Interreg
North-West Europe
REAMIT

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European Regional Development Fund

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Business Prospectus

Improving Resources Efficiency of Agribusiness supply chains by Minimizing waste using Internet of Things sensors (REAMIT)

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BUSINESS PROSPECTUS

REAMIT: Improving Resource Efficiency of Agribusiness supply chains by Minimising waste using Big Data and Internet of Things sensors

Ulster University

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1.0 Market conditions for food waste management in the Agri-Food industry

The agri-food industry is of paramount importance due to its essential role in ensuring food security and meeting the growing demand for food worldwide. It not only provides sustenance for the global population but also drives economic growth, employment, and trade. Numerous countries, particularly those with robust agricultural sectors, rely on the agri-food industry to contribute significantly to their GDP. Despite its importance, the industry faces a significant challenge in the form of food waste. Throughout the entire supply chain, from farm to fork, a substantial amount of food is lost or wasted. This inefficiency not only leads to economic losses but also has profound environmental and social implications.

Reducing food loss

Reducing food loss and waste (FLW) is a significant concern to many fresh food producers due to its high socio-economic costs and its relationship to waste management and climate change challenges[1]. Wasting food when other parts of the world are starving is a moral issue[2]. Another problem is that the earth's resources are finite and must be handled cautiously[3]. To provide a reference as to the magnitude of FLW's cost to Earth's resources, food waste carbon footprint has been estimated at 3.3 Gt of CO2-eq each year, which represents a 6% of global greenhouse gases (GHG) emissions[4]. Furthermore, financial resources are wasted when food is produced but not consumed[5].

In fact, the economic costs associated with food waste have been estimated at nearly USD 1 trillion per year, of which USD 680 billion represent economical loses in developed countries and 310 billion in developing ones[4]. Recognising the urgency and severity of the issue, the global community has placed increasing emphasis on tackling food waste. The 2030 Agenda for Sustainable Development, mainly Target 12.3, explicitly calls for the reduction of food waste along the production and supply chains[6]. This inclusion within the sustainable development goals underscores the global awareness and commitment to address this critical problem in the agri-food industry.

Food waste

Food waste is a pervasive issue throughout the entire agri-food supply chain. In the production stage, multiple factors contribute to waste, including food being left in the field or abattoir, damage by birds and rodents, incorrect timing or poor harvesting techniques, limited skilled workforce and resources, and susceptibility to diseases and pests. Processing and packaging stages can also result in waste due to inefficient techniques, losses during milling, cleaning, and grinding, inadequate quality management, coordination issues in the supply chain, and inaccurate demand forecasting.

Transportation and storage stages pose challenges such as improper storage conditions, inadequate temperature control and monitoring, insufficient infrastructure, pest and disease infestations, spillage, contamination, and temperature maintenance during transfers. In the retailing stage, food waste can occur due to factors like unappealing aesthetics, incorrect use of expiration dates, and ineffective supply chain coordination and demand forecasting leading to unsold food. Lastly, at the consumption stage, food waste arises from forgotten items in refrigerators, improper storage conditions, cooking errors, lack of portion size control, and a general lack of awareness about food waste and methods for utilising food waste effectively.

[1] C. Chauhan, A. Dhir, M. U. Akram, and J. Salo, "Food loss and waste in food supply chains. A systematic literature review and framework development approach," J Clean Prod, vol. 295, p. 126438, May 2021, https://doi.org/10.1016/j.jclepro.2021.126438.
[2] B. E. Roe, D. Qi, and K. E. Bender, "Some issues in the ethics of food waste," Physiol Behav, vol. 219, p. 112860, May 2020, https://doi.org/10.1016/j.physbeh.2020.112860.
[3] J. Cristóbal, V. Castellani, S. Manfredi, and S. Sala, "Prioritizing and optimizing sustainable measures for food waste prevention and management," Waste Management, vol. 72, pp. 3–16, Feb. 2018, https://doi.org/10.1016/j.wasman.2017.11.007.
[4] R. Ishangulyyev, S. Kim, and S. Lee, "Understanding Food Loss and Waste—Why Are We Losing and Wasting Food?," Foods, vol. 8, no. 8, p. 297, Jul. 2019, https://doi.org/10.3390/foods8080297.
[5] EC, "Cutting food waste with technology that keeps produce fresh. European Commission.," https://ec.europa.eu/research-and-innovation/en/projects/success-stories/all/cutting-food-waste-technology-keeps-produce-fresh, 2017.
[6] UN, "UN General Assembly Resolution 70/1 (2015) - Transforming our world: the 2030 Agenda for Sustainable Development. United Nations.," 2015.

Internet of Things

In order to address the pressing issue of food waste throughout the agri-food industry, innovative solutions are needed. One promising avenue for tackling this challenge lies in implementation of Internet of Things (IoT) technologies. By integrating IoT devices and sensors throughout the supply chain, from production to consumption, the producer can gather real-time data and insights that enable proactive decision-making and waste reduction. The utilisation of IoT technologies in the fight against food waste offers numerous benefits. Real-time monitoring of storage conditions, such as temperature and humidity, can prevent spoilage and extend the shelf life of perishable goods. Smart inventory management systems can enhance visibility and traceability, reducing the risk of overstocking and expiration. Furthermore, data analytics and predictive modelling enable proactive decision-making, allowing stakeholders to identify trends, anticipate demand, and optimise resource allocation.

The REAMIT project

The REAMIT project is at the forefront of these efforts with its focus on reducing food waste through IoT technologies. By implementing real-time monitoring systems and data analytics, the project seeks to enhance logistics efficiency, and minimise spoilage. This holistic approach targets key areas of waste generation and allows for precise interventions, ensuring that food reaches consumers in a timely manner and remains fresh throughout the supply chain. Initiatives like the REAMIT project exemplify the power of innovation and collaboration in addressing this critical issue. By harnessing the potential of IoT, we can transform the agri-food industry, ensuring that food resources are utilised efficiently, reducing waste, and moving towards a more sustainable and food-secure future.

1.1 Economic Factors and Market Opportunities

Economic Factors Influencing the Agri-Food Industry and IoT Adoption

Brexit has introduced significant changes to the agri-food sector, affecting trade relationships, customs procedures, and supply chain dynamics. Uncertainty surrounding tariffs and regulatory compliance has led to increased complexities and potential disruptions in the flow of goods. As businesses navigate these changes, there is a growing need for enhanced supply chain visibility and risk management. Here, IoT sensor adoption can play a crucial role in monitoring product movements, ensuring compliance, and identifying bottlenecks, thereby improving overall supply chain efficiency and resilience.

The agri-food industry has also been grappling with inflation and rising operational costs, impacting profit margins for businesses across the sector. Higher input costs and transportation expenses have put added pressure on already thin margins. To address these challenges, agri-food businesses are seeking innovative ways to optimise operations and reduce wastage. IoT sensors offer real-time data insights that enable better resource management, precise inventory control, and predictive maintenance, all of which contribute to cost savings and increased operational efficiency.

Additionally, rising energy costs amidst the cost-of-living crisis have become a significant concern for agri-food businesses aiming to minimise their environmental footprint while staying competitive. By adopting IoT sensors, businesses can identify where energy consumption can be reduced in their facilities, identifying areas for optimisation (like tuning fridge parameters to reduce costs) and implementing energy-saving measures. These sustainability efforts not only reduce operational costs but also enhance brand reputation as consumers increasingly prioritise environmentally responsible practices.

Market Trends and Opportunities

Extensive market research[7] has shown that IoT systems are deployed to monitor many product types throughout the supply chain, good evidence of the diverse nature of Food Loss and Waste Monitoring technologies and the innovative ways in which this technology can be applied.

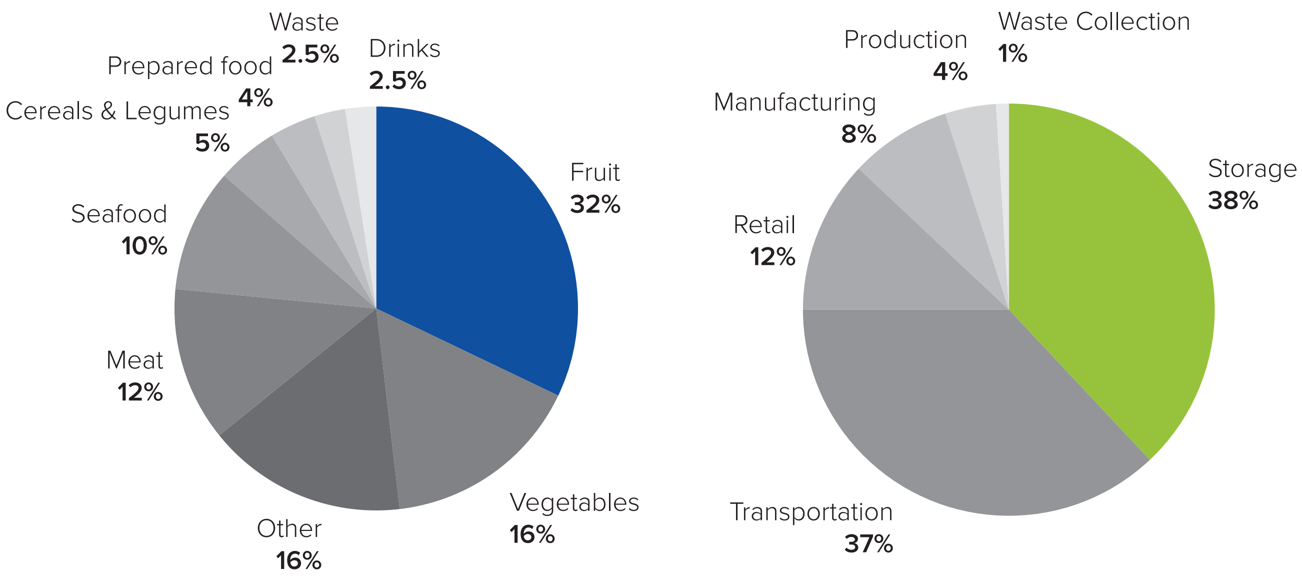


Figure 1. Market data exploring uses of IoT technology throughout the agri-food supply chain.

Survey results[8] indicate that almost three quarters of agri-food businesses consider reducing food waste as a significant objective, with a majority (69%) recognising the potential of IoT technologies to achieve this goal. Businesses believe that IoT adoption will reduce operational costs in the long run (68%) and attract more customers (66%), thus helping them remain competitive in the industry. The data suggests that there is a market trend for IoT sensor adoption. In fact, the perceptions of almost two-thirds of surveyed agri-food businesses is that competitors are already utilising IoT technology, which creates a sense of urgency for businesses to adopt it as well. Demand for sustainable and waste-reducing solutions in the agri-food sector is also coming from suppliers, with 60% of businesses believing that their vendors have expectations for them to use IoT technology, adding external pressure for adoption. These findings highlight the growing recognition of IoT's effectiveness in addressing food waste and the need for businesses to integrate IoT solutions to improve their operations and meet the demands of the evolving industry. Overall, the survey results demonstrate a strong motivation for agri-food businesses to explore and implement IoT technologies in their efforts to reduce food waste and enhance competitiveness.

IoT technology adoption motivation and market trends for agri-food businesses

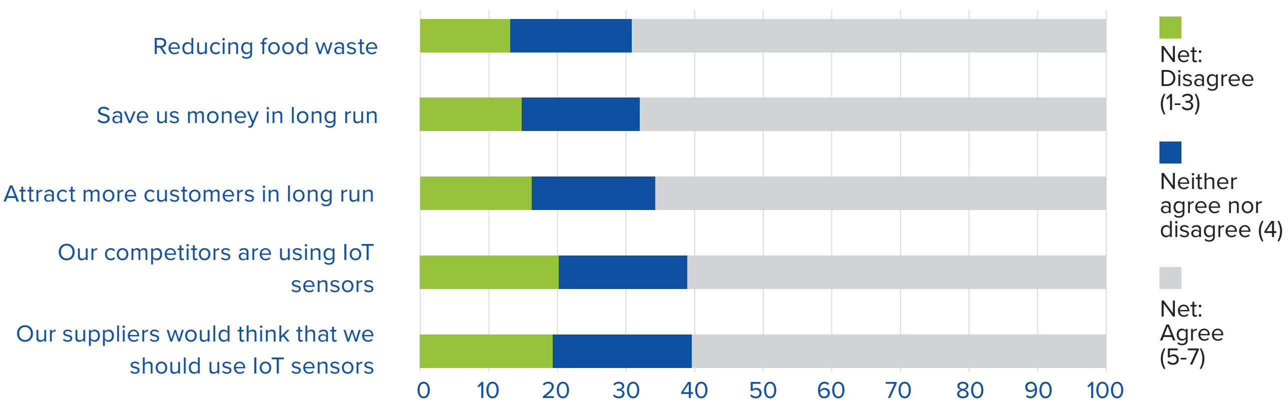


Figure 2. Survey data exploring IoT technology adoption motivation and market trends.

[7] da Costa TP, Gillespie J, Cama-Moncunill X, Ward S, Condell J, Ramanathan R, Murphy F. A Systematic Review of Real-Time Monitoring Technologies and Its Potential Application to Reduce Food Loss and Waste: Key Elements of Food Supply Chains and IoT Technologies. Sustainability. 2023; 15(1):614. https://doi.org/10.3390/su15010614.

[8] 315 agri-food businesses participated in the survey, and while efforts were made to ensure a representative sample, the results may not be fully reflective of the entire agri-food industry. The survey's scope was limited to businesses within the UK and may not account for international variations.

2.0 Market Solutions

In recent years, market solutions leveraging cutting-edge technologies have emerged as powerful tools to address the persistent challenge of food waste within the agri-food industry. Among these solutions, the integration of IoT sensors has garnered significant attention and adoption.

By connecting IoT sensors to the cloud and enabling remote monitoring via user-friendly interfaces such as web-based dashboards or smartphone-based applications, IoT technology offers unprecedented visibility and control throughout the entire food supply chain. This enhanced visibility, traceability, and decision-making capabilities hold great promise in reducing food waste within various stages of food supply chains, from agricultural, produce, distribution and retail.

IoT technologies

IoT technologies have the potential to produce timely warning signals to notify food owners of any changes within the surroundings of their product to help with decision making; whilst IoT enabled devices are capable of working in partnership with a variety of communication networks, storage facilities, algorithms, and visualisations to assist food owners in understanding their food waste.

By combining automated detection algorithms with sensor data and meaningful visualisations, food owners can be notified by the system when it has identified reductions in food quality. This is vital during the early stages as the devices can assist food owners in redirecting food to nearby demand points for sale, before it becomes waste. For example, if there is a malfunction in a temperature-controlled system, a warning could alert the food owner or relevant personnel.

This prompt notification enables them to swiftly take corrective actions, such as adjusting the system, initiating repairs, or transferring perishable goods to alternative storage facilities. By addressing the issue promptly, the risk of food spoilage and waste is mitigated. Alternatively, data collected from different sensors can be integrated and analysed, allowing for a comprehensive understanding of the entire supply chain.

This holistic view enables stakeholders to identify areas of improvement, streamline processes, and optimise resource allocation. IoT devices also have the potential of being combined with externally available data, such as local weather, resulting in Big Data and meaningful insights using modern data analytics techniques.

IoT sensors

Various types of IoT sensors have been deployed for the monitoring of food products to ensure their safety and freshness, including temperature sensors, humidity sensors, pH sensors, gas sensors, optical sensors, and imaging technology.

Temperature sensors are essential for monitoring temperature-sensitive foods like raw meat and dairy products. They help ensure that food is stored and transported within the required temperature range to prevent spoilage or bacterial growth. Challenges in temperature monitoring include device maintenance, equipment malfunctions, and data entry errors.

Humidity sensors measure the moisture content of food, particularly in applications where excessive moisture can lead to microbial growth or degradation. They are used in grain storage to prevent mould and insect infestation, as well as in meat processing to maintain optimal moisture levels during production.

pH sensors play a vital role in monitoring the acidity or alkalinity of food products. They provide valuable information about the quality, freshness, and safety of perishable items. pH sensors are used to assess ripeness, determine storage conditions, control fermentation processes, and detect spoilage and microbial activity.

Gas sensors detect volatile organic compounds emitted by microorganisms. They provide fast assessments of food quality and are small and relatively inexpensive. However, limitations include poor selectivity, sensitivity, and reproducibility.

Optical sensors use light-based technologies to assess and monitor various aspects of food quality. They can measure colour changes, composition, and overall quality. Colour sensors, for example, are used to measure and monitor colour changes in meat and fruits, indicating freshness and ripeness.

Imaging technology, such as computer vision systems, near-infrared spectroscopy (NIRS), Raman spectroscopy, hyperspectral imaging (HSI), and ultrasonic imaging are also used to measure food quality attributes. These technologies provide non-destructive and cost-efficient methods for assessing size, appearance, colour, composition, and defects in food products.

Intelligent packaging is another category of monitoring devices used in food quality. It can monitor quality characteristics, environmental conditions like temperature and humidity, and store data through RFID tagging. Intelligent packaging offers advantages across the supply chain, but it may increase production and development costs and pose challenges in recycling.

Whilst market solutions for reducing food waste through IoT technologies show promise, some limitations exist. A critical observation from the literature is that only approximately 50% of the solutions offer real-time monitoring interfaces, enabling the visualisation of live data on environmental parameters. This hampers the ability to track and respond promptly to changing conditions. Moreover, only around 33% of the studies mention the presence of early warning systems, providing a mechanism to alert personnel when environmental parameters breach safety thresholds.

Another significant omission from the analysed studies is the lack of mention of trip detection systems. Trip detection is a critical component for generating relevant alerts as it automatically identifies when food is in transit, ensuring alerts are triggered only during transportation. Additionally, trip detection has the potential to conserve sensor battery power by minimising monitoring activities when food products are not in transit, leading to extended battery lifespan and reduced environmental impact.

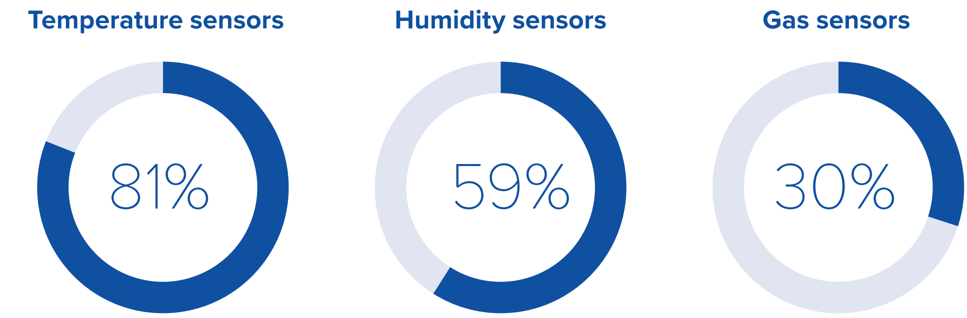


Figure 3. Most common sensing technologies currently in the market.

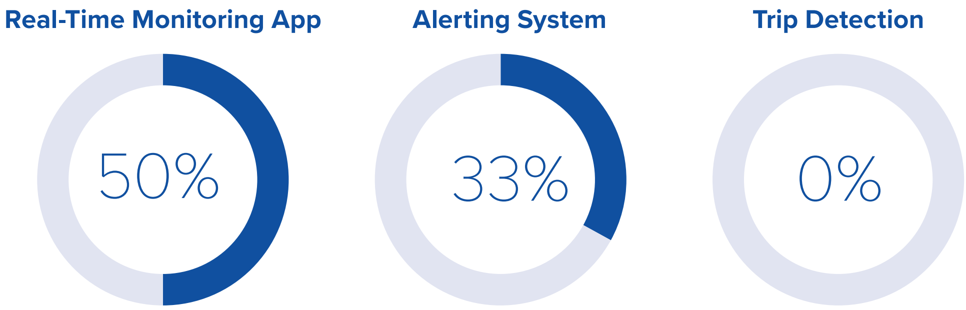


Figure 4. Overview of adoption rate of IoT-based solutions.

Furthermore, there is a notable gap in the provision of integrated analytics engines, which can offer potent real-time insights including seasonality analysis, automated anomaly scoring, and motif detection, effectively uncovering trends contributing to food waste reduction. Another observation is that Raman spectroscopy systems at present are lab based, and while offering non-destructive and accurate insights into food quality, expert knowledge is required to interpret the results. On the other hand, while some smaller handheld spectroscopy solutions do exist with easy-to-understand interfaces, their pre-trained quality models are tailored for very specific use cases, for example meat quality measurement. Addressing these limitations is vital in advancing the effectiveness and efficiency of IoT-based solutions for combating food waste in the agri-food industry.

2.1 The REAMIT project

In our pursuit to address food waste challenges through IoT solutions, we have established a strategic consortium consisting of industry-leading software and IoT hardware companies, academic research institutions, and an agri-food business. These partnerships bring together a wealth of expertise and resources to drive innovation in the agri-food industry. Academic research institutions play a vital role in our consortium.

Research institutions

The University of Bedfordshire and University of Essex offer unparalleled knowledge of the agri-food supply chain, University of Nantes contributes Raman spectroscopy expertise, University College Dublin (UCD) provides life cycle assessment (LCA) expertise, Ulster University offers data analytics capabilities, Nottingham Trent University specialises in communication, and Munster Technological University brings additional data analytics expertise. These partnerships allow us to leverage cutting-edge research, advanced data analytics techniques, and specialised knowledge in specific areas to enhance our IoT solutions.

We have also established strategic partnerships with industry-leading software and IoT hardware companies. Whysor, known for their expertise in developing software solutions for the agribusiness industry, SenX, a leading provider of time series database and analytics platforms, and Levstone, an industry-leading software company specialising in android app development are valuable contributors to our consortium. Additionally, we have partnered with Tektelic, a renowned provider of high-performance IoT hardware solutions, and Digital Matter, a leading provider of IoT asset tracking and management solutions.

Collaborations

These collaborations allow us to combine our IoT technology expertise with their specialised knowledge in developing innovative solutions for the agri-food industry. Through these partnerships, we gain access to cutting-edge technology, industry expertise, knowledge sharing opportunities, and the ability to engage in joint product development and customisation. Within our strategic consortium, we also collaborate with WD Meats, an agri-food business. To further enhance agri-food company involvement, we're also honoured to include Images et Réseaux and Valorial, prestigious French clusters specialised in digital technologies and agri-food collaborations, as valuable members of the REAMIT consortium. These collaborations provide practical industry insights, access to real-world agri-food environments, and the opportunity for testing and validation of our IoT solutions within the food processing and supply chain sector.

By bringing together these strategic partners, including software and IoT hardware companies, academic research institutions, and an agri-food business, we combine expertise in IoT technology, software development, data analytics, specialised research, and practical industry experience.

Through this collaborative ecosystem, we are well-positioned to deliver comprehensive and effective IoT solutions for food waste reduction, tap into cutting-edge technology, leverage industry expertise, and an extended market reach, empowering us to make a substantial impact in the agri-food industry and contribute to a more sustainable and efficient food supply chain.

REAMIT solutions

The REAMIT project offers a range of solutions for agri-food businesses, employing a variety of IoT sensors and integrated big data analytics. These solutions include:

1. **Intelligent alerting based on trip detection for perishable food transportation clients**
2. **Intelligent alerting with anomaly detection for perishable food storage clients**
3. **Real-time Raman spectra analysis for perishable food transportation clients**
4. **Handheld spectrometer for consumer level quality monitoring**

Intelligent alerting based on trip detection for perishable food transportation clients

Introducing an innovative solution for transportation clients, we present our intelligent alerting system based on trip detection for perishable food transportation. This monitoring solution uses cutting-edge cellular communication technology, ensuring seamless real-time data upload during transport. At the core of our system is the Digital Matter Eagle datalogger, a robust cellular IoT device with an IP67 rating. This device can be powered either by 4 x C cell batteries or connected to a permanent power source (6-16 V DC), providing portability and flexibility for installation across various applications.

The Eagle datalogger offers multiple interfaces, including I2C, SDI-12, and RS-485, along with various analogue and digital inputs, enabling seamless connectivity with a wide range of sensors. These sensors include temperature, humidity, pressure, door contacts, and more, allowing customisation based on the specific needs of our clients. The device also features an onboard GPS module and accelerometer, facilitating geofencing, movement detection, and tracking functionalities. It operates on the IoT low power LTE-M (CAT-M1) network and provides third-party cloud integration for efficient data retrieval, visualisation, and analytics.

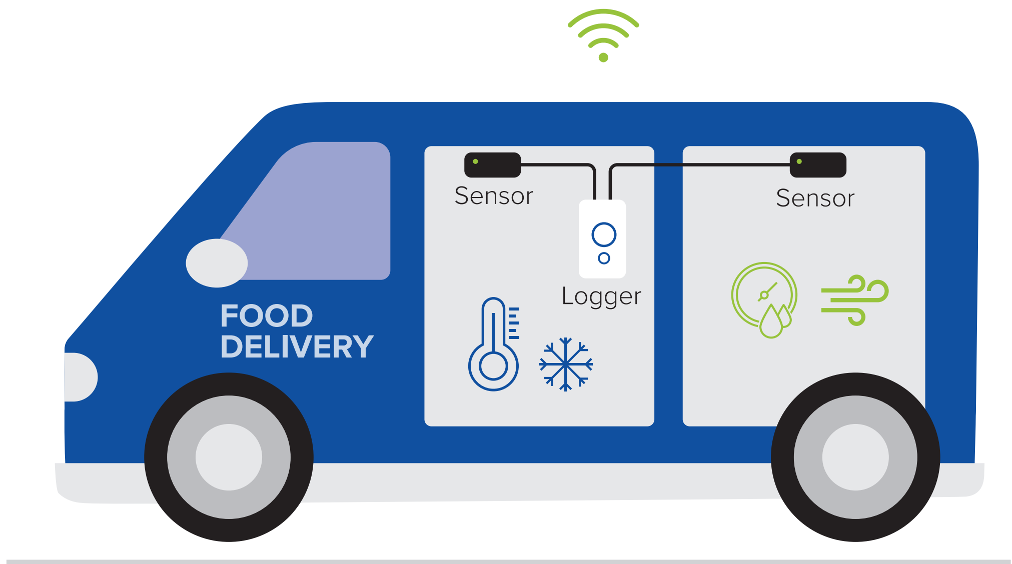


Figure 5. Illustration of installation location within delivery van.

The REAMIT team has crafted a tailor-made intelligent alerting system for use with the Eagle datalogger, ensuring optimal customer experience. Leveraging data reported by the built-in accelerometer, which detects movement and alters the device state from sleep to awake, and GPS logging for determining active movement, we have configured warning alerts (like detected temperature abuse) that trigger only when the perishable food is in transport. This intelligent design prevents false alerts when the vehicle is stationary or not in use, ensuring accuracy and reliability.

The alerts are conveniently delivered via SMS and email, while our responsive web dashboard offers real-time monitoring and customisation of sensor data visualisation. With our solution, transportation clients can rest assured that they will receive timely alerts and have full control over monitoring and managing the quality and safety of their perishable food products during transit.

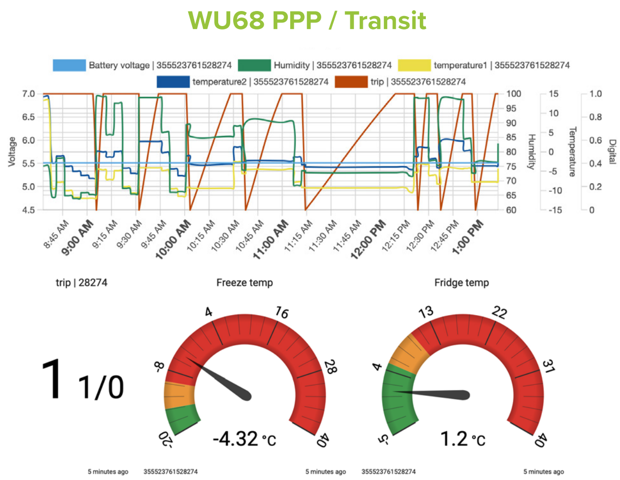


Figure 6. Developed dashboard shows environmental parameters in real-time.

We understand that before investing in any technology, cost considerations play a crucial role. The costs can be categorised into one-time hardware and software expenses and recurring subscription fees. Let's take a closer look, starting with one time hardware costs in Table 1. This is the cost per sensor system for your business.

Cellular IoT Solutions

Digital Matter Eagle Logger	€210
Sensor (e.g., temperature / humidity probe)	€45
SIM card (500mb; ~10 years use)	€10

Table 1. One-time hardware costs.

Additionally, there is a one-time cost entailed in providing the dashboard. To provide a customised and branded experience, an initial white label dashboard with a unique URL (like reamit.whysor.com) is offered at a one-time cost of €1500. The recurring subscription costs are essential for the continued utilisation of the IoT solutions and consist of the following monthly fees in Table 2:

Recurring Subscription Costs

Monthly fee domain of your choice	€150
Monthly fee per device	€1
Monthly fee per weather online device	€1
Monthly fee per data analytics device (based on type)	from €1
Monthly fee per user	€5
Monthly fee per GB storage	€10

Table 2. Monthly costs associated with using the Whysor dashboard platform.

To determine the overall cost per customer, the recurring subscription costs, one-time hardware costs, and the one-time white label dashboard cost should be considered. These costs can be calculated based on the specific requirements of each customer. As an example, one time hardware costs for an agri-food transport business employing 10 intelligent alerting sensor systems with a temperature and humidity probe would be approximately €2550, while one time software costs would cost €1500. Afterwards, a monthly subscription cost of €170 (assuming 2 users, 10 devices, and the monthly domain subscription) would provide the business with access to dashboard and alerting facilities.

Total cost:

€4,050

Monthly cost:

€170

x10

10 sensors

Analytics engine with anomaly detection and intelligent alerting for perishable food storage clients

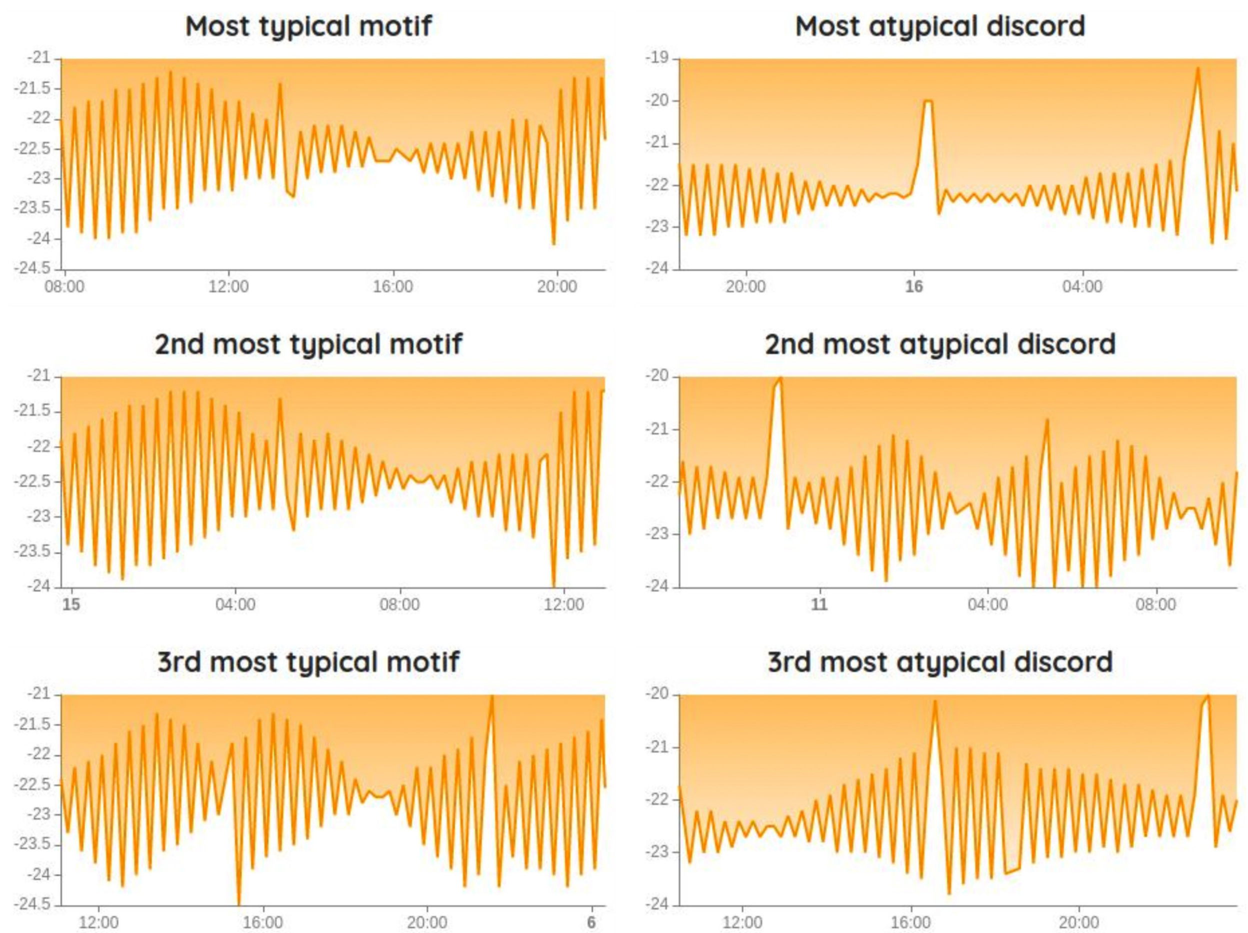
Designed exclusively for perishable food storage facilities, we offer LoRaWAN IoT sensors solutions, and an advanced anomaly detection analytics engine developed by our expert team to help you reduce your food waste. The REAMIT solution enables real-time monitoring of storage conditions and provides alerts in case of any deviations or abnormalities that could affect the quality or safety of stored food.

The analytics engine includes statistical analysis tools to provide a comprehensive description of your data, including the mean, standard deviation, minimum, maximum, median time between each record, potential seasonal cycles, and their associated weights.

Using the cutting-edge matrix profile algorithm allows us to unveil recurring patterns and detect any atypical occurrences for sensors placed in refrigerators and cold room freezers. Through a thorough examination of these computed features, we can help you identify motifs that typically indicate defrost operations in refrigerators and cold room freezers.

The consistent occurrence patterns of these motifs enable us to predict the timing of defrost operations and proactively manage temperature fluctuations, ensuring optimal conditions are maintained and false threshold abuse alerts are not sent.

Figure 7. Identification of recurring patterns by utilising the matrix profile algorithm.



By capturing data from temperature sensors in selected warehouses over specific time periods, we provide you with precise anomaly scores, driven by logical ranges informed by your requirements. The clear visualisations from our forecasting model facilitate anomaly detection, individual sensor forecasting, and quality assessment. For example, we identified seasonal forecast patterns in stationary temperature sensors within cold storage facilities. Additionally, our anomaly detection system has been successfully trialled on refrigerated trucks, highlighting the efficiency of freezing or cooling capabilities during transportation. Positive scores indicate areas for optimisation, while scores close to 0 signify optimal chilling conditions. We offer opportunities to incorporate human feedback, allowing you to refine the AI model based on individual sensor anomaly score neuron models. This iterative process ensures continuous enhancements to your analytics and optimisation efforts. Our solution also provides comprehensive monthly overview reports, presenting anomaly scores for all trips within each month. These reports offer valuable insights for continuous improvement and informed decision-making.

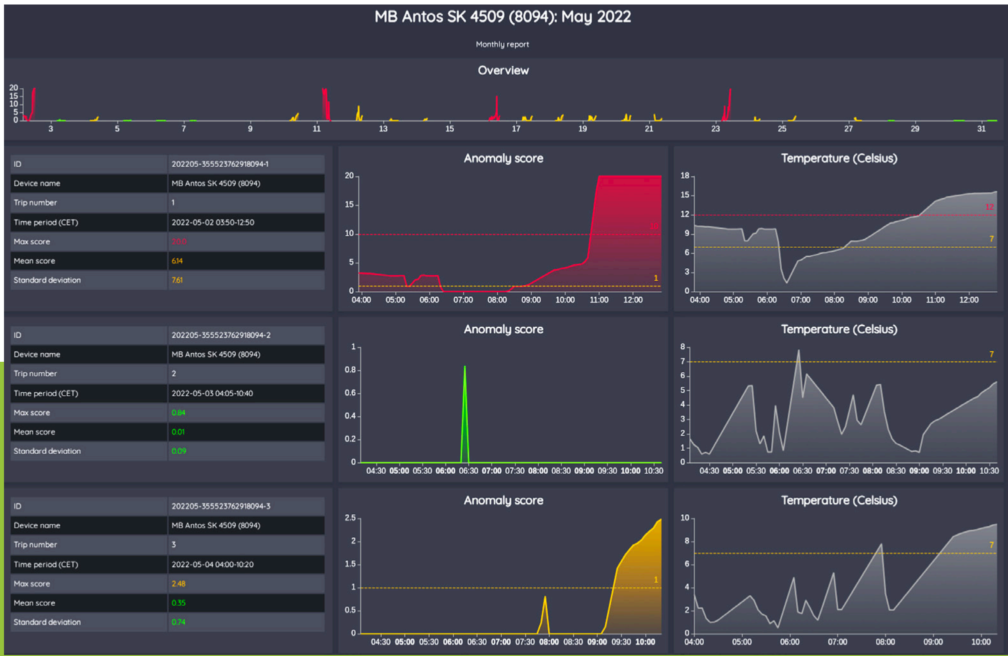


Figure 8. Monthly overview report presenting anomaly scores for all trips per month.

Overall, the solution aims to provide real-time monitoring, anomaly detection, and timely notifications to ensure the quality and safety of stored food in perishable food storage facilities. As per the previous solution offered by REAMIT, one-time hardware and recurring software costs occur when implementing and deploying such technologies. Below in Table 3 is a breakdown of the one-time hardware costs that were showcased within this section.

LoRaWAN Solutions	
LoRaWAN Gateway (e.g., Tektelic)	€460
Sensor, individual unit (e.g., Elsys ELT-2)	€130

Table 3. One-time hardware costs.

To determine the overall cost per customer, the recurring subscription costs (from Table 2), one-time hardware costs, and the one-time white label dashboard cost should be considered.

These costs can be calculated based on the specific requirements of each customer. As an example, one time hardware costs for an agri-food transport business employing 10 LoRaWAN sensors for storage monitoring would be approximately €1760, while one time software costs to develop the dashboard would cost €1500. Afterwards, a monthly subscription cost of €171 (assuming 2 users, 10 sensors, 1 gateway, and the monthly domain subscription) would provide the business with access to dashboard and alerting facilities.

Total cost:

€3,260

Monthly cost:

€171

10 sensors

Real-time Raman spectra analysis for perishable food transportation clients

The REAMIT team has developed an advanced solution for monitoring the quality and freshness of perishable chicken samples during transportation in real time. This innovative system uses Raman spectroscopy to capture the unique molecular 'fingerprint' of the chicken's composition, and automatically applies complex analysis techniques to infer current quality status. By employing the custom designed REAMIT IoT hardware and real-time Raman spectra classification module, clients can remotely scan the chicken samples and make well-informed decisions about their condition throughout the transportation process.

The system incorporates various cutting-edge technologies, including a Raman spectrometer (QE Pro, Ocean Optics), a fiber-optic probe (InPhotonics, RPB78), a 785 nm laser (Oxxius, LBX-785-HPE) as the laser source, a laser controller (Oxxius, LaserBoxx series), a 3-axis motorized platform (Standa, 8SMC4-USB-B8-B9), a lockable box (QUIPO Locker), and a Raspberry Pi Kit for IoT compliance.

A key element of the system is the 4-class chicken freshness model, which is deployed on a local instance of the REAMIT Warp 10 analytics platform. This model is integrated into a customised Raspberry Pi IoT module equipped with an LTE-M shield to ensure seamless remote connectivity during chicken transportation. The combination of the Warp 10 platform and the Raspberry Pi module enables real-time analysis and categorisation of chicken freshness into four distinct classes: "extra-fresh," "fresh," "good," and "expired." This classification system allows for efficient monitoring and management of poultry inventory.

This advanced solution empowers clients in the perishable food transportation industry to maintain the highest quality of their chicken products, reduce waste, and ensure customer satisfaction.

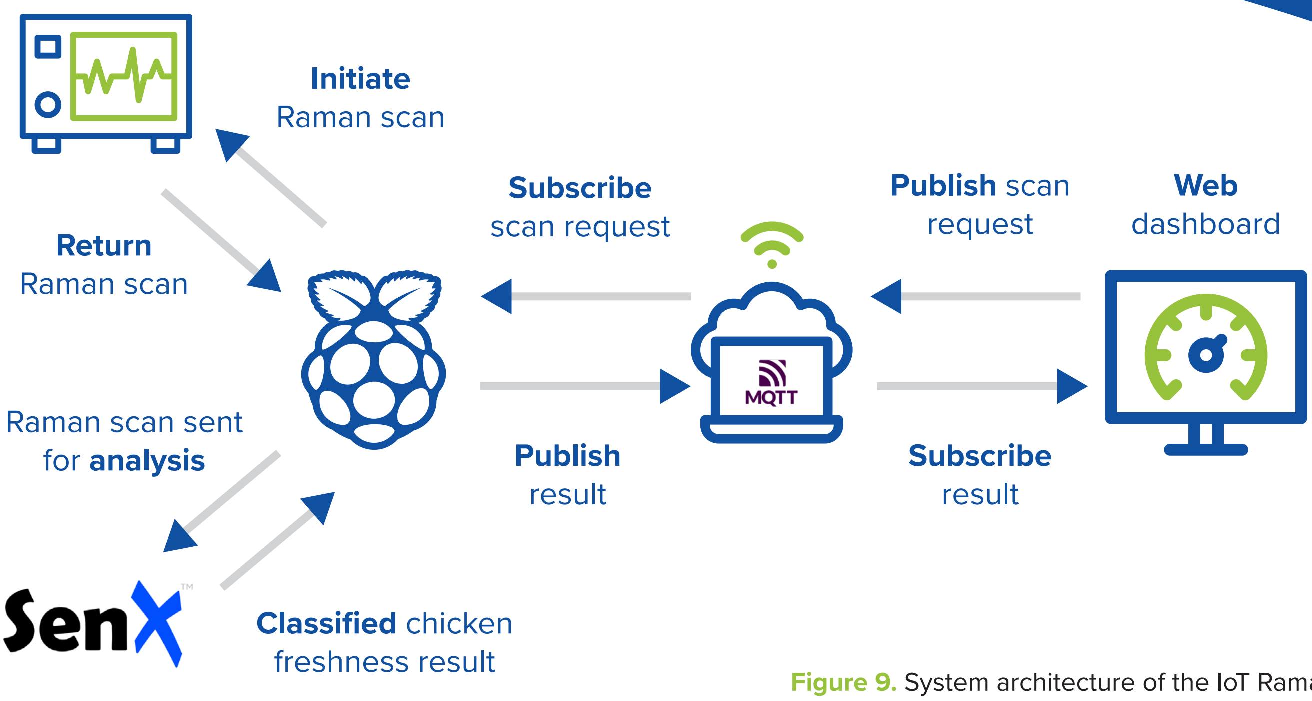


Figure 9. System architecture of the IoT Raman system for chicken classification.

We understand the value of simplicity and efficiency. Our user-friendly interface ensures real-time scanning and analysis with ease. Leveraging MQTT – a lightweight machine-to-machine network protocol – communication between remote devices with limited resources becomes seamless.

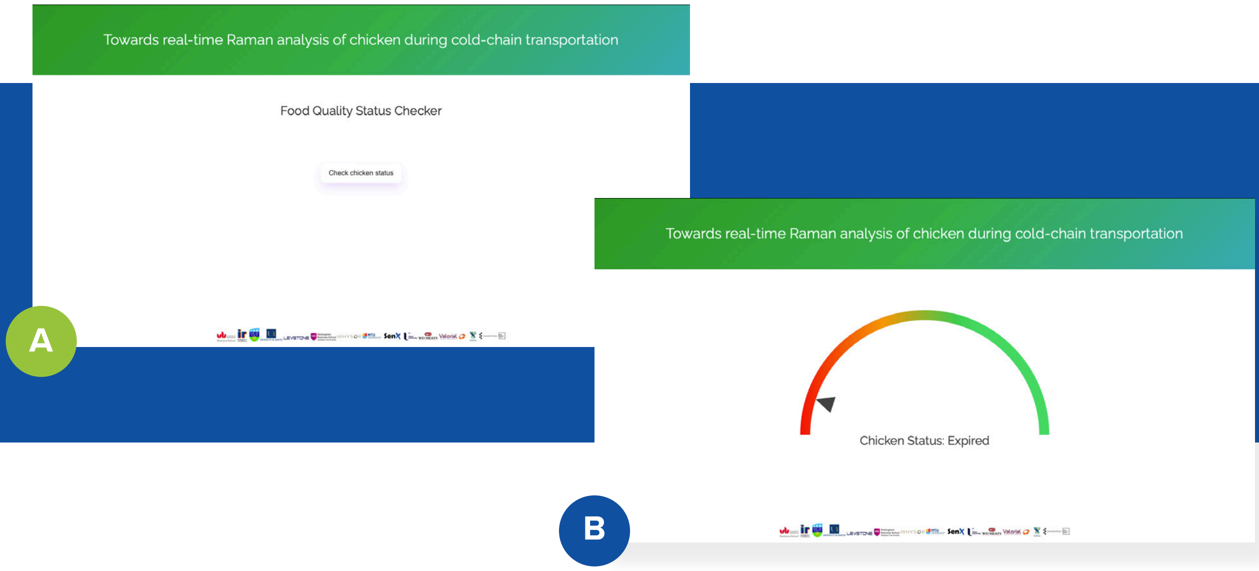


Figure 10. (a) Homepage of chicken classification interface. (b) A freshness gauge visualising the result of a scan that has been remotely triggered and classified using the Warp10 platform, with text below detailing the classification.

While the benefits are immense, we believe in transparency. One-time hardware costs for implementing our IoT Raman System are as follows:

IoT Raman Spectroscopy for transport

Laser	€8000
Spectrometer	€12,000
Enclosed box	€200
Motorised Stage	€7000
Raspberry Pi IoT Module (Pi + GSM Shield)	€175
500mb SIM card	€10

Table 4. One-time hardware costs for the IoT Raman System.

The total cost of the Real-time spectra analysis system appropriate for use during transport would therefore incur a one-time cost of €27,385. In the configuration presented, there would be no subscription costs associated with this hardware.

One-time cost

€27,385

Handheld spectrometer for consumer level quality monitoring

FreshDetect, our cutting-edge handheld fluorescence spectrometer, is now available as a milk quality assessment tool for your business. Powered by sophisticated machine learning classification and regression models, FreshDetect focuses on the riboflavin peak extracted from the raw spectra it records, scientifically linked to pH degradation. With this groundbreaking technology, we go beyond traditional methods, providing you with unparalleled insights into milk freshness and its true expiry date.

freshdetect
food safety - fast and reliable

FreshDetect's robust machine learning models have been trained by research scientists using the riboflavin peak which has been correlated with pH degradation. Using classification modelling, this scientific approach ensures unparalleled accuracy (95%) in assessing milk freshness. Based on a defined pH cut-off, FreshDetect promptly informs you whether the milk is fresh or not, making quality assessment quick and decisive. FreshDetect's trained regression model goes a step further by providing an estimate of the milk's true expiry date. With this invaluable information, you can confidently plan and manage your milk inventory, optimising storage and distribution processes with precision.

Figure 11. FreshDetect BDF-100 handheld spectroscopy unit.

Gone are the days of complex procedures or objective "sniff test" measurements. With FreshDetect, all it takes is a single button press to kickstart the evaluation process. In just a matter of seconds, this handheld device delivers comprehensive, quantitative results, empowering you to make real-time decisions about milk quality. With FreshDetect, you can seize every opportunity to maximise freshness and minimise waste, ensuring your milk products are always at their best.

FreshDetect's user-friendly interface allows anyone in your team to effortlessly operate the device, eliminating the need for specialised training. Its portability ensures that you can carry this powerful tool with you wherever you go, making on-site assessments convenient and efficient. While the benefits of the FreshDetect system are immense, we believe in transparency. One-time hardware costs for implementing our portable milk quality assessment system are as follows:

FreshDetect Solution	
BDF-100 Handheld unit	€ 2500

Table 5. One-time hardware costs for the FreshDetect System.

Rapid

Intuitive

Easy

Non-invasive

Precise

Once the initial investment has been made into a FreshDetect unit, there are no further costs for the upkeep of the system. Therefore, a one-off payment of €2,500 will equip your business with a reliable tool for milk quality monitoring for life!

One-time cost

€2,500

The pH of milk and Riboflavin levels

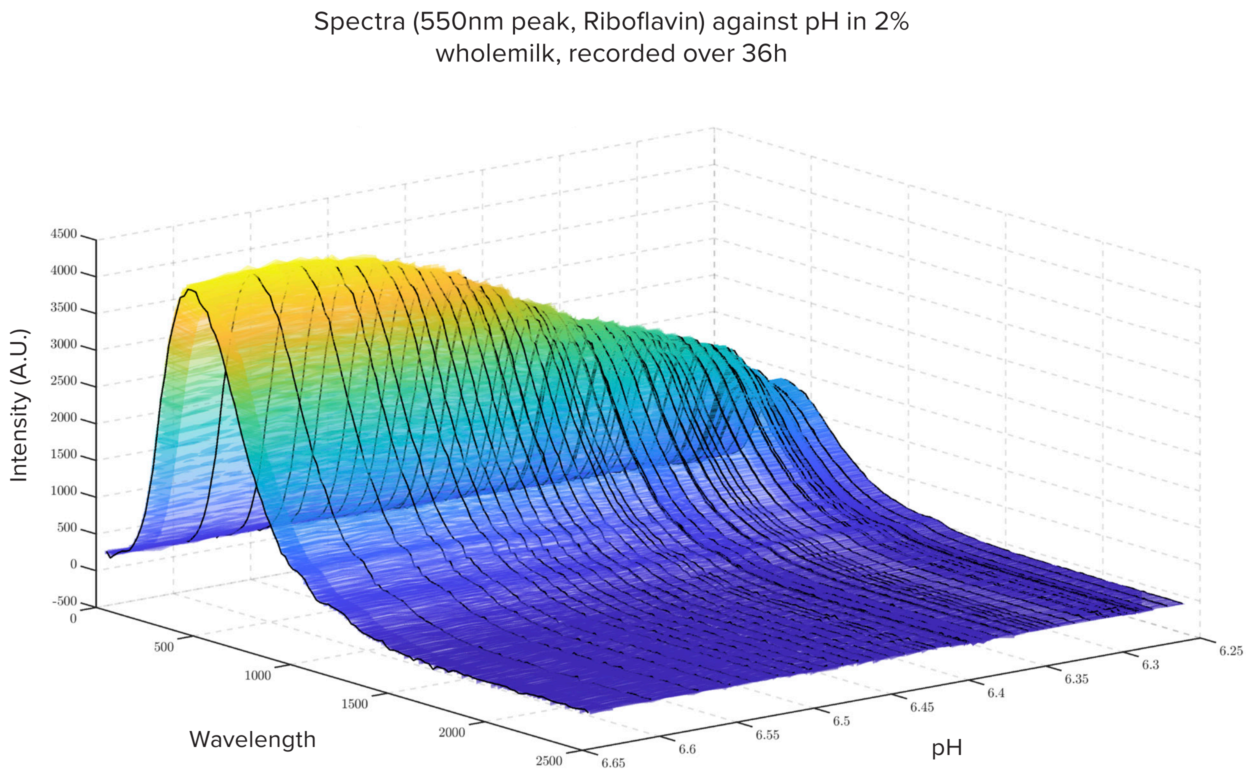


Figure 12. Results highlighting the pH of milk and Riboflavin levels.

2.2 Pilot Projects and Demonstrations

To demonstrate the reliability and effectiveness of our developed solutions, we conducted 10 pilot tests across different client segments. These pilot tests served as a vital validation of our technologies, showcasing their value in real-world scenarios.

Stage of the supply chain	Country	Food waste issue	IoT solution deployed	Applied analytics
Food processing in an Abattoir.	**UK**	Meat waste due to un-uniform temperature distribution in dry ageing chambers (fridges).	IoT temperature and humidity sensors located at multiple points to monitor uniform temperature distribution. Alerts via a smartphone and email.	Ensure uniform distribution of air in the chamber. Send warning alerts if needed.
Food processing in an Abattoir.	**IE**	Meat waste due to un-uniform temperature distribution in dry ageing chambers (fridges).	IoT temperature, humidity, and pressure sensors located at multiple points to monitor uniform temperature distribution. Alerts via a smartphone and email.	Ensure uniform distribution of air in the chamber. Send warning alerts if needed.
Food storage in a frozen food company[9].	**UK**	Food waste due to inadequate temperature in fridges.	IoT temperature sensors located in fridges to monitor temperature. Alerts via a smartphone and email.	Send alerts if temperature is not maintained within a pre-specified threshold.
Donor human milk transportation[10].	**UK**	Food waste due to inadequate temperature during transport.	IoT temperature sensors located in transport options to monitor temperature. Alerts via a smartphone and email.	Send alerts if temperature is not maintained within a pre-specified threshold.
Transport[11].	**UK**	Food waste due to temperature anomalies during transport.	IoT temperature sensors located in fridge and freezer of van to monitor temperature. Alerts via a smartphone and email.	Send alerts if temperature is not maintained within a pre-specified threshold.

[9]Ramanathan U, Ramanathan R, Adefisan A, da Costa TP, Cama-Moncunill X, Samriya G. Adapting Digital Technologies to Reduce Food Waste and Improve Operational Efficiency of a Frozen Food Company—The Case of Yumchop Foods in the UK. Sustainability. 2022; 14(24):16614. https://doi.org/10.3390/su142416614.
[10]Ramanathan U, Pelc K, da Costa TP, Ramanathan R, Shenker N. A Case Study of Human Milk Banking with Focus on the Role of IoT Sensor Technology. Sustainability. 2023; 15(1):243. https://doi.org/10.3390/su15010243.
[11]Gillespie J, da Costa TP, Cama-Moncunill X, Cadden T, Condell J, Cowderoy T, Ramsey E, Murphy F, Kull M, Gallagher R, et al. Real-Time Anomaly Detection in Cold Chain Transportation Using IoT Technology. Sustainability. 2023; 15(3):2255. https://doi.org/10.3390/su15032255.

Table 6. REAMIT pilot demonstrations.

Stage of the supply chain	Country	Food waste issue	IoT solution deployed	Applied analytics
Storage.	**UK**	Food waste due to temperature anomalies / breakdowns at the storage stage of the supply chain.	IoT temperature sensors located in portable cold stores to monitor temperature. Alerts via a smartphone and email.	Send alerts if temperature is not maintained within a pre-specified threshold.
Storage and transport in multiple stages of the supply chain.	**LU**	Food waste due to temperature abuse at the transport and storage stage of the supply chain.	IoT temperature and humidity sensors located at each stage of the supply chain (farm, transport, storage).	ML model for early warning of product degradation given temperature.
Transport.	**NL**	Food waste due to inadequate volume of icepacks used during transport.	IoT temperature sensors located in the grocery transport crates to monitor temperature.	ML model to predict quantity of ice required to maintain temperature given weather and journey length.
Transportation – Chicken quality[12].	**FR**	Chicken quality deterioration during transportation.	IoT-compliant LTE-M Raman Spectroscopy solution deployed in transportation van.	4-class freshness model deployed on Warp10 platform for easy interpretation of quality status by driver. Dashboard for results visualisation.
Consumer – milk quality detection.	**UK**	Food waste (milk) due to removal of best-before dates by UK supermarkets.	Handheld spectrometer trained with milk data to detect milk quality based on recorded spectra.	Regression model to predict milk freshness based on obtained spectra.

[12]Dib OH, Assaf A, Pean A, Durand M-J, Jouanneau S, Ramanathan R, Thouand G. Raman Spectroscopy Application in Food Waste Analysis: A Step towards a Portable Food Quality-Warning System. Sustainability. 2023; 15(1):188. https://doi.org/10.3390/su15010188.

3.0 Business Risk

As with many projects there will always be risks, pertaining to realms such as the market, technology adoption and implementation, regulatory and compliance, and financial and economic to name a few.

Within the market, the agri-tech industry is highly competitive, with numerous established companies and new entrants offering similar IoT solutions to reduce food waste. Increased competition may lead to pricing pressures, reduced market share, or difficulties in acquiring and retaining customers. However, widespread adoption of IoT devices in the agri-food industry to reduce food waste is still in its early stages. The market may not fully accept or embrace our solutions as expected, resulting in slower-than-anticipated revenue growth and market penetration.

In terms of technological and implementation risks, our IoT devices rely on complex technology systems, including sensors, connectivity infrastructure, and data analytics. Technical malfunctions or system failures could disrupt operations, compromise data security, or lead to reputational damage. However, by integrating our IoT devices with existing agri-food systems and infrastructure (Whysor and SenX platforms), this risk should be largely mitigated.

Incompatibilities, interoperability issues, or resistance to change from stakeholders could result in delays, additional costs, or hinder effective implementation. Nonetheless, as demand for IoT solutions grow, we must ensure that our technology infrastructure can scale effectively. Inability to handle increased data volume, processing requirements, or expansion to new markets may impact service quality and customer satisfaction.

As with any project, all operations are subject to various laws, regulations, and industry standards related to data privacy, food safety, and environmental protection. Changes in regulations or non-compliance could result in financial penalties, operational disruptions, or reputational harm. However, when collecting and processing data from IoT devices, there poses inherent risks related to data privacy and security. Breaches, unauthorised access, or data theft could damage our reputation, lead to legal liabilities, and erode customer trust.

And finally, there will always be financial and economic risks. In terms of expanding the project and further developing our IoT solutions, which will potentially require additional capital investments. Failure to secure adequate funding or access to capital at favourable terms may limit growth opportunities or result in financial strain. In addition, the agri-food industry is influenced by macroeconomic factors such as fluctuating commodity prices, inflation, and currency exchange rates.

Economic downturns or disruptions may reduce customer spending, affect demand for our solution, or impact our financial performance. In any such scenarios the benefits of adopting and implementing IoT based solutions to reduce food loss and waste in the agri-Food supply chain must outweigh the business risks, which can normally be countered through smart business planning.

4.0 Cost/Benefit perspective

The cost/benefit perspective of implementing these IoT solutions is crucial for potential buyers, with the initial investment in hardware and software costs, capability development, and environmental costs needing consideration by agri-businesses.

The expenses related to IT infrastructure and the knowledge required to operate these systems are vital cost considerations. For example, market research has revealed that approximately 43% of businesses without IoT technologies expressed a lack of technical knowledge, emphasising the need for educational initiatives and training programs. Furthermore, 56% report inadequate systems to support IoT implementation. Modernising IT infrastructure becomes essential to unlock the potential of IoT solutions and ensure seamless integration with existing systems, which naturally comes at additional cost to your business. Costs associated with capability development initiatives that encompass training, change management, and cybersecurity measures also need to be considered in order to create an enabling environment for the successful implementation and integration of IoT technology.

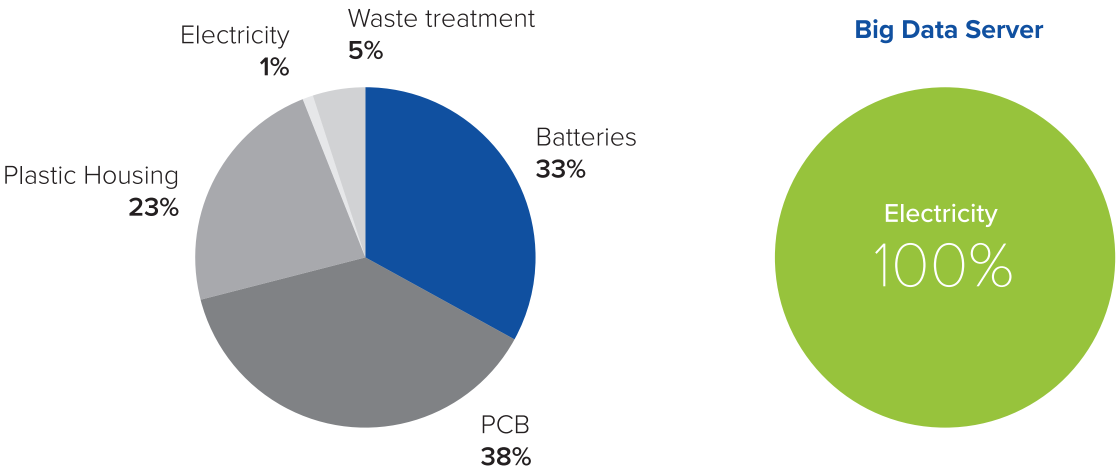


Figure 13. Environmental impact distribution of sensors and Big Data server.

General Environmental Costs of IoT solutions

In today's eco-conscious world, both businesses and individuals are increasingly mindful of their environmental impact. This has led to a growing emphasis on considering environmental costs in decision-making. While technology provides many advantages in efficiency and automation, it's essential to acknowledge that certain solutions may demand significant energy resources to operate optimally. Equally important is the issue of waste generated by these technologies. Hence, careful consideration must be given to how IoT solutions will be recycled or disposed of at the end of their lifecycle. By incorporating sustainable design and responsible disposal practices, we can greatly reduce the environmental footprint of implementing IoT solutions.

Carbon footprint

Sensors

28 kg CO_2 eq

Big Data servers

1.5 kg CO_2 eq

Figure 14. Carbon footprint of sensors and Big Data server.

Key Contributors

Discovering the key contributors to the carbon footprint of sensors and Big Data Servers is vital for crafting targeted strategies to go green. Our life cycle assessment's hotspot analysis has revealed the main culprits impacting sensors' environmental footprint. The printed circuit board (PCB) takes the lead at 38%, closely followed by batteries at 33%, and the plastic housing at 23%. In total, each sensor's carbon footprint amounts to 28 kg CO2 equivalent[13].

As for Big Data Servers, we've found a carbon footprint of 1.5 kg CO2 equivalent per month, per pilot. This impact exclusively stems from electricity consumption for data storage. (Please note that the study does not encompass the server's infrastructure.)

By optimising the production and disposal of critical components like PCBs, batteries, and plastic housing in sensors, and adopting energy-efficient data storage practices for servers, we can pave the way towards a more sustainable and eco-friendly future.

Benefit Perspective

We understand that potential buyers seek a cost/benefit perspective, and the REAMIT solutions have been thoroughly assessed using the life cycle assessment methodology, ensuring their environmental friendliness. While the upfront costs are important to consider, the long-term benefits such as reduced food waste, improved operational efficiency, data-driven decision-making, enhanced supply chain management, and increased customer satisfaction far outweigh the initial investment.

In REAMIT, we've observed that the average impact of pilot companies is mainly influenced by meat, followed by vegetables, electricity, and packaging, with transport and water having a negligible contribution. Understanding these resource influences empowers pilot companies to pinpoint areas for improvement and adopt targeted strategies to reduce their environmental footprint. The data highlights the significance of embracing sustainable practices, making informed sourcing and production choices, and taking the lead with eco-friendly initiatives, just like the ones proposed by REAMIT.

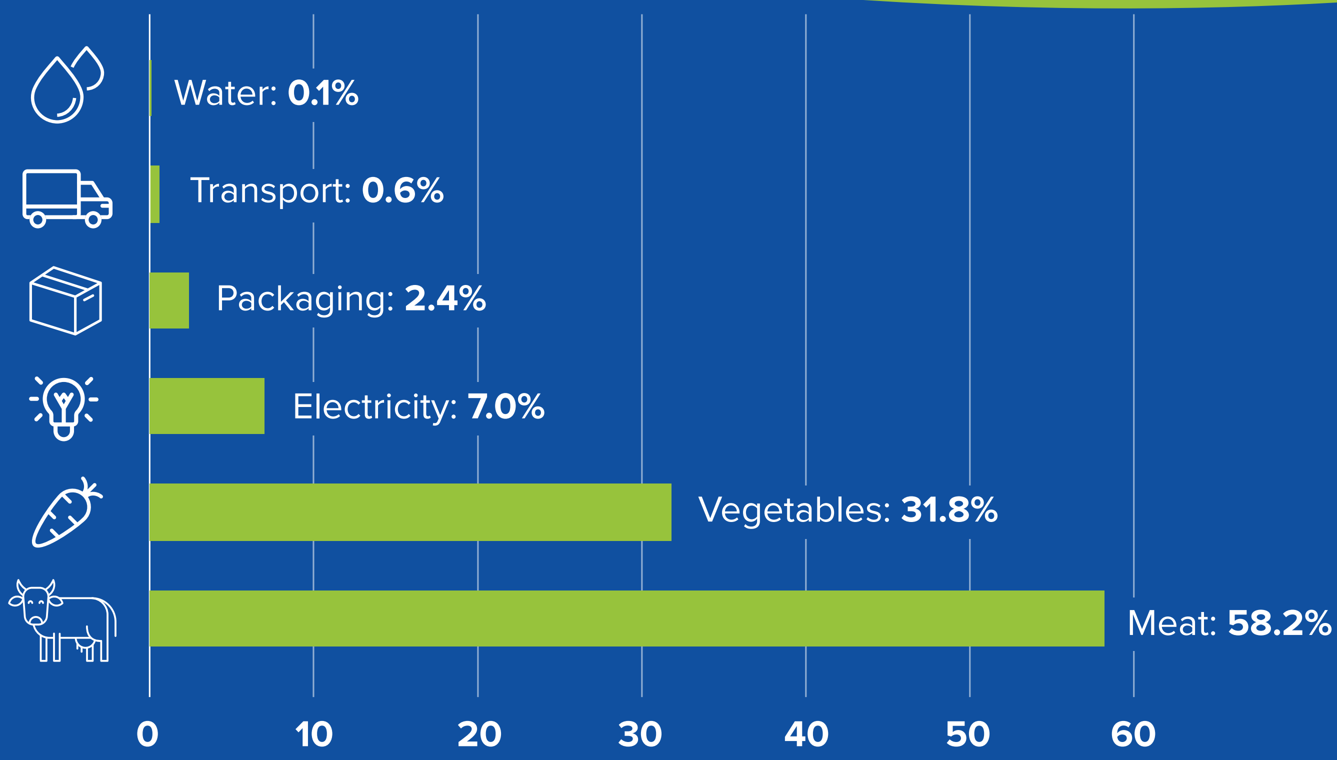


Figure 15. Impact distribution of a pilot company before REAMIT technologies implementation.

[13]da Costa TP, Gillespie J, Pelc K, Shenker N, Weaver G, Ramanathan R, Murphy F. An Organisational-Life Cycle Assessment Approach for Internet of Things Technologies Implementation in a Human Milk Bank. Sustainability. 2023; 15(2):1137. https://doi.org/10.3390/su15021137.

4.1 Life Cycle Assessment after REAMIT technologies

At REAMIT, we're proud to have achieved remarkable reductions in food waste and its environmental impacts throughout our system. This achievement holds profound implications for environmental sustainability and resource conservation. Our reduced wastage leads to remarkable environmental benefits, saving 12.7 kg of CO2 equivalent per kg of food production avoided, a crucial step in combating climate change. Based on this environmental benefit, our solution brings average savings of about 1.06 EUR[14] per kilogram of food production avoided - and that's before we consider the savings in raw materials to your business! Not only that, but it conserves approximately 412 litres of water per kg of food production avoided, addressing global water scarcity concerns. Plus, each kilogram of food avoided saves an average of 0.2 kWh of energy, contributing to a reduction in overall electricity demand and lessening the environmental impact of energy production.

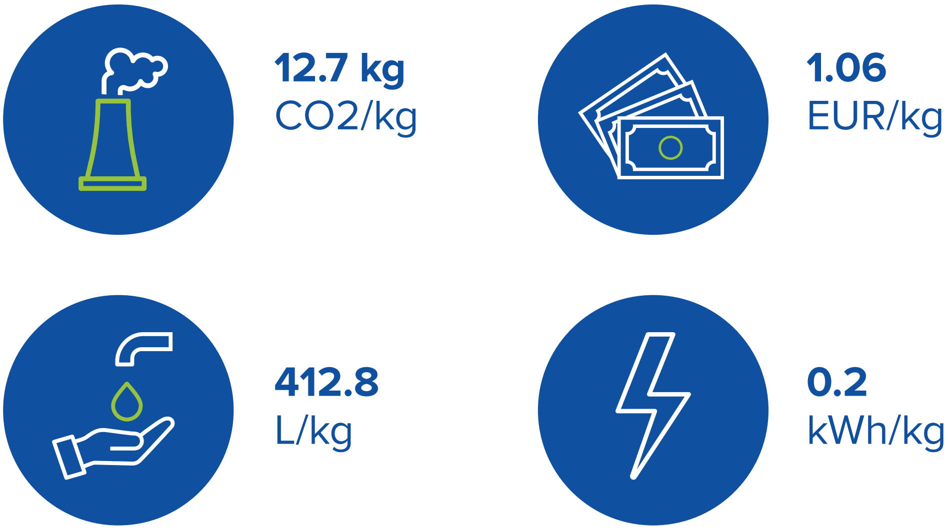


Figure 16. Average impact avoided per kg of food waste after REAMIT technologies implementation.

REAMIT's achievements exemplify how integrating sustainable practices can revolutionise the food industry. Our model fosters enhanced resource efficiency, as shown in Table 7, making strides towards a greener and more responsible approach.

Pilots	UK milk transport	UK frozen food storage	IE abattoir	UK abattoir	UK food transport	LU food transport
Carfon footprint avoided (tCO2 eq)	29.9	129.3	267.2	324.7	668.0	2379.7
Food waste avoided (t)	0.12	10.2	10.2	4.9	86.4	307.8

Table 7. Food waste and carbon footprint avoided due to REAMIT technologies implementation.

[14]Monetising environmental impacts using the method proposed by Weidema (2009). https://doi.org/10.1016/j.ecolecon.2008.01.019.

REAMIT solutions

Our pilot companies have collectively avoided a remarkable 3,798.8 tonnes of CO2 equivalent, combating climate change and lessening the carbon footprint of food production and distribution. In addition, we've successfully avoided a staggering 419.6 tonnes of food waste across the six pilots analysed. Imagine the potential when these technologies scale up!

In a world where sustainable practices hold vital importance, REAMIT solutions stand at the forefront of agri-food transformation. They not only empower data-driven decisions and enhance food quality but also pave the path to a resilient and sustainable future. Through collaboration with academia and industry, our IoT solutions tackle food waste and resource inefficiency head-on. The rigorous pilot tests have underscored their real-world efficacy, while our comprehensive cost/benefit perspective highlights their long-term value. With every kilogram of food, we take a meaningful stride toward building a better world for all. Join us on this transformative journey, and together we can contribute to a brighter and more sustainable future!

5.0 Acknowledgements

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We would like to express our sincere appreciation for the collaborative efforts and support that have enabled the successful execution of this research, which was conducted as an integral component of the REAMIT project. The combined efforts of researchers, developers, industry partners, advisors, and technical teams have created the necessary synergy to produce robust, fit-for-purpose, technological solutions for improving resource efficiency and reducing food waste. This ambitious endeavour was made possible through the funding provided by Interreg North-West Europe grant number 831.

Contact information:

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