NESTLER

WHITE PAPER

Consolidation of Scientific and Technical Innovation

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Executive Summary

As the NESTLER project reaches completion, it delivers a mature and validated framework that operationalizes the One Health concept across agriculture, environmental monitoring, and public and animal health. Over its 42-month implementation, the project has moved beyond fragmented innovation approaches and established a fully integrated ecosystem combining advanced digital infrastructure, artificial intelligence, and circular bioeconomy solutions.

At the core of this achievement lies the NESTLER integrated platform, which consolidates heterogeneous data streams from satellite observations, unmanned aerial vehicles, and IoT sensor networks into a unified analytical environment. Through advanced data aggregation and AI-driven services, the platform enables real-time monitoring, predictive modelling, and decision support across sectors, supporting both operational farm-level decisions and strategic policy planning.

The system has been validated through large-scale pilot demonstrations across six African countries, confirming both its technical robustness and real-world applicability. Measurable results include returns on investment exceeding 100% in aquaculture systems and reaching up to approximately 496% under optimised poultry feed conditions, as well as the training of more than 1,600 farmers and practitioners. These outcomes demonstrate the strong economic viability and scalability of the NESTLER approach.

In parallel, the project has advanced circular bioeconomy solutions, demonstrating that Black Soldier Fly larvae can replace 50–100% of conventional feed ingredients while maintaining or improving productivity. The co-production of frass fertilizer further strengthens soil health and nutrient recycling, contributing to more sustainable and resource-efficient agricultural systems.

Beyond individual innovations, NESTLER's core contribution lies in its system-level integration. By combining digital technologies, biological processes, and socio-economic mechanisms into a cohesive framework, the project enables a shift from reactive to predictive and adaptive management of agri-food systems. As such, NESTLER provides a scalable blueprint for resilient, sustainable, and data-driven food systems within the EU–Africa context and beyond.

Key Innovations and Contributions

The NESTLER project delivers a set of integrated innovations that collectively advance the state of the art in digital agriculture, circular bioeconomy, and One Health implementation:

- **Integrated NESTLER Digital Platform**: A system-of-systems architecture combining environmental, agricultural, and health data into a unified decision-support environment.
- **AI-driven Early Warning Systems**: Advanced machine learning models enabling predictive detection of crop stress, pest outbreaks, and zoonotic disease risks.
- **Federated Learning Framework**: A privacy-preserving approach to distributed AI model training across regions, supporting cross-border collaboration while respecting data sovereignty.
- **Circular Bioeconomy Integration**: Deployment of Black Soldier Fly-based systems transforming organic waste into high-value protein and organic fertiliser.
- **Multi-modal Data Ecosystem**: Seamless integration of satellite, UAV, and IoT data for real-time monitoring and multi-scale analysis.
- **Validated EU–Africa Deployment Model**: Large-scale pilot demonstrations confirming technical feasibility, socio-economic viability, and user acceptance across diverse contexts.

Together, these innovations establish a holistic and scalable framework for transforming agri-food systems through the combined application of digital technologies, biological solutions, and integrated governance approaches.

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1 Introduction and Context

The NESTLER project was conceived in response to a fundamental challenge: the persistent fragmentation across systems responsible for food production, environmental management, and health monitoring. Traditional approaches have treated these domains as largely independent, resulting in inefficiencies, delayed responses to emerging risks, and limited capacity to address systemic challenges such as climate change, zoonotic diseases, and resource depletion.

Within the broader policy context of the European Union's Farm to Fork strategy and the increasing emphasis on One Health approaches, NESTLER aimed to bridge these gaps by developing an integrated framework that combines technological innovation with scientific research and real-world validation. The project has been implemented through a strong EU–Africa partnership, recognising that many of the most pressing challenges related to food security and environmental sustainability are global in nature but require locally adapted solutions.

The comprehensive scope of NESTLER included the development of a digital platform, the integration of multi-source data, the application of artificial intelligence, and the validation of circular bioeconomy solutions. Crucially, the project was designed not only to develop these components but also to demonstrate their effectiveness through pilot implementations under real operational conditions.

The selection of pilot sites across Cameroon, Nigeria, Ethiopia, Rwanda, Uganda, and Kenya ensured that the project addressed a wide range of agroecological conditions, production systems, and socio-economic contexts. This diversity has been instrumental in testing the adaptability and scalability of the NESTLER approach, providing valuable insights into both opportunities and constraints.

At its core, NESTLER has sought to transform the One Health concept from a theoretical framework into a practical and operational system. This required the integration of multiple disciplines, including data science, agronomy, animal health, environmental science, and socio-economic analysis. The project has therefore functioned as a multidisciplinary innovation ecosystem, where knowledge and technologies are continuously exchanged and refined.

1.1 EU–Africa Collaboration and Knowledge Exchange

The EU–Africa partnership at the core of NESTLER represents a critical dimension of the project's success. By bringing together partners from different regions and disciplines, the project has enabled the co-creation of solutions that are both scientifically robust and contextually relevant.

Knowledge exchange has been a central component of this collaboration. European partners have contributed expertise in digital technologies and system integration, while African partners have provided critical insights into local conditions, challenges, and opportunities. This mutual learning process has enhanced the quality and applicability of project outcomes.

The development of the EU–Africa One Health roadmap[1] further strengthens this collaboration, providing a strategic framework for future initiatives. By aligning research, policy, and practice, the roadmap supports the continued advancement of integrated approaches to sustainability and health.

[1] https://nestler-project.eu/wp-content/uploads/2025/10/NESTLER_One-Health-sustainability-roadmap-for-EU-Africa-partnership_v1-1.pdf

2 State of the Art and NESTLER Innovation Positioning

Prior to NESTLER, the state of the art in digital agriculture and environmental monitoring was characterised by the proliferation of specialised tools addressing isolated challenges. Remote sensing technologies provided valuable insights into crop health and land use, while IoT systems enabled localised monitoring of environmental parameters. Artificial intelligence applications were increasingly used for tasks such as yield prediction and disease detection. However, these technologies were rarely integrated into cohesive systems, limiting their overall impact. Similarly, innovations in sustainable agriculture, such as alternative feed sources and organic fertilisers, were often developed independently from digital tools, resulting in a disconnect between biological innovation and data-driven management. This fragmentation hindered the ability to fully exploit synergies across domains.

NESTLER advances beyond this state of the art by adopting a system-of-systems approach. Rather than focusing on individual components, the project has developed an integrated architecture where data collection, processing, analysis, and decision-making are seamlessly connected. The implementation of multi-modal data aggregation protocols enables the combination of satellite data, UAV imagery, and IoT sensor measurements into a unified data ecosystem. This integration is further enhanced by the NESTLER AI framework, which applies advanced machine learning and deep learning techniques to extract actionable insights from complex datasets. The use of federated learning represents a significant innovation, allowing distributed model training across different regions while preserving data privacy and complying with regulatory requirements.

From a scientific perspective, the integration of circular bioeconomy solutions into a digital decision-support framework represents a novel contribution. The combination of insect-based protein systems, frass fertiliser, and AI-driven optimisation enables a closed-loop system where waste streams are transformed into valuable resources and managed efficiently through data-driven insights. In terms of impact, NESTLER shifts the paradigm from reactive management to predictive and adaptive systems. By enabling early detection of risks such as pest infestations, disease outbreaks, and environmental stress, the project supports proactive interventions that reduce losses and improve resilience.

3 NESTLER Integrated Platform and System Architecture

The NESTLER platform is fundamentally aligned with the One-Health concept, which recognizes the strong interdependencies among human health, animal health, plant systems, and the wider environment. The NESTLER integrated platform constitutes the technological backbone of the project. It is designed as a modular and scalable system that integrates data ingestion, processing, analytics, and visualisation into a unified environment. At the data ingestion layer, the platform collects information from a wide range of sources, including Earth observation satellites, UAV-based imaging systems, and IoT sensors deployed in agricultural and environmental settings. These data streams are characterised by high volume, variety, and velocity, requiring robust data management and processing capabilities.

The data aggregation protocols ensure that heterogeneous data sources are harmonised and structured in a way that enables efficient analysis. This includes the implementation of standardised formats, metadata schemas, and data quality control mechanisms. Interoperability is a key feature of the NESTLER architecture. The use of APIs and service-oriented design principles allows the platform to integrate with external systems and data sources, facilitating scalability and future expansion.

The backend layer of the platform hosts the AI services. These services include models for crop monitoring, livestock analysis, environmental risk assessment, and disease prediction. The models are designed to operate both in real-time and in batch mode, depending on the requirements of specific applications. The frontend layer provides user interfaces based on GIS technologies. These interfaces enable users to visualise data, interact with analytical results, and access decision-support tools. The design prioritises usability and accessibility, ensuring that stakeholders with varying levels of technical expertise can effectively use the platform. This allows stakeholders including agronomists, researchers, policymakers, public-health authorities, environmental agencies, and pilot operators/farmers, to collaboratively assess risks and coordinate responses within a shared digital environment. By bridging these traditionally separated sectors, NESTLER contributes to safer food systems, resilient agricultural production, improved zoonotic outbreak preparedness, and sustainable ecosystem management, which are central objectives of the One Health strategy promoted across EU-Africa partnerships.

The architecture is designed to be flexible, allowing for adjustments and updates, and scalable, ensuring it can adapt to increasing demands and evolving technologies. The high-level system architecture of the NESTLER platform is structured into different layers, each one of which is responsible for specific functionalities within the platform. Figure 1 depicts the high-level NESTLER reference architecture.

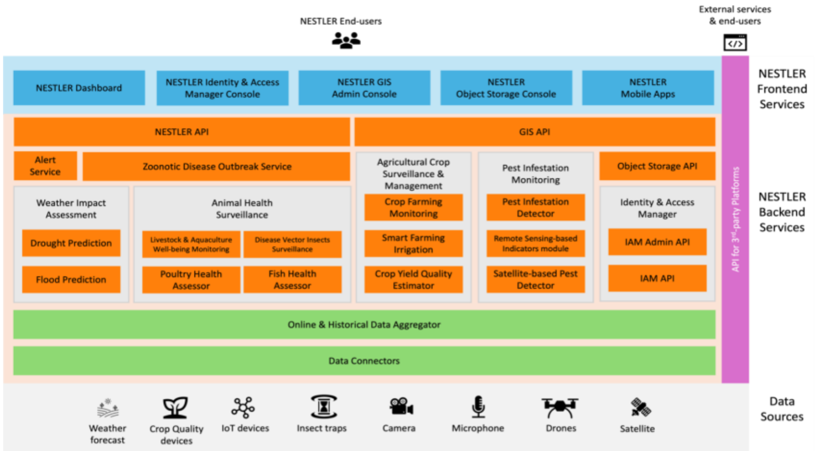


Figure 1: High-level reference architecture overview of the NESTLER platform

At the foundation of the system lie diverse data sources, as outlined below:

- IoT devices are devices within the Internet of Things (IoT) ecosystem, designed to gather diverse types of data, which can be used for real-time monitoring and decision-making in services. In the NESTLER project, data is collected using the SynField platform, which supports connections with the following devices:
    - Weather station, that offers remote monitoring of environmental weather factors.
    - Soil sensors, gathering data related to soil conditions.
    - SynWater, which provides water quality monitoring.
    - SynAir, which provides air quality monitoring.
    - Valves, which used to irrigate or not the crop.
- Quality Measurement Devices extracts measurements related to crop quality characteristics. In the NESTLER project, those devices are used to gather information about the quality of cassava crops.
- Insect Traps are traps that provide remote monitoring of fly and mosquito insects in selected locations of the pilots.
- Drone is a dynamic data source within the system, providing high-resolution aerial imagery and geographic information. In the NESTLER project, drones will be utilized to collect data, providing insights about the biotic stress of crops.
- The camera captures visual information in the form of images and video. In the NESTLER project, the camera is used to gather video data of livestock and aquaculture well-being as well as images of crops.
- Microphone captures surrounding information from the surrounding environment. In NESTLER, microphones are employed to monitor acoustic signals within livestock farming.
- Weather forecast includes data that is both processed by backend services and visualized in the NESTLER dashboard.
- Satellite Earth Observation data provide insights into environmental and agricultural conditions by capturing information across large geographical areas with high temporal frequency. These datasets, derived from remote sensing technologies, enable the monitoring of key variables such as land cover, vegetation indices, soil moisture, and weather patterns.

The platform can integrate and analyse this wide spectrum of inputs from heterogeneous technologies, thereby endowing the system with multi-modality characteristics. On top of the data sources, the platform incorporates building blocks that consume and process that data which constitutes the backend services. The backend services include both components that were implemented during the project and open-source services that have been configured and integrated in the platform.

4 Artificial Intelligence and Advanced Analytics Framework

A central pillar of the NESTLER innovation framework is the development and deployment of advanced artificial intelligence (AI) models, supported by robust data aggregation mechanisms. These models are not designed as standalone analytical tools, but as integral components of a continuous data-processing pipeline that enables both real-time monitoring and predictive decision-making.

The AI framework operates across multiple domains, reflecting the interdisciplinary nature of the One Health approach. In crop production systems, convolutional neural networks and hybrid machine learning models are applied to remote sensing data to detect early signs of plant stress, pest infestations, and nutrient deficiencies. By combining satellite-derived vegetation indices with UAV imagery, these models achieve high spatial and temporal resolution, allowing for precise, field-level interventions.

In livestock systems, AI models analyse behavioural patterns, movement, and physiological indicators using data from video streams, sensors, and acoustic signals. This enables the early detection of anomalies associated with disease or stress. Their integration into the NESTLER platform supports continuous monitoring and early warning, reducing the risk of disease outbreaks while improving animal welfare.

Environmental monitoring constitutes another key application area. AI integrates data from diverse sources—including IoT sensors, satellite Earth observation, drones, and weather services—to provide a comprehensive understanding of environmental conditions. This multimodal approach enables monitoring of climate patterns, soil conditions, air and water quality, and broader ecosystem dynamics. Furthermore, AI models assess climate-related risks such as droughts and floods by combining meteorological, land-use, and soil data, offering predictive insights that support resource planning and risk mitigation.

AI also plays a critical role in enhancing modern cultivation practices. Within the NESTLER platform, data from IoT sensors, weather stations, and satellite observations are leveraged to monitor crop conditions and guide decision-making throughout the cultivation cycle. AI-powered services, such as smart irrigation systems, optimise water usage by analysing soil moisture and environmental parameters, automatically adjusting irrigation to meet crop needs. In parallel, machine learning models support crop health monitoring by enabling early detection of diseases and pest infestations through image analysis and sensor data, facilitating timely and targeted interventions.

A key innovation within NESTLER is the implementation of federated learning. This approach allows AI models to be trained across distributed datasets without requiring the centralisation of sensitive data. In the context of EU–Africa collaboration—where data governance and sovereignty are critical—federated learning provides a practical solution that balances high analytical performance with regulatory compliance.

The effectiveness of these models has been validated through pilot activities, with disease prediction systems achieving high levels of accuracy, including AUC values exceeding 0.9. These results demonstrate the capability of the NESTLER AI framework to deliver reliable and actionable insights across diverse operational environments.

5 Remote Sensing, IoT Integration and Data Ecosystem

The NESTLER framework adopts an integrated and multi-layered approach that combines remote sensing technologies, IoT infrastructures, and a unified data ecosystem to enable data-driven precision agriculture. This approach facilitates the continuous collection, fusion, and analysis of heterogeneous data streams, supporting informed decision-making across diverse agricultural contexts.

At the field level, IoT-based sensing systems, such as Synelixis's SynField smart agriculture solution, provide continuous, high-resolution monitoring of critical environmental parameters. These include microclimatic conditions (e.g., temperature, humidity, air quality), water quality indicators, and, importantly, soil-related parameters such as soil moisture, temperature, electrical conductivity, and nutrient levels. Soil monitoring is particularly essential, as it directly reflects plant growth conditions and resource availability, enabling optimized irrigation, fertilization, and overall crop management strategies.

These in-situ measurements are complemented by remote sensing technologies, creating a comprehensive monitoring framework. Satellite-based Earth Observation provides large-scale, periodic insights into vegetation health, land use, and environmental dynamics, while UAV-based platforms offer high-resolution, near real-time imagery for detailed crop assessment, pest detection, and early identification of stress factors. The synergy between these technologies ensures both localized accuracy and broader spatial awareness.

A key innovation of NESTLER lies in its multi-modal data aggregation layer, where heterogeneous data streams, from IoT devices, remote sensing platforms, and external sources such as weather services, are integrated into a unified and interoperable ecosystem. This integration is supported by reliable communication infrastructures, including long-range wireless technologies and mesh networking, enabling efficient data collection even in remote or infrastructure-limited environments.

Beyond data collection, NESTLER addresses the critical challenge of data integration and harmonization. The project develops protocols and methodologies to ensure consistency, interoperability, and reliability across diverse data sources. Advanced data fusion techniques are employed to combine information from multiple modalities, improving accuracy, reducing uncertainty, and enhancing the overall quality of insights.

Within this unified ecosystem, standardized data models and interoperable interfaces enable scalable analytics and seamless data exchange. Advanced processing techniques, including artificial intelligence and machine learning, transform raw data into actionable insights, such as soil condition trends, crop health indicators, and early warnings for pest infestations or environmental stress.

The resulting data ecosystem supports multi-scale analysis, allowing insights to be generated at both macro and micro levels. For instance, satellite data can be used to identify areas of interest at regional scale, while UAV and IoT data provide detailed, localized information to support targeted interventions and precision farming practices.

Finally, connectivity challenges in remote and rural areas are addressed through innovative communication solutions, including UAV-enabled data collection and mesh networking architectures, as well as optimized data transmission protocols. These approaches ensure reliable data flow even in low-connectivity environments, significantly extending the operational reach and impact of the NESTLER platform.

By effectively combining ground-based sensing with aerial and satellite observations within a robust data ecosystem, NESTLER establishes a comprehensive digital agriculture framework that enhances monitoring capabilities, supports predictive decision-making, and promotes efficient and sustainable resource management.

6 Pilot Demonstrations and Operational Validation

The pilot demonstrations conducted under NESTLER represent a central element of the project, providing real-world validation of its integrated One Health approach. Implemented across six African countries, these activities created a diverse testing environment where solutions could be assessed under different agricultural, environmental, and socio-economic conditions.

The pilots covered agriculture, livestock and poultry farming, aquaculture, and environmental monitoring, reflecting the interconnected nature of food systems. A key strength of the NESTLER approach was the combination of advanced digital technologies—such as AI models, IoT sensors, and data platforms—with biological innovations including insect-based feed and frass fertiliser. This integration demonstrated that the proposed solutions are not only technically feasible, but also economically viable and socially accepted by end users.

In the agricultural domain, pilot activities focused on improving crop productivity through precision farming techniques, real-time monitoring of soil and environmental conditions, and the use of sustainable inputs. In parallel, livestock and poultry pilots demonstrated the effectiveness of insect-based feed, while digital tools enabled continuous monitoring of animal health and behaviour. Aquaculture pilots applied similar principles to fish farming, integrating alternative protein sources and environmental sensing technologies to optimise production conditions.

Environmental monitoring was a cross-cutting component across all pilot sites. Through the use of remote sensing, AI, and GIS-based tools, the project enabled the tracking of climate conditions, early detection of risks such as pests and diseases, and more informed, data-driven decision-making. This holistic integration of environmental intelligence significantly enhanced the resilience and sustainability of the farming systems involved.

The level of engagement and adoption among stakeholders further highlights the success of the pilots. More than 1,400 farmers participated, receiving training and practical support in the use of new technologies and practices. Adoption rates were high, reflecting the tangible benefits observed in daily operations. In addition, consumer acceptance of products derived from insect-fed livestock reached 88%, indicating strong market potential and social acceptance of these innovations.

From an economic perspective, the results were particularly promising. In several pilot cases, farmers reported significant improvements in profitability, while return on investment exceeded 100% in certain contexts. These outcomes demonstrate the capacity of NESTLER solutions to enhance productivity, improve livelihoods, and contribute to sustainable economic development.

At the same time, the pilot activities revealed operational challenges, including limitations in connectivity, logistical constraints, and capacity gaps. These issues were addressed through adaptive strategies such as targeted training programmes, the development of standard operating procedures, and improvements in supporting infrastructure. The NESTLER pilot demonstration activities underlined the effectiveness of an integrated, technology-driven approach to sustainable food systems, providing strong evidence for its scalability and relevance in the broader EU–Africa context.

7 Disease Surveillance and One Health Applications

NESTLER has delivered significant advances in integrated disease surveillance within the One Health paradigm, bridging environmental, animal, and human health domains through data-driven innovation. By systematically combining heterogeneous data streams—including environmental monitoring, IoT-enabled sensors, and agricultural activity records—the project has enabled the development of robust predictive models for infectious disease outbreaks.

A key achievement of the project is the large-scale collection and analysis of vector samples during pilot activities, resulting in a high-quality dataset for epidemiological modelling. These data have supported the development and validation of AI-driven models targeting vector-borne diseases such as dengue and trypanosomiasis, demonstrating strong predictive performance.

The resulting models underpin early warning systems that facilitate timely and targeted interventions, thereby reducing the impact of disease outbreaks on both human and animal populations. Importantly, the integration of environmental and ecological variables significantly enhances predictive accuracy by capturing the complex interactions between climate dynamics, ecosystems, and disease transmission pathways.

Overall, the NESTLER approach exemplifies the value of integrated, cross-domain data analytics in advancing One Health objectives, enabling a more comprehensive understanding of disease risk factors and supporting more effective, evidence-based response strategies.

7.1 NESTLER Zoonotic Disease Outbreak Service (ZDOS)

The Zoonotic Disease Outbreak Service (ZDOS) is a core NESTLER innovation designed to identify and assess the risk of zoonotic disease outbreaks through scalable, data-driven methodologies. The service operationalises daily spatial risk modelling by integrating diverse datasets across consistent temporal and geographical dimensions and applying configurable disease-risk functions.

ZDOS incorporates spatial diffusion modelling based on empirically derived vector movement ranges, alongside time-series forecasting techniques for short-term risk prediction. Its architecture is deliberately disease-agnostic, enabling adaptability across multiple pathogens and vector species. Through the use of plug-in disease data adapters, the system can be rapidly configured for new epidemiological contexts without requiring modifications to the underlying data infrastructure.

The platform ingests heterogeneous data sources—including climate observations, host distribution data, and entomological surveillance records—and transforms them into spatially explicit risk maps. A modular system design separates core data processing pipelines from disease-specific modelling components, ensuring both methodological consistency and flexibility. This enables the system to support historical analysis, real-time monitoring, and scenario-based simulations within a unified analytical framework.

7.2 Surveillance-Based Risk Inference

When entomological surveillance data are available, ZDOS performs spatial risk estimation using interpolation techniques based on inverse-distance weighting with exponential decay. This approach assumes that infection prevalence observed at sampling locations decreases as a function of distance, in accordance with known vector dispersal dynamics.

The resulting methodology generates continuous spatial risk surfaces that incorporate direct measurements of pathogen presence within vector populations (e.g., mosquitoes or flies). This enhances the reliability of risk assessments by grounding predictions in empirical field data.

The NESTLER platform visualises these outputs through an interactive dashboard, presenting end-users with intuitive, location-specific risk indicators for selected diseases at given time points (see Figure 2). This facilitates informed decision-making by stakeholders, including public health authorities, veterinarians, and agricultural practitioners.

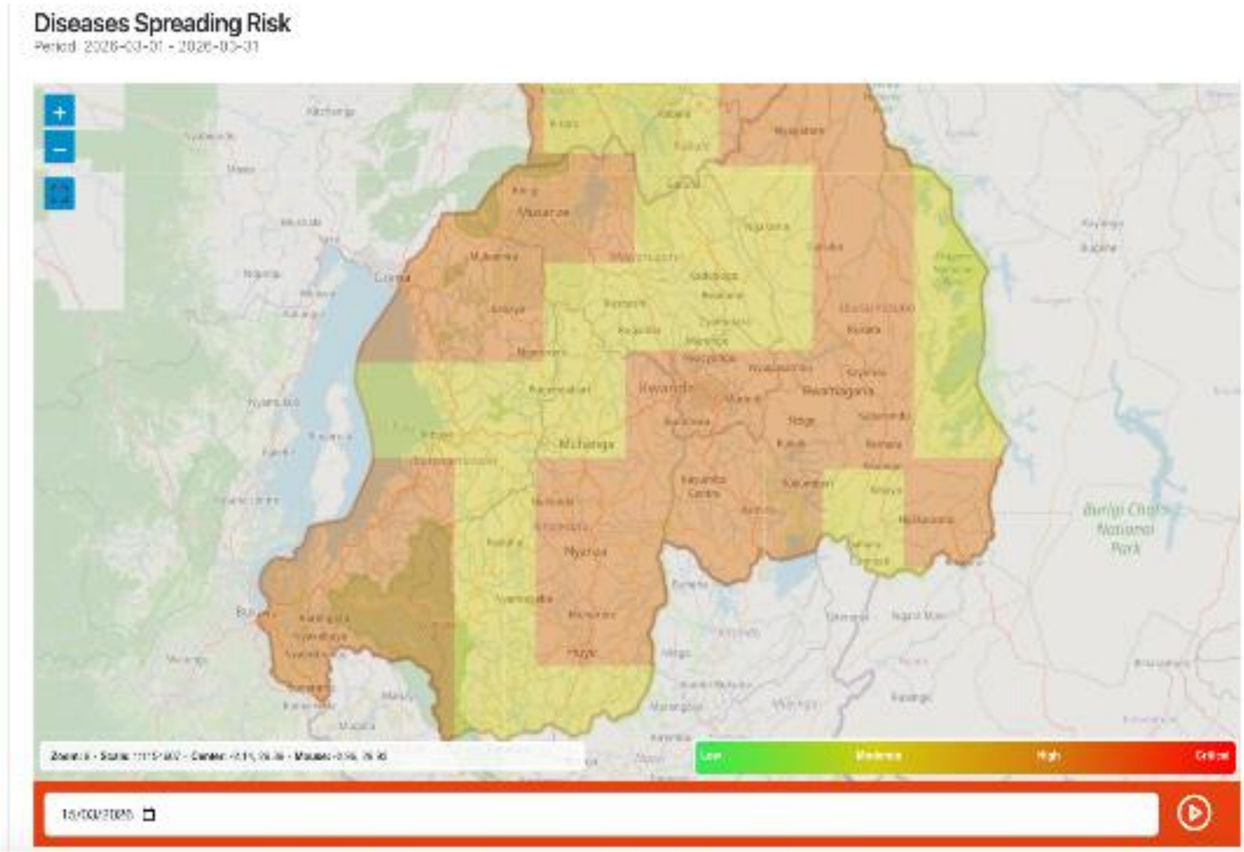
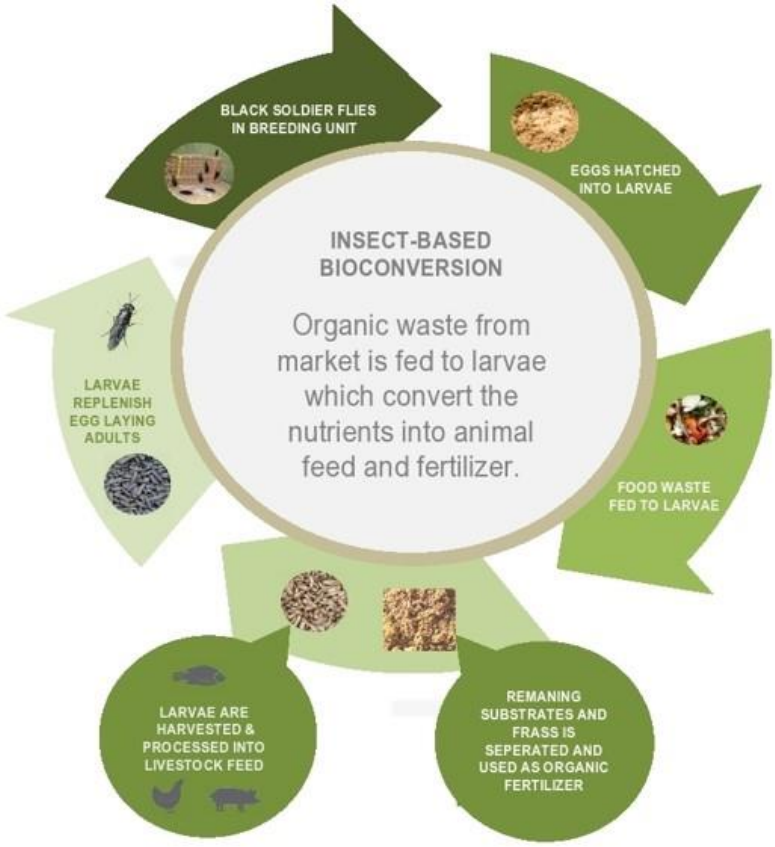


Figure 2: Visualization of the Indicative spreading risk of the selected disease in NESTLER dashboard using colour-based risk categories

8 Scientific Innovation in Circular Bioeconomy

A central scientific contribution of the NESTLER project is the demonstration of a circular bioeconomy model in which organic waste streams are transformed into high-value agricultural inputs through Black Soldier Fly (BSF) larvae production. This system operates at the intersection of waste management, feed production, and soil fertility enhancement, offering a technically validated pathway toward more resilient and resource-efficient agricultural systems.



Within this framework, insect-based protein emerges as a structurally competitive alternative to conventional feed ingredients currently used in poultry and aquaculture systems across Eastern Africa. These systems rely heavily on fishmeal, soybean meal, maize bran, and sunflower cake, each of which presents limitations in terms of cost, nutritional balance, or long-term sustainability. Fishmeal, while nutritionally valuable, is increasingly constrained by high prices linked to declining wild fish stocks, placing it beyond the affordability range of many farmers. Soybean meals, largely imported, is exposed to price volatility and foreign exchange pressures, while also competing directly with human food systems. Cereal-based feeds such as maize bran remain economically accessible but lack sufficient protein content to support optimal animal growth without supplementation. Similarly, sunflower cake provides a regional option but suffers from variability in quality and lower protein levels compared to alternative sources.

Against this backdrop, BSF larvae meal offers a distinct and scientifically supported value proposition. Its protein content typically ranges between 40% and 65%, depending on processing conditions, and its amino acid profile closely resembles that of fishmeal, enabling effective substitution in feed formulations. Crucially, its production is decoupled from global commodity markets, as it is derived from locally available organic waste streams. This characteristic not only enhances supply stability but also embeds feed production within a circular resource system, where waste is valorized rather than discarded.

Experimental results cited in the NESTLER work demonstrate that BSF larvae meal can replace between 50% and 100% of conventional feed ingredients in both poultry and aquaculture systems without compromising performance. On the contrary, feeding trials indicate improvements in key productivity indicators, including growth rates, feed conversion efficiency, and overall animal health. These outcomes are consistent with the nutritional properties of BSFL, which provide both high-quality protein and lipid fractions essential for animal development.

The adoption dynamics observed in the project further reinforce the scientific and practical relevance of this innovation. Farmer preference for BSFL is not driven by a single factor but by the convergence of economic, nutritional, and systemic considerations. From an economic perspective, locally produced insect protein has the potential to reduce feed costs, particularly as production scales and supply chains mature. This is especially significant in a context where dependence on imported feed ingredients exposes producers to external price shocks. Nutritionally, BSFL addresses the limitations of low-protein feed components and enables more efficient livestock and aquaculture production. At the same time, the system contributes to broader sustainability objectives by recycling organic waste into productive use, thereby reducing environmental burdens associated with both waste disposal and feed production.

An equally important dimension of the NESTLER innovation lies in the utilisation of frass, the residual by-product of BSF rearing. Rather than representing waste, frass functions as an organic fertiliser that enhances soil fertility, supports microbial activity, and contributes to increased crop yields under appropriate conditions. This closes the nutrient loop within the agricultural system, linking waste management, feed production, and crop cultivation into a single integrated cycle.

The environmental implications of this system are substantial. Pilot and modelling results indicate that integrating BSF-based solutions into livestock systems can lead to significant reductions in greenhouse gas emissions, including methane and nitrous oxide. These reductions stem both from the diversion of organic waste away from emission-intensive disposal pathways and from the partial substitution of conventional feed ingredients with lower-impact alternatives. In this sense, BSF farming contributes directly to climate mitigation while simultaneously addressing structural inefficiencies in food production systems.

Taken together, the evidence from Deliverable D2.4 positions BSF-based production not merely as an alternative feed technology but as a systemic innovation. It redefines the relationship between waste and production, introduces locally grounded solutions to global supply constraints, and establishes a scalable model for circular agriculture that integrates economic viability with environmental performance.

8.1 Potential of Scaling BSFL

The potential for scaling Black Soldier Fly (BSF) farming in Eastern Africa is driven by the convergence of two key factors:

- the large availability of underutilized organic waste streams
- the growing demand for sustainable feed, fertilisers, and waste management solutions

When supported by appropriate infrastructure, regulatory clarity, and quality standards, BSF systems can move beyond pilot stages and become an integral part of a circular bioeconomy with measurable impacts on economic growth, employment, climate mitigation, and food system resilience.

Significant production capacity exists, as countries such as Ethiopia, Kenya, and Rwanda generate substantial volumes of biowaste that could be converted into insect protein at scale. The efficiency of this process depends on technical parameters such as substrate composition, moisture, and controlled rearing conditions, while successful scale-up requires reliable and decentralized infrastructure, including localized waste collection, processing hubs, and appropriate drying technologies to ensure product quality.

Beyond direct production, BSF farming generates wider economic benefits through its strong linkages with agriculture, waste management, and feed industries. By transforming low-value waste into high-value products, it contributes to economic growth, reduces reliance on imported feed ingredients, and limits exposure to global price volatility. At the same time, the sector has strong employment potential, creating jobs across collection, processing, and distribution activities. These jobs are locally embedded and scalable, offering opportunities particularly in smaller urban and peri-urban areas through the participation of small enterprises and cooperatives.

Environmental benefits are also substantial, as BSF systems reduce greenhouse gas emissions by diverting organic waste from landfill and replacing conventional feed inputs with lower-impact alternatives. These reductions can reach significant levels at national scale, with life-cycle assessments consistently showing much lower emissions compared to traditional waste treatment methods.

In parallel, BSF farming contributes to food and nutrition security by lowering feed costs, improving livestock and aquaculture productivity, and reducing dependence on imported protein sources. The use of frass as an organic fertiliser further strengthens agricultural systems by enhancing soil fertility and crop yields, although its full impact at scale requires further investigation.

Realizing this potential depends on enabling conditions, particularly the establishment of clear regulatory frameworks, standards for product quality and safety, and effective waste governance systems. International experience demonstrates that well-defined rules and coordinated policy support can accelerate the development of the sector, allowing BSF farming to evolve into a reliable and scalable solution within sustainable food systems.

9 Socio-economic Impact and Value Creation

The technological and scientific achievements of the NESTLER project have generated significant socio-economic impact across both Europe and Africa, particularly within the pilot regions. By combining advanced digital technologies with sustainable agricultural practices, NESTLER has contributed to improved productivity, reduced input costs, more efficient use of resources such as water and feed, and enhanced environmental sustainability. At the same time, it has strengthened the resilience of farmers and agri-food stakeholders in the face of climate, market, and health-related challenges.

A key driver of this impact is the integration of IoT devices, AI-based services, and digital platforms that enable real-time monitoring and early warning systems. By combining environmental, climate, and animal data, the NESTLER platform supports the early detection of risks such as pest outbreaks and zoonotic disease spread. This allows for timely and targeted interventions, reducing production losses and mitigating risks. These data-driven tools improve decision-making, optimize resource use, and enhance farm management efficiency, ultimately leading to reduced operational risks, increased productivity, and improved livelihoods, while contributing to food security and sustainable agricultural systems.

In parallel, the project demonstrates the strong socio-economic value of circular economy approaches. By transforming organic waste streams into valuable products such as insect-based protein (BSFL) and organic fertilizer (frass), NESTLER reduces dependency on costly imported inputs like fishmeal and soybean meal, while improving resource efficiency. This approach not only lowers production costs for farmers but also creates new market opportunities and fosters innovation across agriculture, waste management, and technology sectors. It supports the development of locally embedded, resilient value chains that contribute to long-term economic sustainability.

Economic analyses within the project confirm the strong profitability potential of these innovations. In poultry systems, the use of Black Soldier Fly Larvae Meal (BSFLM) has been associated with improved feed efficiency and higher profit margins, with experimental results showing very high returns on investment under optimized conditions, reaching up to approximately 496% in specific feed formulations. In aquaculture, partial replacement of fishmeal with BSFLM has resulted in reduced production costs and ROI values exceeding 100%, demonstrating clear economic advantages. These results show that insect-based feed solutions can enhance farm-level profitability while maintaining or improving production performance.

Beyond direct economic gains, the NESTLER approach delivers broader social and environmental benefits. The development of insect-based value chains creates employment opportunities across multiple stages, including waste collection, processing, feed production, and farming. At the same time, circular production systems contribute to climate change mitigation by reducing greenhouse gas emissions and improving waste management. Modelling results indicate that large-scale adoption of these solutions can lead to significant contributions to GDP growth, job creation, and emissions reduction, reinforcing their role as a systemic solution for sustainable development.

The potential for scaling these innovations is substantial, driven by the availability of underutilized organic waste resources and strong market demand for sustainable feed and fertilizer solutions. However, realizing this potential requires coordinated action, including investments in infrastructure, supportive regulatory frameworks, and access to finance. With the right enabling conditions, these solutions can move beyond pilot applications toward large-scale deployment, transforming agri-food systems and delivering long-term economic, environmental, and societal value.

Capacity building has been a central pillar of this transformation. The project has trained more than 1,600 farmers, youth, and practitioners across Kenya and Rwanda in insect farming technologies and associated practices. In Kenya, over 1,500 participants benefited from structured entrepreneurship and technical training programmes, while in Rwanda, targeted training equipped farmers with both theoretical knowledge and hands-on experience in Black Soldier Fly production. These programmes combined Standard Operating Procedures (SOPs), practical demonstrations, and business development support, enabling participants to establish and scale their own activities. Importantly, the training model promotes knowledge multiplication, as trained individuals are encouraged to transfer their knowledge within their communities, accelerating the diffusion of innovation. This has strengthened local capacities, supported the emergence of new enterprises and value chains, and created a solid foundation for long-term adoption and scaling of NESTLER solutions.

10 Policy, Governance and Regulatory Contributions

An important outcome of the NESTLER project has been its contribution to shaping policy, governance, and regulatory approaches that support sustainable agriculture and the practical implementation of the One Health concept. By combining technological innovation with real-world pilot experience, the project has provided concrete insights to policymakers, regulators, and industry stakeholders on how to enable the transition toward more resilient and circular agri-food systems.

One of the key lessons emerging from the project is that the main barrier is no longer technological readiness, but the need to organize the enabling environment. This includes clear rules, functioning markets, and the right incentives to support adoption at scale. In response, NESTLER has outlined a coherent policy approach that brings together regulatory clarity, quality assurance, infrastructure development, and market creation.

A central priority is the establishment of clear and predictable regulatory frameworks for insect-based products. This involves defining permitted species and input materials, setting hygiene and processing requirements, and ensuring that insect-derived feed and organic fertilizers such as frass meet consistent quality standards. Building trust across the value chain—from producers to farmers and consumers—has emerged as essential, and certification systems play a key role in achieving this. Experiences from other regions demonstrate that well-structured and transparent regulations can significantly accelerate investment and uptake.

At the same time, the project highlights the importance of financial mechanisms that can support early-stage growth and scaling. Blended finance, combining public support with private investment, has proven particularly relevant in reducing risk and encouraging entrepreneurship. Additional tools such as targeted incentives, concessional funding, and public procurement schemes can help create early demand and give confidence to market actors. These measures are especially important for enabling small and medium-sized enterprises to enter and grow within emerging circular value chains.

Beyond regulation and finance, NESTLER has also contributed to new approaches in governance, particularly in relation to data sharing and interoperability. The project has demonstrated the value of integrating data from agriculture, environment, and health domains into unified platforms that support real-time monitoring and early warning. This is particularly important for managing risks such as pest outbreaks and zoonotic diseases. At the same time, addressing issues of data privacy, security, and standardization has been essential to ensure trust and effective collaboration across sectors and regions.

Another important aspect has been the strengthening of institutional capacity and coordination. The project has shown that innovation uptake depends not only on technology, but also on the ability of institutions to support farmers and stakeholders through training, advisory services, and clear guidance. Strengthening extension services, promoting certification and skills development, and fostering collaboration between public authorities, research organizations, and private actors are all critical elements for long-term success.

Overall, the NESTLER project aligns closely with broader European and international priorities related to sustainable food systems, climate action, and food security. By linking circular bioeconomy solutions with digital technologies and the One Health approach, it provides a practical and scalable model for transforming agri-food systems. The experience gained through the project offers valuable guidance for future policies and investments aimed at delivering lasting economic, environmental, and societal benefits.

10.1 Contribution to Standards

In addition to its broader policy contributions, the NESTLER project has delivered tangible results in the area of standardisation, supporting the formal recognition and safe use of insect-based products within agri-food systems.

Through collaboration between research partners and national regulatory authorities, new national standards for insect-based feed have been developed and adopted in Ethiopia. These include:

- **ES 7015:2023 – Dried insect products in animal feeds – Specifications**
- **ES 7016:2023 – Dried insect products as proteins in animal feeds – Guidelines and code of practice**

These standards represent an important step toward creating a structured and trustworthy regulatory environment for insect-based production. They provide clear technical requirements for quality, safety, and processing, helping to build confidence among producers, feed manufacturers, and farmers, while also facilitating market development and trade.

At the continental and international level, the project has also contributed to policy dialogue and coordination. A policy paper developed within the project was presented at a high-level international summit, contributing to discussions on sustainable food systems and innovation. Furthermore, a strategic partnership was established between ICIPE, the African Organisation for Standardisation (ARSO), and the United Nations Economic Commission for Africa (UNECA), with the objective of advancing harmonised African standards and supporting intra-African and global trade.

This collaboration aims to develop continent-wide standards and conformity assessment systems, strengthening the competitiveness and credibility of African agri-food products. It also reflects the broader role of the project in bridging science, policy, and market development, and in supporting the emergence of a coherent regulatory ecosystem for circular bioeconomy solutions.

10.2 Strategic Roadmap for One Health and EU–Africa Cooperation

Beyond immediate policy and regulatory contributions, the project has also developed a forward-looking strategic roadmap to support the long-term implementation of the One Health approach in the context of EU–Africa collaboration. This roadmap provides a structured framework for integrating human, animal, and environmental health, addressing shared challenges such as zoonotic diseases, antimicrobial resistance, and ecosystem degradation.

It outlines key priorities including the strengthening of surveillance and early warning systems, the promotion of cross-sectoral governance, and the use of digital technologies to support data-driven decision-making. The roadmap emphasizes the importance of collaboration, inclusivity, and knowledge co-creation, positioning One Health not only as a scientific concept but as a practical approach to improving resilience, sustainability, and health security across regions.

Importantly, it reflects a shift from isolated interventions toward integrated systems thinking, encouraging coordinated action across sectors, institutions, and geographical boundaries. By aligning technological innovation with policy frameworks and capacity building, the roadmap provides a clear pathway for scaling the outcomes of the project and sustaining its impact beyond its duration.

11 Conclusion and Future Outlook

The NESTLER project has demonstrated that the integration of digital technologies, circular bioeconomy solutions, and One Health principles can deliver tangible and scalable benefits for agri-food systems. By moving beyond fragmented approaches and combining data-driven intelligence with sustainable production models, the project provides a validated framework for addressing complex and interconnected challenges related to food security, environmental sustainability, and public and animal health.

Through real-world pilot implementations, NESTLER has shown that these innovations are not only technically feasible, but also economically viable and socially accepted. The results highlight the potential for significant improvements in productivity, resource efficiency, and resilience, while supporting new value chains and market opportunities.

At the same time, the project has identified the key conditions required for large-scale adoption, including supportive regulatory frameworks, investment in infrastructure, and continued capacity building. The importance of data governance, interoperability, and cross-sector collaboration has also been clearly demonstrated as a foundation for effective One Health implementation.

Looking forward, the NESTLER approach provides a strong basis for further development and replication across regions. Its integrated model can support future research and innovation initiatives, inform policy design, and guide investments aimed at transforming agri-food systems. In this context, NESTLER represents not only a successful research project, but also a practical and scalable blueprint for advancing sustainable, resilient, and interconnected food systems in Europe, Africa, and beyond.

12 About NESTLER Project

NESTLER (oNe hEalth SusTainabiLity partnership between EU–Africa for food security) is a Horizon Europe Research and Innovation Action (Grant Agreement No. 101060762), implemented over 42 months through a multidisciplinary consortium of European and African partners.

The project addresses the fragmentation of food production, environmental management, and health systems by developing an integrated framework that combines digital technologies, scientific research, and circular bioeconomy solutions. At its core is a system-level approach that operationalizes the One Health concept through a unified digital platform, enabling real-time monitoring, predictive analytics, and data-driven decision-making.

Through pilot demonstrations across multiple African countries, NESTLER has validated its solutions under diverse real-world conditions, demonstrating their technical feasibility, socio-economic value, and scalability. By combining innovation, policy engagement, and capacity building, the project provides a practical foundation for advancing sustainable and resilient agri-food systems within the EU–Africa partnership.