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

WPT3 deliverable 2.1: Current and identified future REAMIT technologies

Contents

Executive summary

Reducing food loss and waste is of the highest priority for the EU given the social, environmental and economic costs. In this context, the REAMIT project, funded by the Interreg North-West Europe programme, was launched in January 2019 as a means to make progress towards food loss and waste reduction and lasted until July 2023. The project proposed to adapt and apply existing innovative technologies to food supply chains in the North-West of Europe with the goal of improving their efficiency and lessen their environmental, economic and social impacts. To do so, the project focused on the pilot testing and developing of Internet-of-Things sensors, real-time monitoring applications, alerting systems and data analytics, which was carried out with the essential collaboration of food businesses in the area who joined the project and adopted REAMIT technologies for technology development, food loss and waste reduction and resource efficiency improvement.

The present work consists of a technology assessment based on the works published in the literature, the surveying of companies in the food supply chain, and the overall experience and lessons learned during the project. The aim of this work is to provide an extensive overview of identified IoT solutions for food loss and waste reduction and efficiency improvement to potential IoT adopters in the food supply chain, technology investors and researchers in the field.

The different IoT sensor systems and their components deployed in the food supply chain to monitor key parameters of food quality in real time were identified and outlined, while exemplifying with specific (commercial/industrial) use cases carried out during the REAMIT project. The literature analysis showed that the most frequently measured parameters in the food supply chain were temperature and relative humidity, and many commercial sensors for the monitoring of these are available on the market. However, other parameters can be of great importance to agri-food businesses and may require further attention in the future. After identifying IoT components and systems, to get a better understanding of IoT implementation in commercial settings in the food supply chains, a survey was developed and sent to agri-food companies in the UK which provided 315 valid responses (N = 315). Survey results showed, for example, that more than 70 % of the companies with a lower turnover than a million £ a year were not utilising IoT technology for food loss and waste prevention, in contrast with approximately 55 % of companies over a million reporting the use of IoT. These findings suggested that financial constraint is one of the key factors at play in the implementation of IoT technologies by small enterprises. In terms of motivations to implement IoT systems, reducing food waste was found to be a significant business objective for agri-food businesses, with 72.4 % of the respondents indicating so. At the same time, 69.5 % recognised the potential of IoT technologies to assist them in achieving this objective. These findings demonstrated the widespread recognition of IoT's efficacy in addressing this crucial challenge faced by the food industry. Following the identification of motivators to invest and implement IoT technologies, challenges and shortcomings were identified and supplemented, where possible, with recommendations for future IoT adopters and technology developers. Among these, privacy and data security were found to be barriers in the implementation of IoT-based systems based on our experience gathered in the project. Shortcomings in the implementation of the technologies included, for example, connectivity limitations in certain geographical locations which required the careful screening of IoT devices on the market. Finally, future, potential applications of the REAMIT technologies were identified and outlined in the present work.

1. Introduction

The number of undernourished persons in the world facing hunger in 2021 was 828 million [1]. Moreover, since 1950, the world's population has increased from 2.5 billion to more than 7.7 billion people, and by 2050, this number is expected to reach approximately 9.7 billion [2]. This growth in the world's population will require an increase in food production, thus likely resulting in higher usage of soils, soil resources and water, along with an associated loss of biodiversity, higher emission of greenhouse gases, impact on nitrogen cycles, among other possible adverse consequences [3,4]. Still, even though sustainable and efficient food production is crucial, it is estimated that 1.3 billion tons of food are lost or wasted per year, an amount which roughly equals one-third of all produced globally [5]. In addition, global economic costs related to Food Loss and Waste (FLW) have been estimated at USD 1 trillion annually (figure that does not include costs associated with social and environmental impacts) [6], indicating that FLW has a detrimental, crippling impact on economies around the world. For these reasons, reducing FLW is vital to ensure food security and mitigate climate change and biodiversity loss.

Given the magnitude of FLW and its social, economic, and environmental costs, the United Nations has set in their *Sustainable Development Goals* a target reduction of food loss and waste for 2030 to *halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses* [7]. Likewise, reducing FLW is also of the highest priority for the EU, with figures estimated at 88 Mt or € 143 bn of current annual food waste, having committed to halving food waste by 2030 by focusing on all stages of the food supply chain, from producers to consumers [8].

In this context, the REAMIT project, funded by the Interreg North-West Europe (NWE) programme, was launched in 2019 as a means to make progress towards FLW reduction. The project proposed to adapt and apply existing innovative technologies to food supply chains in the NWE area - due to the amount of interconnected supply chains and large amounts of waste in these countries - with the goal of improving their efficiency and lessen their environmental, economic and social impacts. Although technologies already existed to reduce food waste, the level of implementation of these in the food supply chains was found to be low. REAMIT concluded in July 2023 and was carried out in Ireland, France, the UK, the Netherlands and Luxembourg. The project focused on all types of food products, such as fruit and vegetables, meat, and ready-to-eat meals; and at different stages of the supply chain, from farms and food producers to distribution and logistics companies, to processors, and to wholesalers and retailers. It is worth noting that the project associated with food businesses in the NWE area who joined the project, adopted REAMIT technologies and were essential for pilot testing and progress towards FLW reduction.

1.1 REAMIT technologies overview

REAMIT, for the duration of the project, was adapting existing Internet of Things (IoT) and Big Data technologies to best fit the needs of each of its agrifood business partners. Through testing and adaptation, these technologies were installed and enabled in pilot test companies to continuously monitor food quality and signal potential quality issues. On this last point, for warning of potential quality issues, alerts were configured according to thresholds previously agreed with these companies, e.g., temperature in a fridge going over 4° C, and made so that they would receive a text message on their mobile phones and/or an email according to their preference. To increase user experience, company representatives were given access to a service dashboard, developed by the technological partner of the REAMIT team, Whysor, so that they could access the incoming real-time data at any time – thus, being able to check for themselves that the conditions of their produce were adequate. Finally, by employing data analytics, businesses were provided with insights wherever available. These were related, for instance, to the performance of their refrigeration units, length of cooling periods for their food products, mapping of humidity and temperature levels within their storage rooms, among other examples, with the goal to minimise food waste in a proactive manner.

As a summary, to reduce FLW, the project focused on measuring food quality parameters by fitting real-time (IoT) sensors that continuously monitored and recorded information which, combined with monitoring visualisation tools, alerting of potential quality issues, and data analytics, were utilised to increase efficiency and prevent food from becoming waste.

1.2 Aims and objectives

The present work consists of a technology assessment based on the works published in the literature, the surveying of companies in the food supply chain, and the overall experience and lessons learned during the project. The aim of this work is to provide an extensive overview of identified IoT solutions for FLW reduction and efficiency improvement to potential IoT adopters in the food supply chain, technology investors, as well as researchers in the field. This work also studies how users perceive the usefulness of REAMIT technologies to identify potential bottlenecks in the long-term adoption and proposes new approaches, technologies and applications that can also be developed and implemented in the food supply chain.

2. Conceptual framework

2.1 Food Loss and Waste (FLW)

Food loss and waste has many negative social impacts. As previously mentioned, with the increase in the world's population, the demand for food is on the rise. In fact, the global hunger crisis has reached an alarming level, with 828 million people affected by hunger in 2021. This reflects a remarkable increase of almost 46 million people over the previous year [1]. However, approximately 14 % of the global food supply, which is equivalent to a value of USD 400 bn annually, is still lost between the time of harvest and its arrival on store shelves [9]. Moreover, 17 % of total food available is wasted, with 11 % occurring in households, 5 % in food service, and 2 % in retail settings [10]. The amount of food that is lost and wasted globally is such, that it has the potential to feed 1.26 billion hungry people annually [1].

FLW has serious consequences that go beyond just reducing the amount of edible food available. They also contribute to worsening agricultural efficiency in the future due to adverse effects on natural resources such as soils and water essential for food production. By generating food loss and waste, these valuable resources are squandered. These resources may also include labour, land, and energy [11]. From an environmental point of view, greenhouse gas emissions are directly related to food waste and loss because when food is wasted or lost, all the resources used in its production are also wasted. This includes all the emissions produced throughout the food supply chain. In fact, FLW contributes to approximately 8 - 10 % of global greenhouse gas emissions (GHGs), with implications on climate change, biodiversity loss and pollution. These implications translate into reduced crop yields and they disrupt the entire food supply chain. Therefore, reducing FLW is a crucial strategy for achieving sustainable food systems.

Finally, having mentioned social and environmental impacts, there is a third crucial area that sees severe negative consequences: the economy. Economic resources spent on food that is lost represents a wasted investment that can reduce the income of farmers', butchers', fisheries', processors' – or any actor in the food supply chain – as well as increase consumers' expenses. To governmental institutions, it might mean a reduced budget that could otherwise be used to improve the well-being of their citizens or investments in key infrastructure or technology.

On a global scale, the *Sustainable Development Goal no. 12* of the United Nations aims to address the global problem of FLW by supporting sustainable consumption and production practices that are critical for a more resilient, egalitarian, and ecologically friendly future [7,10]. At a European level, the EU has laid down a series of measures to achieve the reduction of FLW by 50 % by 2030. For the reasons raised above, it is crucial for societies and all their members, including national and local governments, large food producers, small and medium enterprises (SMEs), consumers and beyond, to prioritize and allocate resources towards addressing FLW throughout the entire supply chain, in line with the United Nations' objectives and EU legislation.

To provide an overview of the situations where FLW can occur, the following subsections will provide contextual definitions of food loss and food waste.

Food loss

Food loss refers to a decrease in the mass or quality of the food which happens before reaching the consumer. Food loss includes all quantities of crop, livestock and human-edible commodities that, being discarded or otherwise, do not re-enter in any other utilisation in other contexts such as animal feed or industrial purposes. Food loss can be caused by a variety of factors, including natural catastrophe. However, the primary reason for these losses can be attributed to inefficiencies in the food supply chain. These include inadequate infrastructure and logistics, limited technology, insufficient skills, knowledge, and management capacities; as well as challenges in accessing markets promptly after harvest [12]. Food losses can happen during the harvesting process, in storage, and during processing and transportation [10].

- **Harvest Losses:** harvest losses refer to the loss of food that occurs during harvesting, often attributed to improper harvesting techniques or timing – e.g., early harvesting, which may result in higher moisture content, followed by insufficient drying and increased risk of mould growth, pests, plant disease, and weather conditions [13]. This type of loss may also include produce that was never collected due to labour shortages or low market prices, as well as for not meeting physical appearance criteria [14]. As a matter of fact, fruit and vegetables that do not meet the requirements are often discarded at farms with estimates at 25-30 % of carrots not reaching the market due to aesthetic defects [15].
- **Storage Losses:** storage losses involve food spoilage during storage, whether in warehouses or refrigerated facilities. Factors such as unstable moisture control, contamination and temperature fluctuations can cause storage losses. Excessive moisture can promote mould, fungus, and bacteria growth, leading food to degrade quickly. It can also cause unwanted odours, and the creation of clumps in some food products [16].
- **Processing Losses:** processing losses refers to the reduction in quantity or quality of plants, meat, or fruits during the conversion process into food production. These losses happen due to sorting, cutting, cooking, and packaging. For example, grading processes involve selecting and classifying food products based on quality, size, or appearance.
- **Distribution and Transportation Losses:** distribution and transportation losses refer to food loss during transit from production facilities to retailers or consumers. This can happen due to poor transport infrastructure and delays. Insufficient infrastructure such as improper storage during transportation and poor road conditions, can cause bruise damage and spoilage of food products. Delays in transportation due to the traffic congestion, or unforeseen circumstances can reduce product shelf life and market value [15].

Food waste

Food waste typically refers to food that was not ultimately consumed by humans and that is discarded [17]. Food waste can be the intentional or unintentional discarding from the human food supply chain such as retail, restaurant, food service and household [10]. It should be noted that food waste is also included from hotels, B&Bs, pubs and restaurants, cafes, takeaways and canteens. Food waste can be categorised into three categories which are avoidable, possibly avoidable and unavoidable food waste.

- **Avoidable Food Waste:** Avoidable food waste refers to the food or drinks that were previously in a consumable condition but are discarded instead. This type of food waste can occur due to factors such as over-purchasing, improper storage, lack of cooking expertise [18].
- **Unavoidable Food Waste:** Unavoidable food waste refers to the food that cannot be avoided due to various reasons. This type of food waste is inedible for humans such as bones, eggshells, fruit skins and tea bags [18].

2.2 Food supply chains (FSC)

Up until this point, it has been stressed how paramount it is to reduce FLW throughout the food supply chain for social, economic and environmental reasons. To provide a better understanding about the FSC, the present subsection aims to contextualise and define how the FSC works, what stages it involves, and which are its currently known challenges that technology could help address.

FSC refers to the system that includes all the activities, resources, services and technologies involved in the obtention of food products from their origin to consumption. The food supply chain starts from agricultural harvesting, farming, or fishing of raw materials; followed by storage, transportation, processing, and packaging; then processed foods enter the retailing stage; subsequently finalised with the consumption and disposal of food products. It should be noted that they also include research and development, marketing and other extension services. Each stage within the food supply chain holds a different value to the final product [19].

The production process serves as the initial phase in the food supply chain, starting with raw materials production derived from agriculture, fish farming, or livestock. Agriculture, in this context, involves farming practices focused on cultivating soils to yield crops for harvest. Fish farming refers to the commercially raising fish in a controlled environment for consumption. On the other hand, livestock refers to activities centred around animal husbandry, primarily aimed at producing meat, milk, eggs, or wool. Once raw materials are ready, additional processes, such as baking, heating, fermentation, packaging, labelling, and quality control, are carried out. These processes play a crucial role in transforming the raw materials into the final product [20]. The next stages in the food supply chain are distribution and retail. The purpose of these stages is to connect the food products to the consumers. Finished products are transported to distribution centres which plays an important role in ensuring proper food storage, particularly for some items that require controlled environments with specific temperature and humidity conditions. Maintaining appropriate storage conditions is essential to prevent food spoilage and minimise food loss. Inefficient storage can accelerate the deterioration of food products, leading to losses in terms of quality and quantity [20]. The consumption stage is the final stage in the food supply chain where the food products are purchased, prepared, and consumed by individuals or households. In this stage, consumer choices play a crucial role minimising food waste. Food is usually thrown away due to these reasons overbuying, past best-before date and becoming leftover. By making conscious choices and reducing unnecessary food waste, consumers contribute to a more sustainable and efficient food system [21].

The efficiency and sustainability of the food supply chain can be influenced by various challenges. There are five main concerns in the food supply chain namely (1) lack of traceability, (2) poor communication between parties, (3) struggle to maintain quality control, (4) rising supply chain costs and (5) growing regulations. These issues can make it difficult to achieve food sustainability, which refers to the ability to meet present and future food needs while considering environmental, social, and economic aspects.

Challenges in the food supply chain

- **Lack of traceability:** traceability refers to the ability to accurately track the food product through all the food supply chain. Traceability is essential for companies due to regulatory compliance, marketing strategies, product origin verification, and reacting to safety issues. A lack of traceability can lead to problems in food safety and food quality. Without proper traceability, it is difficult to control quality of food owing to the potential of temperature and humidity fluctuation, illness breakout and contamination. Moreover, traceability can increase customer confidence and loyalty.

Without proper traceability, it becomes challenging to identify the source of a foodborne illness outbreak or contamination event. This can result in delays in identifying and recalling affected products, potentially leading to increased public health risks. IoT, to be more specific blockchain technology, could provide the user real time information and enable them to address quality issues promptly [22].

- **Poor communication between parties:** despite advancements in technology that have enhanced communication channels, there are still existing gaps within the food supply chain which is communication between companies and consumers. Several parties are involved in supply chains, with different backgrounds, the companies might have sufficient knowledge of one another's actions. Inadequate communication gives rise to errors, inefficiencies, excessive waste, and can foster a sense of mistrust between suppliers and their customers. This issue becomes significantly more pronounced when operating on a global scale. Cloud-based networks could help resolve these problems by encompassing the visibility of the complete end-to-end supply chain, near real-time information into demand and supply [23].
- **Struggle to maintain quality control:** quality of food depends on several factors such as fundamental infrastructure, storage, timeliness in transportation and weather. In some areas, bad road conditions and warehouse efficiency can hinder the smooth movement and preservation of food items. In remote areas, damaged roads can pose significant challenges for transporting perishable goods. Uneven surfaces, or limited access routes can lead to delays, increased transportation costs, and product damage. The bumpy ride can cause quality deterioration [24].
- **Rising supply chain costs:** in recent years, the cost of the food supply chain has experienced a significant increase, attributed to various unpredictable circumstances such as pandemic and war. According to data from the United Nations' Food and Agriculture Organization, global food prices have increased by 65% since the beginning of the Covid-19 epidemic, and by 12% in 2022 alone since the beginning of Russia's invasion of Ukraine [25]. To resolve these problems, IoT could be implemented to enhance visibility and tracking of products, allowing companies to optimise logistics operations and reduce losses. Through predictive analytics and demand forecasting, IoT data can provide valuable insights into demand patterns and supply chain disruptions, aiding in inventory optimization and cost reduction.
- **Growing regulations:** it is true that the regulations are enacted to protect people, however the increasing regulations in the food supply chain could contribute to various problems. It could increase the burden for food businesses which lead to higher prices for consumers. The number of regulatory restrictions in the food system has risen by 300% over the past fifty years, with the Food Safety and Modernization Act (FSMA) playing a significant role in this growth [26].

Apart from this, developing countries struggle to ensure a safe and adequate food supply, resulting in economic losses, health hazards, and difficulties integrating into the global trading system. This issue came from over-regulation, selective enforcement, and lack of integration of food laws. For small and medium-sized enterprises (SMEs) in the food sector, compliance with food safety regulations poses additional challenges due to the lack of financial resources and insufficient knowledge that contribute to difficulties in complying with regulations [27].

2.3 The Internet of Things (IoT)

As seen in the introduction section, the main core solution to help in the reduction of FLW proposed by the REAMIT project revolved around the implementation of the Internet of Things (IoT) systems in the supply chain. IoT is a complex cyber-physical system that combines various sensing, identification, communication, networking, and informatics devices and systems, and connects people and things based on interests through the Internet. As a result, anyone, at any time, can more effectively access the information of any object and service through devices and media that are connected to the world wide web [28].

Devices connected to the internet can provide features of identification, sensing, computing, and intelligence and therefore can be considered an integral part of the food supply chain offering a service that collects and aggregates massive amounts of data produced. Applications created on IoT platforms make it possible to collect data, analyse it, and make quicker, better decisions based on it to increase operational effectiveness [29]. Also, by enabling real-time monitoring of the flow of food production, IoT can give stakeholders and management more control over the linked equipment. Additionally, it gives them the freedom to do preventive maintenance and more transparency and visibility in inventory management, allowing them to quickly identify and rectify quality issues.

Architecture of IoT systems

Because IoT uses the internet to connect sensors to real-time monitoring systems, a framework, or architecture, consisting of different layers comprising data collection, communication and deployment of the end-user application must be created to ensure the best possible alerting system, analytics of the recorded data and/or real-time visualisation tools.

As stated below, the sensing, network, service, and application layers made up the core of the IoT architecture [30].

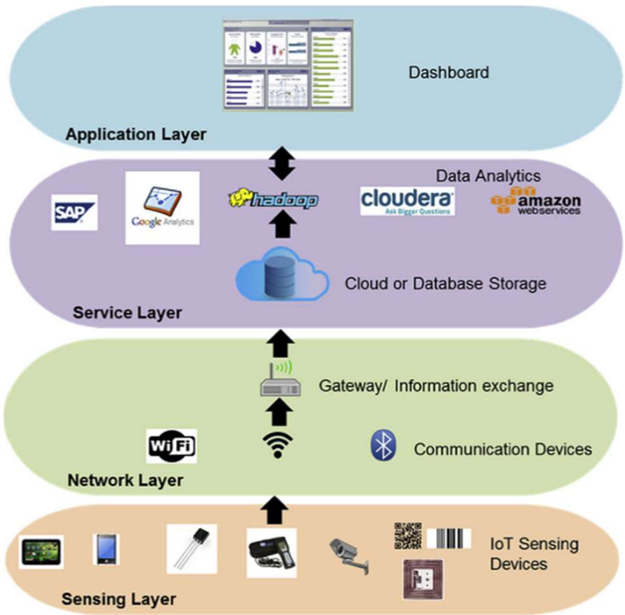

Figure 1: The architecture of IoT in the food supply chain. Source: [28].

- The **sensing layer** is made up of sensors and actuators for detecting, gathering data on physical parameters, and recognizing other intelligent things in its environment.
- The **network or communication layer** oversees processing and transferring sensor data as well as interacting with servers, networking hardware, and other smart objects.

- The **service or storage layer** includes data processing and storage, as well as dedicated functionality for each application and service.
- The **application layer** consists of many applications that supply chain actors can use to examine the information in real time and take the proper actions, such as food traceability modules, production efficiency modules, food quality modules, etc.

Overview of IoT applications in the food supply chain

IoT integration in food supply chain logistics

When it comes to temperature regulation, cleanliness and pest control, traceability, goods management (goods handling, damage, rejection, and safety), and preventative vehicle/container maintenance, the product being carried for food may encounter several difficulties. All operations concerning the movement of food can be tracked using IoT applications. For tracking food products within FSC, Radio Frequency Identification (RFID) technology is one of the most effective and affordable IoT enablers. Food products that are being transported may include specialized but crucial information that can be easily shared via a wireless network using RFID tags. Alerts can be delivered in real-time throughout the supply chain in case of food recalls or food safety problems, and the impacted product can be quarantined. Wireless networking in food delivery trucks is made possible by low-cost wireless remote systems, allowing for the monitoring of food safety while in transit.

For instance, FSC actors can monitor and record temperatures and other variables in real-time with the aid of IoT technology integrated into the Hazard analysis critical control points (HACCP) processes, ensuring optimal cold chain management and compliance with national and international laws. The food delivery vehicles can be equipped with straightforward to sophisticated wireless networking and real-time information access systems. The usage of various vehicle sensing applications is covered by [31], along with connectivity problems caused by the mobility and constrained wireless range of an infrastructure-less network made up exclusively of vehicular nodes. To improve transport efficiency, [32] proposed a design for an intelligent monitoring system based on IoT, including RFID, sensor, and wireless communication technology to track the location of the cargo in real-time as well as the temperature and humidity inside a refrigerator truck.

As seen in Figure 2, one of the most used IoT applications in the food industry is transportation. The food delivery truck can be equipped with sensors to track its location, monitor its temperature, manage, and protect its supplies, determine when the truck requires maintenance, and notify drivers of route adjustments in the event of traffic jams, among other functions. Through IoT, these sensors may be connected and managed.

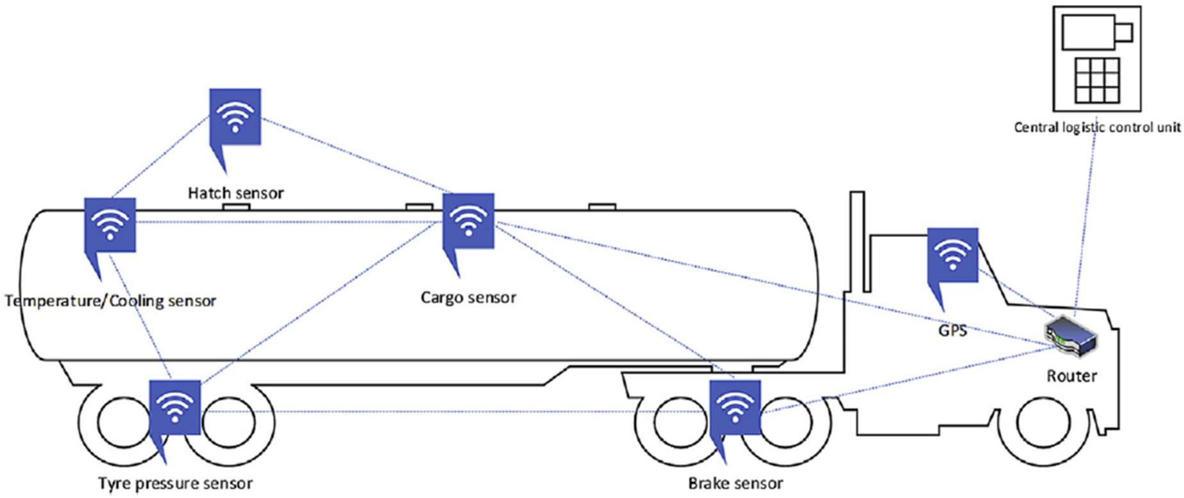

Figure 2: IoT integration in Food haulage trucks. Adapted from: [33].

Waste management through IoT

To attain sustainable FSCs, it has been emphasized the need for increasing food production while using fewer resources [34]. When IoT meets the needs for producing, manufacturing, shipping and supplying food goods with a minimum amount of negative economic, environmental, and societal repercussions, it can be said to be sustainable in the food manufacturing industry [35]. Through connected devices and items, IoT can be used to minimize global emissions and waste [36].

By reducing resource consumption at the beginning and end of the process, Henningsson et al. illustrated the value of resource efficiency in the food industry [37]. They also highlighted the significance of lowering water and electricity use as well as improving effluent quality, which can result in sizable savings. Therefore, by enhancing communication across all the connections (producer, manufacturer, retailer, and consumer) within FSC and adopting evolving technology to decrease labor costs, raw material costs, and utility costs, a more sustainable production and consumption system can be accomplished [37]. Planning and implementing a resource-efficient production system and incorporating resource efficiency in production management requires a thorough knowledge of resource consumption patterns and behaviours [38,39]. Therefore, consumers need more real-time information on resource production and consumer prices to meet these goals [40].

IoT for food safety improvement

Information sharing is important to promote the sustainability of FSC and manage successful collaboration amongst FSC players. The Internet of Things has the potential to carry out information-sharing duties, enabling real-time process monitoring, gathering, and communicating vital information to all the FSC stakeholders, and addressing the issue of FSC transparency. Additionally, IoT enables FSCs to efficiently use virtualizations in supply chain operations, supporting FSCs in coping with items with short shelf lives, erratic supply fluctuations, and tighter food safety and sustainability criteria. The likelihood of food fraud, the use of counterfeit goods, and food-related illnesses have greatly decreased thanks to the deployment of IoT in the FSC. Various sensors are utilized to monitor environmental conditions and product movement (e.g., temperature). Numerous traceability opportunities are made possible using real-time sensors, including the capacity to monitor product locations, production and delivery schedules, ingredient sources, handling practices, and consumption patterns. Additionally, it enables temperature monitoring of key hotspots for food safety inside cold

FSCs. It would be simpler to comply with national and international regulations with the help of IoT. For instance, using digital and automated HACCP, which is currently a regular practice in many FSCs, can produce real and reliable data that can be used to build food safety solutions [41].

The use of IoT to preserve food quality

The quality and specifications of raw materials and final goods can be maintained with the aid of various image-processing technologies and sensors [42]. With the help of these sensors, the product quality can be continuously monitored, and any deviation from the established criteria may be discovered right away and fixed. These sensors also track products, observe personnel activity, and carry out real-time production analysis for efficiency. In the end, this would lead to the improvement of FSC activities.

Paper-based electrical gas sensors (PEGS) can alert users whether food is safe to process or ingest by identifying spoiling gases like ammonia and trimethylamine in meat and fish products [43]. To recognize complex odours, electronic nose systems use a variety of electronic chemical gas sensors [44]. It was effectively utilized for odour quality assessment of food packaging material as well as for quality control, process monitoring, freshness evaluation, shelf-life study, and authenticity assessment on meat, cereals, coffee, mushrooms, cheese, sugar, fish, beer, and other beverages [45]. The consumer now has access to smart packaging options thanks to the integration of gas sensors into food packaging. These advancements have improved food quality, durability, and usability. With a focus on food safety (microbiological growth detection, oxidation, and tamper visibility), food safety (volatile flavours and odour detection), shelf-life monitoring, verification, convenience, and the sustainability of food products, the development of nano sensors will lead to the future of smart packaging [46].

Improving FSC transparency

Transparency in the FSC context can be characterised as the knowledge that all participants in a supply chain network have access to. FSC transparency can show how a product can be tracked from farm to fork, or from where the raw material came from to how it was processed and distributed to customers. In the FSC, blockchain technology can increase transparency. A system based on RFID was proposed for tracking meat from the farm to the butcher [47]. By guaranteeing that consumers have access to traceability information, this RFID-based traceability system involves all supply chain participants along the cattle supply chain to increase consumer confidence in beef products. Like this, Abad et al. used RFID smart tags to monitor the cold chain and enable real-time traceability along an international fresh fish logistic chain [48]. They went on to show that their solution has a lot more advantages than regular traceability tools. A Flexible Tag Datalogger (FTD) was created, developed, and tested by Mattoli et al. to enhance the logistics of shipping, storing, and selling wine bottles as well as assess their safety [49].

3. Current REAMIT technologies

3.1 IoT-based sensor systems for FLW reduction and resource efficiency

The current section examines and identifies the different IoT sensor systems and their components deployed in the food supply chain to monitor key parameters of food quality in real time as seen in the literature, while exemplyfing with specific (commercial/industrial) use cases carried out during the REAMIT project.

Firstly, in order to provide an overview of different IoT sensor technologies and applications, a thorough examination of all published papers in peer-reviewed journals of the last 20 years was performed by the REAMIT team and the relevant finding are presented below. For this study, a total number of 54 articles were finally chosen for review after methodical screening for suitability and relevance.

In the last two decades, various IoT sensor systems were developed and deployed for food quality monitoring. Table 1 presents examples of systems proposed in the literature by type of food, parameters monitored, communication technology used and whether a real-time application and alerting systems were deployed as part of the IoT solution - to provide a quick visual comparison to the REAMIT approach.

Sensors and sensing parameters

At its basic level, a sensor is a detection device that can measure physical or chemical information related to the sample, e.g., temperature; and transform this information into an electrical signal output that can be read and interpreted by another device such as a computer [50]. In the context of FWL reduction, sensors can be applied for the monitoring of multiple parameters depending on the type of food and supply chain stage; and if integrated in an IoT system, the sensor data can be sent to the cloud for remote access in real-time or later retrieval for analysis. For example, a common IoT sensor deployment for storage of perishable foods such as fruits and vegetables involve the monitoring of temperature and humidity given the importance of these two parameters in the preservation of food. It is worth noting that, commercially available IoT sensors or probes commonly incorporate both parameters; thus, making it easy to find a suitable sensor for the desired usage.

The literature analysis showed that the most frequently measured parameter was temperature, which appeared in 81% in the reviewed articles (54 articles in total). This can be explained by its crucial importance in food perishability and freshness, being paramount for microbiological growth and activity. Concerning fruit and vegetables, temperature is the most important factor to monitor and maintain within recommended ranges after harvest [51]; hence the need to monitor temperature effectively. It was also seen that temperature is a very important factor for cold chain storage and transportation of meat, fish and shellfish products as the vast majority of the reported IoT sensor systems incorporated it. In general, temperature is a crucial factor for the average life of all food types as indicated by the Hazard Analysis and Critical Control Points (HACCP) guidelines [52].

Table 1: Real-time food quality monitoring systems found in the literature.

Year	Product	Parameters Monitored	Communication	Real-time app	Alerting system	Reference
2010	Perishable products	T, RH, V, GPS	RFID, GPRS	✓	✓	[53]
2012	Cod	T	WSN	✗	✗	[54]
2014	Perishable products	T	2G	✗	✓	[55]
2014	Banana	T, RH, CO_2	ZigBee	✗	✗	[56]
2015	Chilled lamb products	T	GSM/GPRS	✓	✗	[57]
2016	Fish (tilapia)	T	ZigBee	✓	✗	[58]
2017	Banana	T, RH, CO_2	GSM cellular	✗	✗	[59]
2017	Table grapes	T, RH, VOC	GPRS	✗	✗	[60]
2017	Kimchi	T, RH, GPS	WiFi	✓	✗	[61]
2017	Blackberry	T, RH, CO_2, LI	RFID and WiFi	✗	✓	[62]
2018	Meat and seafood	T, RH, LI	Bluetooth, Wi-Fi and 3G/4G	✓	✓	[63]
2018	Holly	T, RH, CO_2, C_2H_4	4G	✓	✓	[64]
2018	Peach	T, RH, O_2, CO_2, $C2H_4$	4G	✗	✓	[65]
2018	Meals	T	WSN, Bluetooth and 3G/4G	✗	✗	[66]
2018	Fruit	T, RH	GPRS (3G, 4G, LTE)	✓	✗	[67]
2019	Perishable products	T	RFID	✗	✗	[68]
2020	Shellfish	T, RH, O_2, CO_2	Zigbee and GPRS	✓	✗	[69]
2020	Sweet Cherry	T, RH, O_2, CO_2, C_2H_4	USB	✗	✗	[70]
2020	Lettuces	T	WiFi and GPRS	✗	✗	[71]
2020	Pumpkin and oranges	T, RH	RFID, 3G/4G, WiFi, LoRa, NB-IoT	✗	✗	[72]
2020	Meat	T	Bluetooth	✓	✗	[73]
2021	Fruit and Vegetables	T, RH, LI, VOC	WiFi	✓	✓	[74]
2021	Garlic scape	T, RH, VOC, V	4G	✓	✗	[75]
2021	Fruits and vegetables	T, GPS	5G	✗	✗	[76]

T, Temperature; H, Humidity; V, Velocity; GPS, Global Positioning System; RH, Relative Humidity; CO_2, Carbon Dioxide; VOC, Volatile Organic Compound; LI, Light; O_2, Oxygen; C_2H_4, Ethylene.

Another important setup where IoT sensors can be of great use for FLW reduction is during transport of refrigerated foods. Commonly, refrigerated trucks and transport vehicles are set at a fixed temperature that needs to be kept within a safe range throughout: for this purpose, IoT enabled temperature sensors can effectively be used to monitor these parameters during transit, although the IoT architecture deployed needs to account for movement within urban and/or rural areas to be able to send data in real-time. However, while this one temperature approach can be adequate for many setups, it may not be optimal for all types of products to best preserve their safety and quality. As reported though, it can be challenging for logistic companies to remain cost-effective when shipping multiple refrigerated foods if each type has to be kept at a different temperature [57,63]. To address this, an example found in the literature proposed an IoT configuration that consisted of an intelligent system for managing multi-temperature food distribution centres, and that aided in reducing food spoilage by allowing key traceability and product information collected by IoT sensors to be accessed by staff and customers in real-time (see reference [63] for more detail).

The second most frequently monitored parameter was Relative Humidity (RH), understood as the ratio of the current absolute humidity relative to the maximum humidity at a given temperature. Humidity also plays a huge role in microbiological growth and development, and therefore a factor of the utmost importance in food perishability, freshness and safety [77]. In the IoT systems seen in the study of articles, RH was always measured in conjunction with temperature.

In terms of specific commercially available devices, the study showed that the most applied sensors to determine temperature and humidity along the food supply chain consisted of a range of DHT (for instance DHT-11 and DHT-22) and DS (for instance DS18B20 and DS1922L) sensors. These sensors are low cost, basic and slow, but are a suitable fit for users who want to do basic data logging [78]. The two versions are quite similar, but the DHT-22 is of higher accuracy (± 0.5 °C, 2 – 5% RH) and better over a slightly larger range of temperature (-40 to 125 °C) and humidity (0 – 100 %) compared to the DHT-11 (± 2 °C, 5 % RH; 0 – 50 °C, 20 – 80 % RH) [79]. Another sensor that was found in the study was the DS18B20 sensor, a device that can measure temperature with a minimal amount of hardware and wiring. These sensors use a digital protocol called *1-wire* to send the data readings directly to the development board without the need of an analogue to digital converter or other extra hardware. Its accuracy ranges from −10 to 85 °C [80]. The DS1922L on the other hand, is a self-sufficient system that measures temperature and records the result in a protected memory section and the temperature range is − 40 to 85 °C [81]. In the literature, a DS18B20 was used to evaluate the temperature of seafood products (cod) during transportation (see reference [58] for more detail), while the DS1922L was employed to study the temperature of tilapia during transportation and storage (see ref. [54]). Both sensors were found to be efficient for the determination of temperature during the transportation of refrigerated products, but the second offered a broader range of temperatures.

Another parameter of interest to food producers is environmental gas composition and concentration, e.g., oxygen, carbon dioxide, ethane and volatile organic compounds (VOCs). These gases constitute an important parameter to monitor and rapidly address accordingly for many foods such as fruits and vegetables. However, it has been reported that, in general, little attention has been paid to factors other than temperature and relative humidity in monitoring the quality of fruits and vegetables in the cold storage chain [74]. In the literature, examples found included: a real-time IoT system to help overcome the loss of perishable foods including parameters other than temperature and RH such as concentration of CO_2 and light intensity [74]; and a wireless platform system for real-time monitoring of multiple environmental variables, including gas concentration during the movement of foods and perishable goods along the supply chain [51]. For the measurement of ethylene - a phytohormone related to quality and storage life as it induces several chemical and physical changes during the ripening of fruit - a multi-strategy control and dynamic monitoring system for environmental ethylene quantification was proposed (see reference [69]). This system employed a microcontroller as the main control unit, connected to a transmission module communicating via the 4G wireless network.

While the range of options was varied, in the analysis of peer-reviewed articles it was seen that popular gas composition and concentration sensors included the MQ-series (e.g., MQ-2, MQ-5, MQ-7, MQ-135, MQ-136, MQ-137, and MQ-138). These sensors are suitable to detect, measure, and monitor a wide range of gases present in air like methane, ammonia, benzene, carbon dioxide, etc. Given their high sensitivity and fast response time, they are appropriate for different use cases [82]. Another gas monitoring device that was identified in the study was the ATI sensor. These sensors are normally applied to detect oxygen, carbon dioxide and ethylene levels and are designed to detect gases up to 20 ppm [82].

In the FSC, transportation from the source to, ultimately, the consumer, is a must. In this sense, recording reliable location information is the basis for traceability and visibility along the supply chain, which in turn can increase customer assurance and satisfaction in the long run. Some examples were found in the conducted study of literature, though location was not among the most frequent parameters. This may be due to the fact that many articles concerned the production or storage stages rather than transportation itself.

Fruit and vegetable producers may also be interested in the sensing of light. Indeed, light intensity was another parameter that was identified in the study (though appearing much less frequently as compared to the previous parameters). For example, light exposure intensity was evaluated for agricultural product quality decay, along with temperature and RH. These authors developed a Wireless Sensor Networks (WSN) based system and reported an increment of about 1.2 days or 15% of the maximum product useful life of the expected expiration date with their automated, real-time system (see reference [52] for more detail). Finally, other, less frequently measured parameters found in the study included pressure and weight, with four occurrences each; and microbiological concentration, vibration, and air velocity.

From the study, it was concluded that many different components are available on the market and the sensing parameters, and their corresponding ranges of detection will define what sensors are the most suitable for each use case. Given their importance in perishability, temperature and RH were found to be the most important parameters to monitor and correct accordingly to safeguard the quality of food during storage and transport.

<u>REAMIT sensors and sensing parameters</u>

As previously seen, in the project, several agrifood business partners joined REAMIT for IoT implementation and technology development. Thanks to this, REAMIT had the opportunity to pilot test various sensor devices, which were chosen according to the company's needs and challenges regarding FLW. One of our deployments for environmental parameter monitoring for both storage and transport - which monitored temperature and humidity in real-time, as both play a crucial role in the perishability of foods; and as a matter of fact, virtually all of our pilots contained these as key quality parameters - is detailed below as a means to provide a representative example of the REAMIT IoT-sensor solutions that were deployed and that can be of use for future adopters.

In this case, REAMIT needed to find a solution which would allow real-time data to be uploaded while the sensors were moving in trucks. Loggers - term employed here to highlight that, although this is the electronic device that records and sends the data to the cloud, connecting an external sensor/probe to it was needed as opposed to the use of a built-in sensor - with cellular connectivity since they also include the feature of detecting whether a truck is stationary or on the move (trip-detection). A solution was found with Digital Matter (South Africa), who had created a cellular logger device. This logger contains its own sim card and uploads data to the cloud using a 4G connection - in a similar fashion as a mobile phone. Digital Matter offered both a Falcon and Eagle device. For this pilot, the Eagle was selected as, while heavier, offered a longer battery life. The Eagle logger (Figure 3) is customisable and contains I analog and digital inputs allowing for a range of sensors to be configured to best suit the needs of the application. The Digital Matter Eagle loggers are equipped with intelligent firmware which is able to detect whether a logger is moving (in a trip) or not, so that the sending and measuring frequency is increased when the loggers are moving. This ensures maximum data accuracy while also making sure the battery life stays optimal. The Digital Matter Eagle loggers' intelligent firmware can store measurements locally, and transmit the data periodically, e.g., measure every 20 minutes and transmit every 6 hours. Also, when the signal quality is poor and a transmission cannot be completed successfully, the Digital Matter Eagle loggers will try again the next transmission. The loggers are also configurable over the air, so changes to measuring and sending interval can be made on the fly. The costs of the Digital Matter Eagle logger were approximately 156 USD / € 144 / £ 127 (March 2023).

Figure 3: Digital Matter Eagle logger.

As external sensor, the T9602 T/RH I2C probe (Figure 4) by manufacturer Amphenol (USA) was selected because of its low-power characteristics. The costs of the T9602 T/RH I2C probe were approximately € 50 / £ 44 (March 2023).

Figure 4: Amphenol Advanced Temperature and Humidity sensor.

Data communication

In the context of IoT, sensor devices are connected in real-time to other electronic devices, forming an interconnected network to facilitate fast decision-making. Thus, sensors in IoT need to integrate communication technologies that allow continuous, rapid data transfer, as opposed to "non-IoT" enabled systems relying on data logging for later retrieval. There are several different communication technologies available that can achieve real-time data transfer in an IoT system, each with different advantages and disadvantages. In general, wireless communication, compared to wired transmission, provides a higher degree of flexibility in terms of deployment, while not necessarily at a higher cost

[83]. Commonly, wireless data transfer is achieved by using different communication technologies such as Wi-Fi, Radio Frequency Identification (RFID), 3G/4G/5G, among other examples [28].

In the study of literature that was conducted, it was identified that the most frequently used systems were those based on cellular communication technologies. By combining General Packet Radio Services (GPRS), 3G/4G/5G and Global System for Mobile (GSM) into a single category, it was observed that 25.8% of the reviewed publications used these technologies. GSM describes the protocols for second-generation (2G) digital cellular networks. GPRS is a packet-switching protocol still commonly used for wireless and cellular communication services on the 2G and 3G network's global systems. However, over the last years, both GSM and GPRS have been superseded by 4G and 5G mobile data technologies [84]. The mobile networks (3G, 4G and 5G) comprise mobile data connections that use a network of phone towers to pass signals, ensuring a stable and relatively fast connection over long distances [84]. Each generation differs from the others based on its capacities, e.g., speed (lower latency), network volume (higher bandwidth) and accessibility (longer range of service).

Wi-Fi communication is a widespread and easy to install technology, and frequently used in IoT systems [51]. In our study, it was seen that a 21.5 % share of the screened studies employed this technology. An example case found in the literature involved the development a flexible multi-parameter system able to exploit this extensive availability of Wi-Fi networks along the postharvest chain; that is, a system capable of communicating and sending data via Wi-Fi at multiple locations. However, the authors also indicated its disadvantages in terms of energy consumption compared to other wireless technologies, e.g., SigFox, LoRa or ZigBee. The system presented in that article, to overcome this challenge, incorporated synchronisation algorithms to reduce the total amount of time Wi-Fi transceivers were online [51]; a strategy that could be implemented in other setups where this communication technology is preferred.

Another popular, wireless technology is ZigBee, which in our study was found in 11.8 % of the total 54 screened articles. This communication technology is a wireless IoT network-based system that was designed as an open worldwide standard based on IEEE 802.15.4 protocol. Its current use is widely spread in smart home, agriculture and medicine, among other industries. While other wireless communication technologies were designed for achieving higher distances or speed, ZigBee is committed to achieving low-speed, short-distance wireless network transmission, but offering low-power and low-cost applications in battery-powered devices.

Some of the most frequent systems were also those based on RFID (10.7 % of the total studies). RFID technology is a flow control technology widely used in food logistics as it enables traceability throughout the production chain from source to consumer [85]. Oftentimes, installing appropriate IoT systems is off-limits to small agribusiness given their high initial investment costs [72]. An identified example in the literature chose RFID because of its affordability, maturity and wide adoption in the industry, and their efforts revolved around presenting an economical traceability system. However, a drawback that the authors reported was low memory associated with the RFID chips [72].

Bluetooth is a short-range wireless technology standard used for transmitting data over small distances between stationary and mobile devices [86], and it was also observed across the screen publications (7 %). Of note, an article featured this technology to monitor the quality of meat during transportation (see ref. [73]).

Finally, Wireless Sensor Networks (WSN) was found in a few of the screened publications. WSN is formed by arrays of sensors interconnected by a wireless communication network. More specifically, they are made up of sensor "nodes" where each of them shares sensor data and consists of one or more sensing units, an embedded processor, and low-power radios. The nodes can act as information sources but also as "information sinks", receiving dynamic configuration information from other nodes or external entities [87]. Advantages include ease of deployment, low device complication and low consumption of energy [88].

As an overview of the main communication technologies available on the market, Table 2 presents their characteristics in terms of frequency, data rate, range, and energy consumption.

Table 2: Communication technologies' main characteristics. Adapted from: [89] and [90].

Technical features	Wi-Fi	RFID	Zigbee	GPRS/GSM	Bluetooth
Standard	IEEE 802.11	Several	IEEE 802.15.4	-	IEEE 802.15.1
Frequency	2.4 GHz	13.56 MHz	868/915 MHz, 2.4 GHz	850-1900 MHz	2.4 GHz
Data rate	2-54 Mbps	423 kbps	20-250 kbps	20-85 kbps	1-24 Mbps
Transmission range	20-100 m	1 m	10-20 m	10 m	8-10 m
Energy consumption	High	Low	Low	Low	Medium

Bluetooth, ZigBee and Wi-Fi protocols have spread spectrum techniques in the 2.4 GHz band, which is unlicensed in most countries and known as the industrial, scientific, and medical (ISM) band. Bluetooth uses frequency hopping (FHSS) with 79 channels, while ZigBee and Wi-Fi use a direct sequence spread spectrum (DSSS) with 16 and 14 channels, respectively [91]. Based on the bit rate, GPRS and ZigBee are suitable for low data rate applications (such as mobile devices and battery-operated sensor networks). On the other hand, for high data rate implementations (such as audio/video surveillance systems), Wi-Fi and Bluetooth would be better solutions.

As for range, it can be distinguished between short-range networks such as Bluetooth, ZigBee, RFID, or long-range such as Wi-Fi. In general, Bluetooth and ZigBee are intended for WPAN communication (about 10 m), while Wi-Fi is oriented to WLAN (about 100 m). However, ZigBee can also reach 100 m in some applications [92]. ZigBee and RFID are designed for portable devices with short ranges and low battery power. It therefore has a very low power consumption and, in some situations, has no measurable impact on battery life. Wi-Fi and Bluetooth, on the other hand, are made to support devices with a strong power supply and longer connections.

Long-range communication technologies and REAMIT data communication example

Despite the extensive range of options described, based on our experience in the REAMIT project, there are times where technologies with longer ranges are required. In the pilot testing of REAMIT technologies carried out with our associated company partners, a use case that was encountered was the monitoring of fresh and frozen food products while in transit for a wholesale distributor. The IoT solution, in this case, required long-range transmission to connect the sensors to the cloud while the vehicles were on the move in urban and suburban areas while also having low energy consumption to ensure sensor battery maintenance was kept to a minimum. Technologies such as ZigBee and Bluetooth Low Energy (BLE), while delivering on the low-energy aspect, are based on short-range radio transmission and thus require a separate gateway device to interface with the world wide web which we could not deploy given that the IoT solution was intended for vehicles on the move. Solutions to combat the transmission range have been developed based on traditional cellular communication technologies (e.g., GPRS, 3G) [64,65]; however, these systems are power intensive and thus inappropriate for our long-term commercial use case, where low maintenance is a driver toward technology acceptance. Recently, however, a wireless communication technology called Low-Power Wide Area Network (LPWAN) has emerged in response to the demands of IoT applications. As the name suggests, this network operates on low power, has long range, and possesses affordable communication qualities. Sub-GHz unlicensed ISM bands (e.g., 868 MHz in Europe and 915 MHz in the U.S.) are used to operate LPWAN. In urban areas, the network allows for long-distance communication of 1–5 km, while in rural areas, it has a range of 10–40 km [93]. It is also very energy-efficient, with a typical end node (i.e., sensor) battery life of more than 10 years [94]. Because of this, the LPWAN communication protocol is gaining significant traction in both the industrial and research areas. While there are various implementations of LPWAN, the top emerging technologies at the moment are Sigfox, LoRa, NB-IoT, and LTE-M. As discussed, these technologies overcome the high-power consumption of conventional cellular networks and the range limitation of short-range networks while still providing an excellent radio penetration, which allows them to establish connection with objects located in intolerant or severe environments [95].

Sigfox is a wireless company and network operator that launched the first LPWAN technology in the IoT domain in 2009, and it has enjoyed popularity since. The physical layer of Sigfox is characterised by using binary phase-shift keying (BPSK) modulation, an ultra-narrow bandwidth of 100 Hz and broadcasting on unlicensed ISM bands (e.g., 868 or 902 MHz). Its main advantages include a suitable range of 10 km in urban areas and up to 40 km in rural environments, low power consumption, high receiver sensitivity, and low-cost antenna design. However, its maximum throughput is 100 bps.

Another key, energy efficient and popular LPWAN technology that emerged in recent years is LoRa (from “long range”). Likewise, LoRa also uses unlicensed ISM bands (e.g., 868 or 915 MHz), although the modulation relies on chirp spread spectrum (CSS) and the bandwidths are 250 kHz and 125 kHz. It was first developed by in 2009, and in 2015, it was standardised by LoRa-Alliance. LoRa has established itself as a world leader for IoT communication and as such has been rolled out in 42 countries to date. Of these, however, only a select few have countrywide coverage (for example, the Netherlands and France [96]).

Two other popular LPWAN options that were considered were the Narrowband Internet of Things (NB-IoT) and Long-Term Evolution Machine (LTE-M). NB-IoT is part of the 3rd generation partnership project (3GPP) LTE specifications and shares several technical components with LTE. It can coexist with GSM and LTE under licensed frequency bands. Its main advantages are low power consumption, extended coverage and deep penetration [97]. The LTE-M network is derived from the 3GPP 4G LTE standard. Likewise, it also offers a low power consumption, long range and deep penetration. In fact, both NB-IoT and LTE-M share considerable similarities, with their main difference residing in the operational bands they use. Both protocols offer a high degree of compatibility with standard 4G LTE and 5G networks.

In the particular REAMIT use case introduced earlier, the proposed solution utilised LTE-M as the communication protocol as it offered the added advantages of a range of bandwidth, latency, and mobility. It is worth mentioning that when considering the former technologies as candidates for the IoT solution, one of the limitations encountered was the need for a broad network coverage which made us discard some of the previous technologies. In fact, in our experience, this very well constitutes an aspect to consider when designing IoT-based systems.

While having exemplified a REAMIT solution employing LTE-M, it is important to highlight that for several of our pilot tests, the data communication technology that was chosen was LoRa. The key difference in those cases was, however, that those were stationary pilots that monitored storage conditions and did not require the upload of data while on the move. In the countries were widespread LoRa national coverage was not available, we installed a LoRa gateway device in the premises - for instance, in an office space - of our pilot test companies that would receive the signal from nearby sensors - located, for example, in refrigerated rooms - and upload the data to the cloud utilising other communication technologies such as Wi-Fi. While that increased the overall price of the IoT installation, it provided satisfactory results and a successful manner to get around the coverage limitation. Commercial examples employed in REAMIT pilot tests included the Multi-Tech Conduit MTCDT-AEP (Multi-Tech Systems, USA) and the Kona Micro IoT Gateway (Tektelic, Canada).

As a summary of the data communication technologies section, it was observed that it is difficult to determine which communication technology performs the best because the suitability of network protocols is greatly influenced by real-world applications and many other factors need to be considered such as network reliability, roaming capability, price and installation costs. Thus, depending on the use case, local network coverage and funds available for the investment, different technologies can be an adequate fit.

Data Storage

Sensors in an IoT network are continuously collecting and sending information to be processed and modelled through appropriate algorithms, which results in large amounts of data over time. To allow for storage, and even posterior analysis of the recorded data, IoT architectures contain a dedicated storage layer which often employs database management tools with data being stored either locally or remotely.

In general, in the conducted study, reviewing publications from the last two decades, it was seen that the presented IoT systems stored data either locally, using physical servers such as hard disk drives, single-board computers, and databases residing on local drives or local area networks; or remotely, using cloud-based platforms or remote database servers. An example of single-board computers - a complete computer built on a single circuit board; and hence, of compact size - was found in a warehouse management system that employed a Raspberry Pi 2 B+ as the central control unit where a set of Python 2.7 scripts were implemented for the computing of product shelf-life modelling, first-to-expire and first-out management and automatization of pallet transporters for displacement of perishable products (see ref. [52]).

Although a wide diversity of data management solutions was identified, among the range of possibilities reported, one of the preferred options was relational database systems such as Microsoft Structured Query Language database (MS SQL DB) and MySQL server. Relational databases, often referred simply as SQL databases after the query language they are based on, are regarded as highly efficient for storage and management of structured data, i.e., predefined and formatted into precise table fields, delivering data consistency and complex query execution while facilitating the subsequent application of algorithms or Machine Learning (ML) techniques at the same time [98]. SQL database software retrieve and store data from other software applications, which may run either on the same computer or on another computer across a network. As an example of a SQL database implementation, Microsoft SQL server management studio was used for storing and querying data in their proposed real-time temperature and humidity monitoring system of a smart refrigerator (see ref. [99]).

By contrast, a larger number of publications employed cloud server platforms such as IBM cloud, Firebase, ThingSpeak, etc. In this regard, a higher degree of flexibility may be required when working with large sensor generated datasets consisting of not necessarily structured data. NoSQL databases, which were used in several of the selected research articles, allow management of unstructured data, or data of low structuredness level. To do so, it prioritises data availability at the expense of consistency, yet achieving stable, fast read and write operations when dealing with copious amounts of data [61,98]. Specifically, a study in the literature employed MongoDB, which is a flexible open-source NoSQL database [61] that stores data based on collections and documents rather than the two-dimensional row and column approach of relational databases [100]. This way, it allowed storage of the large volumes of unstructured sensor data continuously collected from multiple sensors in their proposed real-time monitoring system of perishable products (see ref. [61]). Likewise, the Firebase Database, a NoSQL cloud database, was identified for a similar use case (see ref. [74]). Elasticsearch was also used once in the literature [101]. Although more commonly regarded as a search and analytics engine, Elasticsearch constitutes an open-source tool, built using Java, that supports storage of data in an unstructured NoSQL format [102].

It was observed that most of the reviewed publications selected cloud databases instead of traditional databases to store and manage their information. The first observed pro of using a cloud is that the data stored in the cloud can be accessed from wherever there is an internet connection [103]. It is also extremely scalable and elastic, giving the opportunity to start small and expand the database if more space is required, mitigating the risk and uncertainties of investing in IT equipment [104]. A final pro is that data is also stored remotely and never stored on the computer, meaning that it will be safe in the cloud if there are technical issues [104]. On the other hand, one disadvantage of using cloud databases is the reliance on an internet connection. If the connection is not strong, some difficulties in accessing the data can be observed. However, some software already allows offline access and synchronises the edits later.

In contrast, the first advantage of using a traditional database is the speed you can up/download data to the server [105]. Having a local server on-site can also increase security because only the organisation can access it physically and digitally [105]. In addition, the companies have total control over the system setup, to make sure it fits their exact needs. The primary disadvantage of having a local database is needing to install and maintain it, as the hardware can be costly and if problems arise there is no cloud provider to handle maintenance requests. Although there is a wide range of equipment options on the market, prices can significantly vary depending on the supplier and specifications of such equipment. Thus, cloud databases represent one of the best solutions for small food companies who lack the financial capacity to invest in uncertain projects. The prices of the cloud servers can be lower, varying from free trials with limited data capacity (e.g., MongoDB and IBM) to various plans depending on an extensive range of features related to apps, cloud, connection, device management, etc. ThingSpeak, for example, has an academic license of $ 250 a year, while the standard version can be more expensive [106]. In other databases, such as Firebase and Ledger, the users only pay for what they use and there are no minimum fees or mandatory service usage, the prices in those cases are $ 5 and $ 0.09 for each GB per month, respectively [107,108].

REAMIT storage solution

While our storage solution may have less applicability for small companies and investors since the project expected high volumes of data from several pilot test companies, readers may benefit from the experience gathered during the project. In our case, REAMIT developed a *Big Data Platform* - or a physical server that could store terabytes (TBs) worth of data - to organise and keep sensor data. For doing so, several pieces of hardware and software tools for data management were deployed. The platform required a capability to collect and store sensor data from all REAMIT corridors; thus, a robust infrastructure and a well-designed system accounting for the necessary data requirements, e.g., frequency, type, and structure of data being retrieved and stored; as well as the desired data format for extraction. Below, in Table 3, the Big Data Platform hardware specifications are listed.

Table 3: Specifications of the physical, Big Data Platform deployed for the REAMIT project.

Type	Device
GPU server	ASUS ESC4000-G4 Server
Processor	2x Intel Xeon Silver 4208 Processor - 8 Cores, 2.10GHz, 11MB Cache (85Watt)
Memory	6x 64GB 2666MHz DDR4 LR ECC DIMM Module
Storage	Crucial 2TB MX500 Series SSD 2.5in SATA3; 2000GB Samsung 970 EVO NVME M.2 SSD
Video memory	NVIDIA RTX 2080Ti Blower Edition Graphics Card PCI-E x16 Gen3, 11GB GDDR6, 4352 CUDA Cores

The software management tool that was chosen was Microsoft SQL Server (see reference [109] for license options and pricing). The REAMIT Big Data Sever with SQL Server provided a means for storing data consistently, enforcing data integrity, and enabling efficient querying and analysis of the stored sensor data from different corridors.

Applications and software

Mobile or desktop visualisation applications can be utilised to facilitate the interpretation of sensor data, not only by IoT service providers, but also by users in the food supply chain themselves, such as farmers, producers or distributors, and by SMEs or big corporations alike. One of the primary uses that food companies can benefit from these applications is by getting real-time access to the environmental or product conditions so that company staff can check the status of their food or raw materials at any time (and make the necessary corrections).

In our study examining research publications, it was seen that the reported systems utilised or developed a mixture of real-time visualisation applications on mobile and desktop using various technologies. Of note, the authors mentioned node.js and Flask for the development of Web-based applications and Java and C# for the development of bespoke offline Windows applications. Off the shelf products like Labview and Matlab’s Simulink have also been utilised for visualisation on the application layer (examples can be found in references [110–112]). Android Studio was mentioned to be used for the development of mobile applications.

It is also worth mentioning the service provided by IBM, the IBM Watson IoT Platform, which allows users to connect devices via API calls (Application Programming Interfaces: roughly, a request from a programme to a server asking to provide information) to see live and historical data and create applications within IBM or other clouds. For instance, the IBM Watson IoT Platform was used to collect, process, and visualise the smartphone readings sent to the IBM cloud via 3G or 4G networks of a meal distribution trolley monitoring system in hospital settings (see ref. [66]).

REAMIT application: the *dashboard*

The use of Internet of Things (IoT) sensors can be of great benefit to the agri-food industry, providing farmers and businesses with real-time data on their crops, livestock, and facilities. However, this data can be overwhelming without an effective way to visualize and analyse it. This is where a dashboard system comes in.

The REAMIT partner, Whysor, was responsible for the development of a web interface, referred to as the dashboard, which was utilized by each pilot study in the project. The dashboard served as a means of data visualisation and provided real-time sensor monitoring functionality for any sensor deployed by the project. Through the implementation of user accounts, permissions could be enabled. This would ensure that pilot companies, or users, would only have access to the data which belonged to them. The dashboard provided the pilot company with intuitive, real-time visualizations of the data generated by their IoT sensors, empowering them to make informed decisions and take actions to improve their operations. Figure 5 shows the implemented REAMIT dashboard.**Error! Reference source not found.**

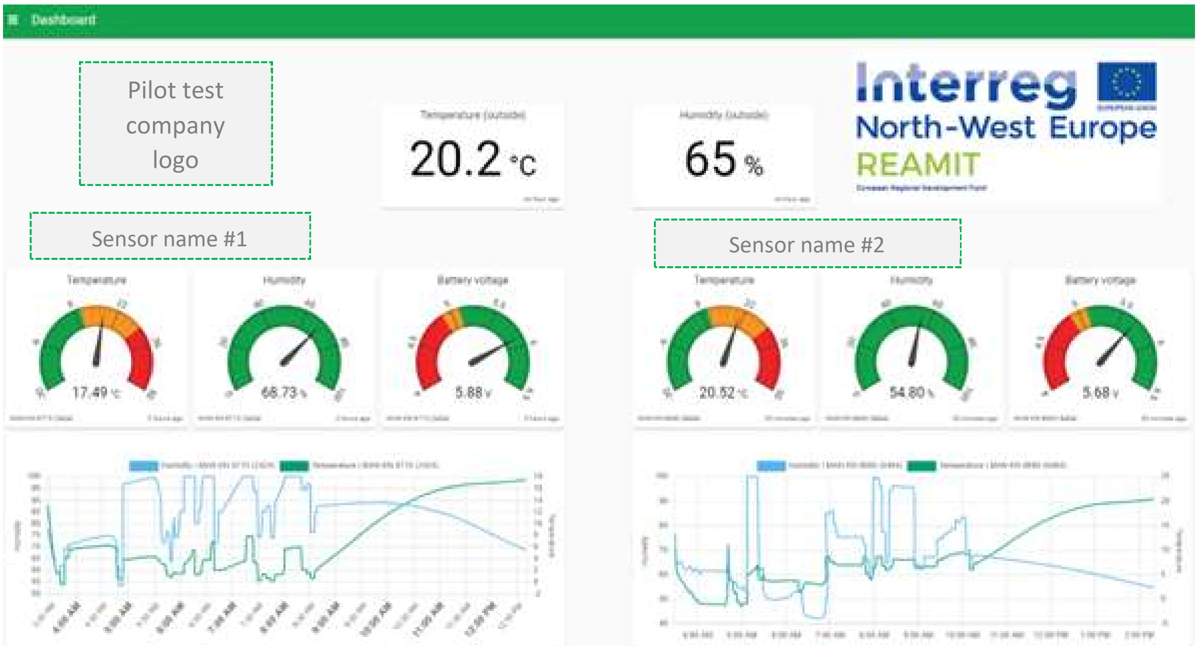

Figure 5: Edited screenshot showing the dashboard interface.

Data analysis

One of the added values that the REAMIT project aimed at providing was the analysis of recorded data over the length of the pilot testing with our associated food companies. The idea behind this was to be able to report insights and recommendations gained from the analysis that the companies could employ to modify one or more of their processes or operations so that FLW reduction and resource efficiency were improved further, by design - and not only through the corrective action when receiving automated alerts.

In this context, as data keeps being collected and stored into appropriate databases, for executing continuous monitoring and control of parameters, algorithms or Machine-Learning (ML) techniques can be applied to extract insights, identify patterns or make predictions, among others. Among the employed ML techniques, our study showed that the preferred options in the literature were supervised learning classification and regression algorithms including Naïve Bayes, ID3, XGBoost, multiple linear regression, non-linear regression, CNN-SVM and others to gain further understanding about the collected data. For example, a multiple non-linear regression model from temperature sensor data was developed to predict the reduction in shelf life of perishables when temperature conditions varied from the theoretical set-point during transportation along the food supply chain (see ref. [71]). In other words, the authors used this model to find a correlation between temperature and loss of shelf life. Another algorithm application example was the use of a combination or hybrid ML algorithm: CNN-SVM (convolutional neural network and support vector machine) (see ref. [113]). The CNN-SVM hybrid is often used to exploit the main advantages of each algorithm, that is, CNN as a powerful tool for feature selection and SVM as an effective classifier. The authors used this technique to evaluate the freshness of salmon during (IoT-enabled) cold storage and classify each salmon sample according to levels of freshness. Another example of ML algorithm application involved testing the accuracy of both Naïve Bayes and decision trees for predicting restaurant demand (see ref. [114]). In this work, the models were trained on waste bin weight data, incremental sales data, and external events data scraped from the internet and social media which could influence demand. The training data were manually labelled with a service-level indicator. Once training was completed, the model was able to predict the production service level required without any human intervention, meaning arriving customers did not need to wait for food to be produced while minimising the amount of food waste generated due to the product's short lifetime. In addition, the study also successfully utilised an unsupervised learning approach to perform outlier detection based on k-means clustering analysis.

It was also observed that researchers in the selected studies preferred to employ either Matlab or Python programming language for data analysis. As for the usage preference among these, it was equally split between Matlab and Python, the latter including Spyder, MicroPython and Python 2.7. One unique approach is noted by Banga et al. who identifies insect infestation during the storage of legumes using acoustic detection methods [115]. For this approach, the authors use Audacity for signal processing, followed by the Pratt tool for spectrogram signal analysis based on Linear predictive coding.

In summary, it was seen that a wide array of ML algorithms, programming languages, visualisation tools and applications were deployed by researchers. While common tools like Python, Matlab, and Labview are recurringly utilised in the articles, each application tends to be unique, perhaps explained by the distinct nature and diversity of the use cases under review. With many different types of produce, supply chain stages, sensing parameters, hardware, communication technologies, etc. being the focus of the research, there is no standard approach to delivering the application layer in a food supply chain IoT system as to date, with a high degree of novelty and experimentation still under development.

REAMIT data analytics example

As previously mentioned, algorithms or Machine-Learning (ML) techniques can be applied to the recorded data to extract insights, identify patterns or make predictions. In the REAMIT project, each pilot was treated with a different approach depending on: supply-chain stage of the business; challenge regarding FLW; accessibility to other types of data to use as labels for the sensor data such as food weight, trip length, refrigeration settings, etc - meaningful and informative labels are used to provide context so that an ML model can learn from it.

In one of our data analytics studies, a regression model to predict temperature rate change during transportation was developed. The first step in producing such model was to prepare a training dataset for building the model. For preparing the training dataset, the data gathered from 117 trips was first compiled and aggregated. Then the data was pre-processed, cleaned, and transformed to a form that was useful for model building. The pre-processed dataset was divided into a training dataset and a test dataset. The ratio chosen for this split was 1:4, meaning that 20% of the data was allocated for testing the model's performance. After preparing the data, various modelling approaches were employed to develop predictive models. Namely, these approaches were linear regression, decision trees, random forest, and neural networks. Each model was trained using the prepared dataset, and their predictive performance was evaluated using the test dataset and the performance was quantified with several statistical measures. These were R^2 and RMSE, and for the linear model, VIF, Durbin Watson Test, F score, and P value were also checked.

Once a reliable model had been developed, it was deployed as a web application for the company users to access it at any time should they want to check potential temperature anomalies based on journey length, weight, package size, among others. For simplicity, the application was designed in such a way that it provided a simple user interface to the user, who could be a delivery personnel or any other stakeholder. The UI, on taking inputs from the user, interacted with a machine learning model in the backend, the details of which were hidden from the user. The user needed to input the value of external parameters for the journey, and then press the button. Upon button click, the application would send the user entered data on the UI to the ML model script deployed in the backend as an input. The model would then take these input values, perform the prediction and send the prediction result back to the user screen, which would display the resulted prediction results to the user. Thus, for the end user, the application looked simple and sleek as it hid the backend complexity from the user. By hiding the model and not exposing the trip data, the application also ensured security.

This User Interface was deployed using R Shiny, a web application framework for R programming language. The codebase includes an app.R script, which is responsible for creating the user interface and establishing the connection with the trained prediction model in the backend.

3.2 IoT implementation, company adopters' profile, motivations and usage

To get a better understanding of IoT implementation in commercial settings in the food supply chains, a survey was developed by REAMIT partners. This survey was sent to agrifood companies in the FSC by the polling and market research agency Survation in the UK and provided 315 valid responses (N = 315). The survey, designed as a quantitative (or numerical) data collection method, consisted of 24 main questions with many containing follow-up (sub) questions of a related nature. These questions aimed at obtaining information regarding the company type, e.g., producer, processor, logistics, etc, and size; whether they were using an IoT solution to reduce FLW or not; if they implemented IoT because they are committed to FLW reduction, climate change mitigation, saving money in the long run or other motivations; the sensing parameters that they actively monitor and/or control; among other examples.

In the following sections, insights obtained from the analysis of the survey are presented as a means to provide an overview of commercial IoT usage in the FSC, especially in terms of their characteristics as a company, their motivations to implement the technology, and the type of use they employ it for on 4 main environmental parameters.

What characteristics do companies in the FSC that implement IoT the most have?

To understand the key factors driving the adoption of IoT technologies for food quality monitoring and the value added IoT technologies provide to the business, this assessment focuses on analysing the profiles of the companies that are currently using IoT sensors. The relationship between the companies that use IoT technologies, and four main aspects will be considered: (1) business activities, (2) size of companies, (3) turnover of companies and (4) age of companies.

<u>Business Activities</u>

Business activities in the FSC industry play a significant role in influencing the implementation of IoT technologies. Different types of business activities have specific needs and challenges that could be solved through IoT technologies. According to the survey, there are six distinct categories representing different company activities: production, processing, wholesale, retailing, logistics and supply chains, and packaging. As observed in Figure 6, companies engaged in processing, production, logistics and supply chain, and packaging were more likely to respond “yes” when asked about their current use of IoT sensors to combat food waste. Among these types of companies, over 70 % of processing companies are IoT users, followed by production companies and logistics and supply chain companies with more than half of each type using this technology. For the companies with packaging activities, the sample size is too small. there was not enough data to conclude the trend. Therefore, this group will be excluded from the analysis. On the other hand, the other business activities showed a higher proportion of negative responses, “no” towards adopting IoT technologies for reducing food waste. Approximately 60 % of retailing companies and 51 % of wholesale companies have reported not using IoT in this regard.

The reason behind this result could be related to the necessity of monitoring quality traceability requirements and optimising processes. For processing, production and logistics and supply chains companies, all the aforementioned factors are crucial to ensure food safety and quality. Environmental conditions such as humidity, temperature and oxygen level could be tracked. Additionally, the movement of products could be tracked during the transportation to reduce loss.

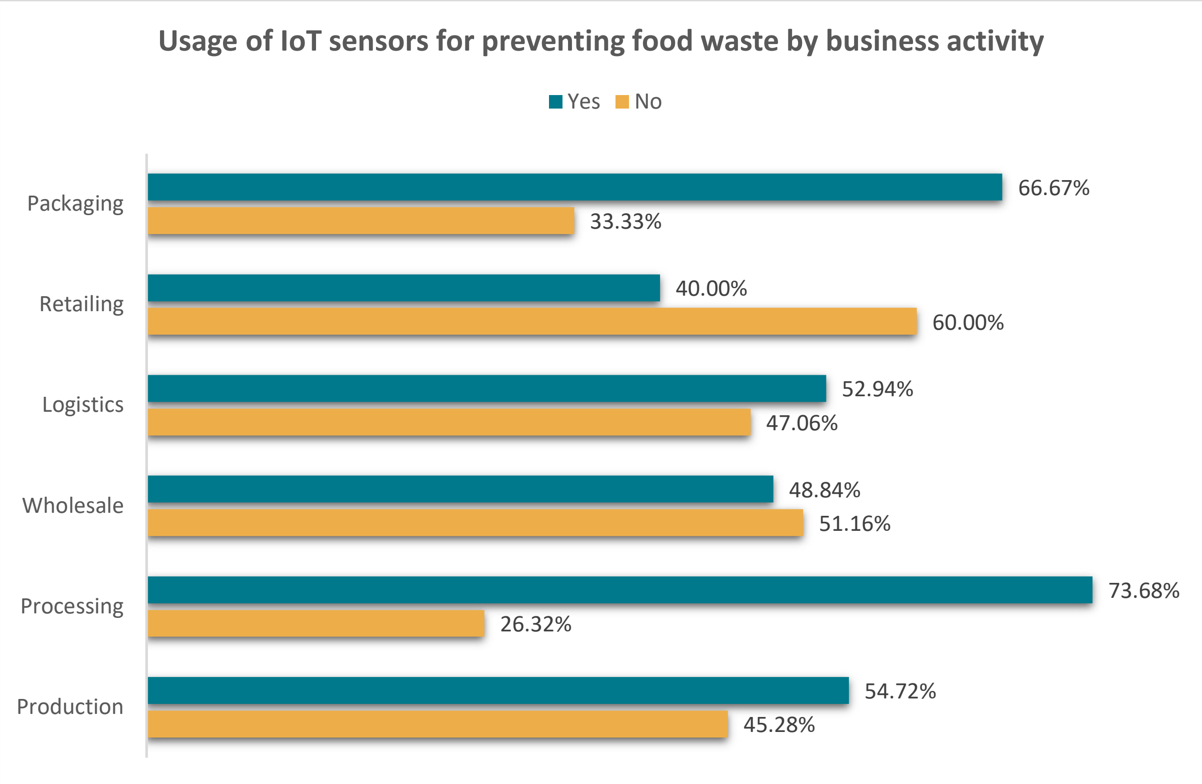

Figure 6: Bar chart showing the percentages of IoT-sensor users for food waste reduction within 6 business-type categories.

Size of companies

The size of a company, specifically the number of employees, has a relationship with the implementation of IoT technologies in FSC companies. Company size influences various factors, including budget allocation, the type of system implemented, stage of development, data management capabilities, regulatory requirements, and quality standards [116].

The chart below reveals that a significant majority, over 70 %, of smaller companies with less than 25 employees do not use IoT sensors for food reduction purposes. The reason could be budget constraints and capability to manage the workforce. With fewer employees, there is a high tendency to believe that the food quality could be monitored without relying on IoT systems, which can be perceived as costly or complex to implement. For medium size companies with 25-50 employees and 51-250 employees, they are more likely to use IoT technologies in their companies, which contribute to approximately 60 percent. With a moderate number of employees, it is typical to have financial resources available for technology implementation. Furthermore, as their operations expand, ensuring effective quality control becomes increasingly challenging, making the adoption of IoT solutions more appealing. Nevertheless, large companies with over 250 employees do not currently employ IoT sensors. Approximately 53 percent of such companies have yet to adopt IoT technologies, while the rest does. The reason to implement IoT in the large size companies could vary depending on factors such as the complexity of their existing systems, the duration of reliance on conventional methods, security concerns surrounding data privacy, and cultural factors within the organisation.

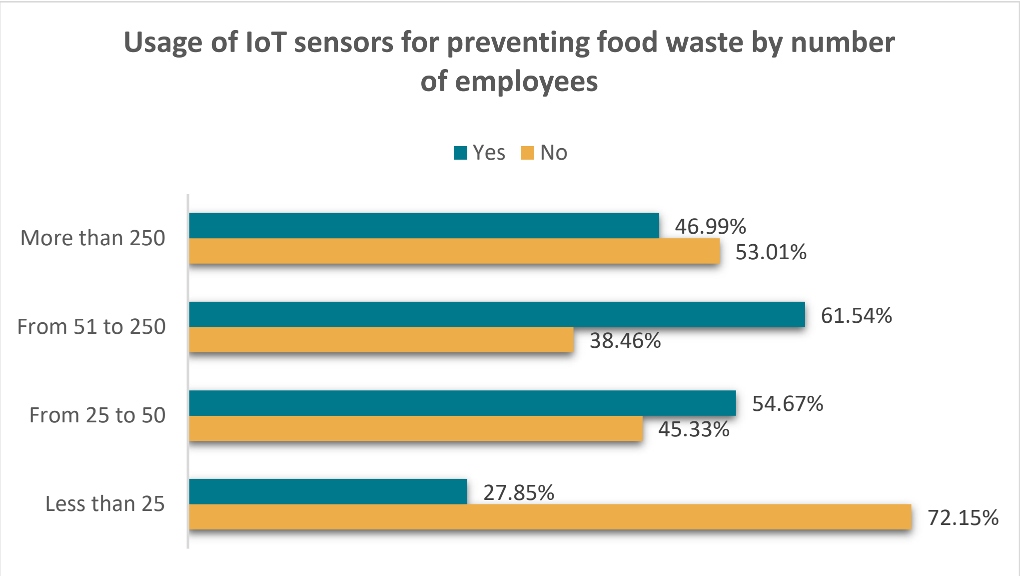

Figure 7: Bar chart showing the percentages of IoT-sensor users for food waste reduction within 4 number-of-employee categories, which grouped businesses from a small number of employees to increasingly larger ones.

Turnover of companies

Turnover of companies represent the total amount of total revenue generated by a company which could reflect financial capability and growth potential of companies. These factors play a significant role in determining whether a company decides to implement IoT technology.

Based on Figure 8, companies with a turnover under a million were less likely to use IoT sensors for food waste prevention. More than 70% of these companies were not utilising this technology. However, a different trend can be observed in the companies with a turnover of more than a million, with approximately 55 % of the aggregated group reported they were using IoT sensors to reduce food loss and waste. These findings suggested that financial constraint is one of the key factors at play in the implementation of IoT technologies by small enterprises.

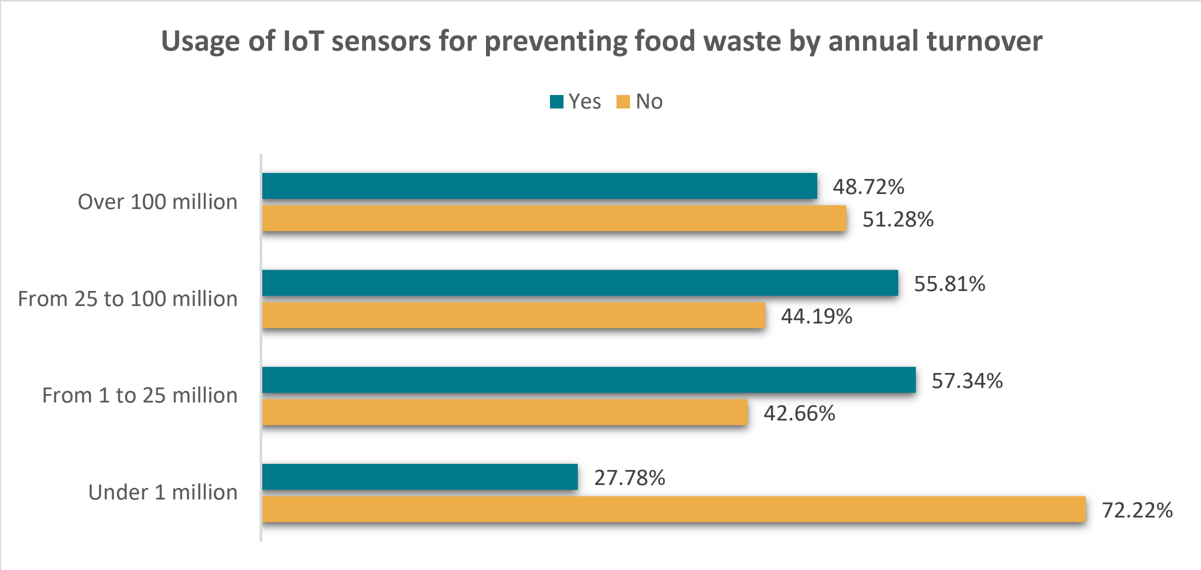

Figure 8: Bar chart showing the percentages of IoT-sensor users for food waste reduction within 4 categories of annual turnover, which grouped businesses from a lower turnover amount to increasingly larger ones.

Age of companies

The age of companies can influence their decision on the adoption of IoT technologies in terms of financial stability and company's culture. Analysing the data shown in, for newly established companies less than a year, many of them have not yet implemented IoT technologies. However, as companies mature, a different trend is observed. Companies that have been operating for 1 - 5 years, 6 - 10 years, and 11 - 20 years are more likely to embrace IoT technologies in their operations. Companies that have been open for more than 20 years show a lower adoption rate of IoT technologies, with approximately 64 % of them not utilising IoT.

The reason behind these results is that for new companies, adopting IoT technologies could be costly, especially when it comes to installation and setup. These companies often have limited financial stability and lots of system change as they are just starting out. On the other hand, companies that have been operating for a while tend to have more established budgets and greater flexibility in adopting new practices. With a stronger financial footing, they are better positioned to invest in IoT technologies to improve operational efficiency. In contrast, older companies may have well-established systems that have been in place for a long time. They may be more resistant to change due to their strong organisational culture and the credibility they have built with their existing systems. The long-standing customer base and their trust in the company's established practices may also play a role in their reluctance to adopt IoT technologies. The company's long-standing client base, as well as trust in the companies may contribute to their reluctance to adopt IoT technology.

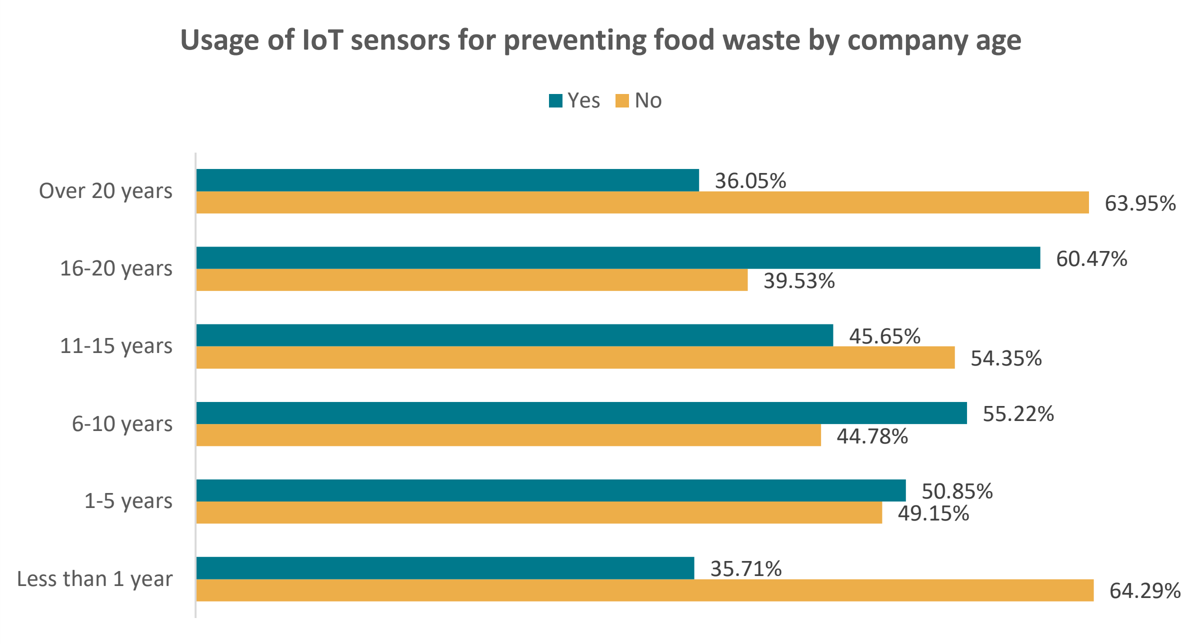

Figure 9: Bar chart showing the percentages of IoT-sensor users for food waste reduction within 6 categories of company's age.

What motivates companies in the FSC invest in and implement IoT systems?

Following the analysis of what profile IoT-enabled companies had – what characteristics related to size, turnover, activity and age of the company appeared to be more frequent among companies that utilise IoT technologies – in this section, the elements that help encourage companies to implement such systems were studied.

Overall, it was observed that companies responded favourably to potential motivators such as: adopting IoT sensors for food and waste reduction improves their image, it saves them money in the long run, it enhances their business value by maintaining food quality, among others. Figure 10 shows some of the most relevant motivation questions that surveyed companies provided responses for. According to the survey results, reducing food waste is a significant business objective for agri-food businesses, with 72.4 % of the respondents indicating so. Moreover, 69.5 % recognised the potential of IoT technologies to assist them in achieving this objective. It is worth mentioning that further survey analysis focusing solely on businesses with food waste reduction as a priority provided a percentage of 79.9 % instead. These findings demonstrated the widespread recognition of IoT's efficacy in addressing this crucial challenge faced by the food industry. Furthermore, it was also observed that over two-thirds of all respondents (67.9%) believed that implementing IoT technologies could reduce costs in the long run, indicating that these technologies could be seen as a valuable investment for businesses. In addition to reducing costs and waste, implementing IoT technologies was also believed to have potential for attracting more customers, with 65.7% of respondents indicating so. This suggested that businesses see IoT technologies as a way to improve their operations and potentially increase their competitive edge. It is also noteworthy that a majority of respondents (61%) believed that their competitors are already using IoT technology. This indicated that businesses may feel pressure to adopt IoT technologies to keep up with their competition. By recognising the significance of IoT adoption for their competitiveness, agri-food businesses are motivated to explore and integrate IoT solutions into their operations to remain competitive and relevant in the evolving landscape of the industry.

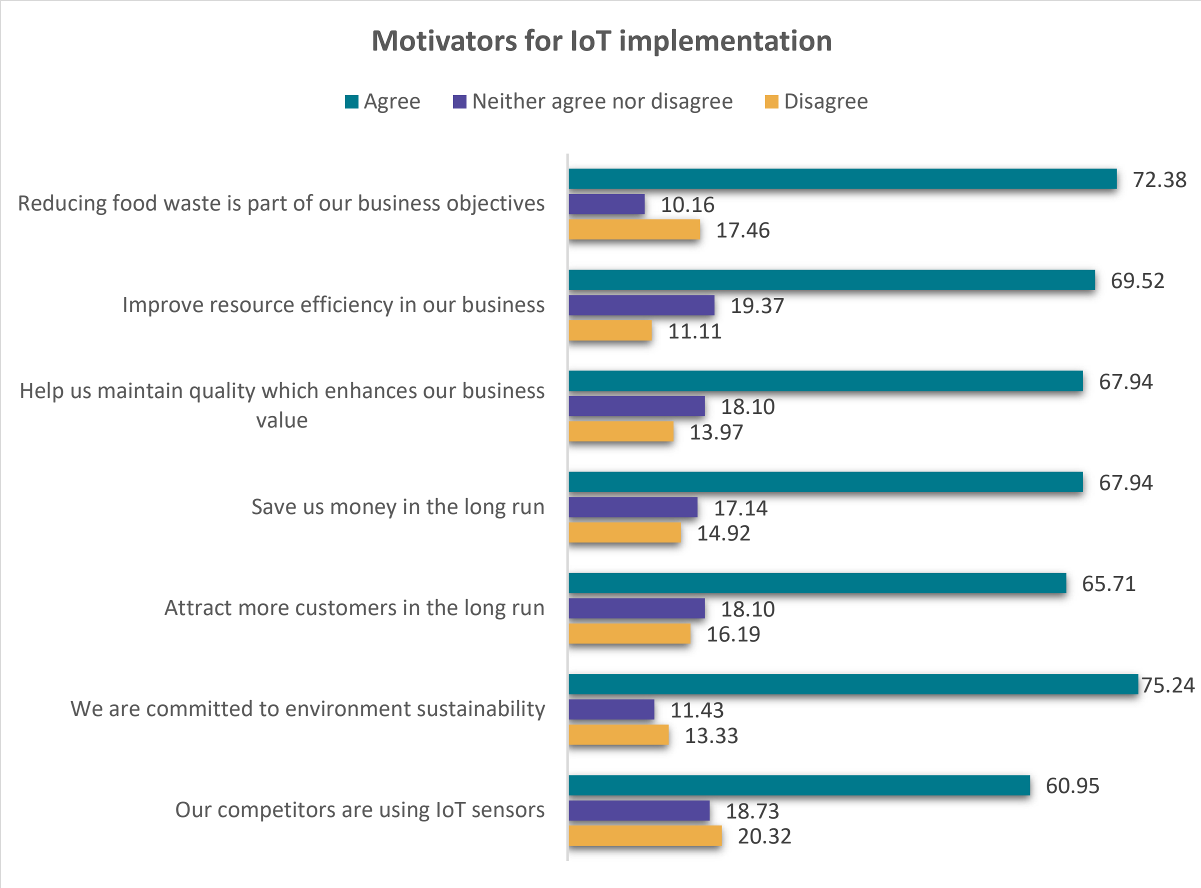

Figure 10: Bar plot showing survey results (percentages) for several motivation questions related to usage of IoT technologies.

Additionally, 75.2 % of the surveyed companies reported being committed to environmental sustainability which suggested that, not only there is an increasing trend in the agri-food sector to become more environmentally friendly, but also that IoT technology is seen as part of the solution towards lessening the environmental impact to a minimum.

What do companies in the FSC use IoT for in the context of waste reduction?

To address this question, a look at the diverse state of monitoring and control of food quality parameters in the agri-food sector as per survey results is shown in Figure 11. In this context, it was observed that there was a notable potential for devices that offer automated monitoring and control systems for temperature, humidity, lighting, and photos. These devices can address the current gaps identified in the survey and contribute to enhancing food quality management in the industry.

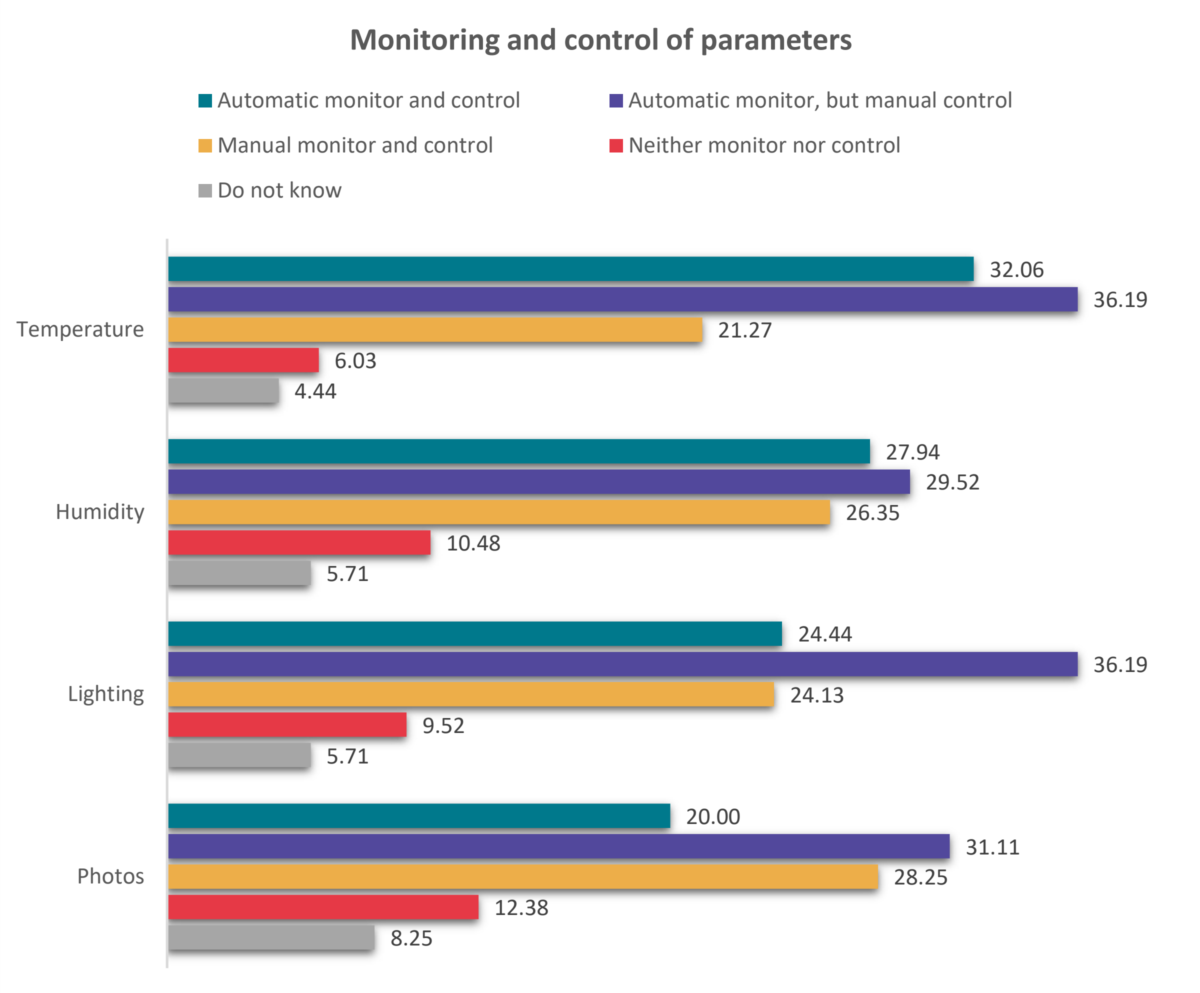

Figure 11: Bar plot showing the percentages for 5 different status of monitoring and controlling temperature, humidity, lighting and photos among surveyed companies.

Although a great portion of companies were still relying on manual monitoring and control of temperature parameters (25.5% manual monitoring and 33.9% automated monitoring but manual control), 28.5% of companies had already implemented both automatic monitoring and control systems for temperature. This indicated a growing trend towards adopting automated solutions in temperature management. Similar to temperature, room for improvement in the adoption of automated systems for humidity monitoring and control was also identified. According to the data, only 17.6% of companies had implemented both automatic monitoring and control systems for humidity. While a considerable portion of companies still relied on manual monitoring and control of lighting parameters (26.7% manual monitoring and 34.5% automated monitoring but manual control), there was an opportunity for growth in devices that provided automated monitoring and control systems for lighting. As per results, 19.4% of companies had implemented both automatic monitoring and control systems for lighting. The survey findings indicated that there was room for improvement in the adoption of automated monitoring and control systems for photo parameters. Only 15% of companies had implemented both automatic monitoring and control systems for photos.

Experience of the REAMIT project: motivations

Based on the experience acquired during the length of the project, working with food companies in the North-West Europe area, the following prominent motivators that would encourage them to use technology for FLW reduction were identified.

Motivators

- **Food quality:** Several firms realized that using technology for continuous monitoring is a very useful way of maintaining food quality while benefiting from FLW reduction. Several food companies engaged in technology development are reporting that they do not incur food waste anymore after the sensor technology is installed and continuously monitored. Technologies have primarily helped these companies improve the quality of their produce, as they can track performance in terms of quality-related variables. Since improving quality can help in multiple ways (e.g., ref. [117], these firms enjoy improving productivity, reduced waste, and increased revenue via higher prices.
- **Reliability:** Food firms have experienced increased reliability of their food processing systems due to the measurement of quality parameters (e.g., temperature and humidity) and continuous monitoring of these parameters. Potential failure issues can be better predicted with these real-time data for increased reliability of their production processes [118].
- **Legal:** Food safety regulations are an important reason companies try to use modern digital technologies to continuously monitor food quality to prevent waste in their organizations. Several companies cited the regulatory requirement on food quality as a main reason for using technology, supporting FWR. Specifically, the Hazard Analysis & Critical Control Point (HACCP) directive, introduced in the EU in the 1990s and modified in subsequent years, expects EU food business operators to implement and maintain a permanent procedure or procedures based on the HACCP principles. The plan should protect food against contamination with bacteria, fungi, viruses and parasites. Maintaining correct atmospheric conditions (temperature, humidity, etc.) that would keep the shelf life of food long enough could be a good plan, which is better served using IoT sensors and other technologies, which would, in turn, help avoid FWR. Thus, some organizations decided that installing sensors can help their adherence to food safety regulations while at the same time helping them in FLW reduction, as echoed in the literature (e.g., [119]).
- **Green image:** Engaging in activities that create waste can be used by firms to project a green image and competitive advantage [120,121]. They can use these efforts to show that they are contributing to improving overall sustainability and helping to save the planet. Explicit associations with established food charities can also be a good motivator for a green image.
- **Pressures from stakeholders:** Commitment from top management and commitment from employees plays a strong role in reducing food waste. Other downstream supply chain partners, by virtue of their position as customers, also exert pressure on reducing food waste. Pressures from other stakeholders, such as the media or the general public, are apparent, considering the higher emphasis on reducing food waste and adopting sustainable food practices in modern days compared to a few decades earlier. These observations are consistent with the tenets of the stakeholder theory [122].
- **Economic factors and survival:** The economic dimension of the additional value derived from the food that has been prevented from going to waste is an important motivator for businesses to use modern technologies. In addition, the reduction in waste disposal costs due to FLW reduction led to more cost efficiency. Some firms realized that their quest to reduce food waste has helped them

find new ways to improve the operational efficiency of their operations, which in turn further reduced costs. The economic dimension manifested in an opposite way when food companies prioritized their survival and were hesitant to engage in innovative technologies during the COVID-19 pandemic, even though they knew the benefits of working on the project. This is consistent with similar observations in the literature [123]. In principle, it is important to ensure that the costs invested in technologies for FLW reduction should compare favourably to the cost of the reduced food waste. The economic analysis is not so straightforward considering the multiple benefits of these technologies for the companies. However, it is important to ensure that the resources spent in producing and installing these technologies should be much lower than the resources saved by the avoided food waste avoided, which can be confirmed with the use of Life-Cycle Assessment (LCA) – a methodology for quantifying the environmental impacts associated to all stages of a product, from the production stage to all the way to disposal.

Overall, the reason behind the companies' decision of IoT could be quality requirements of products, supply chain visibility which directly affects customers trust, operational efficiency, regulatory compliance and financial status of the company [124].

5. The future of REAMIT technologies

5.1 Long-term adoption of REAMIT technologies: barriers and shortcomings

In the survey that was distributed among agri-food businesses in the supply chain, REAMIT included questions regarding current IoT usage, as well as whether the surveyed companies indented to adopt IoT technologies for FLW reduction and resource efficiency improvement in the future or not.

To provide a better understanding of the current usage of IoT in the food supply chain, it is worth noting that the survey results indicated a relatively low adoption of IoT technologies among food supply businesses as 52.4% of the companies were not using any form of IoT technology in their business operations. This result suggested that there may be barriers preventing their widespread implementation. It is, therefore, crucial to address these barriers and accelerate the adoption of IoT technologies in the agri-food industry. One of the barriers that could be identified from the survey was the lack of technical knowledge among respondents. Approximately 43% of participants who do not have IoT technologies implemented expressed their belief that they do not possess the necessary skills to effectively use it. This highlights the need for educational initiatives and training programs to enhance the technical skills of individuals within these companies. Another possible limitation or factor preventing IoT implementation that was identified was a lack of resources. These resources could include financial investments, personnel, or equipment necessary for implementing IoT solutions. Overcoming this challenge would require a strategic approach from company management and collaborative efforts from various stakeholders, governments, and technology providers that play a crucial role in providing financial incentives.

With this being said, among those companies who did not currently use IoT technology, 48.5% indicated that they were interested in implementing it in the future, which demonstrated a growing understanding of the benefits associated with IoT adoption among agri-food businesses and an openness to exploring and embracing new technological solutions.

Experience of the REAMIT project: barriers

Based on the experience of the project, while the motivators seen in the previous section helped reach out to more companies for successful technology demonstrations, some challenges or barriers emerged. These revolved primarily around the collection of sensitive data using IoT sensors. The following are a collection of the most relevant barriers that the project encountered when trying to establish partnership with companies in the FSC, and that future investors and technology developers are encouraged to pay attention and put efforts into mitigating reluctancy for applying IoT technologies.

- **Data security, data sharing, threat from hackers:** One of the first steps in the REAMIT approach to technology demonstrations was to assure the companies that their data was going to be kept safely and securely. Despite this promise, we found that data sharing and security issues could be important barriers on why companies might not be willing to use technology. For example, data that could help measure waste in their system can be potentially used to project the level of inefficiency, which can affect the company’s brand image. This fear was a main barrier in this context. The threat of hacking contributed to this challenge. Shared sensor data to multiple entities in the supply chain (e.g., data analytics companies) could create opportunities for malicious agents to disrupt the food chain via cyberattacks. It is important to ensure that suitable data management plans (e.g., blockchain) are available to minimize data security issues.

- **Privacy:** The perception that using modern digital technologies might infringe on the privacy of potential users was witnessed in our discussion with some food companies. For example, there was hesitation from drivers of trucks to install a gateway in their cabins due to privacy concerns and other concerns such as exposure to radioactivity. In another case, some drivers were not happy to track the location of their vehicles, as it was deemed an invasion of privacy. This adequate consideration of privacy issues could pose challenges to large-scale adoption of the technologies [125].

- **Technological challenges:** Though significant technological developments helped produce relatively inexpensive systems for measuring and monitoring quality parameters, our technology demonstrations did bring more challenging situations that tend to extend the current capabilities. For example, one company wanted to track the temperature of fruits during international flights, which could not be completed cost-effectively with the current technologies available in the market.

- **Trust issues:** A general negative perception from some companies on any IT projects could be seen during the interactions [126]. Given that several IT projects overpromise and under-deliver, we also witnessed the negative perception during our work's early stages. However, as we could show successful technoly developments over time, trust issues became more positive.

Experience of the REAMIT project: implementation shortcomings

In this subsection, challenges (and recommendation to overcome them), especially regarding technical and technological limitations encountered while deploying IoT-based solutions, are outlined. While not extensive of all pilot tests carried out during the project, 6 experiences are presented below with the aim of providing insights to future technology adopters and developers.

REAMIT pilot test no. 1 (Transport, NL)

Table 4: Overview of the IoT solution for the transport pilot test in the Netherlands.

Pilot test characteristics	
Business location	Netherlands
Supply chain stage	Transport
Food loss and waste challenge	FLW due to inadequate volume of icepacks used during transport.
IoT solution deployed	IoT temperature sensors located in the grocery transport crates to monitor temperature.
Applied analytics	ML model to predict quantity of ice required to maintain temperature given weather and journey length.

Table 4 presents the main characteristics of the pilot test carried out in the Netherlands. Regarding technical aspects of the deployed IoT solution, one of the challenges encountered during pilot testing was related to the durability of the sensors. Since these were located inside delivery boxes, sensors had to be able to tolerate pressure and impacts from heavy groceries while in transit: the sensor housing needed to be strong and long-lasting. To prevent this issue, the REAMIT team developed 3D-printed housing structures aimed at absorbing impacts while transport vehicles were on the move. Future technology adopters are encouraged to collaborate closely with sensor manufacturers to guarantee that the chosen sensors are made to endure the demands of their operations. To identify the best sensor solutions that can resist the rigors of transportation, the testing of several sensor options is recommended.

Another issue that was encountered was the need for firmware updates. Our pilot test faced challenges with firmware updates for the sensors, particularly regarding shock detection - a parameter that was monitored alongside temperature. The manufacturer's initial firmware did not provide the desired functionality, and subsequent attempts to update the firmware were delayed. To overcome similar challenges in the future, it is recommended to maintain regular communication with the sensor manufacturer to ensure timely firmware updates.

Finally, challenges to due with communication were also encountered. It was found that progress in the IoT implementation can be hampered by communication lag or slow response times. Communication issues might result from misaligned goals or misunderstandings; therefore, it is recommended that IoT developers and technology adopters understand and agree upon each other's goals and expectations.

REAMIT pilot test no. 2 (Storage & transport, LX)

Table 5: Overview of the pilot test and IoT solution deployed for the storage and transport of food in Luxembourg.

Pilot test characteristics	
Business location	Luxembourg
Supply chain stage	Storage and transport in multiple stages of the supply chain
Food loss and waste challenge	FLW due to temperature abuse at the transport and storage stage of the supply chain.
IoT solution deployed	IoT temperature and humidity sensors located at each stage of the supply chain (farm, transport, storage).
Applied analytics	ML model for early warning of product degradation given temperature.

The main characteristics of this pilot test are shown in Table 5. In this instance, technical challenges arose regarding the testing of connectivity. The REAMIT team was required to spend two months in Luxembourg testing the connectivity of the sensors in various locations and while on the move. The sensors' ability to upload real-time data while inside trucks proved crucial. To overcome this obstacle, it was necessary to test Luxembourg's cellular network and choose loggers with cellular connectivity that could track moving trucks and maximize battery life. Based on this experience, it is highly recommended to anticipate connectivity related issues for the deployment of IoT solutions. In a similar manner, as for the configuration of the loggers and sensors, optimising battery life and ensuring effective data collection required the refinement of the upload frequency parameters and sensor settings. In fact, with the sensors' default settings, the batteries were depleting quickly with all the functionalities chosen for this pilot test. The battery life was increased from 2 months to roughly 8 months by modifying the sensor settings to measure and send data at longer intervals in accordance with the company’s needs. Understanding the needed data frequency and changing the settings accordingly are highly encouraged for extending battery life and lessening the burden of replacing them.

As for the deployed alerting system, initially, there were problems with getting too many alerts from the trucks, which resulted in too many notifications. To prevent erroneous alerts, or users disregarding them as coming at unnecessary times, alerting conditions had to be refined and perfected further. For this, a trip detection mechanism based on vehicle GPS location was included as an extra feature to make sure that notifications were only delivered while trucks were moving and the temperature exceeded the threshold, which reduced the number of unnecessary alerts. For this reason, future adopters are encouraged to implement appropriate trip detection mechanisms.

REAMIT pilot test no. 3 (Transport, UK)

Table 6: Overview of the pilot test main characteristics and IoT solution deployed for the transportation of foods in the UK.

Pilot test characteristics	
Business location	United Kingdom
Supply chain stage	Transport
Food loss and waste challenge	Food waste due to temperature anomalies during transport.
IoT solution deployed	IoT temperature sensors located in fridge and freezer of van to monitor temperature. Alerts via a smartphone and email.
Applied analytics	Send alerts if temperature is not maintained within a pre-specified threshold.

In this pilot test (Table 6), the FLW challenge was related to the delivery vans' refrigeration systems, which in case of malfunction, it could cause the temperature to rise and goods to spoil. A real-time monitoring system was put in place using sensors and cloud connectivity to prevent such situations. This made it possible for abnormalities to be discovered in due time and alarms to be delivered to drivers and warehouse employees, allowing them to take appropriate action before the food became spoiled.

As for technical difficulties, our IoT deployment originally intended to use LoRa sensors for uploading data into the cloud. However, a widespread LoRaWAN network was not accessible in the area where the company was located. The solution to this problem was to upload data to the cloud using cellular loggers that had their own SIM cards and 4G connectivity. The Eagle logger from Digital Matter was chosen for this pilot because it had a longer battery life and could be customised.

The choice and setup of the sensors presented certain challenges. The intended design called for monitoring the vans' both freeze and chill zones, but compatibility problems and the availability of sensors had to be considered. Temperature probes from Amphenol and Maxim Integrated, and customisable loggers from Digital Matter were used for monitoring of the refrigeration zones within the vans. To accommodate the longer cable runs of the sensors, voltage regulators were incorporated into the circuit. Careful consideration was needed while installing the sensors in the vehicles to reduce intrusion and make sure they did not obstruct stock loading and unloading procedures. The loggers were mounted, and the sensors were placed where they were needed using cable ties and adhesive cable tie bases.

Maximising battery life while making sure that precise trip detection was achieved was essential. When the van was not in use, an algorithm was created to put the sensors to sleep to save battery life. Once the van started moving, the device would awaken and start recording information. The trip identification method dramatically decreased maintenance needs and improved battery consumption. Similar implementations are highly recommended in the future.

REAMIT pilot test no. 4 (Processing, UK)

Table 7: Pilot test overview for the processing of food in an abattoir in the United Kingdom.

Pilot test characteristics	
Business location	United Kingdom
Supply chain stage	Food processing in an abattoir
Food loss and waste challenge	Meat waste due to un-uniform temperature distribution in dry-ageing chambers (fridges).
IoT solution deployed	IoT temperature and humidity sensors located at multiple points to monitor uniform temperature distribution. Alerts via a smartphone and email.
Applied analytics	Ensure uniform distribution of air in the chamber. Send warning alerts if needed.

Table 7 shows the main characteristics for the pilot testing of REAMIT technologies in an abattoir in the UK. In this case, the IoT solution aimed at improving the efficiency of the company's dry-ageing process. During dry-ageing, dark facing of meat can occur when moisture evaporates too quickly from the surface of the hanging hindquarters or carcasses, which results in meat (trim) loss; however, tuning of refrigeration parameters can be performed to reduce the amount that needs to be trimmed. As a solution, REAMIT sought the deployment of sensors in the dry-ageing chambers to map the surroundings and pinpoint the perfect settings that would minimise losses while preserving the required softness and flavour of the meat.

Based on the experience gained with the implementation of this IoT solution, dry-ageing process optimisation recommendations are outlined below - which may have applicability in other processes that require the tuning of environmental parameters.

- To utilise the installed sensors to continuously check the temperature and humidity levels in the refrigerated chamber;
- To identify relationships between temperature, humidity, and weight loss through data analytics;
- Methodically check for humidity and temperature settings to determine the ideal conditions that keep weight loss to a minimum without sacrificing quality.
- For further improvement, to periodically examine and alter the parameters depending on the collected data.

REAMIT pilot test no. 5 (Processing, IRE)

This pilot test was of a very similar nature as the one presented above (pilot test no. 4). Details are presented in Table 8.

Table 8: Pilot test overview for the processing of food in an abattoir in the Republic of Ireland.

Pilot test characteristics	
Business location	Ireland
Supply chain stage	Food processing in an abattoir
Food loss and waste challenge	Meat waste due to un-uniform temperature distribution in dry-ageing chambers (fridges).
IoT solution deployed	IoT temperature, humidity, and pressure sensors located at multiple points to monitor uniform temperature distribution. Alerts via a smartphone and email.
Applied analytics	Ensure uniform distribution of air in the chamber. Send warning alerts if needed.

The challenge related to FLW faced by this partner company was that there was a loss of meat with each run of their meat processing procedure, resulting in trimming. This loss may have been caused by temperature changing events like the opening of chamber doors that raised the temperature and altered the moisture content. The company looked for a real-time monitoring solution to address this difficulty and maintain ideal environmental conditions in the chambers. This way, they could keep track of the temperature and humidity levels and respond quickly to any deviations.

Due to a limitation of storage space, this company's refrigeration chambers were not exclusively employed for the dry-aging process, and some areas were used for temporary storage of other types of meat. The dry-aged meat's overall quality and moisture content might have been impacted by this circumstance as loading and unloading operations required the doors to remain open for a certain period. The company was seeking insights on how these operations could be affecting temperature distribution within the chambers, and trying to mitigate it by using this information to plan where to place the hanging carcasses within the chambers and how to best organise the storage conditions.

For the alerting system of temperature and humidity abnormalities, doors opening during loading, unloading, and cleaning activities also presented difficulties. The REAMIT team identified that the alerting system would repeatedly notify them at times when the personnel were aware that the door was open. To overcome this, an external door switch sensor was added to the IoT solution. By determining whether the door was open or closed, the alerting system could be specially designed to alert at different times and frequencies depending on the door status. If the door remained closed, the alerting system would operate normally, quickly signalling any deviation; in contrast, when the door was open, the alerting system would take longer to trigger and would be aimed at alerting that the door would have remained open for too long so that they could reorganise their operations or try to finish the task at hand promptly.

For data analytics, one of the challenges that emerged was the lack of other types of data to use as data labels for the sensor data. Labels were necessary to link temperature and humidity measurements with food loss and refrigeration unit performance. While the pilot test company actively collaborated with REAMIT to provide other sources of information, technical limitations on collecting those limited the overall possibilities of data analytics.

REAMIT pilot test no. 6 (Transport/chicken quality with Raman spectroscopy, FR)

Table 9: Pilot testing of Raman spectroscopy for transport use cases.

Pilot test characteristics	
Business location	France
Supply chain stage	Transport/chicken quality
Food loss and waste challenge	Chicken quality deterioration during transportation.
IoT solution deployed	IoT-compliant LTE-M Raman Spectroscopy solution deployed in transportation van.
Applied analytics	4-class freshness model deployed on a time-series platform (Warp10, SenX) for easy interpretation of quality status by driver. Dashboard for results visualisation.

Table 9 shows the main characteristics of the pilot test carried out in France for the development of Raman spectroscopy as a food quality tool for transport and logistic companies. One of the technical challenges faced during this technology development study was related to the Raman spectrometer: the Raman laser could not operate at temperatures below 10 °C. For this, a heating chamber was added to keep the laser temperature at 18°C. Alternative laser systems that can run at lower temperatures without requiring external heating may be investigated in the future.

It was also discovered during on-road testing that road bumps had an impact on the Raman signal. A sample holder specially designed to better stabilise the food samples and reduce vibrations to alleviate this problem may be developed in future technology development projects. Road vibrations may also be lessened by employing shock-absorbing materials or a more durable mounting mechanism for the Raman sensor. At the same time, obtaining consistent Raman spectra presented difficulties since different food samples, e.g., chicken, had different surface topologies. The pilot test utilised a motorised stage to collect Raman spectra from various zones on the food samples to overcome this difficulty. To assure representative measurements across various surface topologies, it would be crucial to further refine the sample holder or implement adaptive sampling techniques in later testing.

Differentiating food packaging from the food sample may become an issue since the spectral characteristics of the food itself and the Raman bands of food packaging materials like LDPE (Low-Density Polyethylene) might overlap. In the pilot test, distinct chicken-related bands were found by collecting the LDPE spectrum and comparing it to the chicken spectrum. Separating the spectrum contributions of food and packaging materials can be achieved further by using advanced signal processing methods or machine learning approaches.

Another challenge in this pilot test was related to industry involvement. The difficulty arose from a company that was initially chosen for the pilot test, declining to take part in the final stage of installing the Raman system in their vehicle. Establishing clear expectations and agreements with industry partners early on will help future projects overcome this difficulty by ensuring their commitment and active participation throughout all phases of the testing process.

5.2. A look into the future: potential applications of REAMIT technologies

The technologies employed in the REAMIT project have wider applications and scalability potential within and across various business sectors. These technologies, which include sensor-based monitoring systems, data analytics, real-time alerting, and cloud-based platforms, offer valuable solutions for waste reduction, quality improvement, and operational optimisation. Some examples that were identified include:

1. **Farming** [127], where the application of REAMIT technologies can contribute to sustainable practices and improve yield and product quality by providing valuable insights into soil conditions, temperature, moisture levels, and crop health, enabling farmers to make data-driven decisions or irrigation, fertilisation, and pest control;

2. **Greenhouses and agricultural controlled environments** [128], where these technologies can be applied to monitor and regulate parameters such as temperature, humidity, and lighting conditions, allowing precise control over plant growth and optimising crop yields and resource utilisation;

3. **Wine and beverage production** [129], where these technologies can be employed to monitor and control fermentation processes, storage conditions, and aging environments;

4. **Manufacturing and industrial Processes** [130], where REAMIT technologies can be scaled for quality control, waste reduction, and operational optimisation. Real-time monitoring of critical parameters such as temperature, pressure, and humidity could help identify deviations, prevent defects, and enhance product quality. Moreover, if combined with data analytics, these industries can be provided with further insights for process optimisation, predictive maintenance, and waste reduction;

5. **E-commerce** [131], where these technologies can be used to monitor and optimise the storage and transportation of perishable goods, ensure product quality, reduce waste, and prevent losses due to improper handling or storage. Additionally, these technologies can enable retailers to implement predictive analytics to anticipate demand, optimise inventory management, and improve overall supply chain efficiency.

As previously discussed, REAMIT technologies could be applied to other business sectors for purposes not related to food monitoring. Similarly, in this instances, IoT-based solutions can also be deployed to optimise resource efficiency and reduce waste, where applicable. These may include the healthcare and pharmaceutical industry where real-time monitoring of temperature, humidity, and other environmental factors can ensure the integrity of medicines, vaccines, and biological samples [132]. Another example includes the energy sector, where these technologies can help identify areas of energy inefficiency, detect anomalies in consumption patterns, and enable proactive maintenance to prevent equipment failures [133].

These examples demonstrate the wide-ranging scalability and applicability of the technologies employed in REAMIT across various business sectors. By leveraging sensor-based monitoring, data analytics, and real-time alerting, organisations can optimise their operations, reduce waste, improve product quality, and achieve sustainability goals. As these technologies continue to evolve and advance, their potential for scalability and cross-sector adoption is expected to grow, providing immense value to businesses across industries.

Nevertheless, by using other types of sensors and incorporating other digital technologies into the IoT solutions, possibilities of future REAMIT technologies can be further expanded. Below is a list of concepts of growing interest in the field.

Integration of spetroscopic techniques into IoT systems

Opportunities arising from the integration of spectroscopic and imaging techniques in IoT networks can be exploited in a similar fashion as the REAMIT project pilot tested an IoT-enabled Raman spectroscopy system for food quality monitoring. Although several of these techniques have been broadly researched for real-time food monitoring applications, to the best of our knowledge, their development and full integration in IoT systems has not been paid enough attention in the literature. Examples of these technologies, besides Raman spectroscopy, may include Near-infrared (NIR), Fourier transform infrared (FTIR), 3D fluorescence and Laser-induced breakdown spectroscopy (LIBS), among others.

Each of these techniques offers its own advantages that can be used in the food supply chain. A recent example found in the literature developing one of these spectroscopy methods reported that, for producers and technologists, the fodder on dairy farms must be of a certain calibre; however, the technology required to meet these requirements is frequently pricy and difficult to operate. The authors proposed the nutritional analysis of fodder from dairy farms by using a portable NIR spectrometry system. The resulting data was uploaded and processed in the cloud using IoT tools, after which they could became available on any device. Moreover, a machine learning model was developed to examine the nutritional value of dairy farm feed, and the instrument was put into use to comprehend the relationship between the observed spectrum and the concentration of the compounds of interest (see reference [134] for more detail).

The concept of industry 4.0

Industry 4.0 will allow linking the people, product, and the process to digitize the manufacturing process and incorporate versatility in the production lineup and at times make independent decisions. It encourages the development of "smart factories," where cutting-edge technical advancements will lead to an increase in machine communication and improved machine flexibility in response to changing production demands through the processing of sensor data at the machine level. To improve operational efficiency, it also entails connecting information systems and disseminating critical data throughout the whole supply chain [28].

The easy access to affordable sensor and information technology has given FSC actors a greater chance to capitalize on IoT-powered applications. The actors who are linked to the internet are more efficient, productive, quick, and thought to be smarter than their rivals who are not. Food and beverage supply chains will gain the most from this because it will lower the frequency of product recalls, increase resource efficiency, and meet a wider range of client expectations [28].

Another benefit of Industry 4.0 is the predictive maintenance feature, which enables sensors to put on different equipment in factories, transportation vehicles, etc. to continuously gather and analyze data on that equipment's status and forecast probable breakdowns. The seamless and timely manufacturing, transport, and significant reduction in waste and breakdowns provided by predictive maintenance can be of great assistance to FSC actors and increase the supply chain's effectiveness [28].

Robotics

Due to their effective operation, which enables increased repeatability with speed and accuracy, as well as their durability, which will allow them to carry out tiresome and undesirable jobs in challenging circumstances. Lastly, they are capable of being versatile, adaptive, and reconfigurable to create a range of goods using a variety of procedures. These qualities of robots make them perfect for use in the food industry [28].

A lamb processing factory created by Scott Technology processes 600 carcasses each hour using robots [135]. While ABB Robotics produced a robot called Flexipicker that can execute up to 200 picks/minute if fitted with an appropriate gripper based on the foodstuff being handled, KUKA Robotics has developed robots that can function 100% efficiently in challenging situations like 30 °C.

Further Big Data analytics

To make timely and better decisions, smart manufacturing entails developing manufacturing intelligence through the collection of real-time data. With the deployment of IoT, a tremendous volume of data, also known as Big Data, is anticipated to be generated across the FSC. Big data analytics is the act of examining large and diverse data sets using tools like Statistical Process Monitoring to find hidden patterns, unrecognized correlations, market trends, and consumer preferences that can help with making wise business decisions. It will lead to the growth of intelligent manufacturing. The analysis of big data will be the most important component for competitiveness, efficiency, innovation, growth, and development, according to a McKinsey report [28].

With regards to product pricing, product promotion, new product creation, and demand forecasting, big data complements FSCs. Through a case study of a beverage producer, illustrated how a new food product can be produced and introduced in the lowest amount of time [136]. Big data harvesting creates new opportunities for generating new products, enhancing current product lines, and discovering relevant consumer insights [137].

Augmented Reality

The term "augmented reality" refers to a real-time, direct, or indirect experience of a physical environment that has been supplemented by digital data. With augmented reality, the user can interact with the real world or a product [138]. The use of augmented reality could offer a creative simulative solution that helps in streamlining supply chain procedures in today's fiercely competitive food industry. In addition to enhancing supply chain operations, it may also improve product or process development, leading in shorter lead times, lower costs, and higher quality.

By scanning the interactive labels, augmented reality within FSCs could offer useful information on food or food goods. It aids in grabbing clients' attention and gaining an advantage in a cutthroat market. Additionally, in comparison to conventional labelling, it offers more comprehensive information. Customers' experiences are enhanced, and their loyalty is increased by allowing them to touch the goods Diseno 2012. The augmented technology might be used by food producers to tell consumers on the nutritional value and makeup of their products [139] and to alter the hue of unappealing dishes [140].

Cyber security

According to Trustwave's (2019) Global Security Report, the food and beverage industry was responsible for 7% of all reported data breaches. Some security vulnerabilities that influence FSC actors include outdated firewalls, risky remote access, operating system flaws, shoddy security setups, defective security rules, a lack of personnel training, negligence, and inadequate change control procedures [141]. Theft of data, data disclosure to the public, data loss, data corruption, and data falsification are all security risks to FSCs [142]. Ransomware infected the Cadbury facility in Tasmania in 2017, stopping production and causing the company's growth to decline by 3% in the second quarter [143].

Simulation

The simulation software enables FSC actors to mimic the actual supply chain system using real-time data. Prior to any actual production or transition, the actors will be able to digitally test, evaluate, and optimize the parameters [144,145]. There are many simulation programs on the market right now, including ARENA Simulation Software, TrackSYS, Tecnomatix, and FlexSim. To comprehend, analyse, and evaluate potential strategies and situations ahead, a case study was done to construct a new brewery with all the supply chain operations within the brewery that were simulated. This moves improved early startup decision-making in terms of cost planning, reducing downtimes, and any other production-related difficulties.

Blockchain integration

A blockchain makes guarantee that all parties may view transactions simultaneously and in real time. With the use of FSCs, the final customer or retailer would be able to know who their manufacturing partner or suppliers had dealt with. Since none of these transactions are contained in a single database, obtaining the information is practically impossible.

Due to its complexity and confidentiality, global FSCs are frequently opaque and lacking in credibility. Transparency has become the top requirement for every FSC because of food crises like the 2013 horse meat scandal in Europe and the 2008 Chinese milk crisis [146].

It is possible to follow the movement of food through the supply chain, provide food history, and identify the source location of food products thanks to blockchain's capacity to provide every supply chain player with end-to-end visibility [147]. Any player within the supply chain cannot edit, delete, or amend any data without the consent of other network members due to the tamper-proof nature of blockchain technology. The risk of food fraud can be decreased thanks to this function, which also speeds up food delivery, increases productivity, optimizes inventory control, and reduces waste and expense.

Intelligent packaging

Interactive, aware, and intelligent food packaging solutions have been created because of ongoing IoT research and technology advancements [148]. Through sensing, detecting, or recording any changes in the food product, its packaging, or the environment it is stored in, this packaging system can aid in the continuous monitoring of food for its quality and safety. Along with information on food quality and safety, it may also give details on sourcing, processing, movement of the product through the supply chain, preparation instructions, packaging date, batch, weight, and any other details that would be helpful to the consumer [149].

A subset of the Internet of Things is smart or intelligent packaging [150]. It may establish communication with sensors on the package, including RFID, Bluetooth, Near-Field Communications (NFC), and smart labels, by combining IoT and Big Data to build an interface. These tools enable supply chain participants to track and keep an eye on various environmental conditions across the FSC. The use of IoT-based packaging can improve decision-making, reduce the likelihood of product recalls, boost accountability, and promote transparency.

Conclusions

This work was intended for future IoT-based monitoring system future adopters, investers and researchers. It identified the different IoT sensor systems and components deployed in the food supply chain to monitor key parameters of food quality in real time and provided specific (commercial/industrial) examples that were implemented during the REAMIT project. It also provided an understanding of the current status in the implementation of IoT technologies for food loss and waste prevention in the food supply chain and shed light on future implementation trends, which are expected to entail for an increasing number of companies to adopt this technologies due to a variety of benefits such as costs savings, customer appreciation, but also environmental objectives and a sense of social responsibility.

The literature analysis showed that the most frequently measured parameters in the food supply chain were temperature and relative humidity, and many commercial sensors for the monitoring of these are available on the market. However, other parameters can be of great importance to agri-food businesses and may require further attention in the future. As for data communication technologies, it was observed that different communication technologies could be a good fit depending on the use case, local network coverage and funds available for the investment.

After identifying IoT components and systems, to get a better understanding of IoT implementation in commercial settings in the food supply chains, a survey was developed and sent to agri-food companies in the UK which provided 315 valid responses (N = 315). The survey results showed, for example, that more than 70 % of the companies with a lower turnover than a million £ a year were not utilising IoT technology for food loss and waste prevention, in contrast with approximately 55 % of companies over a million reporting the use of IoT. These findings suggested that financial constraint is one of the key factors at play in the implementation of IoT technologies by small enterprises. In a more general sense, a lack of resources also including personnel, technical knowledge or equipment necessary for implementing IoT solutions was also identified a limiting factor. Overcoming this challenge requires a strategic approach from company management and collaborative efforts from various stakeholders, governments, and technology providers that play a crucial role in providing financial incentives. In terms of motivations to implement IoT systems, reducing food waste was found to be a significant business objective for agri-food businesses, with 72.4 % of the respondents indicating so. At the same time, 69.5 % recognised the potential of IoT technologies to assist them in achieving this objective. These findings demonstrated the widespread recognition of IoT's efficacy in addressing this crucial challenge faced by the food industry.

Following the identification of motivators to invest and implement IoT technologies, challenges and shortcomings were identified and supplemented, where possible, with recommendations for future IoT adopters and technology developers. Among these, privacy and data security were found to be barriers in the implementation of IoT-based systems based on our experience gathered in the project. Efforts in securing the privacy and data of companies need to be put in the future to motivate further agri-food companies in implementing IoT-based technologies. Shortcomings in the implementation of the technologies included, for example, connectivity limitations in certain geographical locations which required the careful screening of IoT devices on the market. Finally, future, potential applications of the REAMIT technologies were identified and outlined and included for instance, the application of REAMIT technologies in farming, greenhouses, e-commerce, but also in other industries such as pharmaceutics and the energy sector. The combined use of IoT with newer technology developments was also presented and provided an understanding for concepts such as Industry 4.0 or Intelligent Packaging.

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