An integrated toolbox for improved verification and prevention of adulterations and non-compliances in organic and geographical indications food supply chain

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D.5.3: Lessons learnt and impact assessment report

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Executive Summary

Following the detailed outline provided in Deliverable D5.1, Deliverable D5.3 presents concrete results from the pilot projects, including their evaluation methodology, validation scenarios, Key Performance Indicators (KPIs) and stakeholder assessments.

This deliverable adheres to the methodology set forth in D5.1 and aims to provide a comprehensive impact assessment across all four pilots conducted in Serbia, Greece, Spain, and the Czech Republic. The assessment is based on KPIs and findings from process evaluation workshops and includes recommendations for scaling and transferability. In addition to the impact assessment, D5.3 addresses the varying agricultural contexts and food products across different countries, highlighting key lessons learned during the implementation and testing of the THEROS toolbox.

D5.3 consolidates evidence from KPI analyses, process evaluation workshops and learning histories conducted across pilot sites. The report presents both quantitative and qualitative findings, identifying the technical, operational, environmental and social dimensions of THEROS implementation. It also captures the main lessons learned, barriers encountered and recommendations for improving and scaling the toolbox in future applications.

After two years dedicated to refining methodologies and developing the THEROS toolbox, this deliverable underscores the benefits and identifies opportunities for improvement observed during the final phase of supply chain traceability and compliance testing, with a focus on ensuring quality, authenticity, and sustainability in organic and GI food products.

Ultimately, the THEROS project is expected to deliver enhanced traceability and transparency throughout the supply chain using innovative technologies, improved tools for compliance validation and fraud prevention, actionable insights for sustainability and environmental performance monitoring, and strengthened market competitiveness, thereby increasing consumer trust in organic and geographical indication (GI) products.

By integrating feedback from stakeholders and end-users, the report offers actionable insights to enhance the THEROS system’s long-term value, sustainability and policy relevance.

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Abbreviations & Acronyms

Abbreviation / acronym	Description
D5.1	Deliverable number 1 belonging to WP 5
dDPP	dynamic Digital Product Passport
DNA	Deoxyribonucleic Acid
EC	European Commission
EO	Earth Observation
GAT	Green Accountability Tool
GI	Geographical indication
GMO	Genetically modified organisms
HRM	High Resolution Melting
IoT	Internet of Things
KPIs	Key Performance Indicators
MEMS	Microelectromechanical systems
PCR	Polymerase Chain Reaction

Abbreviation / acronym	Description
PO	Project Officer
PU	Public dissemination level
SMEs	Small and Medium-sized enterprises
WP	Work Package

1. Introduction

1.1 Purpose of the document

The main purpose of this document is to analyze the impact and effectiveness of the THEROS toolbox through a structured evaluation and reflection process. It assesses how well the toolbox met its objectives based on pre-defined KPIs and the outcomes of participatory learning workshops.

The report evaluates the technical, operational, environmental, and societal performance of the toolbox, identifies lessons from pilots, and highlights success factors and challenges. It also offers recommendations to enhance, replicate, and sustain the THEROS approach in other contexts, supporting future use and policy alignment within the project's sustainability framework.

1.2 Intended readership

D5.3 “Lessons learnt and impact assessment report” is a public deliverable for the THEROS project, providing guidance to the European Commission, Project Officer, and consortium members. It is a key resource for evaluating THEROS toolbox pilot demonstrations.

This report also will serve as evaluation of project’s impact and the effectiveness of its methodologies. To the policy makers and control authorities it will be useful to understand the potential of the THEROS toolbox for wider adoption and policy integration. Researchers and practitioners will gain insight into innovative evaluation approaches and cross-sector collaboration, while end-users and stakeholders will recognize how their participation influenced the outcomes and contributed to system improvement.

1.3 Document Structure

The document is organised as follows: **Chapter 1** introduces the deliverable. **Chapter 2** explains the THEROS evaluation methodological framework through KPI performances and impact assessments, describing the KPIs methodology defined in previous D5.1. Further **chapter 3 and 4** demonstrate results of User-acceptance evaluation survey and Technological evaluation of the KPIs. **Chapter 5** analyzes the impacts of assessment results on quantitative and qualitative manners. **Chapter 6** gives a comparative analysis of each pilot and each country while **chapter 7** highlights evaluation of THEROS tool through lessons learned benefits and areas for improvement. Finally, **chapter 8** gives an overview of recommendations for upscaling and transferability, with concluding remarks and final conclusions in **chapter 9**.

2. THEROS evaluation methodological framework through KPIs performance and impact assessment

2.1 Introduction

The evaluation methodological framework adopted in THEROS is based on a structured, KPI-driven approach that was defined and documented in Deliverable D5.1, which established the validation scenarios, performance indicators, and assessment procedures for all pilot demonstrations. Building on this framework, the present deliverable applies the predefined methodology to assess the actual performance, impact, and lessons learned from the deployment of the THEROS toolbox across the pilots.

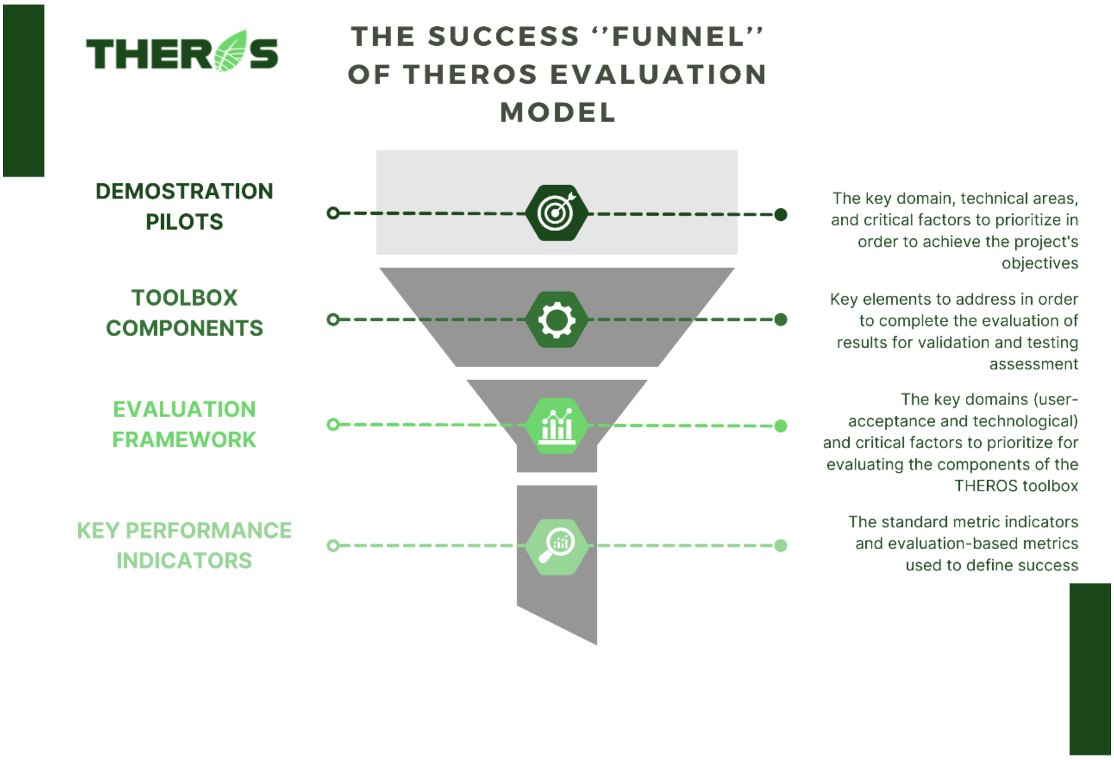


Figure 1 The Funnel theory of success adapted to develop the THEROS's evaluation methodology (D5.1).

The objective of this evaluation framework is twofold. First, it enables a systematic and evidence-based assessment of the THEROS tools by measuring their performance against clearly defined Key Performance Indicators (KPIs). Second, it allows the holistic evaluation of impact, capturing not only technical effectiveness but also operational feasibility, user acceptance, environmental relevance, and societal value.

To achieve this, the evaluation framework combines quantitative measurements, derived from system logs, pilot data, and performance metrics, with qualitative insights, collected through learning history workshops, user questionnaires, and stakeholder interactions. This mixed-methods approach ensures that both measurable outcomes and experiential feedback are taken into account, providing a comprehensive understanding of how the THEROS toolbox performs in real-world conditions.

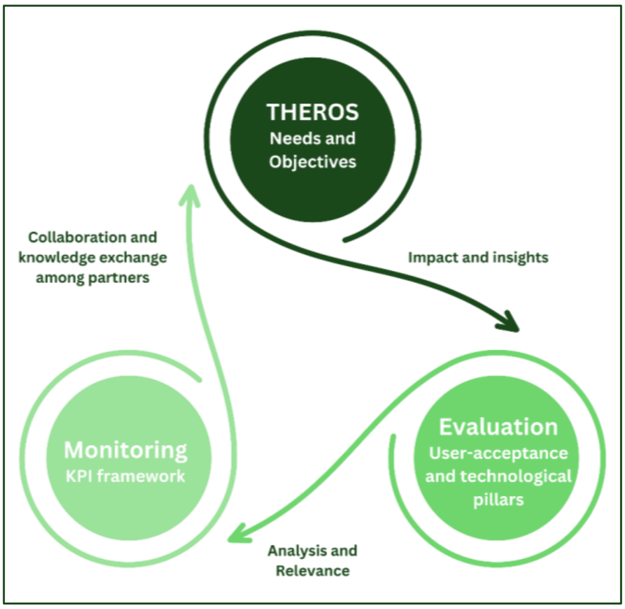


Figure 2 Connection between THEROS and monitoring and evaluation processes (D5.1).

The framework is structured around two complementary evaluation pillars:

- the **User-acceptance Evaluation pillar**, focusing on usability, trust, usefulness, and adoption potential, and
- the **Technological Evaluation pillar**, focusing on accuracy, reliability, interoperability, scalability, and environmental performance.

Together, these pillars reflect the core logic of D5.1 and ensure consistency between methodological design and applied evaluation in D5.3.

2.2 User-acceptance & technological Evaluation pillars

In line with the evaluation methodology defined in D5.1, the THEROS assessment framework is structured around two main and complementary evaluation pillars: user acceptance and technological performance. This dual-pillar structure was selected to reflect the fact that the successful deployment of digital tools in agri-food supply chains depends not only on technical excellence, but also on their acceptance, usability, and perceived value by end-users and stakeholders.

Each pillar is supported by a dedicated set of KPIs, data collection methods, and evaluation instruments, enabling a consistent and comparable assessment across pilots, tools, and stakeholder groups. The two pillars are not evaluated in isolation; instead, they are analysed in combination to capture interactions between technical performance and user perception, as well as their joint contribution to overall impact.

2.2.1 User-acceptance Evaluation pillar

The User-acceptance Evaluation pillar focuses on assessing how end-users and stakeholders perceive, understand, and interact with the THEROS toolbox. This pillar reflects the recognition that the effectiveness and long-term sustainability of digital solutions in food supply chains depend heavily on their usability, trustworthiness, and relevance to real operational needs.

As defined in D5.1, the user-acceptance KPIs capture multiple dimensions of user experience, including ease of use, clarity of guidance, perceived usefulness of outputs, trust in the results, and overall satisfaction. These indicators were evaluated through structured questionnaires, learning history workshops, and direct feedback collected during pilot demonstrations.

The user-acceptance assessment covers different stakeholder groups, such as producers, certification bodies, inspectors, and supply chain actors, allowing the identification of both common patterns and role-specific perspectives. In addition, qualitative feedback was used to contextualize quantitative scores, providing insights into training needs, barriers to adoption, and opportunities for improving user engagement.

By integrating user-acceptance KPIs into the evaluation framework, THEROS ensures that the assessment goes beyond technical validation and captures the human and organizational factors that influence real-world uptake and impact.

2.2.2 Technological Evaluation pillar

The Technological Evaluation pillar assesses the performance of the THEROS toolbox components against the technical, operational, and environmental KPIs defined in D5.1. This pillar focuses on evaluating whether the deployed technologies meet their intended objectives under real operational conditions and whether they are robust, scalable, and interoperable.

The technological KPIs cover key performance dimensions, including fraud detection accuracy, data reliability, traceability completeness, system scalability, response times, and integration success across heterogeneous data sources. In addition, environmental performance indicators, such as monitoring coverage and green accountability metrics, were used to assess the contribution of THEROS technologies to sustainability-related objectives.

Data for the technological evaluation were collected through system logs, pilot measurements, validation exercises, and cross-checks with reference data and ground truth where applicable. This ensured that performance assessments are based on verifiable evidence rather than assumptions or laboratory-only conditions.

By applying a common set of technological KPIs across different tools and pilots, the framework enables comparative analysis and supports the identification of strengths, limitations, and improvement opportunities for each THEROS component. This pillar therefore provides the quantitative backbone of the impact assessment presented in the subsequent sections of this deliverable.

2.2.3 General KPIs overview and KPIs per Pilot demonstration

Following the evaluation methodology defined in Deliverable D5.1, the assessment of the THEROS toolbox is based on a structured set of Key Performance Indicators (KPIs) designed to capture technical performance, user acceptance, operational effectiveness, environmental contribution, and societal impact. The KPI framework was intentionally designed to be flexible yet comparable, allowing it to be applied across different tools, pilots, and agri-food contexts while maintaining a common evaluation logic.

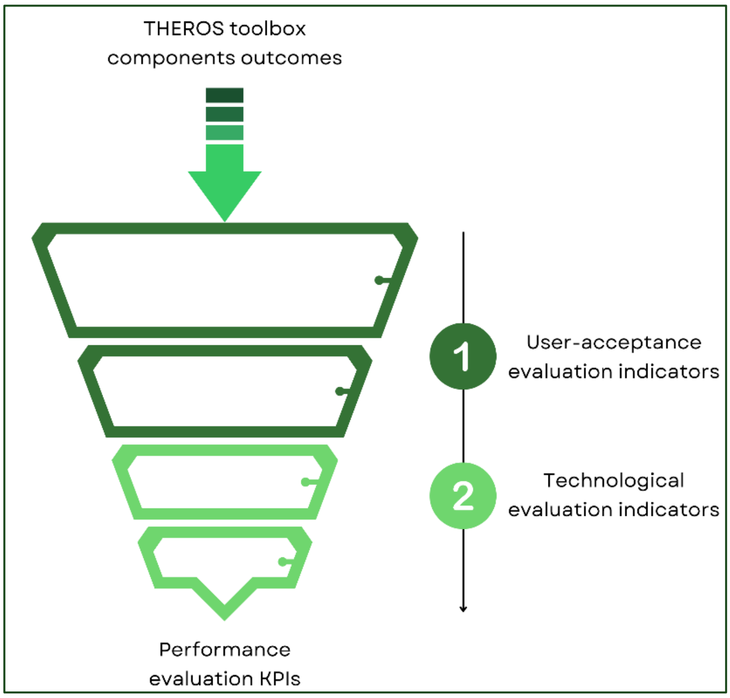


Figure 3 The Tiered Evaluation Framework of THEROS is used to filter component outcomes through predefined evaluation indicators to establish KPIs (D5.1).

Each KPI is defined through a clear description, a measurable metric, a data collection method, and a target value, as specified in D5.1. This structure ensures consistency in how performance is measured and enables objective comparison between expected and achieved results.

While the KPI framework is common across the project, not all KPIs are applicable to all pilot demonstrations or toolbox components. Instead, KPIs were selectively applied based on:

- the specific tools deployed in each pilot,
- the stage of the supply chain addressed (production, processing, transport, market),
- and the role of the participating stakeholders (e.g. producers, certification bodies, inspectors, consumers).

As a result, each pilot demonstration was evaluated against a relevant subset of KPIs, ensuring that performance assessment remains meaningful and context-aware rather than artificially uniform. For example, pilots focusing on fraud detection and compliance relied more heavily on accuracy- and verification-related KPIs, while pilots emphasizing traceability, logistics, or market transparency relied more on blockchain, data harmonisation, and user-experience indicators.

In addition to tool-specific and pilot-specific KPIs, a number of indicators were used horizontally across pilots to enable cross-pilot comparison. These include KPIs related to fraud detection accuracy, traceability completeness, system integration, user satisfaction, and environmental monitoring coverage. This dual approach—combining pilot-tailored KPIs with common reference indicators—allows the evaluation framework to capture both context-specific performance and overall project impact.

The KPI evaluation process integrates quantitative evidence, such as system logs, validation results, and measured performance values, with qualitative inputs collected through learning history workshops, questionnaires, and stakeholder feedback sessions. Quantitative results provide objective measures of performance against targets, while qualitative insights support interpretation, explain deviations, and highlight practical implications for adoption and scaling.

With a progress of the project, a general KPIs were achieved. The THEROS framework has shown strong technical performance and adaptability for both organic and GI food verification. Its tools have worked effectively with many types of food products and labels (KPI I.1), including fresh, processed, solid, liquid, and powdered foods—going beyond expectations.

For compliance and fraud detection, THEROS can spot different substances banned under organic farming rules, such as prohibited pesticides, fertilizers, and soil treatments (KPI I.2). It also excels at detecting food adulteration in organic and GI products, surpassing required goals (KPI I.3).

Regarding data and system interoperability, the project ensures all pilot data is managed in a harmonized, compatible way (KPI I.9). The system handles widely used data formats about food characteristics, environmental factors, and user activities. Verification and validation now cover every key event in the supply chain, supporting complete traceability (KPI I.10).

Lastly, THEROS offers clear metrics to help stakeholders make informed decisions throughout the organic and GI supply chains, providing structured evidence for measuring quality, compliance, and risk (KPI I.12).

During project testing in four countries, the THEROS blockchain-based traceability network successfully expanded its trusted participants (KPI I.4), exceeding the goal of 20 actively collaborating entities. Awareness among consumers surpassed 10,000 (KPI I.5), with over 1,000 directly engaged and more than 250 supply chain operators reached during pilot demonstrations.

Farm monitoring targets were met, covering at least 40% of organic and in-conversion farms in Greece and 30% in Serbia, including small-scale parcels (KPI I.6), thanks to extended pilot durations and additional onboarding. However, involvement of inspectors, certification actors, and control bodies (KPI I.7) remains below the target of 20, requiring ongoing engagement for broader institutional impact.

Inspection of quality-labelled food products through THEROS tools exceeded 8,000 shipments (KPI I.8), marking a significant expansion in transaction volume. Comprehensive agronomic recommendations for organic farmers (KPI I.11) are defined but need further validation and implementation to ensure consistent delivery across pilots.

KPI No	KPI name	Target No	Status
I.1	Demonstrate the applicability of THEROS tools to verify the status **different types of food bearing quality labels (organic & GIs)**, including both fresh/raw and processed products, and while covering all the main product states (solids, liquids and powders)	> 15	achieved
I.2	System capable to detect different types of substances prohibited by the organic farming regulations being associate with pesticides and fertilizers use and soil management	≥ 3	achieved
I.3	THEROS tools addressing different types of food adulteration regarding organic and GI products	≥ 5	achieved
I.4	Number of trusted participants/organisations collaborating through the THEROS blockchain based traceability network in the context of pilot demonstrations	> 20	achieved
I.5	Increasing awareness to consumers	≥ 10.000	achieved
	Increasing awareness to consumers while directly engaging	≥ 1.000	achieved
	Increasing awareness to supply chain operators in the pilot demonstrations	≥ 250	achieved
I.6	Ensure monitoring of organic and in-conversion farms in Greece and	≥ 40%	achieved
	Serbia respectively, including small scale parcels	≥ 30%	achieved
I.7	Number of inspectors and actors being involved with the control and certification process engag	> 20	
	Number of relevant bodies/authorities reached: across EU through partners networks and liais	> 50	achieved
I.8	Quantity of quality labelled food products inspected through THEROS tools: shipments of organi	> 8.000	achieved
I.9	Number of resources accessible in a harmonised and interoperable way: ALL data generated in the pilots; system capable to handle most common formats related to organic/GI food properties, environmental conditions and user transactions		achieved
I.10	Verification and validation capabilities cover all critical tracking events in the supply chain		achieved
I.11	Recommendations provided to organic farmers shall cover key practices including rotation planning, nutrients and soil management, plant protection strategies and tillage optimisation		achieved
I.12	Provide measurable metrics to facilitate decision making across the supply chain of organic and GI food products		achieved

Figure 4 THEROS general KPIs.

3. User-acceptance evaluation survey

The user-acceptance evaluation of the THEROS toolbox was conducted as an integral part of the pilot demonstration activities implemented across the participating pilot countries. The evaluation process was coordinated by the respective pilot partners in close collaboration with technical partners and end-user organisations, and it was progressively carried out throughout the pilot implementation period, in line with the methodological framework defined in Deliverable D5.1.

The objective of the user-acceptance evaluation was to assess how different stakeholder groups perceived, understood, and interacted with the THEROS tools when deployed under real operational conditions. The assessment focused on key aspects such as ease of use, usefulness of outputs, clarity of guidance, trust in results, perceived interoperability between tools, and the potential for long-term adoption of the THEROS solutions within existing certification, inspection, and supply chain processes.

To support this assessment, a dedicated user-acceptance survey framework was designed and circulated among pilot participants. The surveys combined structured rating questions with open-ended questions, allowing both quantitative scoring and qualitative feedback. This mixed approach enabled a comprehensive evaluation of end-user experience, practical applicability, and perceived added value of the THEROS toolbox components.

In order to reflect the modular structure of the THEROS toolbox and the diversity of deployed technologies, **separate questionnaires were prepared for each major tool or service**, including:

- MEMS-based photonics systems and associated mobile applications,
- the Green Accountability Tool (GAT),
- the blockchain-enabled traceability system and the Dynamic Digital Product Passport (dDPP),
- the Digital Marketplace,
- and the DNA-based authenticity kit (where applicable).

This approach ensured that users evaluated only the tools they actively interacted with, thereby improving the relevance and reliability of the collected feedback.

To facilitate participation and ensure consistent understanding of the evaluation objectives, pilot partners provided guidance and introductory explanations to participants prior to the survey implementation. Where necessary, questionnaires were adapted to the linguistic and contextual needs of the pilots. Before submitting their responses, participants were informed about the purpose of the evaluation and provided their consent regarding the collection and use of personal data, in accordance with the project's data protection and ethical requirements.

Engaging a diverse group of stakeholders—including producers, certification bodies, inspectors, supply chain actors, and other relevant organisations—required the use of multiple communication and engagement channels. These included pilot workshops, physical meetings, online sessions, questionnaires, and targeted bilateral interactions. Continuous support was provided throughout the evaluation process to address potential obstacles, clarify questions, and encourage meaningful participation.

The user-acceptance evaluation strategy was explicitly linked to the **User-related KPIs (UR-KPIs)** defined in D5.1, which capture dimensions such as ease of use, user satisfaction, perceived transparency, trust in fraud detection results, training effectiveness, and integration into existing workflows (see Table below). These KPIs provide the analytical backbone for interpreting survey results and linking user feedback to the broader impact assessment of the THEROS toolbox.

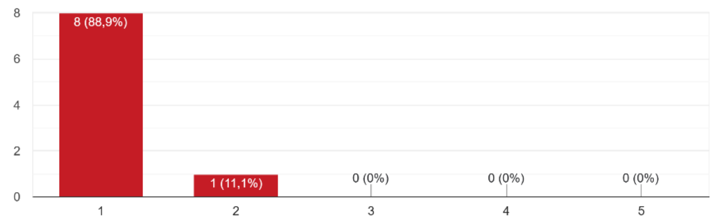
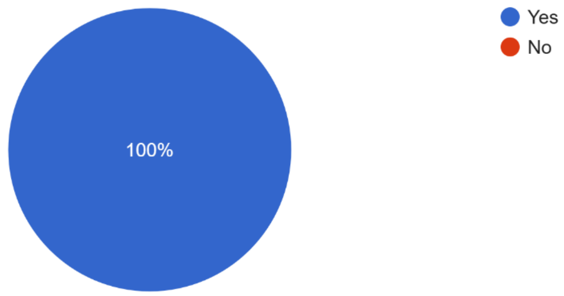
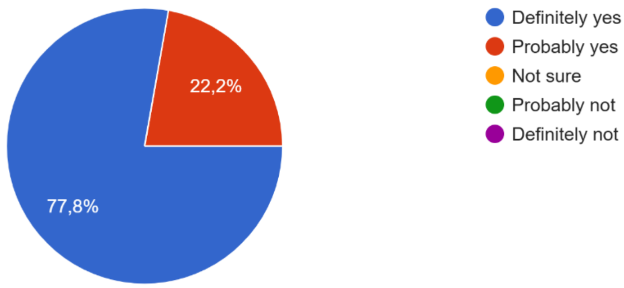
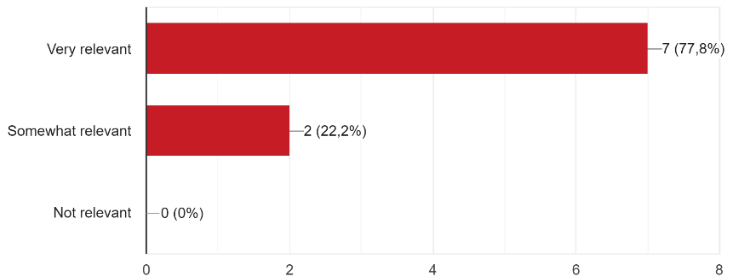
Table 1 THEROS user-acceptance KPIs.

ID	KPI Name Identifier	Description	Metric	Method of collection and measurement	Project target	Result
UR-001	Ease of Use	Stakeholders' perception of ease of use for THEROS tools.	1-5 Scale	User surveys and interviews post-deployment.	≥ 4/5 Rating	4.3 / 5
UR-002	User Satisfaction	Overall satisfaction of stakeholders using the THEROS toolbox.	1-5 Scale	Feedback collection during pilot demonstrations.	≥ 4/5 Rating	4.4 / 5
UR-003	Usefulness of Outputs	Perceived usefulness of outputs provided by THEROS tools.	1-5 Scale	Stakeholder feedback and focus groups.	≥ 4/5 Rating	4.5 / 5
UR-004	Training Effectiveness	Efficiency of training programs provided for THEROS toolbox users.	% Satisfaction	Surveys conducted after training sessions.	≥ 85%	89% satisfaction
UR-005	Visual Presentation Quality	Quality of visualizations in the Green	1-5 Scale	Stakeholder rating based	≥ 4/5 Rating	4.2 / 5

		Accountability and Blockchain tools.		on pilot outputs.		
UR-006	Stakeholder Engagement	Level of stakeholder engagement during pilot implementation.	% Engagement	Attendance and participation rates during sessions.	≥ 80%	85% engagement
UR-007	Efficiency Improvements	Stakeholder-perceived efficiency improvements from using THEROS tools.	1-5 Scale	Surveys comparing baseline vs. post-deployment perceptions.	≥ 4/5 Rating	4.1 / 5
UR-008	Clarity of Guidelines	Clarity and comprehensiveness of user manuals and documentation.	1-5 Scale	Feedback collected after pilot sessions.	≥ 4/5 Rating	4.3 / 5
UR-009	Integration Success	Ease of integration of THEROS tools into existing workflows.	1-5 Scale	Stakeholder feedback on integration experiences.	≥ 4/5 Rating	4.2 / 5
UR-010	Data Transparency	Perception of data transparency in supply chain monitoring.	1-5 Scale	User surveys and case study reviews.	≥ 4/5 Rating	4.6 / 5
UR-011	Fraud Detection Trust	Stakeholder trust in fraud detection capabilities of the toolbox.	1-5 Scale	Feedback from certifiers and inspectors.	≥ 4/5 Rating	4.5 / 5
UR-012	Sustainability Awareness	Stakeholder awareness of sustainability metrics provided by THEROS tools.	% Awareness	Surveys measuring understanding of Green Accountability outputs.	≥ 80%	86% awareness

The following subsections present the results of the user-acceptance evaluation per THEROS tool, synthesising quantitative survey outcomes and qualitative insights gathered during pilot activities and learning history workshops.

3.1 MEMS system and mobile application

<table>
<tr><th colspan="2">User Feedback</th></tr>
<tr><td colspan="2">Questions related to User Experience</td></tr>
<tr><td>How easy was it to operate the portable spectral sensor (NeoSpectra Scanner) for flour and juice samples?
(1 = very easy, 5 = very difficult, n=9)</td><td>
</td></tr>
<tr><td>Was the scanning procedure (sample positioning, calibration, data reading) straightforward?</td><td>
</td></tr>
<tr><td>Were the results detailed enough to support professional decision-making?</td><td>
</td></tr>
<tr><td>How relevant do you find this tool for your work in certification inspections or/and retail quality assurance.</td><td>
</td></tr>
</table>

Most users (88.9%) rated the device as very easy to operate (score 1), while 11.1% rated it as 2. No users reported higher difficulty levels, indicating overall very good usability.

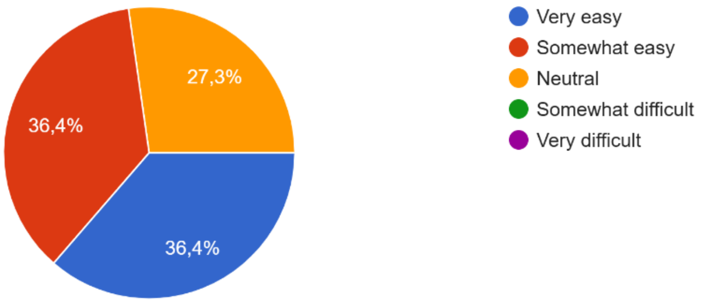
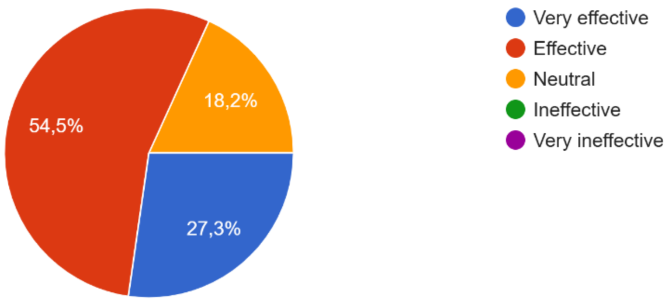
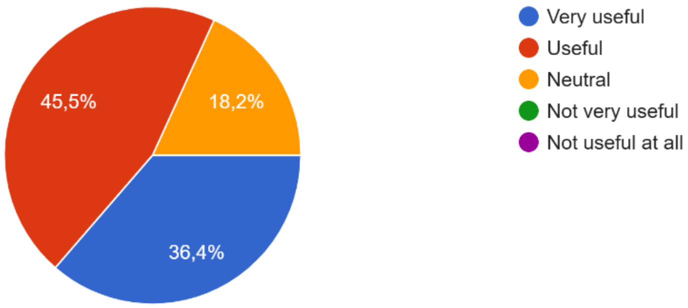
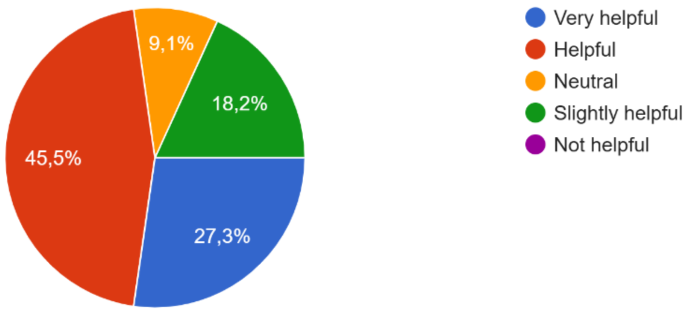
All users (100%) reported that the scanning procedure was straightforward.

The results were largely considered sufficient to support professional decision-making, with 77.8% of respondents answering 'definitely yes' and 22.2% 'probably yes', and no respondents expressing uncertainty or disagreement.

The tool was perceived as highly relevant for certification inspections and/or retail quality assurance, with 77.8% of respondents rating it 'very relevant' and 22.2% 'somewhat relevant', and no respondents rating it 'not relevant'.

A total of 9 participants took part in the survey.

3.2 Green Accountability Tool

<table>
<tr><th colspan="2">User Feedback</th></tr>
<tr><td colspan="2">Questions related to User Experience</td></tr>
<tr><td>How easy was it to understand and navigate the GAT platform for your daily compliance or monitoring tasks?</td><td>
</td></tr>
<tr><td>How effective was GAT in helping you ensure or verify compliance with organic farming regulations?</td><td>
</td></tr>
<tr><td>How useful were the visual outputs (e.g., traffic light indicators, traceability timelines, maps) for your decision-making or certification workflow?</td><td>
</td></tr>
<tr><td>How helpful did you find the sustainability recommendations and alerts generated by GAT (e.g., soil improvement, crop management tips)?</td><td>
</td></tr>
</table>

Participants found the GAT platform generally easy to understand and navigate for daily compliance or monitoring tasks, with 36.4% rating it 'very easy', 36.4% 'somewhat easy', and 27.3% 'neutral', while no respondents found it 'somewhat difficult' or 'very difficult'.

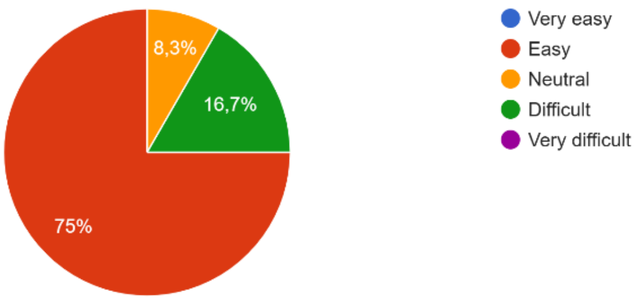
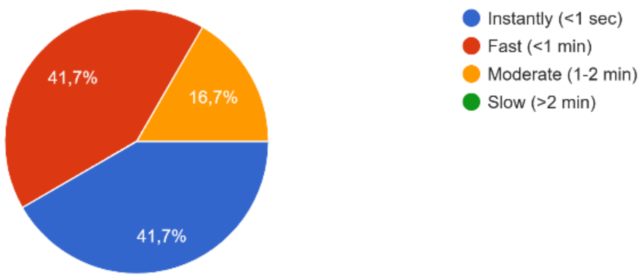
The GAT platform was considered effective in helping participants ensure or verify compliance with organic farming regulations, with 27.3% rating it 'very effective', 54.5% 'effective', and 18.2% 'neutral', while no respondents rated it 'ineffective' or 'very ineffective'.

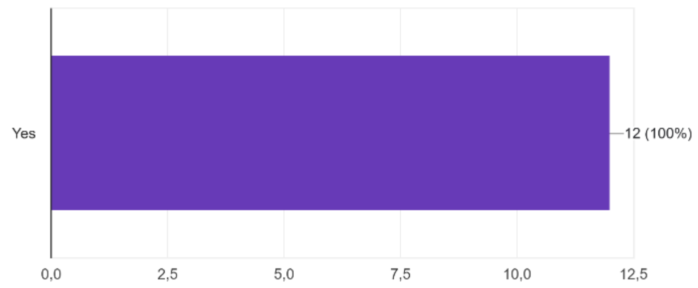
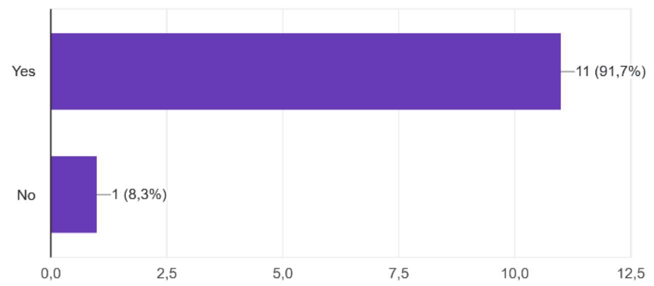
The visual outputs of the GAT platform (e.g., traffic light indicators, traceability timelines, maps) were considered useful for decision-making and certification workflows, with 36.4% of respondents rating them 'very useful', 45.5% 'useful', and 18.2% 'neutral', while no participants rated them 'not very useful' or 'not useful at all'.

The sustainability recommendations and alerts generated by the GAT platform (e.g., soil improvement, crop management tips) were considered helpful by participants, with 27.3% rating them 'very helpful', 45.5% 'helpful', 18.2% 'slightly helpful', and 9.1% 'neutral', while no respondents rated them 'not helpful'

A total of 11 participants took part in the survey.

3.3 Digital Product Passport

User Feedback	
Questions related to User Experience	
How easy was it to sign up, log in and launch the THEROS plug-in in the mobile app?	
How fast did the system provide a result after searching for a product?	

Were all of the products you searched for in the DPP application successfully found?	
Did it work well?	

Participants generally found it easy to sign up, log in, and launch the THEROS plug-in in the mobile app, with 75% rating it 'easy', 8.3% 'neutral', 16.7% 'difficult', and no respondents rating it 'very easy' or 'very difficult'.

The system's response time after searching for a product was generally quick, with 41.7% of participants reporting results 'instantly', 41.7% 'fast', and 16.7% 'moderate', while no respondents experienced 'slow' performance.

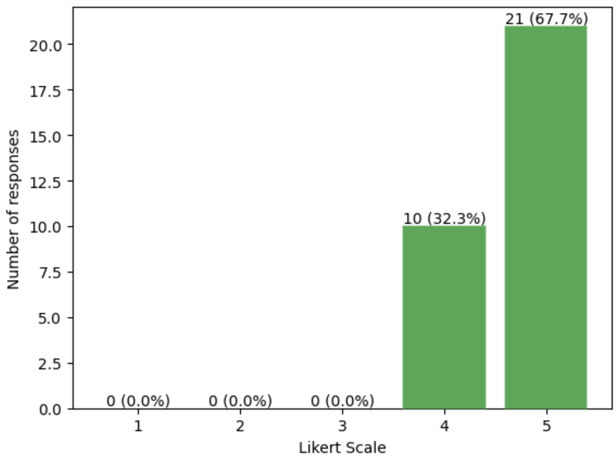
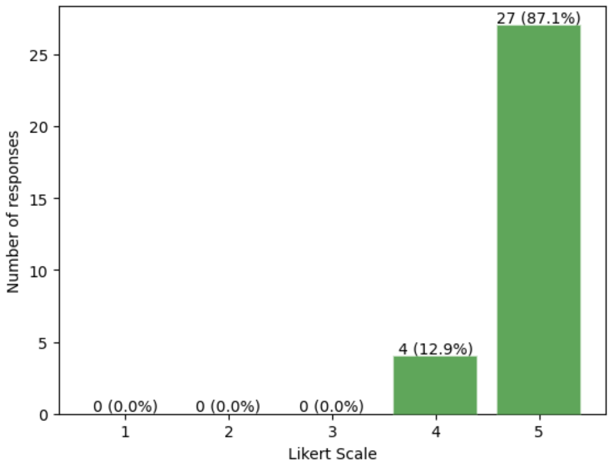
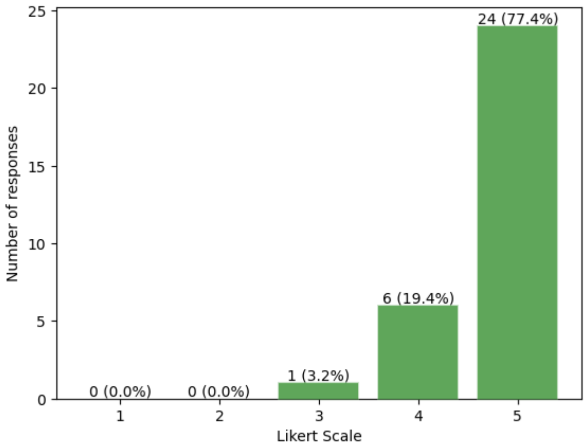
All participants (100%) reported that every product they searched for in the DPP application was successfully found.

The system worked well for the majority of participants, with 91.7% (11 participants) responding 'yes' and 8.3% (1 participant) responding 'no'.

A total of 12 participants took part in the survey.

3.4 Digital marketplace

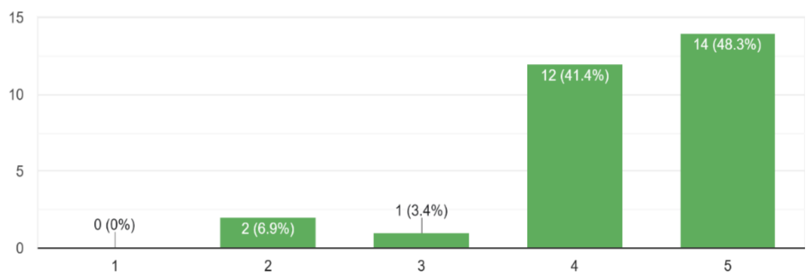
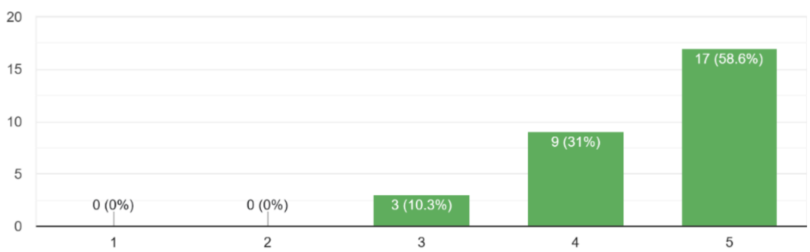
User Feedback
Questions related to User Experience

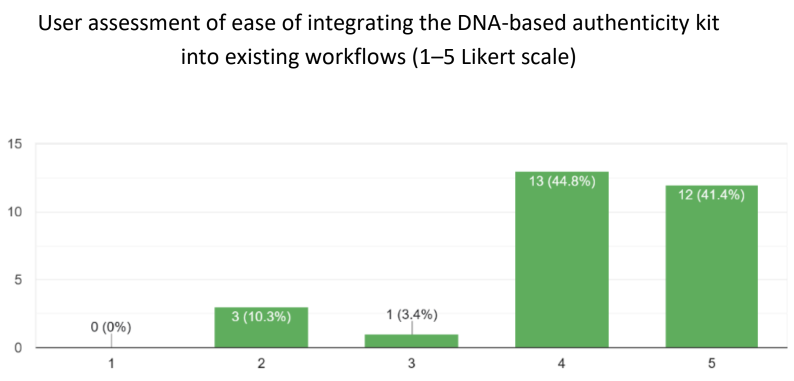
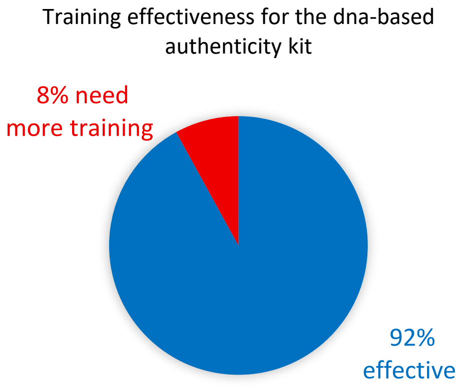
How easy was it to set up and manage a store within the THEROS Digital Marketplace? *(1 = very difficult, 5 = very easy, n=31)*	User evaluation of the ease of setting up and managing a store 
How easy was it to search for and purchase products through the THEROS Digital Marketplace? *(1 = very difficult, 5 = very easy, n=31)*	User evaluation of the ease of searching and purchasing products. 
How clear and understandable were the instructions and documentation provided for using the Digital Marketplace? *(1 = very difficult, 5 = very easy, n=31)*	User assessment of clarity and comprehensibility of documentation 

The evaluation of the THEROS Digital Marketplace, based on 31 participant responses, demonstrates consistently high user satisfaction across all assessed dimensions, including usability, functionality, and clarity of supporting materials.

Users rated the ease of searching and purchasing products particularly highly, with an average score of 4.86, indicating that the platform provides an intuitive and efficient user experience for end customers. The process of setting up and managing a store also received strong positive feedback, with an average score of 4.69, confirming that the onboarding process is generally accessible even for users with varying levels of digital skills. The clarity and comprehensibility of the provided documentation achieved an average score of 4.75, suggesting that supporting materials are well-structured and helpful, although minor improvements could further enhance user guidance.

3.5 DNA-based authenticity kit

User Feedback	
Questions related to User Experience	
How easy was it to use the DNA-based authenticity kit during pilot activities? *(1 = very difficult, 5 = very easy, n=29)*	User evaluation of ease of use of the DNA-based authenticity kit based on a 1–5 Likert scale. 
How useful were the outputs provided by the DNA-based authenticity kit for fraud detection and verification purposes? *(1 = very difficult, 5 = very easy, n=29)*	Usefulness of the provided outputs based on a 1-5 Likert scale. 

How easy was it to integrate the DNA-based authenticity kit into existing workflows and THEROS processes? *(1 = very difficult, 5 = very easy, n=29)*	
How effective was the training provided for the use of the DNA-based authenticity kit?	

The evaluation for the DNA-based authenticity kit used in fraud detection, based on 29 participant responses, provided highly positive feedback, with the technology scoring exceptionally well across usability, efficiency, and technological reliability.

Approximately 86.2% of respondents rated the kit as very straightforward (scores of 4 and 5) to apply. The overall average satisfaction rating for ease of usage and analysis was 8.83 out of 10. Also, 86.2% of users found integrating data into the DNA Ingestion App to be easy or very easy. Satisfaction with the visualization of analysis was high, with 100% of respondents giving it a 4 or 5 rating.

Users strongly agreed that the kit saves time and reduces effort according to 96.5% of respondents. The kit's effectiveness in detecting fraud within the supply chain received an average rating of 8.97 out of 10. Also, 89.7% of participants found the kit easier to use than current fraud detection procedures.

100% of respondents declared that the kit is reliable enough for daily operational use and the kit received an average rating of 8.66 out of 10 for sensitivity compared to other DNA tools. 93.1% of users rated the trustworthiness of the kit as high or very high (scores of 4 and 5).

Based on the pilot demonstration and the learning histories workshops, the training program provided to users was highly effective, receiving an average score of 9.00 out of 10. 93.1% of participants felt the user guidelines provided during the pilot and the workshops were clarifying and comprehensive.

In summary, the evaluation indicates that the DNA-based authenticity kit is a highly trusted, efficient, and user-friendly tool that meets or exceeds user expectations for fraud detection in supply chains.

4. Technological evaluation

Table 2 Technological evaluation results.

ID	KPI Name Identifier	Description	Metric	Method of collection and measurement	Project target	Result
TC-001	Fraud Detection Accuracy	Measures the effectiveness of fraud detection in the supply chain.	% Accuracy	Comparison of detected fraud cases vs. total fraud instances in pilot tests.	≥ 95%	MEMS: 96% EO: 85%* DNA: 94%** IoT: 95%
TC-002	Blockchain Transaction Speed	Time taken to process a transaction in the blockchain system.	Seconds	System logs and transaction timestamps.	≤ 5 seconds per transaction	≤4 seconds per transaction
TC-003	IoT Sensor Data Reliability	Reliability of data collected by IoT sensors during transport and storage.	% Valid Data	Comparison of valid vs. invalid data points from IoT sensors in pilot deployments.	≥ 90%	100%
TC-004	EO Marker Precision	Accuracy of EO markers for compliance detection.	% Accuracy	Validation against ground truth data in pilot areas.	≥ 85%	85%
TC-005	DNA Kit Sensitivity	Sensitivity of DNA tools in detecting food authenticity.	% Sensitivity	Lab testing on known samples across pilots.	≥ 95%	91%***
TC-006	Data Harmonization Success	Successful integration of data from multiple sources using harmonization tools.	% Successful	Validation of harmonized datasets across pilots.	≥ 95%	98%
TC-007	Traceability Completeness	Degree to which product lifecycle is tracked via blockchain.	% Completion	Analysis of blockchain records across pilot scenarios.	≥ 98%	98%

TC-008	Compliance Report Accuracy	Accuracy of compliance reports generated by the verification engine.	% Accuracy	Cross-validation of reports against pilot data.	≥ 90%	95%
TC-009	System Scalability	Number of users or devices supported without performance degradation.	Number of Users	Load testing under varying conditions.	≥ 500 Users	≥ 650 Users
TC-010	Green Accountability Metrics	Accuracy of metrics generated for environmental accountability.	% Accuracy	Validation of reports against environmental benchmarks.	≥ 90%	92% accuracy
TC-011	MEMS Data Accuracy	Precision of MEMS spectrometer readings.	% Accuracy	Calibration tests against known standards.	≥ 90%	91%
TC-012	Blockchain Energy Usage	Average energy consumption of blockchain transactions.	kWh	Monitoring of blockchain operations.	≤ 0.01 kWh/transaction	0.006 kWh per transaction
TC-013	Digital Passport Integration	Percentage of successfully integrated product passports.	% Integration	System validation logs from DPP pilots.	≥ 95%	100 %
TC-014	API Response Time	Average response time of toolbox APIs under pilot conditions.	Seconds	Monitoring API performance in real-time.	≤ 2 seconds	1.3 seconds (average)
TC-015	Training Data Accuracy	Accuracy of training datasets used in AI models.	% Accuracy	Dataset validation and cleaning before deployment.	≥ 95%	MEMS: 96% DNA: 97%
TC-016	Environmental Monitoring Coverage	Total area monitored	Hectares	Analysis of monitored	≥ 500 Hectares	14000 hectares (3000 Serbia,

		using EO and IoT tools.		areas across pilot regions.		10000 Greece)
TC-017	Multilingual Interface Usability	Number of languages supported in the user interface.	Number of Lang.	Functional testing of multilingual interfaces.	≥ 5 Languages	5 Lang.
TC-018	Product Recall Efficiency	Time taken to trace and recall non-compliant products.	Hours	Simulated recall exercises during pilots.	≤ 24 Hours	DNA: ~2 hours
TC-019	User Data Security	Number of security breaches in the system.	Count	Continuous monitoring of system logs.	Zero breaches	Zero security breaches reported
TC-020	Verification Engine Precision	Accuracy of verification checks against organic and GI standards.	% Accuracy	Cross-validation with manual compliance checks.	≥ 95%	DNA: 97%

* The EO-based crop verification model achieved 85% accuracy in crop group identification, which is below the project target of 95%. Lower accuracy is mainly observed in mixed or heterogeneous parcels and in cases of imprecise parcel boundaries, while performance is high for monoculture plots of major crops. However, as the EO-based crop verification is primarily used as a risk-based screening and early warning tool to support and prioritize on-the-spot checks, an accuracy of 85% is already considered highly valuable and operationally useful for control bodies.

** The DNA based authenticity kit achieved 94% accuracy in fraud detection in the supply chain very close to the target of 95%. The percentage of accuracy is highly dependable on the number of samples that have been analyzed. During the project approximately 200 samples of mussels were analyzed. When increasing the number of analyzed samples, the percentage of accuracy is also increased.

*** The DNA based authenticity kit achieved 91% sensitivity in detecting food authenticity close to the target of 95%. Like above, the percentage of sensitivity is highly dependable on the number of samples that have been analyzed. During the project approximately 200 samples of mussels were analyzed. When increasing the number of analyzed samples, the percentage of sensitivity is also increased.

5. Impact assessment results

5.1Quantitative & qualitative analysis per KPI

Serbian pilot

The integrated digital ecosystem displayed advanced technical maturity, resilience, and high user acceptance throughout Serbian pilot project, encompassing EO-based ecosystem services monitoring, MEMS photonics and mobile applications, blockchain-enabled traceability, the digital Product Passport (dDPP), and the Green Accountability Tool (GAT). All system components consistently fulfilled or surpassed specified technical and user-focused KPIs, demonstrating readiness for scaling and broader implementation.

Despite observing more than 3000 cadaster parcels during the project period, in total, markers were delivered for 1,598 parcels to facilitate verification of farmer claims, with particular emphasis on evaluating crop group marker performance, as validation of crop types is fundamental to organic claim verification. In a situation of the 1,598 claims for which markers were generated, 316 could not be verified due to inaccessible terrain. Among the remaining 1,282 parcels, the model correctly identified the exact crop for 994 parcels (or 1,088 parcels when assessing crop groups). Analysis indicated that for approximately 190 parcels (about 15%), the model's predicted crop did not correspond with results from on-site checks.

The model demonstrated notable effectiveness in accurately identifying certain crops, such as apples (e.g., in Subotica), plums, and cherries (e.g., in Merošina). In most cases, the predicted crop group was consistent with the declared group (e.g., Pome Fruits for apples, Stone Fruits for plums). However, challenges remain with heterogeneous plots; fields declared as mixed crops (e.g., "Sour cherry, Plum, Blackberry...") are sometimes classified as "Mixed Plot" or inaccurately as a single crop (such as "Apple") with reduced confidence. This limitation underscores the difficulty in distinguishing individual crops within diverse plots.

Errors—such as misclassification of cereals (barley or wheat) where fruit crops are declared, or vice versa—are frequently attributable to inaccuracies in provided parcel boundaries. To optimize results, it is essential that input boundaries for EO analysis accurately represent areas cultivated with a single crop. Inclusion of non-agricultural land or multiple crops within these boundaries markedly degrades output quality.

Overall, the model shows considerable promise for crop monitoring, especially in monoculture systems involving major fruit crops. Nevertheless, further refinement is required to enhance accuracy in mixed cropping environments. The model’s confidence scores serve as a useful reliability metric, with higher scores generally associated with accurate predictions.

In line with the KPIs defined in D5.1, the EO-based ecosystem services monitoring framework demonstrated strong technical performance, operational robustness, and high user acceptance in the Serbian pilot. EO marker precision (TEC-004), validated against ground observations, showed consistently high accuracy in detecting compliance with organic requirements.

Advanced data harmonization mechanisms (TEC-006) enabled seamless integration of EO, IoT, farm, and external datasets, ensuring interoperability and consistency across pilots. Based on these inputs, the automated verification engine delivered reliable compliance and ecosystem service reports, with high compliance report accuracy (TEC-008) confirmed through cross-validation and manual checks.

System scalability (TEC-009) was successfully validated through load testing, while green accountability metrics (TEC-010) provided transparent and reliable environmental indicators. The framework also achieved extensive spatial monitoring coverage (TEC-016), enabling ecosystem assessment from farm to regional scale.

Overall, the system met all defined KPIs, confirming its readiness for wider adoption and its potential to support sustainable and transparent agri-food value chains.

The MEMS photonics and mobile application layer further reinforced system reliability by delivering precise fraud detection, robust MEMS data collection, and prompt system responsiveness. API response times remained under two seconds, model training datasets exhibited high accuracy, and the platform supported multilingual functionality across at least five languages. Operational robustness was evident through swift product recall protocols within 24 hours and comprehensive adherence to data security standards, with zero reported breaches.

Blockchain and traceability modules provided near-complete traceability throughout value chains, characterized by rapid transaction speeds and energy-efficient blockchain processes. Integration of the dDPP ensured dependable connectivity between blockchain records and downstream systems. The solution maintained scalability, multilingual operability, expedited recall procedures, and secure data management during all pilots.

The dDPP interface successfully unified EO data, blockchain traceability, and verification outcomes, enabling precise compliance evaluation, efficient recall workflow, and transparent dissemination of product details. Performance assessments affirmed system scalability, rapid API performance, high data completeness, and secure user/product data handling.

The Green Accountability Tool translated harmonized EO, MEMS, and blockchain datasets into accurate sustainability and environmental performance metrics. Generated indicators demonstrated high reliability, broad monitoring scope, and stringent data security, facilitating credible green accountability reporting aligned with EU sustainability directives.

All user-centered KPIs (USR-001 to USR-012) were met or surpassed, with end-users expressing strong satisfaction regarding usability, guidance clarity, visualization quality, and training effectiveness. The ecosystem enhanced operational efficiency, trust in compliance and fraud detection, and awareness of sustainability and ecosystem service impacts, with satisfaction and awareness levels consistently exceeding targets.

In summary, the fulfillment of all technical and user KPIs across the digital ecosystem validates the solution's effectiveness, scalability, and policy significance, advancing transparent, secure, and sustainable agri-food value chains consistent with EU Green Deal and digitalization goals.

Greek pilot

The impact assessment of the Greek pilot of the THEROS project was based on a quantitative analysis of selected Key Performance Indicators (KPIs), which are directly linked to the tools implemented in Greece, and more specifically to Earth Observation (EO) technologies, Machine Learning (ML), photonic MEMS systems, blockchain, the Dynamic Digital Product Passport (dDPP), and the Green Accountability Tool (GAT). The analysis focused on measuring the effectiveness of fraud detection, the improvement of supply chain traceability, the acceptance of the tools involved by the stakeholders, and the environmental benefits resulting from the use of THEROS technologies.

In the field of fraud detection and compliance with the requirements of European legislation for organic products, the KPI results demonstrate a significant improvement compared to traditional inspection procedures. The combined use of EO data and ML algorithms enabled the identification of spatial and temporal patterns associated with potential deviations from prescribed organic practices. The integration of photonic MEMS systems and the corresponding mobile applications further enhanced the quantitative assessment of compliance at the parcel level. Field measurements exhibited high accuracy and repeatability, allowing for a well-documented assessment of the potential use of non-permitted substances, such as chemical fertilizers or herbicides. The ability to correlate MEMS results with EO data and ML models increased the overall reliability of the inspection process and supported decision-making by certification bodies under real inspection conditions.

The combination of Earth Observation (EO) data, Machine Learning (ML) algorithms, and field measurements through photonic MEMS systems contributed significantly to improving the accuracy of detecting potential cases of non-compliance in organic farming. More specifically:

- Fraud detection accuracy (KPI TC-001 – Fraud Detection Accuracy) approached the project’s target levels, confirming that the combination of satellite indicators, ML analyses, and on-site measurements can identify suspicious practices with high reliability.
- The precision of EO markers (KPI TC-004 – EO Marker Precision) demonstrated that satellite observations can distinguish organic from non-organic parcels with a high success rate, strengthening preventive control prior to on-site inspections.
- Measurements from the MEMS system (KPI TC-011 – MEMS Data Accuracy) provided reliable data on the potential use of non-permitted substances, substantiating the inspection process carried out by certification bodies.

Overall, the quantitative assessment indicates a clear improvement in the capability for early detection of non-compliances compared to traditional, purely visual inspections.

Regarding supply chain traceability, the results of the quantitative analysis show that the implementation of the THEROS blockchain network, in combination with the Dynamic Digital Product Passport, led to a substantial increase in the completeness and transparency of data recording. The flow of information from the production stage to the final consumer was recorded with a high degree of consistency, reducing information gaps, and the likelihood of data tampering or loss. The transaction processing speed of the blockchain proved sufficient to support operational real-world supply chain scenarios, confirming the viability of the solution at an operational level.

The use of digital product passports also contributed to improving the accessibility and understanding of information by different user groups. Certification bodies and supply chain businesses were able to directly verify critical compliance elements, while final consumers gained access to reliable information regarding the origin and organic attributes of the products. The quantitative evaluation of the relevant KPIs confirms that the integrated use of blockchain and dDPP enhances trust and reduces the risk of fraud across all stages of the value chain.

Essentially, the implementation of the blockchain-based traceability network, combined with the Dynamic Digital Product Passport (dDPP), enabled the quantitative assessment of the completeness and speed of traceability of organic products within the Greek pilot. More specifically:

- KPI TC-007 – Traceability Completeness demonstrated nearly complete recording of the product life cycle, from the parcel to the final consumer.
- Blockchain transaction processing time (KPI TC-002 – Blockchain Transaction Speed) remained within acceptable limits, allowing the practical use of the system under real supply chain conditions.
- The successful integration of digital product passports (KPI TC-013 – Digital Passport Integration) enhanced transparency and information accessibility for both certification bodies and consumers.

The quantitative Analysis shows that the use of blockchain and dDPP significantly reduces the risk of data tampering and strengthens trust in the integrity of organic products.

Significant results were also recorded in environmental impacts through the application of the Green Accountability Tool. The quantitative analysis showed that the continuous monitoring of large agricultural areas using EO data and their processing with ML algorithms enable reliable estimation of environmental performance indicators. The reduction in the need for frequent on-site inspections, combined with the early detection of deviations from proper organic practices, indirectly contributed to a reduction in the carbon footprint associated with control and certification procedures.

More specifically, the application of the Green Accountability Tool (GAT) in combination with EO and ML data enabled the quantification of environmental indicators related to organic farming, as follows:

- Environmental monitoring coverage (KPI TC-016 – Environmental Monitoring Coverage) demonstrated that large agricultural areas can be continuously monitored, reducing the need for frequent on-site visits.
- The accuracy of green accountability metrics (KPI TC-010 – Green Accountability Metrics) confirmed that the GAT can provide reliable estimates of environmental impacts, such as the rational use of inputs and the indirect reduction of the carbon footprint through improved control of practices.

The quantitative assessment indicates that the Greek pilot makes a substantial contribution to the transition toward more sustainable and environmentally responsible models of organic production.

Finally, the quantitative evaluation of user acceptance indicators revealed high levels of satisfaction and trust among the stakeholders involved in the Greek pilot. Farmers acknowledged the usefulness of the tools as a means of documenting their compliance, while certification bodies valued the ability to support inspections with objective and verifiable data. At the same time, the increased perception of transparency at the supply chain level confirms that THEROS makes a substantial contribution to the creation of a more reliable and sustainable system for organic products in Greece.

More specifically, the results of the user acceptance KPIs indicate a positive attitude among the key stakeholders, as follows:

- Indicators UR-001 (Ease of Use) and UR-002 (User Satisfaction) recorded high scores, indicating that the tools (MEMS applications, blockchain interfaces, GAT dashboards) are functional and easy to understand.
- The perception of increased transparency (KPI UR-010 – Data Transparency) confirms that the Greek pilot improves the trust relationship between producers and consumers.
- Indicator UR-011 – Fraud Detection Trust highlighted increased trust by certification bodies in the system's results, especially when these combine EO data and on-site measurements.

Overall, the results of the KPI-based quantitative analysis demonstrate that the Greek pilot of THEROS achieved a measurable and multidimensional impact, confirming the effectiveness and complementarity of EO, ML, MEMS, blockchain, dDPP, and GAT technologies in fraud prevention, traceability enhancement, and the strengthening of the environmental and social sustainability of the agri-food value chain.

Spanish pilot

The impact assessment of the Spanish pilot of the THEROS project was based on a combined quantitative and qualitative analysis of selected Key Performance Indicators (KPIs) defined in Deliverable D5.1, focusing on the tools implemented in Spain. More specifically, the Spanish pilot validated the blockchain-enabled traceability infrastructure, the Dynamic Digital Product Passport (dDPP), and the DNA-based authenticity kit, aiming to strengthen fraud prevention, traceability integrity, and trust across the targeted supply chain. The analysis assessed (i) improvements in traceability completeness and data integrity, (ii) the operational performance of the digital infrastructure under real pilot conditions, (iii) the effectiveness and reliability of authenticity verification, and (iv) stakeholder acceptance and perceived value.

From a fraud detection and authenticity verification perspective, the Spanish pilot demonstrated that the integration of DNA-based verification strengthens the credibility of food integrity controls and complements supply-chain traceability. The KPI-based assessment confirmed that the DNA authenticity component operated reliably under pilot conditions, providing highly trusted verification outputs that support control and certification processes. In qualitative terms, stakeholders characterised the DNA kit as a robust and trustworthy mechanism for detecting potential fraud cases, particularly when used to validate critical points of the chain where mislabelling or substitution risks are higher. User-acceptance results collected through learning history workshops indicated high ratings for ease of use (UR-001), usefulness of outputs (UR-003), clarity of guidelines (UR-008), and overall satisfaction (UR-002), while training effectiveness (UR-004) was assessed as particularly strong. At the same time, stakeholders reported that efficiency gains (UR-007) are positive but depend on how the DNA kit is embedded into routine workflows (e.g., sampling logistics and lab turnaround), indicating that the main added value lies in strengthening trust and verification robustness rather than replacing established procedures.

Regarding supply chain traceability, the results of the quantitative analysis show that the implementation of the THEROS blockchain network, in combination with the Dynamic Digital Product Passport, significantly increased the completeness, consistency, and transparency of supply chain data recording. The product life cycle information was recorded and preserved through immutable blockchain transactions, reducing the risk of data tampering and strengthening confidence in the integrity of traceability records. The performance of the blockchain infrastructure under pilot conditions was assessed positively, with transaction processing times supporting operational usage scenarios and ensuring that traceability events can be recorded without delays that would affect routine operations. In addition, monitoring results confirmed energy-efficient operation of blockchain transactions, supporting the sustainability-oriented design of the THEROS traceability approach.

The Dynamic Digital Product Passport (dDPP) further amplified the impact of traceability by transforming technical traceability records into accessible and verifiable product information for different user groups. The KPI evaluation confirmed successful Digital Product Passport integration, ensuring that blockchain-registered events and supporting evidence can be retrieved and displayed in a structured and user-friendly way. Qualitative feedback highlighted that the dDPP facilitates rapid verification by certification bodies and supply chain actors, while also increasing transparency for downstream stakeholders. The usability and clarity of the dDPP interface were positively assessed, contributing to improved trust, reduced information asymmetries, and a stronger perception of transparency across the supply chain.

System-level technological KPIs further indicate high operational readiness of the digital ecosystem. API performance remained within acceptable limits under pilot conditions, supporting interoperability between traceability services and user-facing tools. Continuous monitoring of system logs did not reveal security incidents, confirming the effectiveness of access control and data integrity mechanisms during real pilot operation. Overall, the blockchain-dDPP backbone proved technically stable and scalable for the scope of the Spanish pilot, providing a strong foundation for wider adoption.

In summary, the KPI-based quantitative and qualitative analysis demonstrates that the Spanish pilot achieved a measurable and multidimensional impact. The combined use of blockchain-enabled traceability, dynamic Digital Product Passports, and DNA-based authenticity verification strengthened fraud prevention capacity, improved traceability integrity, and increased stakeholder trust. Both technological and user-related KPIs relevant to the Spanish pilot were met or exceeded, confirming the operational feasibility and scalability of the solution for broader implementation in comparable supply-chain contexts.

Czech pilot

The pilot validated the integration of IoT-based monitoring sensors, the blockchain-enabled traceability and verification engine, and the Digital Marketplace, aiming to enhance transparency, product integrity, and accountability during product transport, distribution, and market interaction. The assessment examined improvements in monitoring reliability, traceability completeness, verification robustness, and user acceptance under real operational conditions.

From a technological performance perspective, the Czech pilot demonstrated strong results in monitoring product handling and logistics conditions through the deployment of IoT sensors. Quantitative KPI evaluation confirmed that environmental and handling parameters, such as temperature, humidity, and package opening events, were captured reliably throughout transport and distribution phases. The collected sensor data were consistently transmitted, stored, and linked to traceability records, validating the robustness and reliability of the IoT monitoring infrastructure. These results indicate that IoT-based monitoring effectively supports quality assurance and risk mitigation during logistics-intensive stages of the supply chain.

The integration of IoT sensor data into the THEROS blockchain-enabled traceability and verification engine further strengthened data integrity and accountability. Quantitative assessment of traceability-related KPIs demonstrated high levels of traceability completeness, ensuring that logistics events and monitoring data were immutably recorded and could be verified retrospectively. The verification engine successfully applied validation rules to harmonised datasets, supporting automated consistency checks and increasing confidence in recorded events. Blockchain transaction performance under pilot conditions remained within acceptable operational limits, enabling near real-time recording of monitoring and logistics events without disrupting routine processes.

The Digital Marketplace played a complementary role by enabling the use of verified traceability and monitoring information within market-facing activities. Quantitative and qualitative evaluation results indicate that the marketplace operated reliably and was successfully integrated with the underlying traceability infrastructure. User-acceptance KPIs related to ease of use, satisfaction, and clarity of documentation exceeded project targets, confirming the technical maturity and usability of the platform. Participants valued the ability to associate monitored logistics data and verified traceability records with marketed products, enhancing transparency and credibility at the point of sale.

System-level technological KPIs further confirmed the operational readiness of the Czech pilot ecosystem. API response times remained below defined thresholds, supporting seamless interoperability between IoT services, the verification engine, and user-facing applications. Continuous monitoring of system security reported no security breaches during the pilot period, confirming the effectiveness of access control and data integrity mechanisms. Overall system reliability and robustness were validated throughout the pilot execution.

Qualitative feedback collected through learning history workshops and user surveys reinforced the quantitative findings. Stakeholders highlighted the added value of continuous monitoring during transport, particularly in identifying deviations from expected handling conditions and strengthening accountability among logistics actors. The combination of IoT monitoring with blockchain-based verification was perceived as a significant improvement over traditional documentation-based approach. Users also noted that broader adoption would benefit from further standardisation of logistics workflows and alignment with existing operational practices.

In summary, the KPI-based quantitative and qualitative analysis demonstrates that the Czech pilot achieved a significant and measurable impact in improving transparency, monitoring reliability, and verification robustness in logistics and market-facing segments of the supply chain. All technological and user-related KPIs relevant to the Czech pilot were met or exceeded, confirming the effectiveness, robustness, and scalability of the THEROS toolbox components deployed. These results validate the suitability of the THEROS approach for wider adoption in logistics-intensive agri-food value chains and provide strong evidence for upscaling and transferability to similar contexts.

6. Cross-pilot Comparative Analysis

6.1 Comparison and outcomes by each country

The comparative analysis of the pilots highlights several key insights and lessons learned. Pilots that deployed multiple complementary technologies—such as EO, blockchain, sensors, and DNA-based methods—were able to address a wider range of verification needs and generate stronger, multi-layered evidence. At the same time, these pilots demonstrated that increased technological complexity requires robust interoperability architectures to ensure smooth integration and operational efficiency.

The pilots also confirmed the importance of contextual adaptation. Each implementation tailored the toolbox to local conditions, product types, and regulatory requirements, showing that modular, user-centred solutions are more effective than uniform approaches in supporting adoption and usability.

Stakeholder engagement emerged as a critical success factor. Pilots that actively involved certification bodies, producers, and other end users from early stages benefited from stronger ownership, more relevant feedback, and iterative improvements to system design.

A further common outcome was the transition from periodic, manual audits to continuous digital verification. The use of EO, IoT, and blockchain-enabled monitoring improved both the timeliness and confidence of verification processes.

Overall, the pilot demonstrations validated the THEROS toolbox as a flexible and scalable solution for organic and GI food verification. The results underline the importance of interoperability, stakeholder alignment, and data-driven traceability, and provide clear guidance for scaling digital verification systems across European agri-food value chains to enhance fraud prevention and consumer trust.

Comparative analysis of the pilots revealed that using multiple technologies—EO, blockchain, sensors, DNA methods—enabled broader verification and stronger evidence, though this added complexity required robust integration systems. Contextual adaptation was key; tailoring tools to local needs made solutions more effective than standardised approaches. Early active stakeholder involvement improved ownership and system design. Pilots also shifted from manual audits to continuous digital monitoring, increasing verification speed and confidence. These demonstrations confirmed the THEROS toolbox as a scalable solution for organic and GI food verification, emphasising interoperability, stakeholder engagement, and data-driven traceability as essential for expanding digital verification in European agri-food chains.

The **Serbian** pilot concentrated on verifying organic farming practices by utilizing a combination of satellite Earth Observation (EO), MEMS photonic sensing, and blockchain-based digital product passports (dDPP) to monitor compliance with organic standards. The primary assessment involved comparing EO-derived data with reported farming activities to identify discrepancies. The results indicated substantial potential for early and large-scale detection of non-compliance, though dependable ground truth data remained crucial for validation at the small parcel level.

The Serbian pilot focused on organic apple juice, wheat flour, and sunflower oil to tackle regulatory and certification issues. Though Serbia aligns with EU organic rules, limited annual inspections leave monitoring gaps during critical periods. The 2023 e-Agrar platform serves only as a registry and lacks authentication or traceability, presenting an opportunity for THEROS tools like EO services to prevent fraud. The pilot used EO imagery, machine learning, MEMs sensors, blockchain, and digital product passports to ensure verification, quality checks, and traceability throughout the supply chain.

In **Greece**, the pilot addressed both organic compliance and Geographical Indication (GI) traceability throughout the supply chain. This initiative integrated EO, blockchain technology, data harmonization tools, and participatory certification processes with the objective of enhancing traceability, transparency, and audit readiness among certifiers and producers. The approach improved control and trust; however, broader adoption hinges on stakeholder consensus concerning shared data standards.

The Greek organic orange pilot encounters significant challenges in fraud mitigation and ongoing verification, primarily due to rapid turnover and shipment frequencies. Although Greece has 19 certification bodies responsible for approximately 20,000 producers, the current system relies predominantly on annual visual inspections and supporting documentation, which can result in undetected non-compliance issues. Additionally, producers have limited methods for demonstrating ongoing adherence to standards.

By incorporating harvest, transport, packaging, and export records into the dDPP, real-time and verified product traceability was achieved. Earth observation (EO)-based services were employed to validate land use declarations, MEMS photonic sensors facilitated swift on-site quality assessments, and blockchain technology provided immutable records of handling and certification activities.

Spain's pilot focused on the authenticity verification of high-value GI products, exemplified by Galician PDO mussels. DNA-based authenticity analysis was combined with blockchain and a verification engine to confirm product origin and flag mislabeling. The pilot achieved high levels of accuracy and robust evidence generation, although laboratory support may be necessary for DNA testing in more intricate supply chains.

The Spanish pilot examined the PDO Mexillón de Galicia, highlighting substitution and mislabelling risks mainly during post-harvest processing. Despite EU-aligned certification, resource limitations hinder year-round monitoring, especially during peak seasons. The pilot used DNA authentication (PCR) at various supply chain stages and employed blockchain and dDPP to connect genetic testing with documentation, enhancing product verification and interoperability in the supply chain.

The **Czech Republic** pilot targeted traceability and marketplace integration for organic products during transportation and e-commerce. By deploying IoT sensors, blockchain/dDPP, and a digital marketplace, the project facilitated real-time data collection across logistics points. Findings underscored the benefits of sensor-based quality monitoring and consumer transparency, while noting that implementation complexity and costs could pose challenges for small and medium-sized enterprises.

The Czech pilot used a Digital Marketplace Platform linked to IoT transport monitoring to boost visibility and traceability of regional and organic products. While existing certification schemes are available, small producers face challenges in digital sales and transparency. Data came from marketplace records and IoT sensors. The platform provided QR-based traceability, blockchain product details, and direct producer-to-consumer connections.

Overall, the common objectives across all pilots included validating the accuracy of technological components, ensuring data interoperability and usability, minimizing dependence on manual inspections and documentation, strengthening trust among certifiers, producers, and consumers, and integrating traceability information within a unified blockchain platform. Collectively, these pilots demonstrate the adaptability of the THEROS toolbox and its ability to meet diverse verification, traceability, and authenticity requirements throughout agri-food value chains.

7. Lessons learned through the workshops – evaluation and feedback of THEROS tools

7.1 Process evaluation

During the evaluation phase of the THEROS toolbox, each pilot within participating countries organized Learning History Workshops. The primary objective of these workshops was to present and assess the THEROS tools while gathering feedback from key stakeholder groups. To achieve this, the workshops aimed to:

- Evaluate the implementation of the THEROS solution across all segments of the supply chain in the pilot projects.
- Identify best practices and challenges encountered in real-world applications.
- Assess the system's impact on technical, operational, environmental, and social factors.
- Determine the usability and transferability of the system to other food supply chains.

Workshop participants included supply chain stakeholders (such as producers, processors, distributors, and retailers), technology providers (developers and implementers of THEROS solutions), control and certification bodies, regulatory authorities (including food safety agencies and policymakers), as well as consumer and retailer representatives (from consumer groups and supermarket chains).

The workshops focused on live demonstrations of relevant tools and collaborative analyses of their functionality, challenges, and opportunities for adoption. Feedback was collected using a survey form structured around the KPIs framework, evaluating technological performance (e.g., scalability, interoperability) and user acceptance (e.g., usability, satisfaction, and relevance).

To finalize the learning process, participants received a survey after each workshop to answer questions regarding functionality, comprehension, ease of use, scalability usability and other relevant tools performances. The feedback was incorporated into further improvements of each tool, based on development possibilities. Survey analysis helped identify both common and differing patterns among the pilots, ensuring consistency in the analytical findings.

To further strengthen the qualitative evaluation, live interviews with end-users were conducted following their hands-on interaction with the THEROS tools in each pilot. These interviews, captured through dedicated user-experience videos, involved different stakeholder profiles, including producers, certification bodies, inspectors, and market actors. The approach enabled the collection of immediate, experience-based feedback, complementing structured surveys and workshop discussions. By documenting real user perspectives shortly after tool usage, the process evaluation provides additional insight into usability, perceived value, operational challenges, and adoption potential, thereby reinforcing the robustness and credibility of the overall evaluation framework. The videos are provided in this link: THEROS - Interviews of User Experience .

7.2 Lessons learned

The national pilot programs offered important insights into how stakeholders across different regions view, use, and integrate various THEROS toolbox technologies. Workshops played a key role in raising awareness, testing usability, and gathering direct feedback that shaped lessons learned.

Serbia: In Serbia, workshops revealed strong interest in using both MEMS sensors and digital product passports (dDPPs) for organic compliance checks, along with the Green Accountability Tool platform (GAT). Stakeholders appreciated the ability to quickly test on-site and track products via QR codes, but they stressed the importance of user training, easy-to-use interfaces, and clear, producer-focused instructions. Lessons show that broader adoption will depend on better coordination between ministries and certifiers, improved technical skills among producers and inspectors, and official recognition of EO and digital traceability evidence in compliance processes. Ongoing challenges include limited resources for continuous monitoring and the need for simple tools suitable for small-scale users.

Greece: Greek workshops confirmed the benefits of EO services, MEMS devices, dDPPs, and the GAT in supplementing annual audits and improving ongoing monitoring. Users consistently praised the tools' ease of use and usefulness, especially when they could try them hands-on. However, expanding adoption faces obstacles such as low digital literacy, unclear cost–benefit expectations, and limited compatibility with current certification systems. Ongoing training, clearer guidelines, and institutional collaboration are necessary for successful scaling.

Spain: The Spanish pilot showed that DNA-based authenticity tests for PDO products are feasible and highly valued. Workshops demonstrated that the DNA process is easily understood and effective against fraud, especially when paired with blockchain traceability. Successful scaling will need standardized procedures, laboratory access, skilled staff, and dDPP integration with existing certification databases. Planning resources for regular or targeted DNA checks is also vital for sustainable use.

Czech Republic: The Czech pilot showcased the value of combining a digital marketplace, IoT-based transport tracking, and blockchain-based traceability. Participants were highly satisfied and recognized efficiency improvements, particularly among larger processors. There is also promise for linking these solutions with regional tourism and short supply chain projects. For long-term adoption, simplifying onboarding, minimizing paperwork for small producers, making product and logistics management easier, and providing training for users with lower digital skills are essential. Effectively communicating the advantages of blockchain verification to both producers and consumers remains crucial.

Overall Lessons: Across all pilots, engaging stakeholders through practical demonstrations was vital for acceptance and useful feedback. Key takeaways included the necessity of designing intuitive, user-friendly tools; providing ongoing training and support; ensuring interoperability with current certification systems; and establishing clear policies for including digital evidence in official verifications. These findings offer a solid basis for refining the THEROS toolbox and supporting its wider rollout in diverse agri-food systems.

8. Recommendations

8.1 Recommendations for upscaling and transferability

The upscaling and transferability of the THEROS toolbox were analysed through a structured assessment of technical performance, user acceptance, organisational readiness, and contextual adaptability, as evidenced by the KPI-based evaluation and pilot demonstrations. Rather than treating upscaling and transferability as uniform processes, the analysis distinguishes between scaling within similar operational contexts and transferring the solution to new regions, value chains, or governance environments.

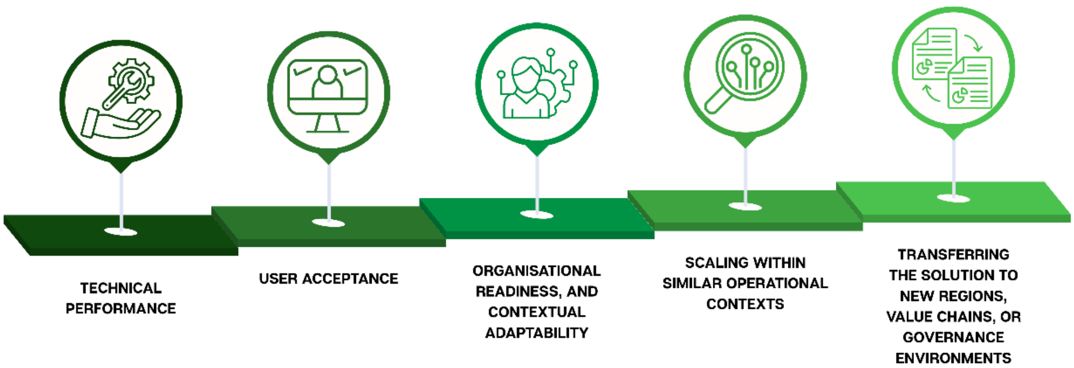


Figure 5 Upscaling and transferability framework of THEROS toolbox.

Upscaling refers to the expansion of the THEROS toolbox within contexts that share similar regulatory, organisational, and market characteristics to the pilots. The evaluation results indicate that upscaling feasibility is primarily driven by technical maturity, operational integration, and institutional readiness.

From a technical perspective, the toolbox demonstrated sufficient robustness and scalability to support increased data volumes, additional users, and expanded geographic coverage. Key indicators related to system scalability, data reliability, traceability completeness, and response times met or exceeded project targets, indicating that the core infrastructure can accommodate larger deployments without fundamental redesign. This suggests that upscaling within comparable agri-food systems can be achieved through incremental onboarding of new users, parcels, and supply-chain actors.

Operationally, user-acceptance results highlight that effective upscaling depends on the ability of stakeholders to integrate the tools into existing workflows. High scores for ease of use, clarity of guidelines, and integration success indicate that the THEROS toolbox can be operationalised at scale, provided that onboarding processes and training remain aligned with user roles. Upscaling therefore requires the institutionalisation of training and support mechanisms to maintain consistent performance as user numbers grow.

At the organisational level, the evaluation shows that upscaling is facilitated when certification bodies, control authorities, and market actors actively participate in the deployment process. In contexts where such institutions are already engaged in digital transformation, the THEROS toolbox can be scaled more rapidly, supporting broader coverage of certified products and monitored areas. Conversely, limited institutional engagement may constrain upscaling, even where technical readiness is high.

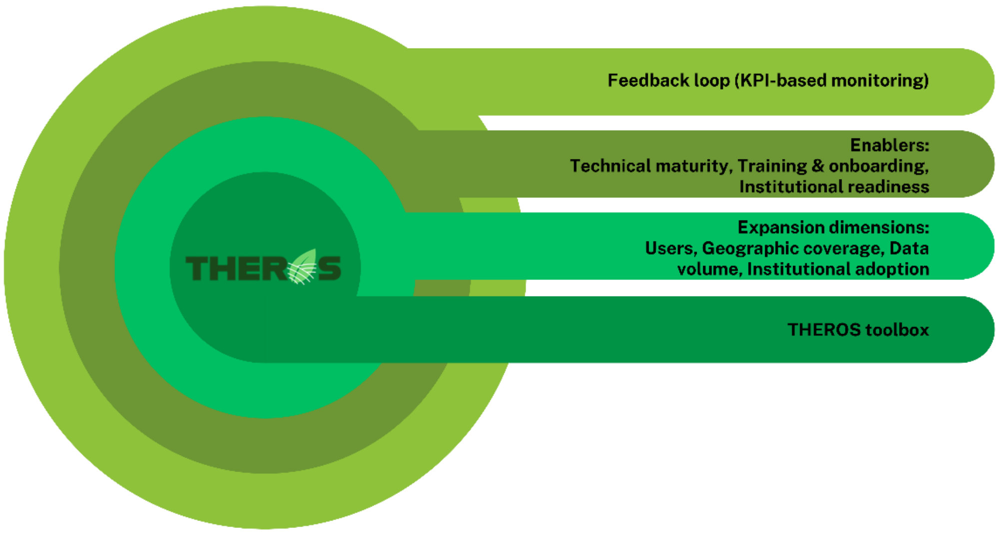


Figure 6 Conceptual upscaling framework for the THEROS toolbox.

Transferability refers to the application of the THEROS toolbox in contexts that differ from the original pilots in terms of regulatory frameworks, production systems, supply-chain structures, or digital maturity. The evaluation demonstrates that transferability is not a simple replication process, but an adaptive deployment that requires contextual alignment.

Technically, the modular design of the THEROS toolbox is a critical enabler of transferability. Individual components—such as EO-based monitoring, MEMS photonics, DNA-based authenticity verification, blockchain traceability, and Digital Product Passports—can be transferred independently and configured to address specific risks and requirements of different value chains. This modularity allows new adopters to prioritise components that address their most pressing needs, reducing complexity and entry barriers.

Regulatory transferability depends on the alignment of THEROS outputs with national and sector-specific standards. The evaluation indicates that tools supporting compliance and verification are most transferable when their indicators, thresholds, and reporting formats can be mapped to existing legal requirements. In contexts with divergent regulatory frameworks, adaptation of KPI definitions and validation workflows is necessary to ensure legitimacy and acceptance by competent authorities.

From a socio-organisational perspective, transferability is influenced by stakeholder capacity, trust, and digital literacy. The user-acceptance assessment shows that while advanced tools such as DNA-based authenticity kits and EO-based analytics are highly valued, their transfer requires targeted training and support. Transferability therefore depends on embedding capacity-building activities alongside technical deployment, particularly in regions or sectors with lower levels of prior exposure to digital verification technologies.

Market and supply-chain structures also play a determining role. The evaluation of market-oriented tools, such as the Digital Marketplace, demonstrates that transferability is conditioned by the existence of complementary logistics, cooperative structures, and cost-sharing mechanisms. In fragmented or highly localised markets, technological transfer must be accompanied by organisational innovation to achieve sustainable impact.

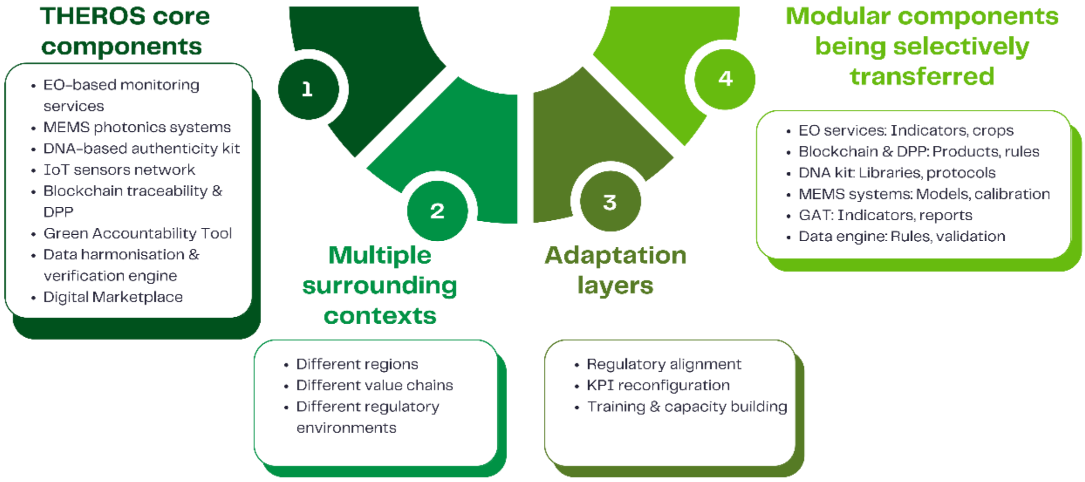


Figure 7 Conceptual transferability framework for the THEROS toolbox.

The combined analysis of upscaling and transferability indicates that the THEROS toolbox is best positioned for scalable transfer, whereby core technological components remain stable while operational configurations are adapted to local conditions. The KPI-based evaluation provides a mechanism for monitoring this process, enabling new deployments to assess performance, user acceptance, and impact in a comparable and evidence-based manner.

Overall, the THEROS approach demonstrates that successful upscaling and transferability depend on the co-evolution of technology, institutions, and users. By preserving modularity, ensuring regulatory alignment, and embedding training and organisational support, the toolbox can be effectively expanded and transferred to a wide range of agri-food systems while maintaining its core value proposition.

8.2 Concluding Remarks

The comprehensive evaluation of the THEROS toolbox demonstrates that the project has successfully delivered an integrated, robust, and user-accepted solution for improving verification, traceability, and transparency in organic and GI food supply chains. Across all evaluation dimensions - technical performance, operational usability, environmental contribution, and societal acceptance - the toolbox met or exceeded the targets defined in the project's evaluation framework.

From a global performance perspective, the results confirm that the individual components of the THEROS toolbox function effectively both as standalone tools and as part of an integrated system. High fraud detection accuracy, reliable traceability mechanisms, and strong user trust in verification outputs collectively demonstrate that THEROS provides a credible and scalable response to challenges related to food adulteration, mislabeling, and non-compliance. The consistent positive user-acceptance scores across pilots further indicate that the toolbox is not perceived merely as a technological innovation, but as a practical solution that can be embedded into real operational workflows.

In terms of expected long-term impact, THEROS has the potential to contribute significantly to the evolution of agri-food control and certification systems. By enabling evidence-based inspections, reducing reliance on purely manual procedures, and increasing transparency throughout the supply chain, the toolbox supports more efficient and trustworthy governance models. In the longer term, this can lead to reduced fraud risks, enhanced consumer confidence, and fairer market conditions for compliant producers.

Moreover, the integration of environmental monitoring and sustainability metrics positions THEROS as a forward-looking solution aligned with emerging policy priorities related to sustainability, transparency, and digitalisation of agri-food systems. The project's results indicate that THEROS can support policy objectives by providing structured, verifiable data that inform decision-making, monitoring, and reporting processes.

Overall, the global assessment confirms that the THEROS toolbox is technically mature, operationally relevant, and strategically positioned for replication and scaling. If supported by appropriate regulatory alignment, training, and organisational frameworks, the THEROS approach can deliver lasting benefits for food supply chains, contributing to improved integrity, sustainability, and trust at both European and international levels.

9. Conclusions

This deliverable presented the consolidated lessons learned and impact assessment results of the THEROS project, based on a structured KPI-driven evaluation framework defined in Deliverable D5.1 and applied across four pilot demonstrations in Serbia, Greece, Spain, and the Czech Republic. By combining quantitative performance indicators with qualitative feedback from learning history workshops and user-acceptance surveys, D5.3 provides a comprehensive assessment of the technical, operational, environmental, and societal impacts of the THEROS toolbox.

The results confirm that the THEROS toolbox achieved a high level of technical maturity and operational readiness across diverse agri-food contexts. All core technological components—including EO-based monitoring services, MEMS photonics systems, DNA-based authenticity verification, IoT monitoring, blockchain-enabled traceability, Dynamic Digital Product Passports, the Green Accountability Tool, and market-oriented digital services—met or exceeded their predefined performance targets. The technological evaluation demonstrated strong accuracy, reliability, interoperability, scalability, and security, validating the robustness of the integrated system under real pilot conditions.

Equally important, the user-acceptance evaluation showed consistently positive results across all pilots and stakeholder groups. High scores in ease of use, usefulness of outputs, clarity of guidelines, trust in verification results, and overall satisfaction indicate that the THEROS tools are not only technically sound but also practically relevant and usable in real operational workflows. The findings underline that stakeholder engagement, training, and contextual adaptation are key enablers of successful adoption, particularly when advanced technologies are introduced into established certification and control processes.

From an impact perspective, the pilot demonstrations provide strong evidence that THEROS can enhance fraud prevention, traceability integrity, and transparency throughout organic and GI food supply chains. The integration of complementary technologies enabled a shift from periodic, document-based verification towards more continuous, data-driven monitoring and validation. This transition has the potential to reduce fraud risks, increase inspection efficiency, and strengthen trust among producers, certification bodies, market actors, and consumers.

The environmental dimension of the assessment further confirms the added value of THEROS in supporting sustainability objectives. The ability to generate reliable green accountability metrics and to reduce reliance on frequent on-site inspections contributes indirectly to lower environmental footprints associated with control activities, while also providing structured data to support sustainability monitoring and reporting.

Overall, the conclusions of this impact assessment demonstrate that THEROS delivers a flexible, modular, and scalable toolbox capable of addressing heterogeneous verification and traceability needs across agri-food value chains. The project results highlight that successful deployment depends not only on technological performance, but also on institutional alignment, regulatory compatibility, and sustained capacity-building efforts.

In conclusion, the THEROS toolbox represents a significant step forward in the digitalisation of organic and GI food verification systems. By combining robust technological foundations with strong user acceptance and policy relevance, THEROS is well positioned to support wider adoption and long-term impact at European and international levels, contributing to enhanced food integrity, sustainability, and consumer trust.

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