain limited so far. In the Netherlands, a strong research–farmer network and intensive farmer-to-farmer exchange sustain effective local coordination and learning around Planty Organic, yet links into national advisory structures, value-chain actors and policy debates are only thinly developed. In the UK, coordination around Thallo is highly effective within a narrow private–research network, supported by concentrated private funding, but weakly connected to wider advisory systems, farmer communities and public authorities, leaving the innovation only lightly anchored in the broader AKIS.

Where diverse actors, robust infrastructures and bridging coordination mechanisms are well developed and aligned, innovations are better able to move from pilots towards broader adoption and to influence policy and market framings of nutrient management. Where these elements are partial, informal or confined to a narrow niche, rich local learning and technical progress can occur, but scaling and system-level influence remain more fragile, more dependent on a few key organisations or individuals, and more exposed to regulatory or funding changes.

Overall, the comparison shows that transformations in nutrient management are emerging not through a single "big push", but via multiple, context-specific pathways built on incremental adjustments, iterative learning and evolving coalitions. Local initiatives generate new practices, evidence and coordination formats that can, under favourable AKIS conditions, feed into policy development, advisory agendas, market arrangements and wider discourses on circularity. By systematically comparing actor diversity, knowledge and financial infrastructures and coordination mechanisms – and their linkages to the wider AKIS – this report provides an analytical basis for understanding how different AKIS configurations enable or constrain such pathways. It thereby offers a foundation for future work in trans4num and beyond on how to strategically strengthen AKIS – for example through targeted support to intermediaries, improved access to advisory services, more coherent and accessible funding architectures and better integration of value-chain and civil-society actors – so that diverse local innovations can more effectively contribute to sustainable and circular nutrient management in European intensive farming systems.

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