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Environmental footprint savings of reducing food loss and waste from digital tools in the European Union: A scenario-based life cycle assessment approach

Supervisor
Prof. Alessandro Manzardo

Student
Haida Wasim
ID 2086032

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ABSTRACT

The widespread issue of food loss and waste throughout the global food chain has led to the emergence of digital technologies. The study aims to employ a scenario-based life cycle assessment (LCA) approach to comprehensively assess the potential environmental benefits of implementing digital technologies in mitigating food losses and waste throughout the fresh food supply chain. Evaluating RFID technology for fresh milk via LCA methodology shows that the environmental benefits from reduced food waste significantly outweigh the impacts of RFID tags, with a net positive effect (exceeding 5 times). The LCA results are being used to assess impact reduction across various categories in each EU-27 country and estimate overall future impact reductions due to RFID tags. The Monte Carlo simulation has been carried out to provides insights into the effectiveness and feasibility of utilizing digital solutions as a means of achieving sustainability goals within the EU. The findings of the study provide evidence-based recommendations and insights to policymakers, industry stakeholders, and other relevant actors on strategies for leveraging digital solutions to achieve sustainable food systems.

ASTRATTO

Il problema diffuso della perdita e dello spreco alimentare lungo tutta la catena alimentare globale ha portato all'emergere delle tecnologie digitali. Lo studio mira a utilizzare un approccio di valutazione del ciclo di vita (LCA) basato su scenari per valutare in modo completo i potenziali benefici ambientali derivanti dall'implementazione delle tecnologie digitali nella mitigazione delle perdite e degli sprechi alimentari lungo tutta la catena di approvvigionamento degli alimenti freschi. La valutazione della tecnologia RFID per il latte fresco tramite la metodologia LCA mostra che i benefici ambientali derivanti dalla riduzione degli sprechi alimentari superano significativamente gli impatti dei tag RFID, con un effetto netto positivo (superiore a 5 volte). I risultati dell'LCA vengono utilizzati per valutare la riduzione dell'impatto in varie categorie in ciascun paese dell'UE-27 e stimare le riduzioni future complessive dell'impatto dovute ai tag RFID. La simulazione di Monte Carlo è stata effettuata per fornire informazioni sull'efficacia e la fattibilità dell'utilizzo di soluzioni digitali come mezzo per raggiungere obiettivi di sostenibilità all'interno dell'UE. I risultati dello studio forniscono raccomandazioni e approfondimenti basati sull'evidenza ai politici, alle parti interessate del settore e ad altri attori rilevanti sulle strategie per sfruttare soluzioni digitali per realizzare sistemi alimentari sostenibili.

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1 INTRODUCTION

1.1 OVERVIEW OF FOOD LOSS AND WASTE

The widespread issue of food loss in the global food supply chain, which sees around one-third of all food produced globally—equivalent to a staggering 1.3 billion tons—going to waste each year due to various factors (FAO, 2011). These factors include quality deterioration throughout the supply chain, leading to significant quantities of food being discarded by consumers and retailers. This wastage not only represents a loss of resources but also contributes to environmental degradation, making it a critical challenge for sustainable development efforts.

Reducing food loss and waste (FLW) is a crucial step towards achieving a more sustainable food system, as highlighted by its inclusion in the Sustainable Development Goals (SDGs) set by the United Nations (UN). Goal 12.3 specifically aims to halve FLW by 2030. This issue has significant negative economic, social, and environmental consequences, with the annual cost of global FLW estimated at around 2.6 trillion dollars (FAO, 2014).

The global challenge of malnutrition persists alongside the pressing issue of food waste (FW), further pressurized by the growing world population. Each region highlighting significant disparities in food loss (FL) rates across different countries and food products. For instance, focusing on fresh fruits and vegetables report losses ranging from 14% to a staggering 70% per product, underscoring the magnitude of the problem. FW, particularly in the context of fresh fruits and vegetables, remains a critical challenge for global food security. The inefficiencies within the supply chain contribute significantly to this issue, emphasizing the need for enhanced management strategies (Jedermann et al., 2014). These inefficiencies result in significant quantities of food becoming unfit for consumption before it even reaches the end consumer. Despite efforts such as SDGs, which aim to reduce FL by 2030, the current food system remains far from achieving these targets, highlighting the need for more effective solutions. (Gokarn & Choudhary, 2021).

Of the total food produced, 13.8% is lost during post-harvest, processing, and production phases, while 17% is wasted at the household, food service, and retail levels. Household FW averages 74 kg per capita per year worldwide, with similar values observed across countries with varying income levels. The food service sector, including restaurants and food processing industries, is responsible for a substantial portion of FW production, with a global average of 32 kg per capita per year (UNEP Food Waste Index Report 2021)

To address this challenge, transitioning towards sustainable food systems that encompass various aspects, including sustainable production, harvesting, and reduced food loss. This holistic approach involves not only optimizing existing processes but also incorporating measures such as integrated land-use planning, land restoration, and promoting diets with a lower environmental footprint.

The emergence of Industry 4.0 and the widespread adoption of Internet of Things/Food (IoT) technologies present promising opportunities to tackle FLW within the supply chain. By leveraging IoT sensors and data analytics, it becomes possible to monitor and manage food quality and conditions in real-time throughout the supply chain, as shown in figure 1-1. This enables more efficient management practices, such as optimizing storage conditions and logistics, thereby reducing the likelihood of food spoilage and waste. While IoT offers significant potential benefits in mitigating FL, it is essential to consider its environmental impacts, including the energy and resources required for manufacturing, operation, and eventual disposal of IoT devices. Additionally, there is also the need for the life cycle assessment (LCA) to evaluate the overall environmental footprint of implementing IoT solutions in the food supply chain comprehensively (Ranganathan et al., 2022). The LCA is employed to evaluate environmental savings and the contribution of digital monitoring interventions to sustainable business management.

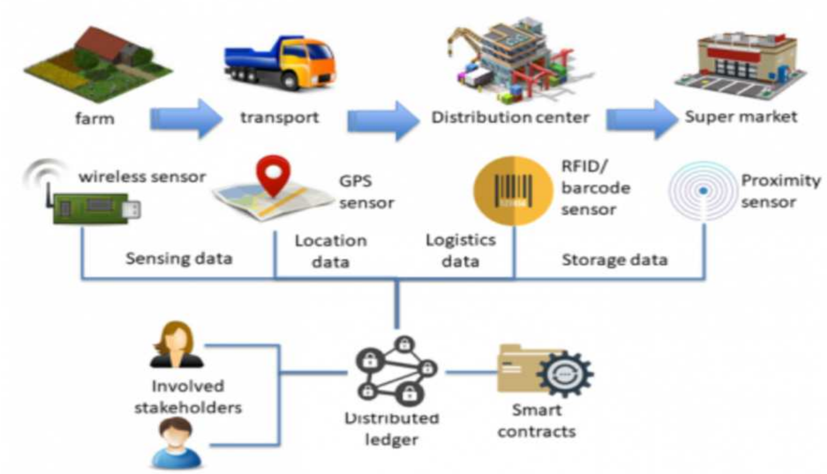


Figure 1-1 Life cycle of agri food products (Farm-to-Fork (F2F))

The integrated approach combines shelf-life monitoring, food loss reduction strategies, and LCA to quantify the environmental impacts of IoT sensor modules accurately. By analyzing the benefits of reduced FL alongside the potential environmental consequences of IoT implementation, decision-makers can make more informed choices regarding sustainable sensor materials and technologies.

1.1.1 Global Food Loss and Waste

The pervasive issue of FLW throughout the global food chain, reveals that roughly one-third of all food produced for human consumption is lost or wasted annually, translating to a staggering 1.3 billion tons (FAO, 2011, n.d.). Approximately 14% of all food produced globally is lost from the post-harvest stage up to, but excluding, the retail stage (FAO, 2019). This not only signifies a monumental waste of resources utilized in food production but also contributes significantly to unnecessary greenhouse gas emissions. (Global Food Losses and Food Waste)

The United Nations Environment Programme (UNEP) Food Waste Index further highlights the global challenge of FW. In 2019, an estimated 931 million tons (Mt) of FW were generated worldwide. Household, food service, and retail sectors contribute significantly to this waste, with households alone accounting for 61% of global food waste.

FLW occurs at various stages of the supply chain, spanning from initial agricultural production to final household consumption. Particularly in high income nations, a significant portion of food is squandered at the consumer level, whereas in low-income countries, losses predominantly occur during earlier stages of the chain (Global Food Losses and Food Waste).

The massive generation of FW incurs significant environmental, economic, and social costs. For example, FAO data from 2007 highlights the consequences of FW, including the emission of 3.3 gigatons of CO_2 equivalent (CO_2 eq) into the atmosphere, the consumption of 250 cubic kilometers of surface and groundwater, and the occupation of 1.4 billion hectares of land annually (FAO, 2011).

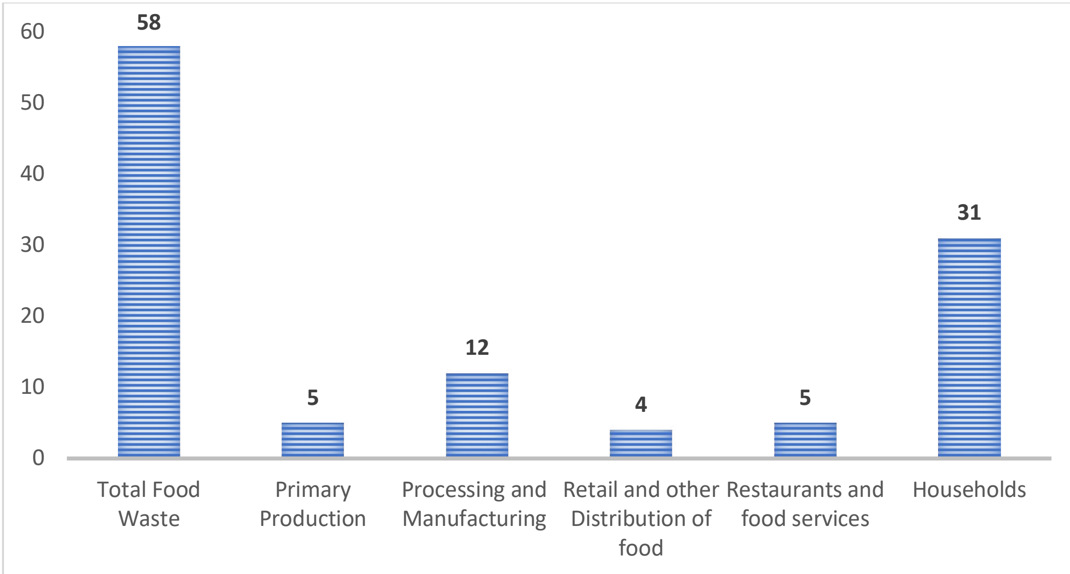
On a per capita basis, industrialized nations exhibit disproportionately higher rates of food wastage compared to their developing counterparts. In low-income countries, the root causes of food losses often originate from financial constraints, managerial shortcomings, and technical limitations, which impede efficient harvesting techniques, storage practices, and infrastructure development. On the other hand, in medium to high-income countries, FLs are more closely tied to consumer behavior and coordination issues within the supply chain.

1.1.2 Food Waste Estimation in the EU

In Europe, up to 100 Mt of FW are generated annually, equivalent to around 200 kilograms per capita. The FW is responsible for approximately 170 Mt of CO_2 emissions per year, as reported by the European Commission (EC) in 2010. The economic costs of FW globally were estimated to be a staggering $1055 billion (FAO, 2011). Beyond its economic and social implications, FW poses significant environmental challenges. It accounts for approximately 16% of total greenhouse gas emissions from the European Union (EU) food system. Addressing FW is crucial for mitigating climate change and preserving natural resources.

At the EU level, the aggregate FW measured in 2021 exceeded 58 Mt of fresh food mass, as shown in figure 1-2. Among these figures, household food waste constituted a substantial portion, surpassing 31 Mt of fresh food mass and accounting for 54% of the total. Following, the processing and manufacturing sector emerged as the second-largest contributor, comprising 21% of the total share. Within this sector, the measured food waste amounted to over 12 Mt of fresh food mass.

The remaining share, constituting a quarter of the total FW, was distributed across several sectors. The primary production sector accounted for 5 Mt, representing 9% of the total FW. Similarly, the restaurants and food services sector contributed more than 5 Mt, also comprising 9% of the total. Lastly, the retail and other distribution of food sectors contributed slightly above 4 Mt, making up 7% of the total (Food Waste and Food Waste Prevention – Estimates – Statistics)



Data are estimated (Mt of fresh mass)

Figure 1-2 Food waste estimations in the European Union, 2021(Statistics | Eurostat)

Despite the abundance of FW, a significant portion of the population in the EU faces food insecurity. The estimation of approximately 10% of food made available to the EU consumers, including retail, food services, and households, is wasted. Concurrently, over 37 million people within the EU cannot afford a quality meal every second day, underscoring the paradoxical nature of FW and food insecurity existing side by side (Eurostat, 2023).

In the EU, the total input of around 150 Mt milk commodities results in approximately 6.8 Mt of FW generated along the food supply chain (FSC), as shown in Table 1. The largest share is generated at the consumption level, equal to 4.2 Mt, representing more than half of the total FW (Caldeira et al., 2019)

Table 1 Total milk quantity available in the EU, and FW calculated along milk supply chain

Food Group	**EU available(Mt)**	**Food Waste (Mt)**					
		Primary Production	Processing & Manufacturing	Retail & Distribution	Consumption		**Total FW**
					Households	Food services	
Milk	**150,2**	0,5	1,1	0,4	4,2	0,6	**6,8**

Overall, in the EU alone, over 58 Mt of FW are generated annually equating to an average of 131 kilograms per inhabitant (Eurostat, 2023), as shown in figure in 1-3. The economic value associated with this waste is estimated to be around 132 billion euros (SWD (2023)). The households emerged as the primary contributors to FW, accounting for 54% of the total. This equates to approximately 70 kg per inhabitant. Household FW, for instance, nearly doubled the amount generated by sectors involved in primary production and the manufacture of food products and beverages. Specifically, these sectors contributed 11 kg and 28 kg per inhabitant, respectively, constituting 9% and 21% of the total FW. Restaurants and food services were found to generate approximately 12 kg of FW per person, accounting for 9% of the total. Meanwhile, the retail and other distribution sectors were identified as having the least amount of FW, with approximately 9 kg per inhabitant, representing 7% of the total.

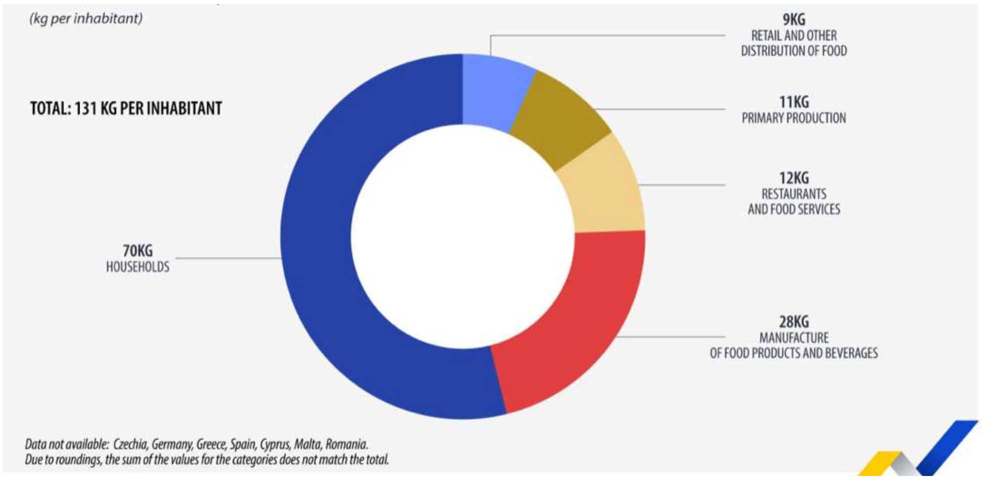


Figure 1-3 Food waste in the EU by main economic sectors, 2021 (Food Waste and Food Waste Prevention – Estimates – Statistics)

1.2 FOOD SENSOR TECHNOLOGIES

The integration of sensors and data-driven automation offers benefits at every stage of the food production and supply chain processes, ensuring quality control, optimization, and safety. From crop monitoring to post-harvest quality assessment, sensors could monitor factors like color, firmness, and sugar content, optimizing growth conditions, minimizing losses, and ensuring product suitability for different destinations. Integrated into packaging materials, sensors enable real-time assessment of product status, ensuring only safe and high-quality products reach consumers. Moreover, in supply chain management, sensors provide continuous monitoring, accurate location tracking, and real-time visibility, enhancing transparency, traceability, and efficiency while reducing food waste and ensuring the delivery of high-quality, safe food products to consumers.

1.2.1 Sensor Selection

Proper sensor selection involves a thorough understanding of the sensor's capabilities, limitations, and compatibility with the specific application. Factors such as measurement range, accuracy, response time, and sensitivity must be carefully evaluated to ensure that the chosen sensor meets the requirements of the monitoring system. The considerations such as maintenance requirements, calibration procedures, and cost-effectiveness play a crucial role in the selection process.

On-line or in-line sensors offer real-time monitoring capabilities, providing instantaneous measurements directly within the process line. These sensors enable continuous process control, allowing operators to make immediate adjustments to maintain optimal conditions. On the other hand, *off-line or at-line sensors* involve manual sampling and analysis, which may not provide real-time data but are still valuable for batch processing and quality control checks.

The following factors are considered while selecting the sensor according to Chen et al. (2024).

- **Sensor Accuracy:** Accuracy is crucial as it determines how closely the sensor's measurement reflects the true value of the parameter being measured. High accuracy ensures reliable data for process control and quality assurance.

- **Calibration:** Sensors often require periodic calibration to maintain accuracy. Understanding the calibration requirements and procedures is essential for ensuring consistent and reliable measurements over time.

- **Size of the Sensor:** The physical size of the sensor can impact its suitability for the intended application. In some cases, space constraints may necessitate the use of compact sensors, while in others, larger sensors may be preferred for increased robustness or sensitivity.

- **Cost of the Sensor and Cost of Replacement:** Cost considerations are important, especially for large-scale industrial applications where multiple sensors may be required. It is essential to weigh the initial cost of the sensor against its long-term reliability and performance.

- **Output Repeatability:** Repeatability refers to the sensor's ability to produce consistent results under the same conditions over time. A sensor with high repeatability ensures consistent performance and minimizes variability in measurements.

- **Circuit Complexity:** The complexity of the sensor's circuitry can impact factors such as power consumption, signal processing capabilities, and compatibility with existing control systems. Simple, robust circuits are often preferred for industrial applications to minimize maintenance and troubleshooting requirements.

- **Resistance to Contamination:** Industrial environments can expose sensors to various contaminants such as dust, moisture, chemicals, and particulate matter. Sensors designed to resist contamination are better suited for such environments, as they maintain accuracy and reliability in the face of adverse conditions.

- **Reliability of the Sensor**: Reliability is paramount, particularly in critical applications where sensor failure can have significant consequences. Sensors with a proven track record of reliability and durability are preferred to minimize the risk of costly downtime or product quality issues.

1.2.2 Types of Sensors:

Because of their broad compatibilities and functionalities or applications different types of sensors are used in the food processing industries, as explained in Table 2.

Table 2 Types of Sensors (Patel & Doddamani, 2019)

No.	Types of Sensors	Sub Types	Composition	Energy Use in Production	Applications in Food Processing
1	Proximity sensors	Inductive, capacitive, and ultrasonic	aluminium, brass, copper and stainless steel	6.63 µA or 100 mW	detecting the presence or absence of food items during various stages of food processing, packaging, and handling
2	Thermo sensors	Resistance temperature detector, infrared sensor, thermistor and thermocouple	platinum, nickel, or copper.	0.5-5 mW	process control, food inspection, freezers, fermenting units, baking ovens, and cooking and smoking units.
3	Humidity sensors	Optical, gravimetric, capacitive, resistive, piezoresistive, and magnetoelastic	polymer films such as polyimides or cellulose acetates	2.6-8 mW	measure the moisture content in food products in baking, drying, and storage.
4	Bio-sensor	Amperometric conductometer, thermometric biosensor and potentiometric	organic polymers, sol–gel systems, and semiconductors, among other conducting composites.	16-18 mW	determination of the composition, degree of contamination of raw materials and processed foods, and for the on-line control of the fermentation process
5	Pressure sensors	Absolute, gauge, vacuum, differential and sealed	silicon, ceramic, stainless steel	0.5-2 mW	monitor and control fluid pressure in processing equipment (pumps, filters, and packaging machines)
6	E-tongue taste sensors		lipids/polyvinylchlo ride(PVC) membranes, metals, stainless steel	0.6-5mW	based on taste sensing, classification of fruit juices, test for bacterial growth in milk or water quality, wine quality
7	Gas sensor	Electrochemical, catalytic, infrared and photoionization	carbon nanotubes, Graphene, metal/metal oxide nanoparticles, 2D nanomaterials and hybrid nanostructures	210 mW	detecting and monitoring the presence of gases such as carbon dioxide, oxygen, and ethylene in food storage facilities and packaging environments.

8	RFID and GPS Sensors	Low, high and ultra-high frequency RFID, Mobile, Plug-in Play and Wired GPS/ELD	plastic, metal, ceramic, rubber, silicon	30-50 mA	tracking and tracing food products throughout the supply chain to ensure freshness, quality, and to prevent counterfeiting.
9	PH-sensor	Combination, differential, laboratory, and process	polymers, chemicals, metal oxides, and titanium nitride (TiN)	500-800 mW	monitoring acidity levels, ensuring product safety, microbial control, and desired taste profiles

1.2.3 Advantages of Sensor Technologies from Farm to Fork

- **Continuous Data Collection:**

One of the most notable advantages of sensing technologies is their ability to continuously collect and report data in real-time. This continuous monitoring offers unprecedented insights into various processes within the food industry, including chemical changes during manufacturing and the progression of spoilage. By providing a constant stream of data, these sensors enable a deeper understanding of the complexities involved in food production, storage, and distribution. This information is invaluable for optimizing processes and ensuring product quality and safety throughout the supply chain.

- **Food Safety and Security Concerns:**

In recent years, concerns regarding food safety and security have become increasingly prominent. Substandard food quality has been linked to various issues, including fraud, contamination, and public health risks. In response to these concerns, both consumers and regulatory bodies are placing greater emphasis on ensuring the safety and quality of food products. This necessitates compliance with stringent quality control standards and guidelines, as well as transparency in labeling and information provision for consumers.

- **Analytical Methodologies:**

Traditional analytical methods such as liquid chromatography (LC), gas chromatography (GC), and high-performance liquid chromatography (HPLC) have long been utilized in food analysis. However, these methods often require extensive sample preparation and have lengthy analysis times, making them less suitable for evaluating fresh food products with short shelf lives. Moreover, the complexity of sample preparation steps can introduce inaccuracies and false positives, further complicating the analysis process (Cozzolino, 2022).

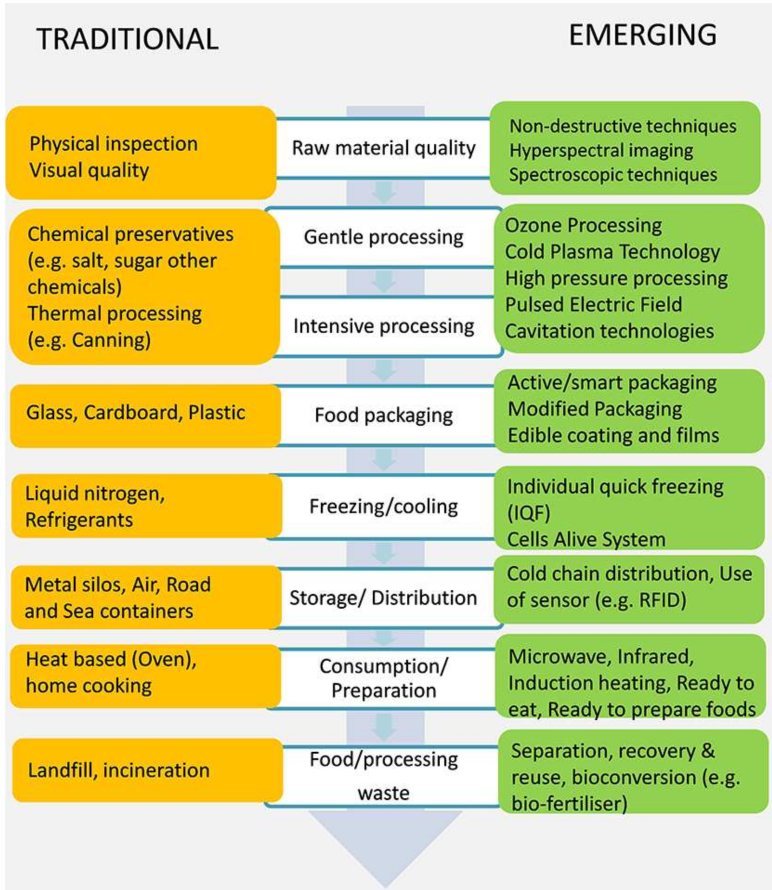


Figure 1-4 Traditional and emerging technologies used along the food chain (Knorr et al., 2020)

The figure 1-4 illustrates the advantages of sensor technologies from farm to fork by highlighting the shift from traditional methods to advanced, non-destructive techniques and real-time monitoring. These emerging technologies enhance quality control, optimize processing and storage, and reduce waste, ultimately improving the overall efficiency and sustainability of the food supply chain.

1.3 FOOD PACKAGING

The food industry is increasingly prioritizing packaging development for several reasons. Firstly, packaging plays a crucial role in preserving food effectively and minimizing packaging waste, while also ensuring the production of high-quality products with longer shelf lives. Secondly, packaging serves a vital protective function for food products, safeguarding them from physical damage, contamination, and spoilage during storage and transportation. Thirdly, packaging plays a key role in attracting customer interest by providing essential information about the packaged products and influencing customers' perceptions, including product attractiveness and purchase decisions. As shown in figure 1-5 traditional food packaging offers limited information, basic protection, and manual monitoring, but smart food packaging, provides enhanced protection, traceability and safety, real-time monitoring, and interactive features. This highlights the advanced capabilities and benefits of smart packaging in improving food safety and quality.

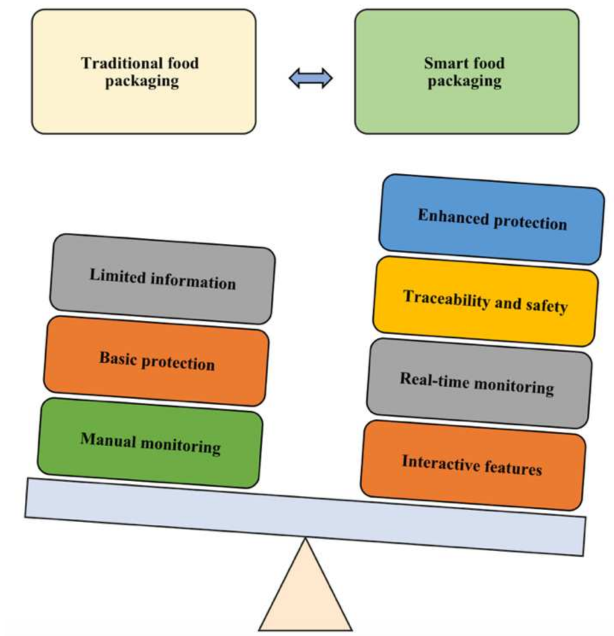


Figure 1-5 Traditional VS Smart Food Packaging (Bhatlawande et al., 2024)

Properly implemented food packaging processes are essential to guarantee the safety of consumable products and maximize their shelf life. One of the innovation solution is the development of new types of packaging, including intelligent packaging, active packaging, and smart packaging. As shown in Table 3, *active packaging,* contains active compounds that prolong the shelf life of food products by releasing substances that inhibit bacterial growth and absorb oxygen and water vapor within the packaging, *intelligent packaging* integrates indicators, sensors, and data carriers to monitor factors such as freshness, carbon dioxide, oxygen, and temperature of food products in real-time. As shown in Figure 1-6, *smart packaging* combines elements of both intelligent and active packaging, offering comprehensive monitoring and preservation capabilities. (Dirpan et al., 2023a)

Table 3 Classification of Active & Intelligent Packaging (Bhatlawande et al., 2024)

Active Packaging	Intelligent Packaging
Oxygen scavenger	Intelligent indicators
CO2 scavenger	Time-temperature indicators
Ethylene scavenger	RFID & NFC tracking system
Self heating/ Cooling can	Gas & quality sensors
Anti-oxidant releasers film	Interactive packaging

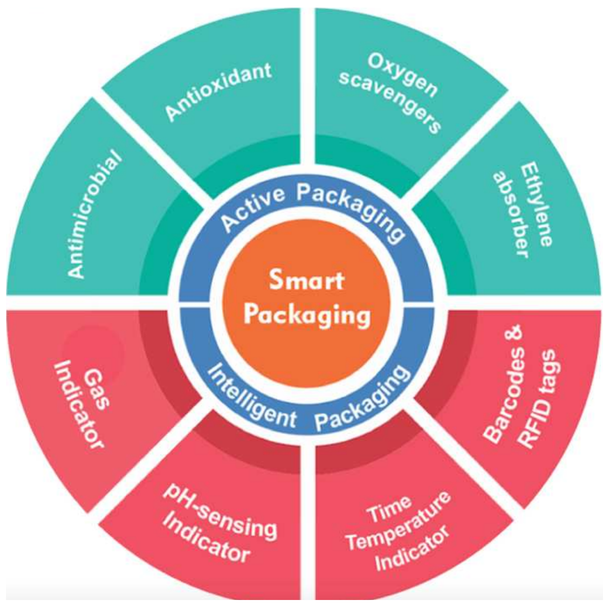


Figure 1-6 Principle of Smart Packaging (Dirpan et al., 2023b)

The assessment of smart packaging technology within the food sector is critical given the increasing concerns about food waste and foodborne diseases on a global scale. With approximately one third of all food produced being lost or wasted and an estimated 600 million people suffering from foodborne illnesses each year (Havelaar et al., 2015), smart packaging offers a potential solution to address these pressing issues. By reducing food waste and enhancing food safety, smart packaging technology holds promise in improving the efficiency, safety, and sustainability of the food supply chain (Dirpan et al., 2023a).

RFID and NFC technologies have become integral components of smart food packaging, enabling seamless tracking and tracing of products throughout the supply chain. By attaching RFID tags or NFC-enabled labels to food packages, companies can monitor the location, temperature, and other pertinent data in real-time, enhancing traceability, reducing the risk of counterfeiting, and bolstering food safety measures. This advanced monitoring capability facilitates quick recalls in the event of contamination or other hazards, minimizing potential health risks to consumers and safeguarding brand reputation. The adoption of RFID and NFC technologies in food packaging not only optimizes operational efficiency but also fosters consumer confidence by ensuring the authenticity and safety of the products they purchase (Bhatlawande et al., 2024).

1.4 OBJECTIVE

The objective of the thesis is to evaluate the environmental footprint savings achievable through the reduction of food loss and waste facilitated by digital tools within the European Union. Especially, this study aims to employ a scenario-based life cycle assessment (LCA) approach to comprehensively assess the potential environmental benefits of implementing the RFID technology in mitigating food loss and waste throughout the EU's raw milk supply chain. Through detailed analysis and modeling, the study seeks to quantify the environmental impacts associated with food loss and waste, and to explore how the adoption of digital tools can contribute to minimizing these impacts. It also provides insights into the effectiveness and feasibility of utilizing digital solutions as a means of achieving sustainability goals in the context of FLW reduction within the EU.

Specifically, the study aims to achieve the required objectives through a step-by-step strategy:

- **Conducting Literature Review**

Reviewing existing studies on FLW in the EU focusing on traceability, IoT, applications and benefits of RFID technology in fresh food supply chain management. Also, examine previous LCA studies related to food supply chains and digital interventions.

- **Collecting Baseline Data**

Collecting all the data on current FLW levels in the EU's raw milk supply chain including information on the environmental impacts associated with different stages of the milk supply chain and RFID tag from production to disposal by using data and assumptions relevant to each scenario to simulate potential outcomes.

- **Establishing the LCA Framework**

The study aims to ensure the LCA framework aligns with ISO standards by defining the LCA methodology to be used, including system boundaries, functional units, and key impact categories (e.g., carbon footprint, energy use, water consumption).

- **Performing Environmental Impact Assessment**

Analyzing the environmental impacts of the milk supply chain without RFID and each RFID tag from its production to disposal. Then by comparing the results to identify potential environmental savings obtained from RFID tagging of fresh milk within the EU.

- **Conducting Scenerio Analysis**

By performing scenerio analysis, the study identifies the environmental reductions obtained through RFID tagging of fresh milk for each country in the EU and identifies the most critical environmental impact categories affecting the environmental benefits of RFID technology within the EU and estimated future reductions.

- **Discussion & Future Recommendations**

It also aims to discuss the limitations and challenges faced by RFID technology to quantify the potential environmental benefits and footprint savings achievable through the adoption and utilization of digital tools for reducing FLW within the EU. Based on the findings of the study, it provides evidence-based future recommendations and insights to policymakers, industry stakeholders, and other relevant actors on strategies for leveraging digital solutions to achieve sustainable food systems and reduce food loss and waste within the EU. These recommendations will aim to provide guidance on best practices for implementing RFID technology to maximize environmental benefits.

By addressing these objectives, the study aims to systematically evaluate the environmental footprint savings achievable through RFID technology in reducing FLW in the EU's milk supply chain and contributing valuable knowledge and insights to the ongoing efforts towards achieving sustainable food systems and reducing FLW in the EU.

2 LITERATURE REVIEW

The literature review focuses on existing studies examining FLW, highlighting the substantial environmental impacts of inefficiencies in the supply chain. The researches have documented the potential of digital tools, such as RFID technology, to enhance supply chain management by providing real-time monitoring and data analytics, which can significantly reduce food spoilage and waste. Previous LCA studies have demonstrated the benefits of digital interventions in food supply chains, though comprehensive assessments specifically targeting the raw milk supply chain are limited. Accurate measurement of FLW is essential for identifying inefficiencies, developing waste reduction strategies, and assessing intervention effectiveness. Digital tools play a crucial role in FW reduction efforts by enabling precise measurement, tracking, and analysis of waste streams in food service operations. To address this challenge, cutting-edge technologies, LCA models, and strategic approaches are explored to monitor and optimize food shelf life within the supply chain, emphasizing interdisciplinary collaboration among experts in sensor systems, communication science, predictive biology, food technology, and supply chain management.

2.1 TRACEABILITY IN FOOD SUPPLY CHAIN

The Food and Drug Administration (FDA) defines traceability as the ability to follow the movement of a product and its ingredients through all stages of production, processing, and distribution, both backward and forward (Ranganathan et al., 2022). Ensuring traceability throughout the agricultural supply chain is essential for maintaining food safety, accountability, and sustainability. While current traceability protocols often fall short of achieving comprehensive end-to-end traceability, advancements in technology offer promising solutions. Technologies such as blockchain, RFID, IoT sensors, and cloud-based platforms enable real-time capture, storage, and analysis of traceability data, enhancing visibility and transparency across the supply chain. These systems facilitate prompt identification of issues or risks and enable targeted interventions to mitigate them effectively.

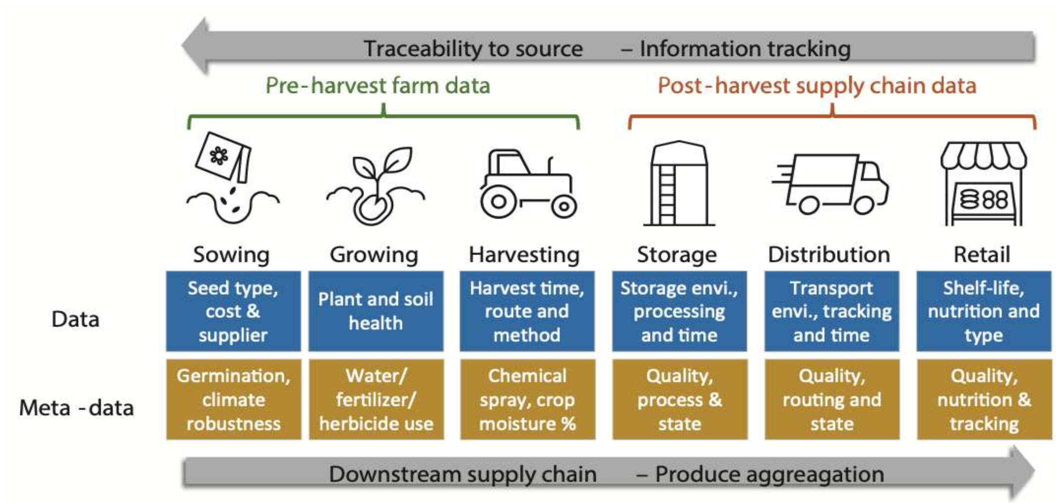


Figure 2-1 Traceability in the Agricultural Supply Chain (Ranganathan et al., 2022)

The figure 2-1 illustrates the flow of data and metadata along the food supply chain, from pre-harvest stages (sowing, growing, harvesting) to post-harvest stages (storage, distribution, retail). It highlights the traceability and information tracking of various parameters, such as seed type, soil health, harvest methods, storage conditions, and product quality, enhancing overall supply chain transparency and efficiency.

In the food supply chain, traceability works by capturing and recording detailed data at each stage, from pre-harvest activities (such as seed type and soil health) through to post-harvest processes (including storage conditions, transportation, and retail shelf-life). This comprehensive tracking allows for quick responses to any quality or safety concerns, ensuring that any compromised products can be efficiently identified and removed, thus maintaining overall supply chain integrity and food safety.

2.2 INTERNET OF FOOD/THINGS (IoT)

The emergence of IoT technologies offers a transformative potential in revolutionizing various stages of food production and supply chains. By integrating terrestrial and remote sensing capabilities, IoT facilitates precise management of agricultural processes, optimizing resource utilization while providing real-time monitoring and decision-making capabilities. Despite its significant impact on pre-harvest activities, its potential in post-harvest food loss remains largely untapped, necessitating scalable and cost-effective infrastructure to integrate IoT solutions into existing supply chain systems (Ranganathan et al., 2022). Through the deployment of IoT-enabled sensors and monitoring devices, real-time data on environmental conditions can be collected, enabling early detection of deviations and timely interventions to prevent food spoilage. Moreover, IoT-enabled traceability solutions enhance food safety, quality, and informed decision-making across the supply chain, ultimately contributing to the reduction of FLW, improved food security, and enhanced sustainability in the food system.

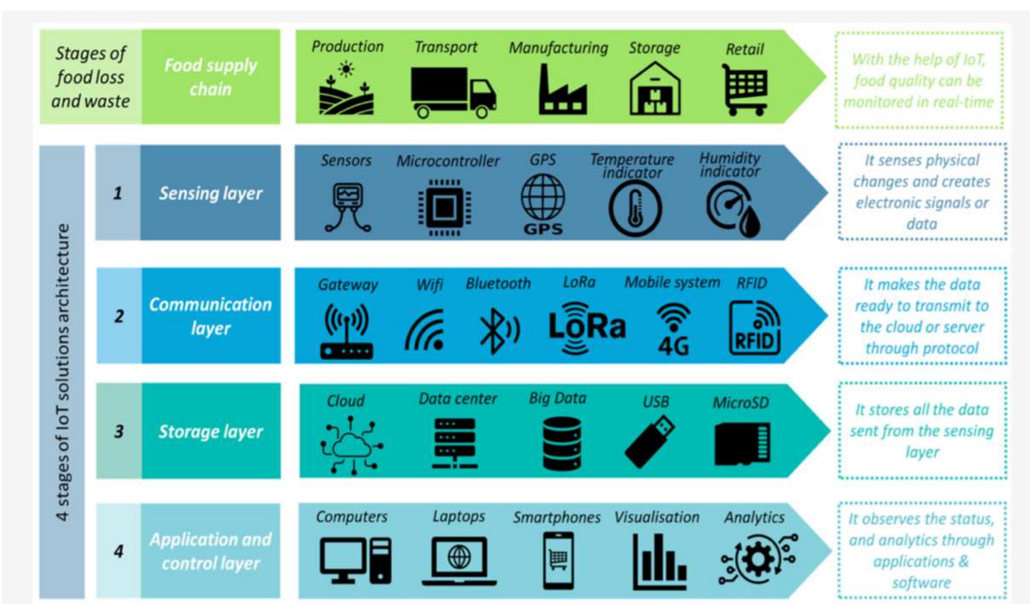


Figure 2-2 IoT architecture: (1) sensing layer, (2) communication layer, (3) storage layer, and (4) application and control layer (da Costa et al., 2022)

Referred to Zhu et al. (2022b), this approach integrates IoT sensor technology into the food supply chain through a structured process. Sensor modules embedded within food containers capture data on parameters such as temperature, humidity, ethylene levels, and environmental factors crucial for product quality and shelf life. Using a combined Wi-Fi and GPRS system, the collected data is transmitted in real-time across the supply chain as shown in figure 2-3. Stakeholders at the management level analyze this data to make informed decisions regarding storage, transportation, and logistics processes, often leveraging machine learning algorithms for predictive analytics. In response to detected anomalies or specific conditions, actuators within the sensor modules or smart devices execute commands to adjust settings or implement corrective actions as necessary, ensuring optimal product quality and safety.

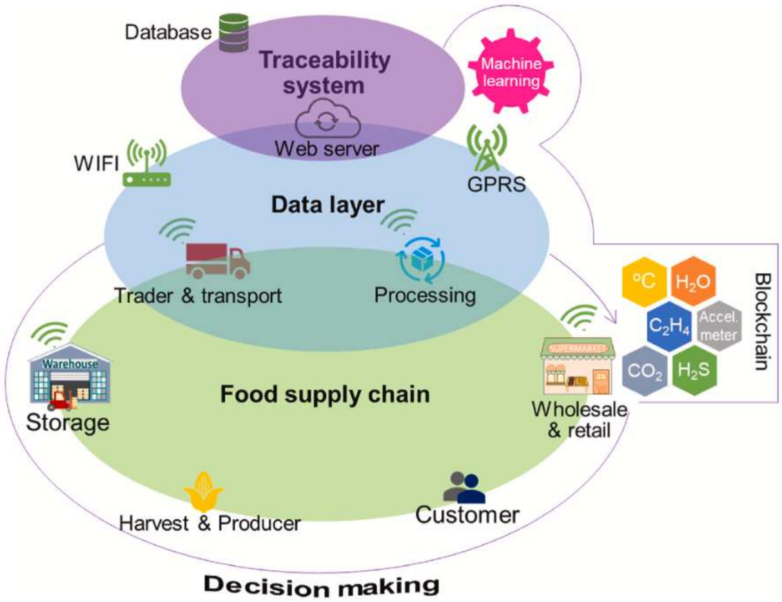


Figure 2-3 The design of the IoT system integrated with the food supply chain for environmental impact assessment (Zhu et al., 2022b)

2.3 RFID TECHNOLOGIES IN FRESH FOOD SUPPLY CHAIN

RFID technology is increasingly utilized in fresh food supply chain management for its potential to optimize logistics processes and reduce costs. It has been found that approximately 27% of fresh product waste at retail stores stemmed from incorrect replenishment policies, leading to cases of products expiring in the backroom due to improper rotation (Bertolini et al., 2013a). Unlike traditional barcodes, RFID tags can store more information and facilitate streamlined product identification, leading to increased automation, efficiency, and decreased labor costs. However, the deployment of RFID may also introduce environmental burdens due to the need for additional technical equipment and a large number of tags (Jedermann et al., 2014). Therefore, comprehensive assessments of RFID's environmental impact, including manufacturing, deployment, and end-of-life management, are necessary to fully understand its sustainability implications. Advancements in sensing and communication systems offer opportunities for real-time monitoring of product quality and environmental conditions within the supply chain. Wireless transmission of sensing data and developments in environmental sensing, such as ethylene and mould detection, present promising avenues for improving food quality supervision (Jedermann et al., 2014). By modeling the environmental impacts of RFID deployment across various stages of the product life cycle, the valuable insights into the trade-offs and opportunities associated with RFID adoption has taken into account and assess its potential contribution to sustainability in supply chains (Bottani et al., 2014a).

An RFID tag, also called a transponder, is a compact device affixed to an object for identification and tracking purposes. As shown in Figure 2-4, it comprises a microchip, antenna, and substrate or encapsulation material. The microchip stores data, while the antenna facilitates data transmission and reception. Together, the microchip and antenna form the inlay, which is then encased in protective material like paper, plastic, or film. Typically, the tag's size is determined by the antenna's dimensions, as the microchip is usually quite small. RFID tags come in various shapes, sizes, and protective housings, with the smallest commercially available tags measuring just 0.4 × 0.4 mm^2 and thinner than a sheet of paper.

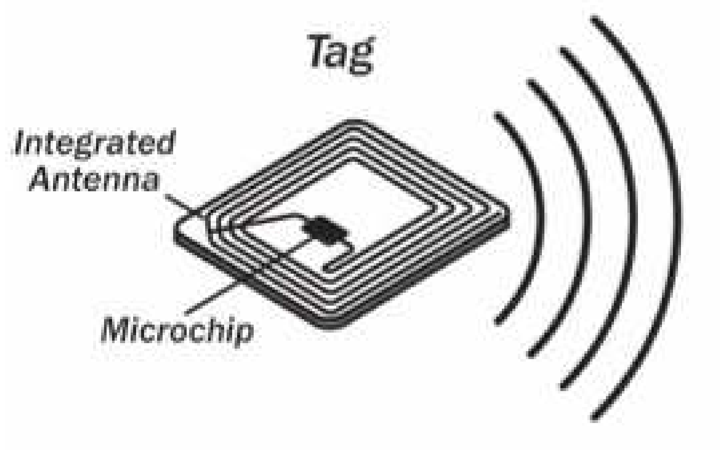


Figure 2-4 Components of RFID Tag

3 METHODOLOGY

3.1 LIFE CYCLE ASSESSMENT

The LCA is a tool for evaluating the environmental impacts of products or services across their entire lifecycle, from extraction of raw materials to final disposal. This "cradle-to-grave" approach allows for a comprehensive understanding of the environmental implications associated with a particular product or service. By examining factors such as resource use, energy consumption, emissions, and waste generation at each stage, LCA enables decision-makers to identify opportunities for improvement and make informed choices to minimize environmental harm.

The standardized framework provided by ISO 14040 (ISO 14040:2006) and ISO 14044 (ISO 14044:2006,-Life Cycle Assessment) ensures consistency and comparability in LCA studies, facilitating communication and decision-making across different stakeholders. By following the four main phases, as shown in figure 3-1, outlined in ISO 14044:2006 (Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation), LCA practitioners can systematically evaluate the environmental performance of products or services and identify opportunities for optimization.

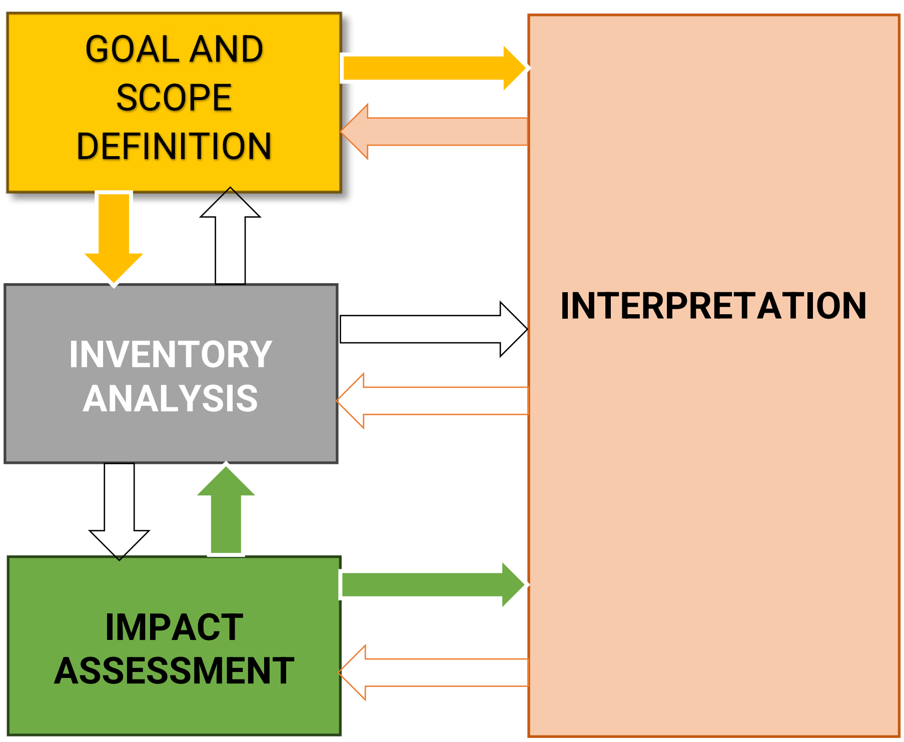


Figure 3-1 Life Cycle Assessment Framework

3.2 GOAL & SCOPE DEFINITION

3.2.1 Goal Definition

In 2022, the European Union's raw milk production reached 160.0 million tonnes, primarily consisting of cows' milk at 96% (Eurostat, Milk and Milk Product Statistics). The main goal of this study is to assess the environmental impact reduction obtained by RFID tagging of fresh milk, along each category, for each of the countries included in the EU-27. It is perfomed by analyzing the environmental profile of RFID technologies when used to identify fresh milk packaged in cartons following LCA framework. It conducts a comparative analysis to evaluate the environmental burdens associated with RFID implementation against the food savings achieved. Especially, the comparison seeks to determine whether employing RFID for tagging fresh milk cases is environmentally sustainable or not for the EU.

As discussed by Bertolini et al., (2013a), with the RFID implementation, a strict FIFO policy could be enforced, reducing waste caused by expired shelf life and thus lowering the associated environmental impact.

Total Fresh milk wastage at store = 27%
Total Fresh milk reaches expiry = 9.6%
Amount of product Saved with RFID tag = 27*9.6 = 2.6% (Environmental Savings)

However, the environmental impact of the RFID tag's life cycle, reflecting the additional environmental burden introduced by applying this technology to fresh products is also considered.

3.2.2 Scope Definition

The scope of this study involves conducting a LCA to evaluate the environmental impacts associated with the implementation of RFID technology in the fresh food supply chain (FSC) at the EU level. The assessment will consider the entire life cycle of RFID technology, from manufacturing and deployment to use and disposal, and examine its environmental footprint in comparison to conventional identification and tracking methods. The study will analyze various environmental factors, such as energy consumption, greenhouse gas (GHG) emissions, resource depletion, and waste generation, to provide insights into the overall sustainability of RFID implementation in the fresh food supply chain.

3.2.3 Functional Unit

The functional unit of this study is defined as the environmental impact reduction per 1 liter of fresh milk packaged in a carton using RFID technology throughout its supply chain in the EU. The RFID tag is assigned to product cases, with each containing 12 items of fresh milk, thus allocating approximately 8.3% of the tag's life cycle to each functional unit. This unit serves as the basis for evaluating the environmental impacts and sustainability of RFID technology when applied to the identification and tracking of perishable products like fresh milk.

3.2.4 System Boundaries

The system boundary for RFID tagging of fresh milk include evaluataion of two different system boundaries i.e one for life cycle of milk and the other is for RFID tag's life cycle. All the processes and impacts of the processes that has been involved in the both boundaries has been analyzed right from cradle to till the end of life of the product.

The LCA model of the RFID tag, as shown in figure 3-2, includes all phases from raw material extraction to final disposal, with a cut-off threshold of 1% of the total mass for neglected elements. The life cycle phases considered include raw material extraction, component manufacturing, assembly, transport, and end-of-life management. The RFID reader's life cycle is not assessed due to its negligible impact per tag read, considering its use over multiple tags throughout its lifetime. Similarly, other equipment used for tag reading in the supply chain, such as RFID gates, are excluded due to their high volume of tag reads relative to their individual environmental impact.

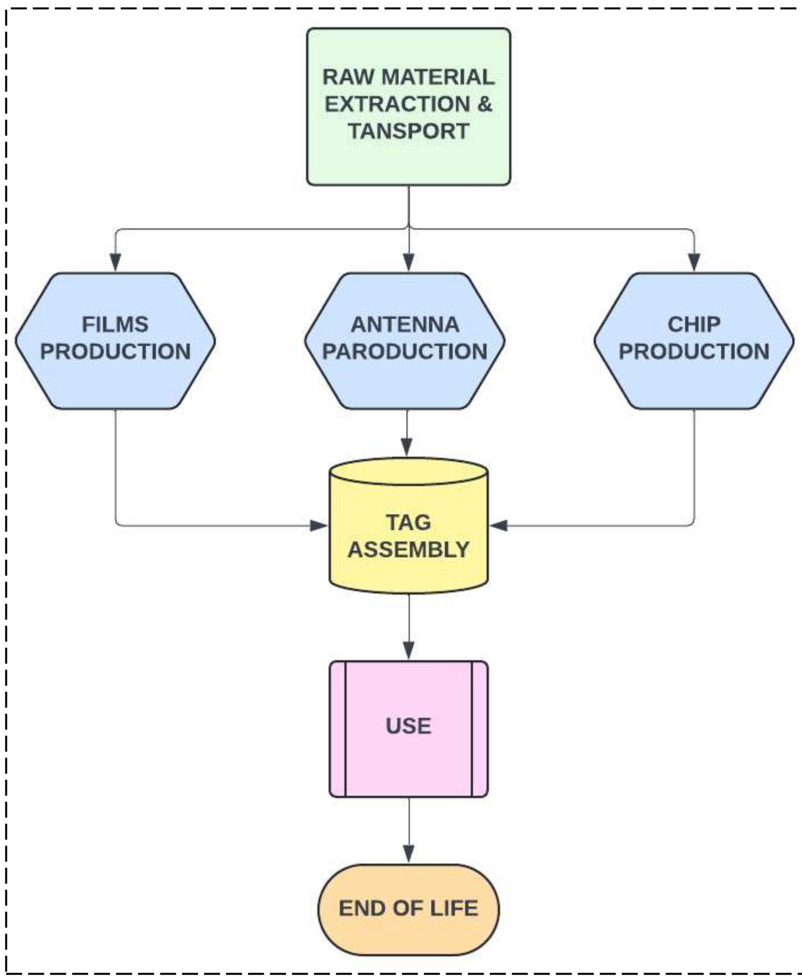


Figure 3-2 System Boundary for RFID tag's life cycle

The LCA of fresh milk encompasses both milk production and packaging with system boundaries extending to end-of-life operations such as the collection and landfill disposal of expired products and packaging materials. The milk production process, as outlined in figure 3-3, includes raw milk production at farms, transport to dairies, pasteurization, production, filling and packaging, and delivery to distribution centers. The system boundaries encompass all these phases, including crops cultivation for fodder production and direct emissions on the farm. It includes various aspects such as the production and transport of feed, fertilizers, pesticides, and packaging materials, as well as waste disposal and treatment. While buildings, infrastructure, and equipment are not within the system boundaries. In this study, a conservative approach was adopted, allocating all impacts to milk production in line with the goals. The environmental impact of milk production and packaging is considered, excluding only the refrigerated storage phase in the distribution center. As milk and its packaging are typically disposed of together, either through landfilling or alternative methods such as recycling or remanufacturing, it is considered that landfill disposal as the end-of-life scenario. This comprehensive approach allows for the evaluation of the environmental sustainability of the entire fresh milk supply chain.

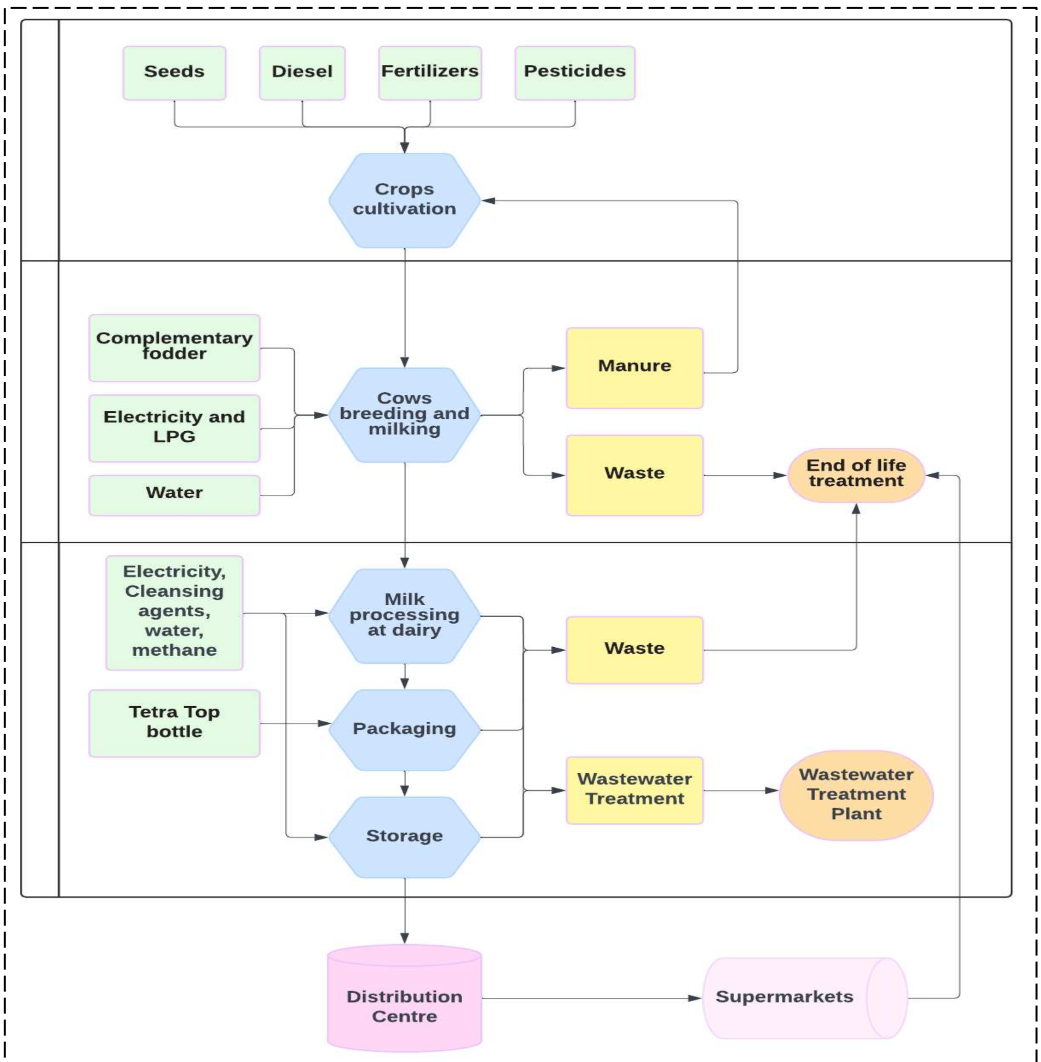


Figure 3-3 System boundary for life cycle of milk

In milk processing and packaging, RFID tags help track batches, thereby optimizing processing and reducing spoilage. In storage and distribution, RFID enhances logistical efficiency, lowering fuel consumption and emissions by reducing unnecessary transportation and storage durations. At the supermarket level, RFID ensures better stock management, reducing waste and ensuring milk freshness. Analyzing these impacts within the LCA framework helps quantify environmental benefits across the EU-27 countries by considering the reduced waste, energy savings, and lower emissions attributed to RFID technology.

3.2.5 Data Collection and Assumptions

Data for the LCA will be collected from a variety of sources, including literature reviews, International Reference Life Cycle Data System ILCD Handbook., databases like Ecoinvent, and industry reports from Smartrac company. Assumptions regarding the implementation and effectiveness of RFID in reducing milk wastage will be made based on available evidence and expert knowledge.

3.2.6 Environmental Impact Categories

The environmental impact categories considered in the assessment for RFID tagging of fresh milk include: climate change, ozone depletion, human toxicity cancer effects, human toxicity non-cancer effects, particulate matter, ionizing radiation human health, ionizing radiation ecosystems, photochemical ozone formation, acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, land use, water resource depletion, and fossil resource depletion.

3.2.7 Impact Assessment Method

In the impact assessment method, described in section 4, a comprehensive analysis has been carried out to evaluate the environmental impacts of RFID tagging for fresh milk. This involved obtaining detailed impact data for both RFID tags and milk, covering the entire lifecycle from production to disposal. By analyzing all the data, a comparison is obtained for the environmental impacts associated with RFID implementation against the baseline impacts of milk production and disposal without RFID. This comparative analysis allowed for a thorough assessment of the overall impact reduction in various categories attributable to RFID tagging of fresh milk. The results provide insights into how RFID technology can contribute to mitigating environmental impacts within the EU dairy supply chain.

3.2.8 Uncertainties Analysis

To achieve the main goal of assessing the environmental impact reduction achieved by RFID tagging of fresh milk across various categories in the EU, an uncertainty analysis was performed using a Monte Carlo simulation with 1000 runs. More details on calculating the uncertainty factors are provided in the section 4.3. This analysis was designed to account for and quantify the variability and uncertainty inherent in the data and assumptions used in the study. Fresh food supply chain accounting involves various sources of uncertainty, such as systematic errors, methodological errors, data processing errors, conversion from amounts to weight, and assumptions. By conducting this simulation, the study aimed to identify the potential range of environmental impacts reduction and determine the reliability of the results under different scenarios. The Monte Carlo simulation provided a robust framework for evaluating the sensitivity of the environmental impact reduction to various input parameters, thereby enhancing the credibility and robustness of the study's findings.

3.2.9 Scenario Analysis

By examining milk production data for each EU-27 country and assessed the environmental impact reductions achieved through RFID tagging of fresh milk, this analysis involves modeling various scenarios to quantify reductions in categories such as climate change, land use, and acidification, particulate matter, etc. for each country. By comparing scenarios with RFID implementation, identification of the specific environmental benefits of RFID tagging is obtained. Furthermore, a temporal comparison across different years to observe trends and changes in impact reductions, highlights the most significant improvements over time. This comprehensive analysis provided a detailed understanding of milk production and the environmental benefits of RFID technology across the EU-27, with insights into country-specific and year-specific variations.

On basis of this total milk production data from each country in EU-27, as shown in table 4, the total impact reductions achieved through RFID tagging of fresh milk in each of these countries has been discussed thoroughly in section 4.4.

Table 4 Annual EU-27 Milk Production 2015-2023 ('000 tons) (Statistics | Eurostat)

EU-27	2015	2016	2017	2018	2019	2020	2021	2022	2023
Belgium	4.831,31	:	4.974,07	5.088,13	5.231,65	5.365,73	5.251,58	5.270,59	4.661
Bulgaria	566,31	609,63	660,83	712,50	717,80	758,83	736,70	726,88	690
Czechia	:	:	:	3.033	3.074	3.192	3.129	3.173	3.223
Denmark	5.278,90	5.385,00	5.525,40	5.615,00	5.619,90	5.671,75	5.648,60	5.664,92	5.685
Germany	:	:	:	32.491	32.442	32.549	31.942	31.947	32.424
Estonia	729,70	719,75	751,65	779,96	777,76	801,57	821,22	829,90	860,
Ireland	7.196,37	7.690,90	8.307,10	8.647,80	8.957,60	9.316,30	9.552,00	9.087	8.710
Greece	1.350,73	1.421,00	1.465,28	1.498,30	1.472,62	1.542,79	1.593,18	1.582,34	:
Spain	:	:	:	:	:	:	:	:	:
France	26.461,05	25.781,06	25.684,85	25.672,53	25.711,67	25.770,48	25.417,90	25.242,61	23.427
Croatia	:	:	:	453	436	434	429	405	377
Italy	13.158,47	13.321,70	13.623,01	13.804,97	13.925,59	13.399,80	13.902,71	13.850,25	12.911
Cyprus	220,62	254,86	280,33	292,09	305,37	345,13	380,27	364,61	304
Latvia	:	:	911,01	832,83	871,82	880,51	907,82	909,98	829
Lithuania	:	:	:	1.367	1.358	1.360	1.349	1.363	1.352
Luxembourg	:	:	:	:	:	:	:	:	:
Hungary	:	:	:	1.535	1.576	1.626	1.739	1.700	1.652
Malta	41,57	43,13	41,03	40,41	41,27	42,11	39,85	39,18	37,

Netherlands	14.024,00	15.090,00	15.169,00	14.872,00	:	:	15.461,36	16.031,61	13.901
Austria	3.215,11	3.271,64	3.381,99	3.379,53	3.267,51	3.289,48	3.285,24	3.401,32	3.243
Poland	10.876,26	11.142,63	11.648,93	11.936	12.178	12.446	12.493	12.771	12.976
Portugal	2.008,99	1.935,43	:	1.894	1.892	1.920	1.909	1.851	1.891
Romania	1.070,42	1.153,83	1.249,91	1.385,19	1.320,76	1.350,56	1.341,72	1.360,53	1.205
Slovenia	572,30	583,66	598,40	591,38	581,54	585,26	591,27	576,75	559
Slovakia	:	:	:	818	815	834	823	824	807
Finland	2.398,13	2.389,71	2.365,90	2.353,69	2.329,66	2.362,13	2.271,90	2.215,57	2.196
Sweden	2.956,48	2.883,99	2.830,71	2.773,52	2.716,15	2.785,17	2.794,37	2.773,20	2.819

Special Value (:) = Data not available

As shown in figure 3-4, the countries, like France, Germany, and the Netherlands, the dairy production surpasses the domestic demand. So, these countries are well-positioned to export a diverse array of dairy products. On contrary, other countries, like Italy, have insufficient dairy production to meet their domestic needs and thus rely heavily on imports. In certain countries, such as Poland, milk production falls short of the volumes required by dairy processors for their operations (Statistics | Eurostat).

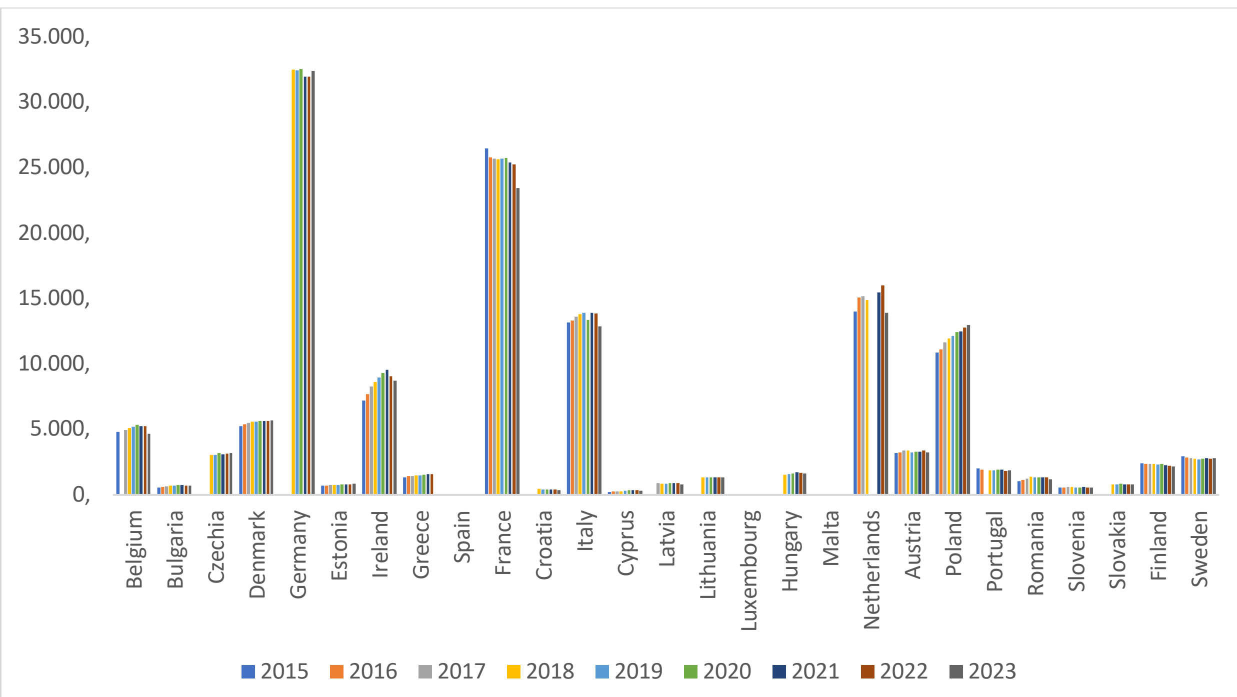


Figure 3-4 EU-27 Milk Production 2015-2023

3.3 LIFE CYCLE INVENTORY

3.3.1 Inventory analysis for the fresh milk life cycle

The production of a high-quality (HQ) milk brand sourced from two dairy factories, A and B, which collect raw milk from a total of 18 farms as described in Table 5. Dairy A obtain milk from 5 farms, while Dairy B sources from 13, with approximately half of their output dedicated to this particular brand. Notably, suppliers to Dairy B, located in mountainous regions, exhibit a lower average yearly production compared to those of Dairy A. To ensure a representative sample, farms were categorized by size (small, medium, large) based on daily milk production, with three farms from each dairy selected as representatives for data collection. This sample accounted for 60% of the total raw milk production, with the remaining farms classified based on their production volume. The study weighted data from these farms to calculate the inventory required for producing 1 liter of HQ milk.

For each farm involved in the study, comprehensive data were collected encompassing various aspects of agricultural operations. This included details on crop cultivation for fodder production, such as cultivated hectares, seed usage, and the application of fertilizers and pesticides, particularly for maize cultivation. Moreover, information on dairy cow populations, milk production, and feed composition—comprising both farm-produced forage and purchased feed—was gathered. Energy consumption, waste production, and water usage were also documented, with consideration given to the associated environmental burdens. Waste management practices, including the disposal of plastics, oils, and packaging materials, were accounted for, alongside water consumption for cleaning and sanitation purposes. Additionally, emissions related to fertilizer usage were estimated, focusing on N_2O and NH_3 airborne emissions, while methane emissions from dairy cows were assessed based on a predetermined reference value.

Table 5 Inventory analysis for dairy farms (Fantin et al., 2012)

Parameters	Units	Milk Suppliers of Dairy A			Milk Suppliers of Dairy B		
		Farm A1	**Farm A2**	**Farm A3**	**Farm B1**	**Farm B2**	**Farm B3**
Size of farms	L/farm.day	Small	Medium	Large	Small	Medium	Large
		(<2000 L/d)	(2001-6001 L/d)	(>6001 L/d)	(600 L/d)	(601-1000 L/d)	(>1001 L/d)
Dairy cows	cows/farm.yr	111	190	588	32	43	120
Other cattle	cows/farm.yr	97	205	600	28	41	110
Milk Production	L/farm.day	714300	1930000	5730000	221000	29200	1033000
	L/cow.day	22	32	32	20	22	28
Land for fodder production	ha/farm	58	70	310	34	43	70
Fodder Produced on farm							
Maize Silage	ton/farm.yr	1400	2200	10000	280	400	900
Maize Grains	ton/farm.yr	:	400	1200	:	:	:
Barley Grains	ton/farm.yr	23	:	:	:	:	:
Barley Silage	ton/farm.yr	:	:	560	:	:	:

Rye Grass silage	ton/farm.yr	:	:	1200	:	:	:
Hay	ton/farm.yr	400	:	:	250	180	400
N from manure	kg N/farm.ha	156	172	167	80	30	122
N from chemical fertilizers	kg N/farm.ha	22	129	68	83	79	147
P from manure	kg P/farm.ha	54	192	148	45	51	82
P from chemical fertilizers	kg P/farm.ha	8	0	0	10	13	17
Electricity Consumption	kWh/farm.yr	19000	80500	335000	14700	23000	26800
Purchased feed							
Ground Maize	ton/farm.yr	220	300	:	:	66	115
Straw	ton/farm.yr	30	280	540	0,5	:	15
Hay	ton/farm.yr	:	440	1210	22	:	81
Cotton seeds	ton/farm.yr	:	:	300	:	:	:
Soy seeds	ton/farm.yr	:	:	260	:	:	:
Soy flour	ton/farm.yr	:	:	830	:	:	:
Complementary fodder	ton/farm.yr	140	370	220	110	60	250
Energy consumption							
Diesel	L/farm.yr	25000	82000	125000	8800	10000	47000
GPL	L/farm.yr	710	3200	3600	2700	0	0

Special Value (:) = Data not available

Following the milking process and storage at farms, raw milk is transported to dairies where it undergoes quality control checks. Dairy A accounted for 85% of the overall production of the HQ milk, while dairy B contributed 15%. Both dairies also produced other milk variants. The total production volume of HQ milk amounted to 7.7 million liters. Yearly data on electricity and methane consumption were collected from each dairy. This data is then allocated on a mass basis according to the yearly overall milk production and the specific yearly production of the HQ milk product, as shown in Table 6.

At the dairies, the milk undergoes a pasteurization process, beginning with preheating to 51°C and skimming, which removes impurities and adjusts the milk to the desired fat content. In the second step, the milk is heated to a temperature range of 74-77°C for 15 seconds to ensure pasteurization. Following this, the milk is rapidly cooled down to 2°C and then stored. This process ensures that the milk is safe for consumption and retains its nutritional quality. The next phase involves packaging the milk in Tetra Top® bottles, which are produced directly at the dairies. These bottles are made of paperboard with an injection-moulded plastic top. After the milk is filled into the Tetra Top® bottles, they are capped, packed into cardboard boxes, placed on pallets, and wrapped with polyethylene films. This packaging process ensures that the milk is protected and remains fresh until it reaches the consumer. Once packaged, the milk is stored in refrigerated cells using cooling fluids such as glycol to maintain the required temperature. The packaged milk is then delivered to distribution centers. The trucks, storage silos, and pasteurization plants are cleaned using Cleaning in Place (CIP) systems, which involve several rinses with hot and cool water, along with the use of sodium hydroxide and nitric acid. The environmental burdens associated with the production of these cleaning agents and other detergents used for disinfection and maintenance were assessed. Data on water consumption for pasteurization, cleaning, and sanitizing at the dairies were also collected. These cleaning processes are crucial for maintaining hygiene and ensuring the safety of the milk. Data were collected on the amount and destination of waste produced at the dairies, which mainly includes plastic, oils, cardboard, and paper. Dairy B operates its own wastewater treatment plant, whereas Dairy A discharges its wastewater directly into a municipal wastewater treatment plant. To calculate the inventory of 1 liter of HQ milk, the data were weighted by the HQ milk production volume of the dairies. This approach ensures that the inventory accurately reflects the production processes and environmental impacts specific to the HQ milk product. By combining primary data on electricity and methane consumption, packaging materials, water use, and waste management with secondary data from Ecoinvent, a detailed and accurate inventory was developed, providing insights into the sustainability and environmental footprint of HQ milk production, as shown in Table 6.

For milk transportation to stores and supermarkets by trucks, an average distance of 100 km for product delivery is adopted as an assumption based on literature (Spielmann et al., 2007). As for disposal operations, we assumed an average distance of 50 km between the retail store and the landfill, based on interviews with retailers. In addition to the average distance of 50 km between the retail store and the landfill, disposal operations include several key treatment processes. Upon arrival at the landfill, waste undergoes sorting and separation, compaction to optimize space, and covering to minimize exposure and reduce environmental hazards. Environmental controls such as leachate management and gas collection systems are implemented to prevent soil and water contamination and to capture methane emissions.

Table 6 Materials and energy consumption at dairies

Parameters	**Units**	**Dairy A**	**Dairy B**
HQ milk production	L /year	6,546,500	1,160,870
Water	m^3 / L	4.6E-03	4.0E-03
Electricity	KWh / L	5.6E-02	1.1E-01
Methane	m^3 / L	9.0E-03	2.7E-02
Detergents	kg / L	1.1E-04	2.5E-04
Nitric acid	kg / L	5.8E-04	9.6E-04
Sodium hydroxide	kg / L	1.7E-03	3.1E-03
Wrapping film	kg / L	5.9E-04	3.8E-03
Cardboard	kg / L	1.8E-02	8.1E-03

Note: Data refer to the production of 1L of HQ milk.

3.3.2 Inventory analysis for the RFID tag's life cycle

The RFID tag comprises several components laminated together, with the main elements being the silicon chip for storing information and the aluminum antenna for capturing radio frequency waves. Data on component materials and weights were provided by the Smartrac company (*Avery Dennison Smartrac | Avery Dennison | RFID*, n.d.) as shown in Table 7 below. For the antenna and chip production, data from studies on similar processes were utilized, with adjustments made for differences in thickness and complexity. Energy consumption during assembly and transportation activities was also considered, with estimates based on data provided by Smartrac and relevant literature. Transportation distances and modes were assumed based on typical manufacturing and distribution processes, with environmental impact assessments conducted using inventory data.

From a functional perspective, the RFID tag comprises two primary components: the silicon chip, responsible for storing tag information, and the aluminum antenna, enabling the capture of radio frequency waves from reader antennas (Bottani et al., 2014b). The chip consists of silicon and a tetravalent metal semiconductor, while the antenna is exclusively made of aluminum, produced through a deposition process. Adhesive layers, composed of acrylic and epoxy resins, are used to join these elements together. Consequently, the total weight of a tag amounts to approximately 0.2 grams, as provided by Smartrac company (Avery Dennison Smartrac | Avery Dennison | RFID, n.d.).

A conservative approach was taken, estimating the environmental impact of the tag antenna by reducing the impact of the printed wiring board antenna by a factor of 4, likely resulting in an overestimation of the tag antenna's real environmental impact. The environmental impact of the chip production for integrated circuits was estimated with a conservative approach halving the impact due to the thinner tag chip compared to the wafer which has 2.5 times more thickness than tag chip as described in the literature, likely resulting in an overestimation of the tag chip's environmental impact (Hischier, 2009).

The amount of electricity consumed during the assembly phase is approximately 0.007 kWh per tag as provided by Smartrac company and the environmental impact of energy consumption during the phase, was evaluated in the study conducted by Hischier et al., 2007 using the European electricity mix data i.e 2.915.687,269 GWh (Eurostat, 2023).

With regard to the transport activities, the following considerations are taken into account. The RFID tag's antenna and chip, typically manufactured in China, are air-shipped about 6,000 km to Smartrac headquarters in Stuttgart, Germany, then trucked 200 km to Stuttgart. Other tag components are sourced from suppliers near Smartrac's headquarters, with a 200 km truck journey. Outbound transport to Italian retail sites involves a 1,000 km plane journey from Frankfurt to Milan, plus a 200 km truck journey to the deployment sites (Spielmann et al., 2007).

RFID tags attached to milk cartons end up in landfills, where they contribute to electronic waste. Once a milk carton is emptied, consumers typically dispose of it along with household waste. In most cases, the entire carton, including the RFID tag, is thrown into a general waste bin rather than being separated for recycling. The unsorted waste, including milk cartons with RFID tags, is then transported to landfills. In the landfill, RFID tags, along with other waste materials, are deposited and buried. Given the small size and quantity of RFID tags, the overall impact is relatively minimal compared to other electronic waste.

Table 7 Inventory analysis for each tag composition

Component	Material	Description	Weight (g)	%
Face material	Polymer	PET	0.024	11.27%
Adhesive	Adhesive	Acrylate	0.036	16.89%
IC	Ceramics	Si	0.000149	0.07%
ACA	Adhesive	Epoxy based material	0.000021	0.01%
Antenna	Metals	Al	0.00963	4.52%
Adhesive	Adhesive	Acrylate	0.0072	3.38%
Substrate	Polymer	PET	0.1	46.96%
Adhesive	Adhesive	Acrylate	0.036	16.89%

4 IMPACT ASSESSMENT

The data gathered in the inventory analysis serve as the foundation for the impact assessment phase, which aims to analyze the potential environmental impacts of the system in terms of emissions, environmental releases, and resource consumption. The analysis focuses solely on the classification and characterization stages of impact assessment. This method facilitates the proper application of characterization factors for impact assessment, as advised in the ILCD guidance document (European Commission, 2010). The method encompasses a range of impact categories, including climate change, ozone depletion, human toxicity (cancer and non-cancer effects), particulate matter, ionizing radiation (human health and ecosystems), and various others. These categories are evaluated using characterization models and factors classified into different levels i.e interim based on their quality, with interim being the least mature.

4.1 OVERALL IMPACTS

Both the positive and negative impacts resulting from RFID tagging fresh milk are being considered, beginning with an assessment of two LCA models: the environmental burden from manufacturing one RFID tag and from the life cycle of 1 litre of fresh milk disposed in a landfill.

4.1.1 Impact analysis for RFID tag and fresh milk

Table 8 presents the impact assessment results (positive contribution) of one RFID tag, illustrating the environmental burden caused by each tag's life cycle.

Table 8 Impact analysis for RFID tag

Impact category	Unit	Total
Climate change	kg CO_2 eq	0.0329
Ozone depletion	kg CFC-11 eq	3.03E-09
Human toxicity, cancer effects	CTUh	5.03E-09
Human toxicity, non-cancer effects	CTUh	2.86E-09
Particulate matter	kg PM2.5 eq	1.21E-05
Ionizing radiation HH	kg U235 eq	0.0171
Ionizing radiation E (interim)	CTUe	5.31E-08
Photochemical ozone formation	kg NMVOC eq	7.69E-05
Acidification	molc H+ eq	0.000156
Terrestrial eutrophication	molc N eq	0.000264
Freshwater eutrophication	kg P eq	2.39E-05
Marine eutrophication	kg N eq	2.97E-05
Freshwater ecotoxicity	CTUe	0.0663
Land use	kg C deficit	0.0272
Water resource depletion	m3 water eq	5.76E-05
Mineral, fossil & renewable resource depletion	kg Sb eq	1.2E-07

Figure 4-1 visually represents these results, highlighting the contribution of each process to the tag's overall environmental impact. Notably, the antenna manufacturing stands out with the highest environmental impact across all categories, contributing from 36% to 73%, averaging at 64%. Besides, chip manufacturing demonstrates significant impact, ranging from 11% to 43%, with an average contribution of 20%. While the assembly process also makes a notable contribution (averaging at 11%), transport activities have a comparatively lesser impact, averaging at 3%. Other processes collectively contribute less than 2% to the total impact.

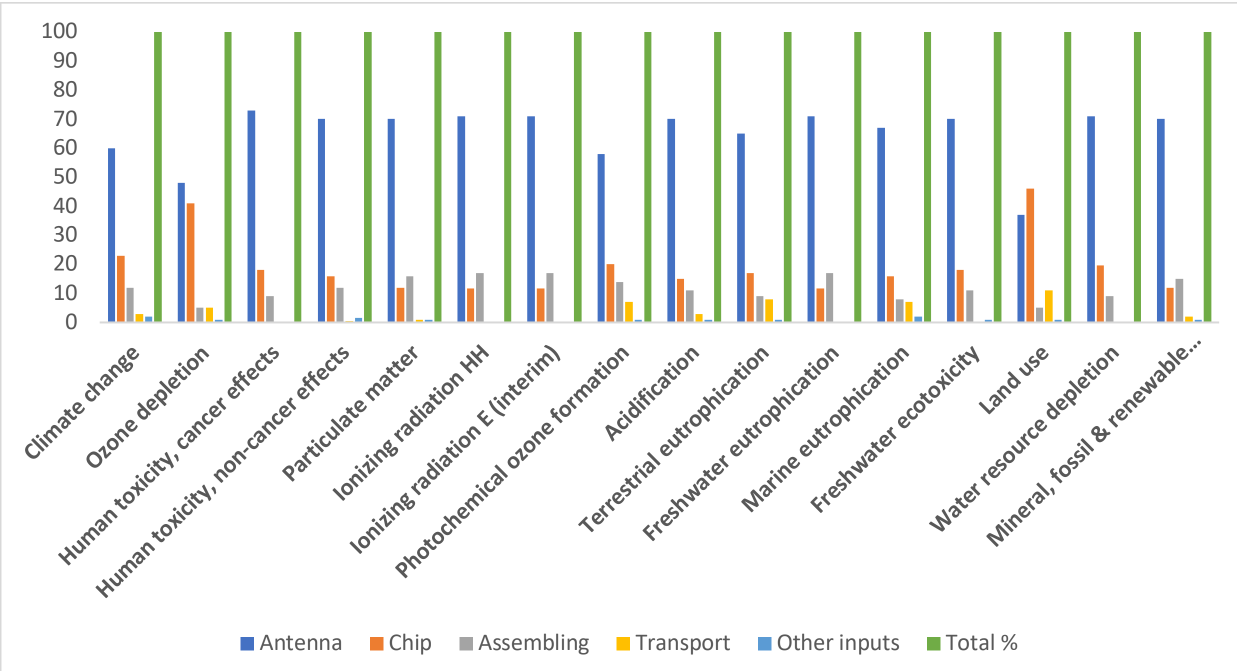


Figure 4-1 Impact Analysis for RFID tag

The environmental impacts of 1 litre of fresh milk is analyzed across various categories. The calculations shown in Table 9 encompass all phases of the milk's life cycle, from the farm phase to its disposal in a landfill. Notably, the impacts from fodder production through product delivery to the distribution center indicate that these phases contribute to approximately 90% of the total impact. Consequently, the life cycle phases like milk transportation to the retail store and disposal in a landfill, contribute to the environmental impact by approximately 10%.

Table 9 Impact analysis for fresh milk from farm to EOL phase

Impact category	**Unit**	**Total**
Climate change	kg CO_2 eq	1.34
Ozone depletion	kg CFC-11 eq	6.63E-08
Human toxicity, cancer effects	CTUh	3.1E-08
Human toxicity, non-cancer effects	CTUh	3.8E-07
Particulate matter	kg PM2.5 eq	0.00109
Ionizing radiation HH	kg U235 eq	0.087

Ionizing radiation E (interim)	CTUe	2.66E-07
Photochemical ozone formation	kg NMVOC eq	0.00369
Acidification	molc H+ eq	0.0386
Terrestrial eutrophication	molc N eq	0.169
Freshwater eutrophication	kg P eq	0.000172
Marine eutrophication	kg N eq	0.00916
Freshwater ecotoxicity	CTUe	1.7
Land use	kg C deficit	20.9
Water resource depletion	m^3 water eq	0.0132
Mineral, fossil & renewable resource depletion	kg Sb eq	6.75E-07

4.2 CONTRIBUTION ANALYSIS

Assessing the environmental sustainability of RFID technology deployment for tagging milk product cases involves a comprehensive analysis of both positive and negative impacts. Table 10 provides a detailed breakdown of these impacts for each milk case, offering insights into the relative contributions of RFID implementation. The positive impact, equivalent to 8.3% ((1/12)*100) of a tag's life cycle, reflects the attachment of RFID tags to milk cases, each containing 12 items. Similarly, the "Avoided milk disposal" column quantifies the benefits of RFID deployment, representing 2.6% of the milk life cycle. By considering both positive and negative impacts, the overall environmental impact of RFID implementation could be assessed. Among the impact categories, one particularly important outcome is the reduction in CO_2 equivalent achieved through RFID deployment. For each functional unit, the RFID implementation leads to a decrease of approximately 32 grams (i.e., 0.0027–0.0349) of CO_2 equivalent. This reduction is significant, especially considering the pressing issue of global warming and the imperative to curb greenhouse gas emissions.

Table 10 Comparison of positive and negative impacts of RFID implementation for fresh milk tagging

Impact category	**Unit**	**Tag life cycle**	**Avoided milk disposal**	**Variation**	**Percentage ratio**
Climate change	kg CO2 eq	0.0027	0.0349	-0.0322	7.74%
Ozone depletion	kg CFC-11 eq	2.5E-10	1.72E-09	−1.47E-09	14.53%
Human toxicity, cancer effects	CTUh	4.2E-10	8.06E-10	−3.86E-10	52.11%
Human toxicity, non-cancer effects	CTUh	2.4E-10	9.88E-09	-9.64E-09	2.43%
Particulate matter	kg PM2.5 eq	1,00E-06	2.83E-05	−2.73E-05	3.53%
Ionizing radiation HH	kg U235 eq	0.00143	0.00226	-0.00083	63.27%

Ionizing radiation E (interim)	CTUe	4.42E-09	6.93E-09	-2.51E-09	63.78%
Photochemical ozone formation	kg NMVOC eq	6.4E-06	9.6E-05	−8.96E-05	6.67%
Acidification	molc H+ eq	1.3E-05	0.001	-0.000987	1.30%
Terrestrial eutrophication	molc N eq	2,00E-05	0.0044	-0.00438	0.45%
Freshwater eutrophication	kg Peq	1.99E-06	4.48E-06	-2.49-06	44.42%
Marine eutrophication	kg N eq	2.46E-06	0.00024	-0.000237	1.03%
Freshwater ecotoxicity	CTUe	0.0055	0.0442	-0.0387	12.44%
Land use	kg C deficit	0.002	0.545	-0.543	0.37%
Water resource depletion	m3 water eq	4,00E-06	0.000343	-0.000339	1.17%
Mineral, fossil & renewable resource depletion	kg Sb eq	1,00E-08	1.75E-08	-7.5E-09	57.14%

Examining the data reveals significant reductions in various environmental impact categories due to RFID deployment. Notably, terrestrial eutrophication, land use, acidification, human toxicity non-cancer effects, particulate matter, and water resource depletion demonstrate the most substantial reductions. The progress of environmental performance is very significant across the different impact categories. For example, approximately 50% reduction in impacts is indicated by human toxicity, cancer effects, human health ionizing radi- ation, ionizing radiation ecosystems, freshwater ecotoxicity and resource depletion. On the other hand, other impact categories, the reduction accounts for more than 85%. On average, the environmental benefits exceed the impacts by more than 5 times, indicating a clear net positive outcome from RFID implementation. Furthermore, these reductions underscore the potential of RFID technology to mitigate environmental harm across multiple dimensions, contributing to overall sustainability goals.

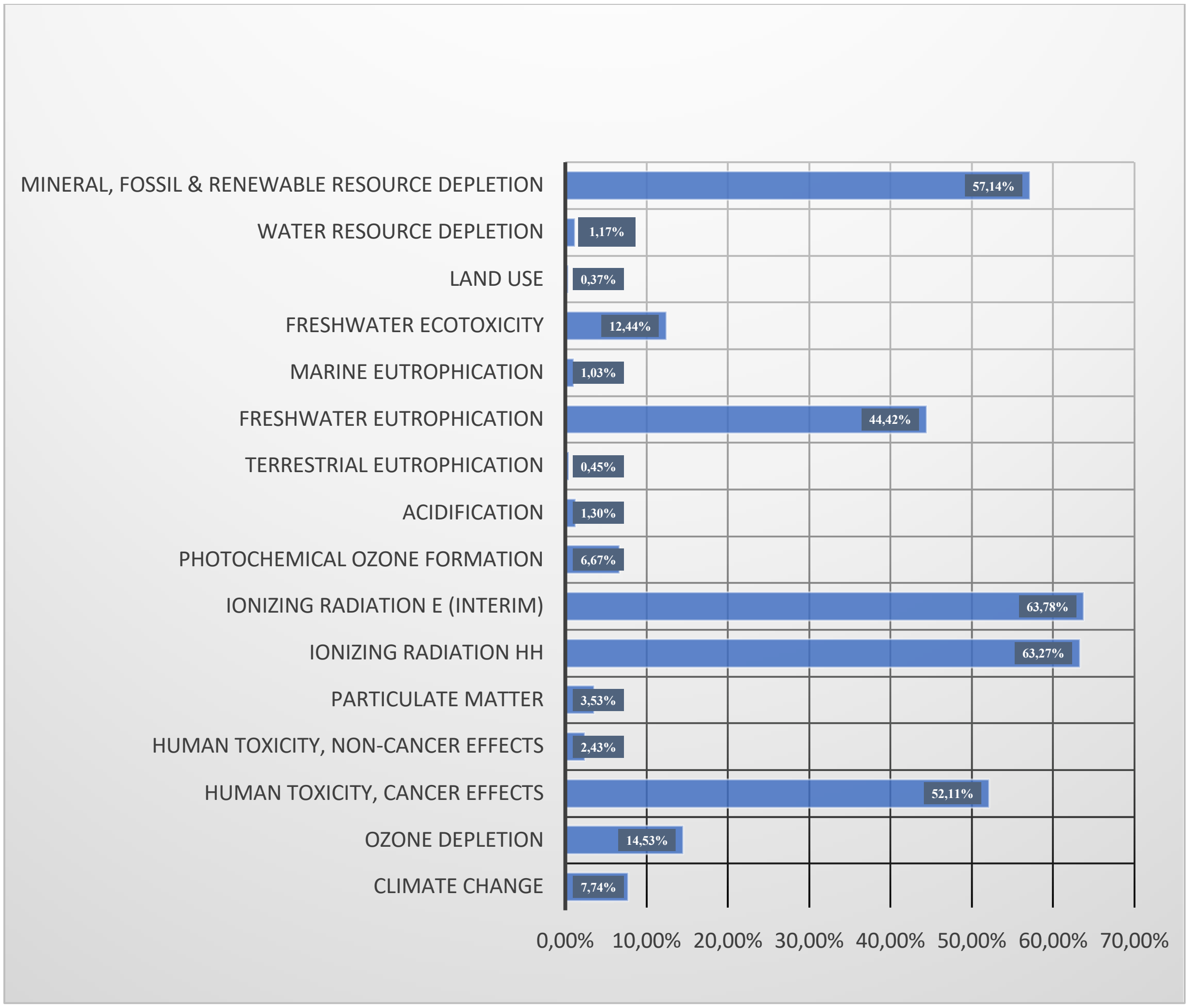


Figure 4-2 Comparison of positive and negative impact of RFID implementation for fresh milk tagging

A comparative analysis between the environmental burdens of the milk life cycle and the impacts alleviated through RFID technology implementation has been carried out. The findings of the analysis illustrate a reduction in environmental burdens across various categories owing to RFID deployment. For instance, CO_2 equivalent emissions decrease by 2.40% when RFID is utilized to prevent product loss as shown in Table 11. Notably, climate change, ozone depletion, human toxicity (non-cancer effects), particulate matter, and other categories experience reductions exceeding 2%, highlighting the significant environmental benefits associated with RFID technology adoption in milk supply chain.

Table 11 Percentage due to RFID tagging

Impact Category	Unit	Total Milk Emissions	Reduction	Percentage Reduction (%)
Climate change	kg CO2 eq	1,34	0,0322	2,40
Ozone depletion	kg CFC-11 eq	6,63E-08	1,47E-09	2,22
Human toxicity, cancer effects	CTUh	3,10E-08	3,86E-10	1,25
Human toxicity, non-cancer effects	CTUh	3,80E-07	9,64E-09	2,54
Particulate matter	kg PM2.5 eq	0,00109	2,73E-05	2,50
Ionizing radiation HH	kg U235 eq	0,087	0,00083	0,95
Ionizing radiation E (interim)	CTUe	2,66E-07	2,51E-09	0,94
Photochemical ozone formation	kg NMVOC eq	0,00369	8,96E-05	2,43
Acidification	molc H+ eq	0,0386	0,000987	2,56
Terrestrial eutrophication	molc N eq	0,169	0,00438	2,59
Freshwater eutrophication	kg Peq	0,000172	2,49E-06	1,45
Marine eutrophication	kg N eq	0,00916	0,000237	2,59
Freshwater ecotoxicity	CTUe	1,7	0,0387	2,28
Land use	kg C deficit	20,9	0,543	2,60
Water resource depletion	m3 water eq	0,0132	0,000339	2,57
Mineral, fossil & renewable resource depletion	kg Sb eq	6,75E-07	7,50E-09	1,11

Note Data refer to per 1L of HQ milk.

The comprehensive assessment is conducted on the fresh milk produced in ten years from 2017 to 2027 (OECD-FAO Agricultural Outlook 2018-2027 : DAIRY) indicates the by the implementation of RFID tagging on the fresh milk supply chain, a significant reduction in environmental burdens across various categories can be observed, as provided in Table 12. Notably, climate change, land use, ozone depletion, human toxicity (non-cancer effects), particulate matter, and other categories experience reductions that highlights the significant environmental benefits associated with RFID technology adoption in milk production

Table 12 Impacts reduction in OECD countries due to RFID tagging of fresh milk from 2017 to 2027

		Years	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Total
		Total Milk Production	353152	358372	360596	363534	366442	369512	372555	375692	378746	381881	384900	**4065382**
Impact Category	Unit	Percentage Reduction												
Climate change	kg CO2 eq	2,4	847565	860093	865430	872482	879461	886829	894132	901661	908990	916514	923760	**9756917**
Ozone depletion	kg CFC-11 eq	2,22	783997	795586	800523	807045	813501	820317	827072	834036	840816	847776	854478	**9025148**
Human toxicity, cancer effect	CTUh	1,25	441440	447965	450745	454418	458053	461890	465694	469615	473433	477351	481125	**5081728**
Human toxicity, non-cancer e	CTUh	2,54	897006	910265	915914	923376	930763	938560	946290	954258	962015	969978	977646	**10326070**
Particulate matter	kg PM2.5 eq	2,5	882880	895930	901490	908835	916105	923780	931388	939230	946865	954703	962250	**10163455**
Ionizing radiation HH	kg U235 eq	0,95	335494	340453	342566	345357	348120	351036	353927	356907	359809	362787	365655	**3862113**
Ionizing radiation E (interim)	CTUe	0,94	331963	336870	338960	341722	344455	347341	350202	353150	356021	358968	361806	**3821459**
Photochemical ozone formati	kg NMVOC eq	2,43	858159	870844	876248	883388	890454	897914	905309	912932	920353	927971	935307	**9878878**
Acidification	mole H+ eq	2,56	904069	917432	923126	930647	938092	945951	953741	961772	969590	977615	985344	**10407378**
Terrestrial eutrophication	mole N eq	2,59	914664	928183	933944	941553	949085	957036	964917	973042	980952	989072	996891	**10529339**
Freshwater eutrophication	kg Peq	1,45	512070	519639	522864	527124	531341	535792	540205	544753	549182	553727	558105	**5894804**
Marine eutrophication	kg N eq	2,59	914664	928183	933944	941553	949085	957036	964917	973042	980952	989072	996891	**10529339**
Freshwater ecotoxicity	CTUe	2,28	805187	817088	822159	828858	835488	842487	849425	856578	863541	870689	877572	**9269071**
Land use	kg C deficit	2,6	918195	931767	937550	945188	952749	960731	968643	976799	984740	992891	1000740	**10569993**
Water resource depletion	m3 water eq	2,57	907601	921016	926732	934282	941756	949646	957466	965528	973377	981434	989193	**10448032**
Mineral, fossil & renewable r	kg Sb eq	1,11	391999	397793	400262	403523	406751	410158	413536	417018	420408	423888	427239	**4512574**

The figure 4-3 shows impacts reduction in OECD countries due to RFID tagging of fresh milk from 2017 to 2027 (M). The approximate highest impact reduction is observed in human toxicity, particulate matter, land use acidification.

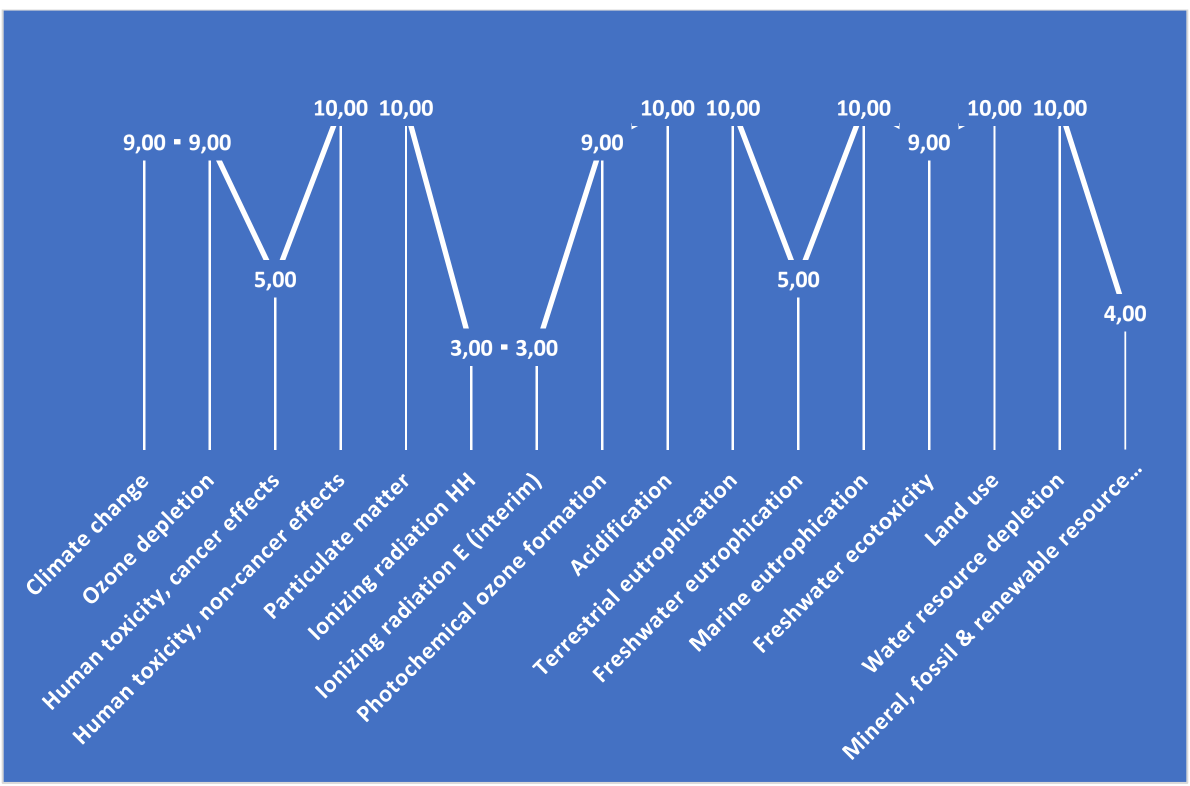


Figure 4-3 Impacts reduction in OECD countries due to RFID tagging of fresh milk from 2017 to 2027 (M)

4.3 UNCERTAINTIES ANALYSIS

The figure 4-4 shows the results of a Monte Carlo simulation with 1000 runs, which was conducted to assess the environmental impact reduction achieved by RFID tagging of fresh milk across various categories in the European Union. This analysis is a crucial part of understanding how effective RFID tagging can be in reducing the environmental footprint associated with the fresh milk supply chain. The x-axis displays intervals representing different ranges of environmental impact reduction values, labeled with intervals like [841455, 1761455], [1761455, 2581455], and so on. The y-axis indicates the frequency or count of simulation runs that fall within each intervals range, illustrating how often a particular range of impact reduction values occurred in the simulation. The chart displays a distribution of the environmental impact reduction values from the Monte Carlo simulation, with each bar representing the number of runs (out of 1000) that resulted in impact reductions within the corresponding interval range on the x-axis. The height of each bar signifies the frequency of those values. The shape of the chart suggests a normal or near-normal distribution, with most values clustering around the central intervals and fewer values in the extreme intervals. This indicates that the majority of the simulation runs resulted in environmental impact reductions within a certain middle range, with fewer runs showing very low or very high reductions.

The purpose of performing the Monte Carlo simulation in this study was to quantify the variability and uncertainty in the data and assumptions used in assessing the environmental impact reduction achieved by RFID tagging of fresh milk. The Monte Carlo simulation provides a robust framework to evaluate the sensitivity of the environmental impact reduction to various input parameters, which helps in understanding the reliability and robustness of the study's findings under different scenarios. The distribution as shown in the figure 4-4 reflects the range of possible outcomes given the inherent uncertainties in the data, such as systematic errors, methodological errors, data processing errors, and assumptions. The central tendency (most frequent values) observed in the chart indicates the typical impact reduction expected, while the spread (width of the distribution) indicates the variability and uncertainty in the results. The Monte Carlo simulation enhances the credibility and robustness of the study by providing a detailed picture of how different input uncertainties affect the final results. It allows to assess the likelihood of different impact reduction outcomes and helps in identifying scenarios where RFID tagging is most and least effective. This comprehensive analysis is crucial for strategic planning and policy-making, ensuring that decisions are based on a thorough understanding of potential outcomes and their probabilities. It offers valuable insights into the range and distribution of environmental impact reductions achieved by RFID tagging of fresh milk in the EU.

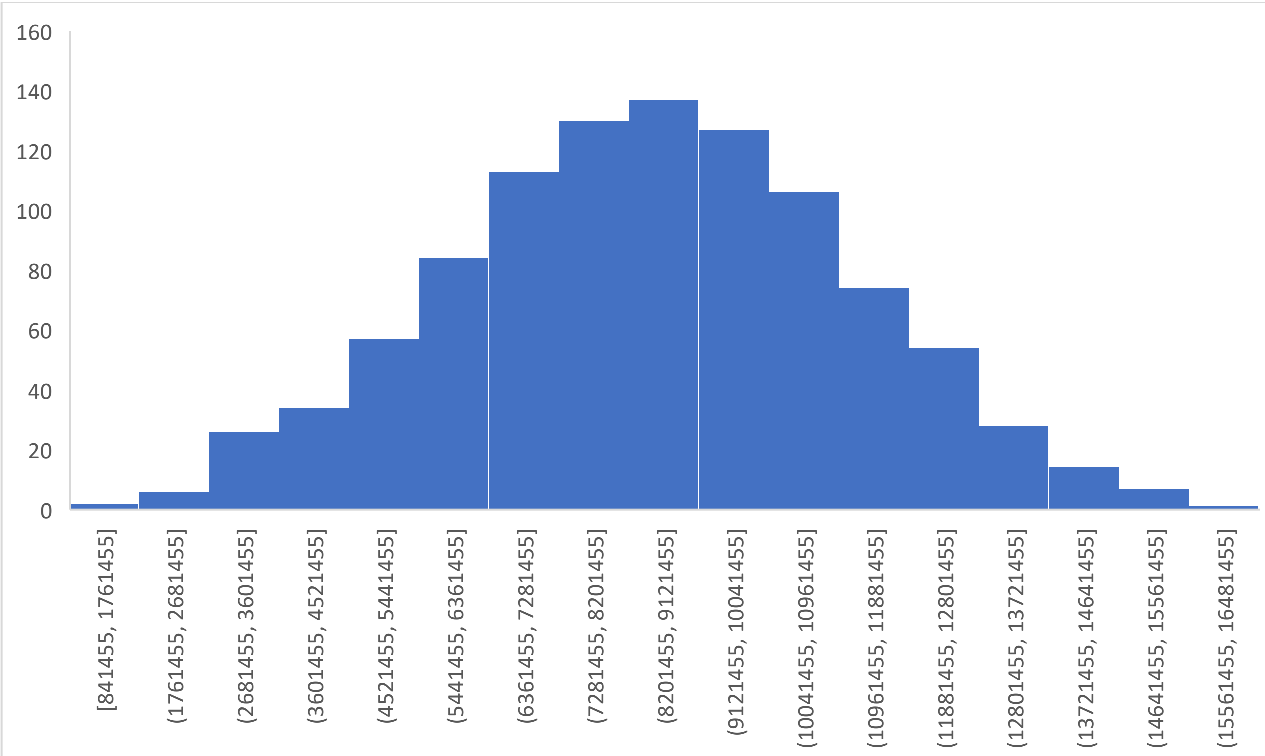


Figure 4-4 Environmental Impact Reduction from RFID Tagging of Fresh Milk: Monte Carlo Simulation Results

4.4 SCENARIO ANALYSIS

The scenario analysis presents the environmental impact reductions achieved by various categories across European countries, focusing on the years 2015 through 2023. Each country's results, explained by the bar chart, exhibit consistent trends in reducing environmental impacts across a range of categories. These categories include mineral, fossil, and renewable resource depletion; water resource depletion; land use; freshwater and marine ecotoxicity; freshwater, marine, and terrestrial eutrophication; acidification; photochemical ozone formation; ionizing radiation (both E (interim) and HH); particulate matter; human toxicity (non-cancer and cancer effects); ozone depletion; and climate change. The bar charts use different colors to represent each year, from 2015 (blue) to 2023 (gray), enabling a clear visual comparison of trends and variations within each environmental category over the observed period. This color-coding highlights how the magnitude of impact reductions varies year by year, indicating both improvements and any potential reductions in specific environmental metrics. Notable reductions are observed in several key areas in Germany, France, Netherlands and Poland. For instance, significant declines in climate change impacts, particulate matter, water resource depletion and land use suggest the positive outcomes of the RFID tagging of fresh milk over these years. These reductions indicate that efforts to mitigate environmental degradation through RFID tagging of fresh milk have been largely successful. This detailed breakdown provides valuable insights into which areas have seen the most significant improvements and which might require additional focus. The detailed categorization and annual breakdown of these reductions across the EU-27 provide valuable insights into the effectiveness of these RFID technology, guiding future strategic planning to further enhance environmental sustainability.

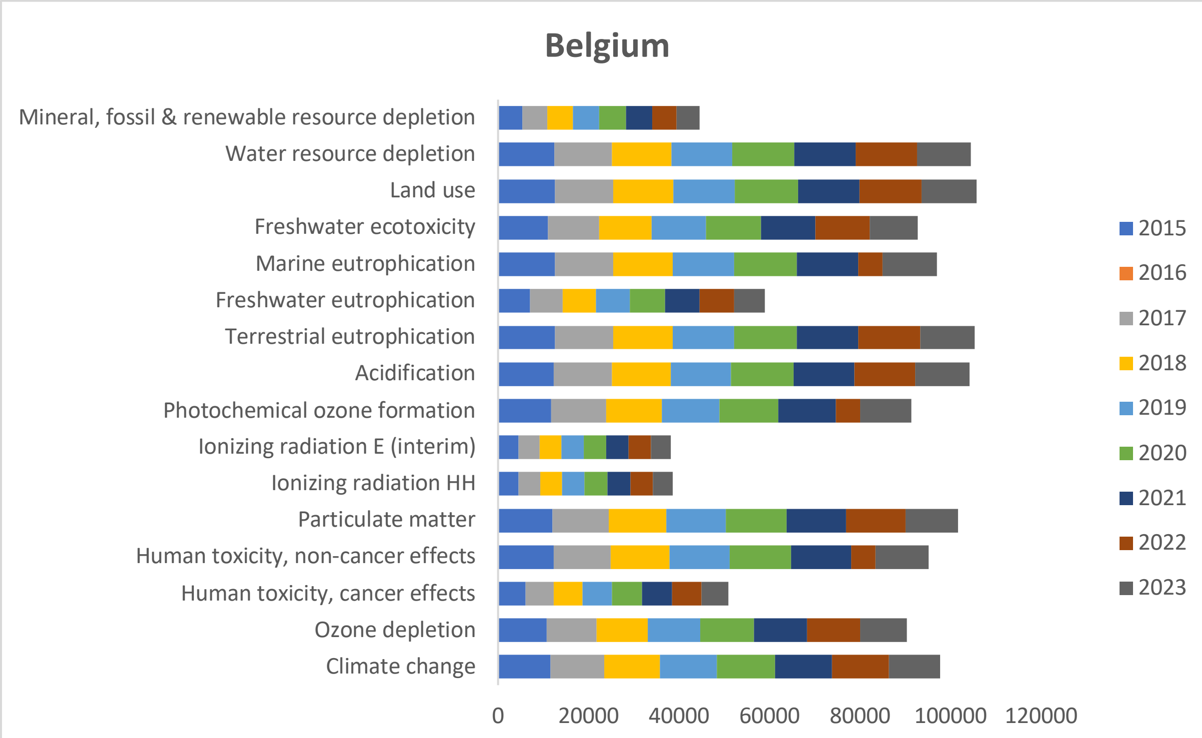


Figure 4-5 Impact Reduction Due to RFID tagging of milk in Belgium 2015-2023 ('000 tons)

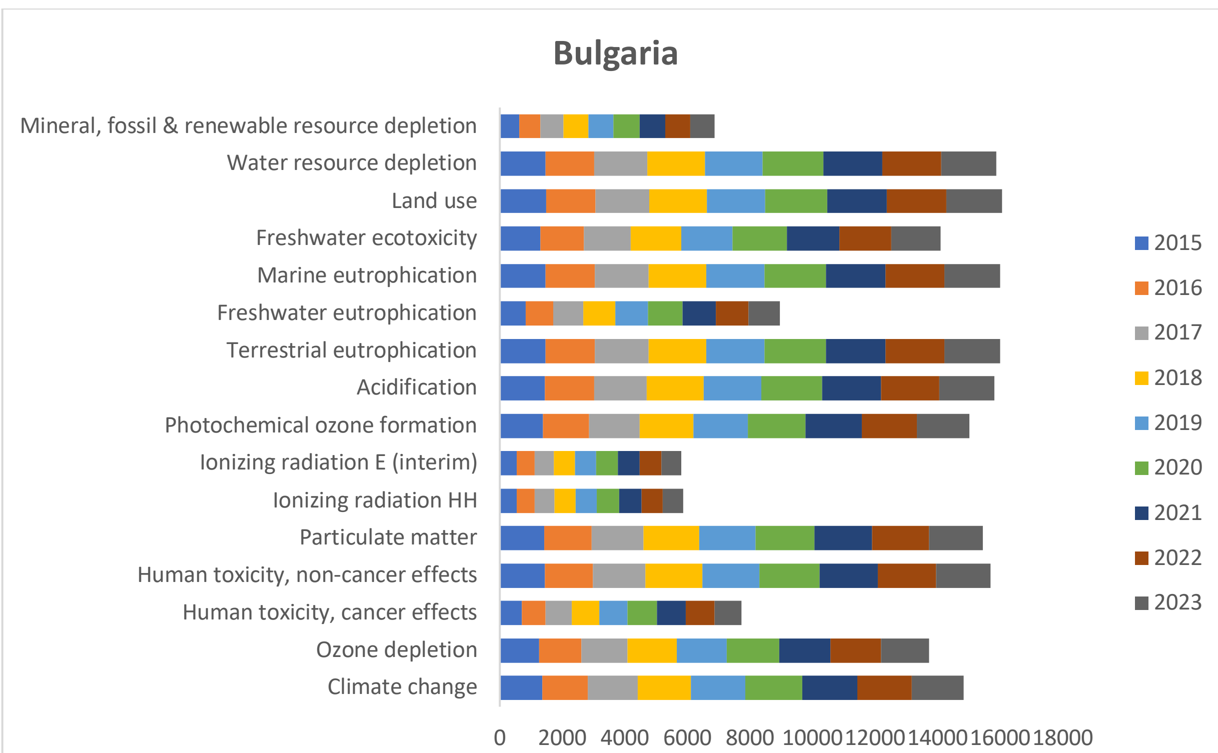


Figure 4-6 Impact Reduction Due to RFID tagging of milk in Bulgaria 2015-2023 ('000 tons)

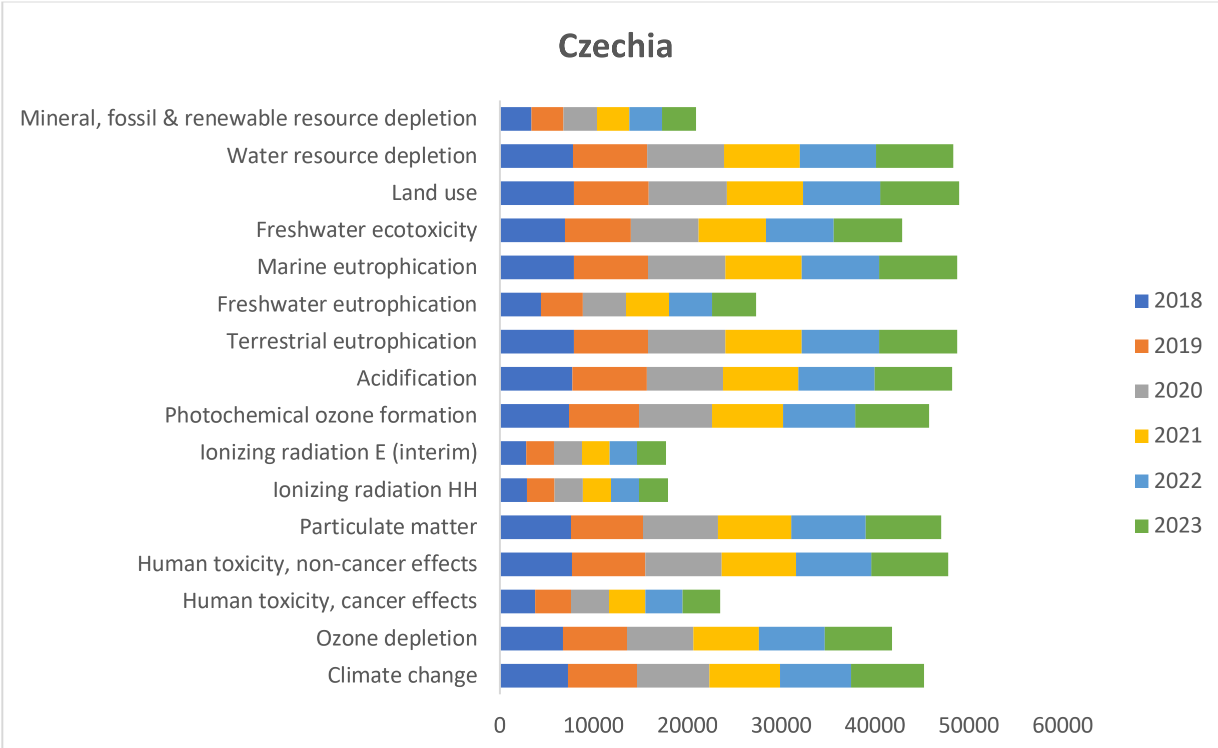


Figure 4-7 Impact Reduction Due to RFID tagging of milk in Czechia 2015-2023 ('000 tons)

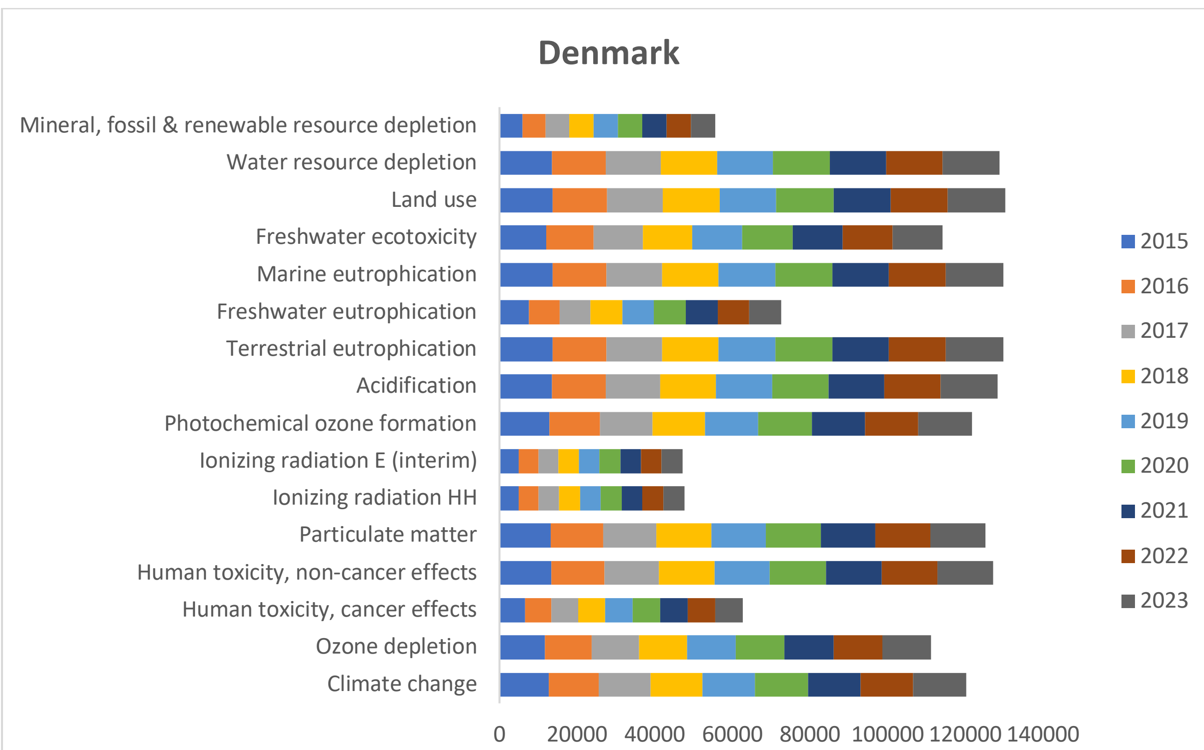


Figure 4-8 Impact Reduction Due to RFID tagging of milk in Denmark 2015-2023 ('000 tons)

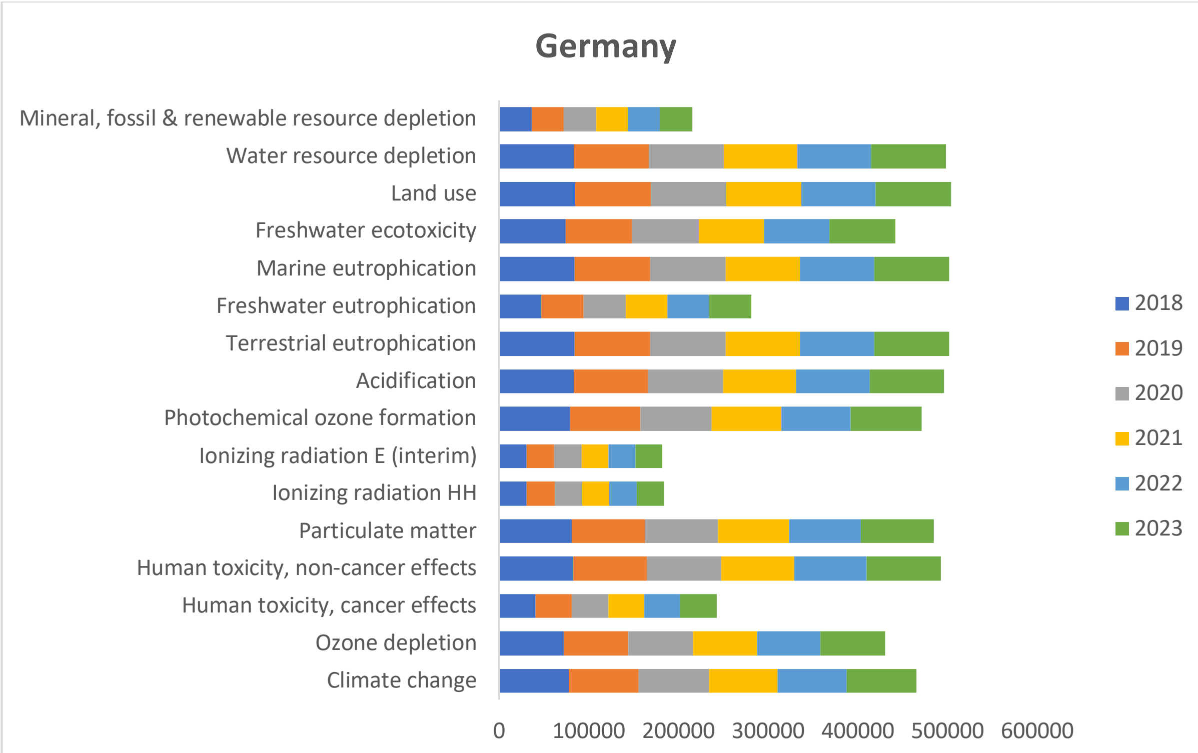


Figure 4-9 Impact Reduction Due to RFID tagging of milk in Germany 2015-2023 ('000 tons)

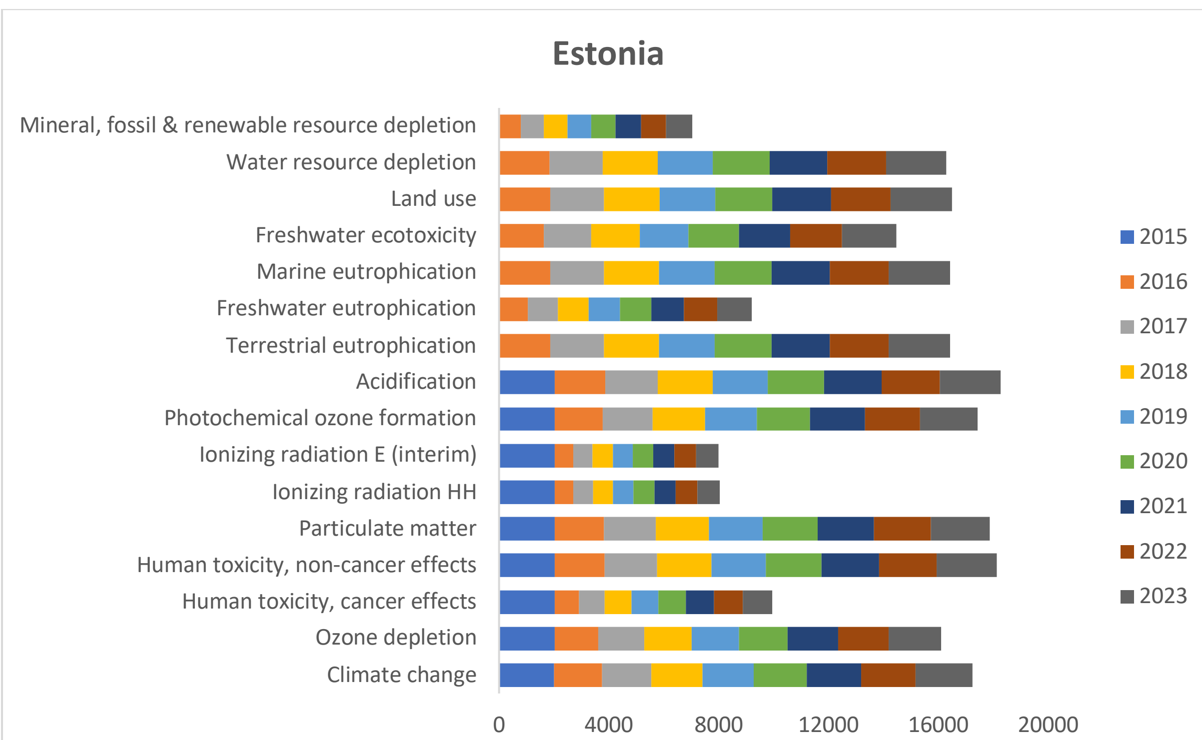


Figure 4-10 Impact Reduction Due to RFID tagging of milk in Estonia 2015-2023 ('000 tons)

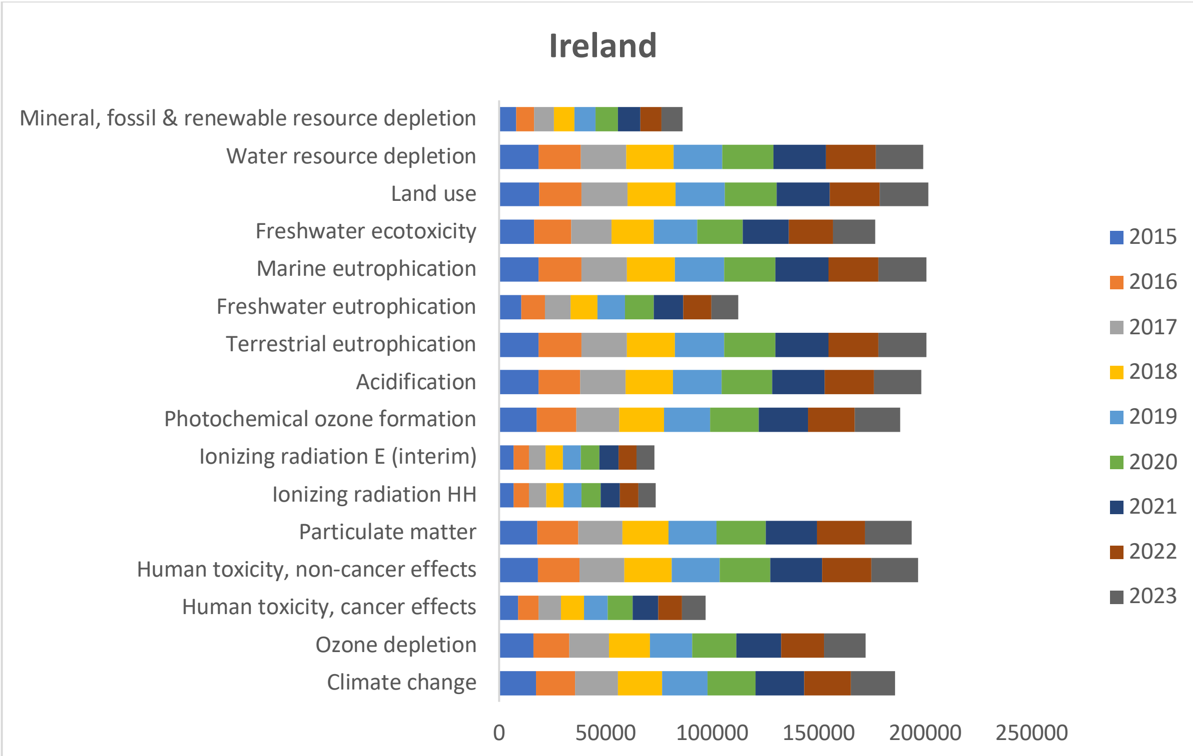


Figure 4-11 Impact Reduction Due to RFID tagging of milk in Ireland 2015-2023 ('000 tons)

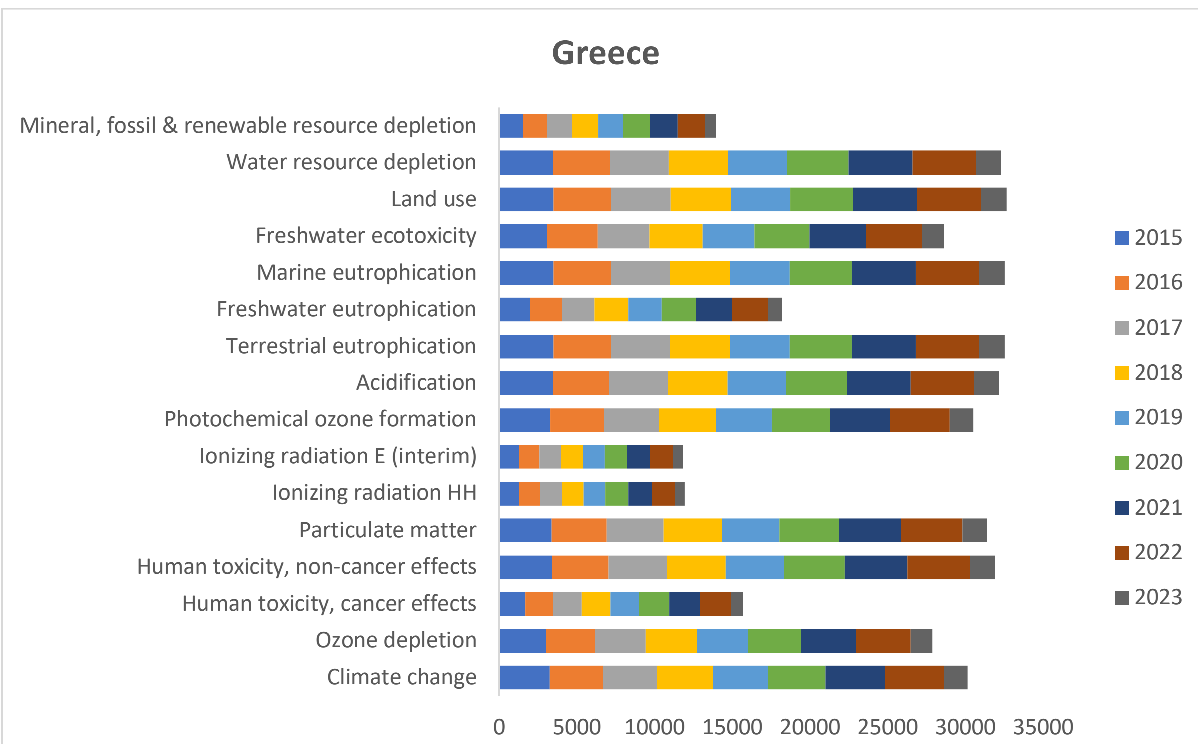


Figure 4-12 Impact Reduction Due to RFID tagging of milk in Greece 2015-2023 ('000 tons)

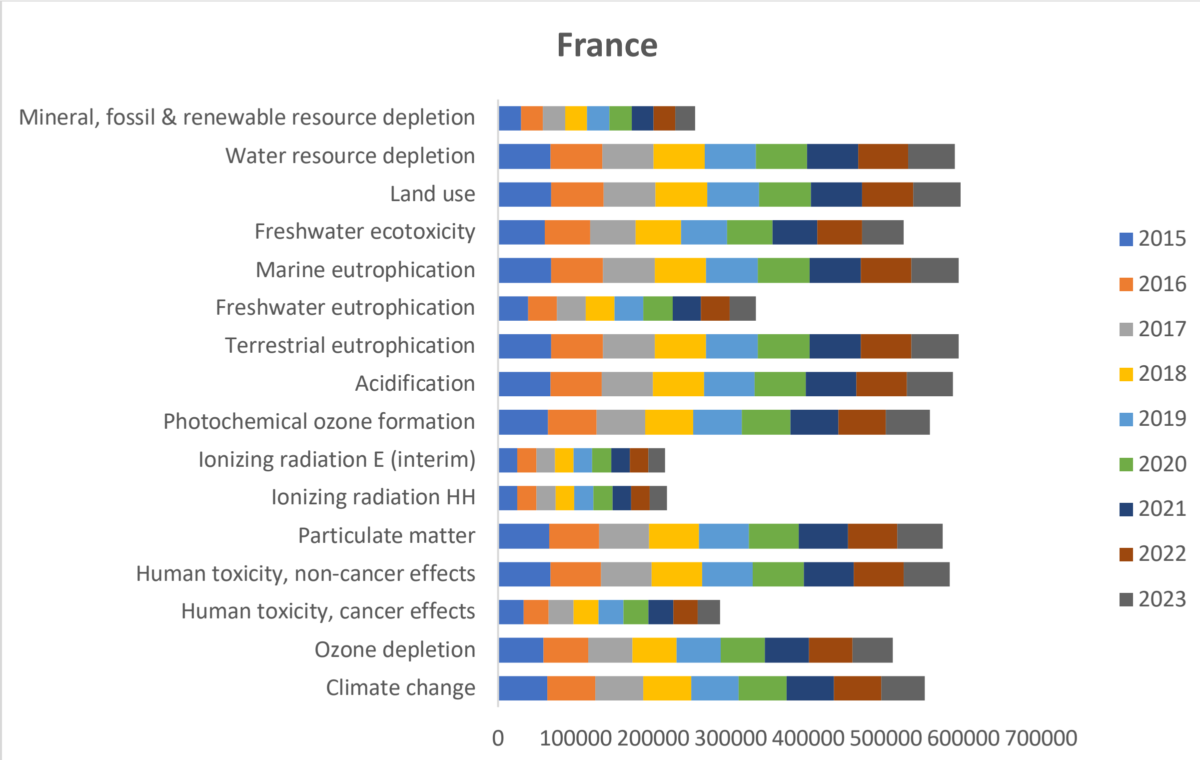


Figure 4-13 Impact Reduction Due to RFID tagging of milk in France 2015-2023 ('000 tons)

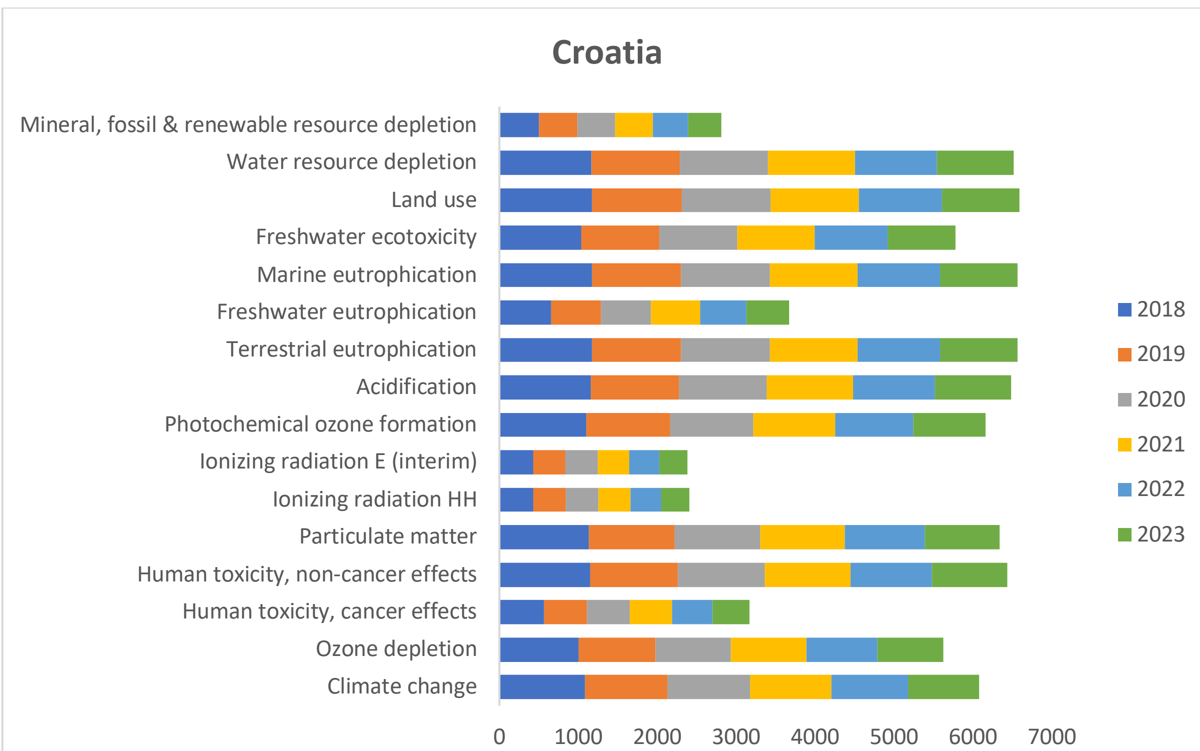


Figure 4-14 Impact Reduction Due to RFID tagging of milk in Croatia 2015-2023 ('000 tons)

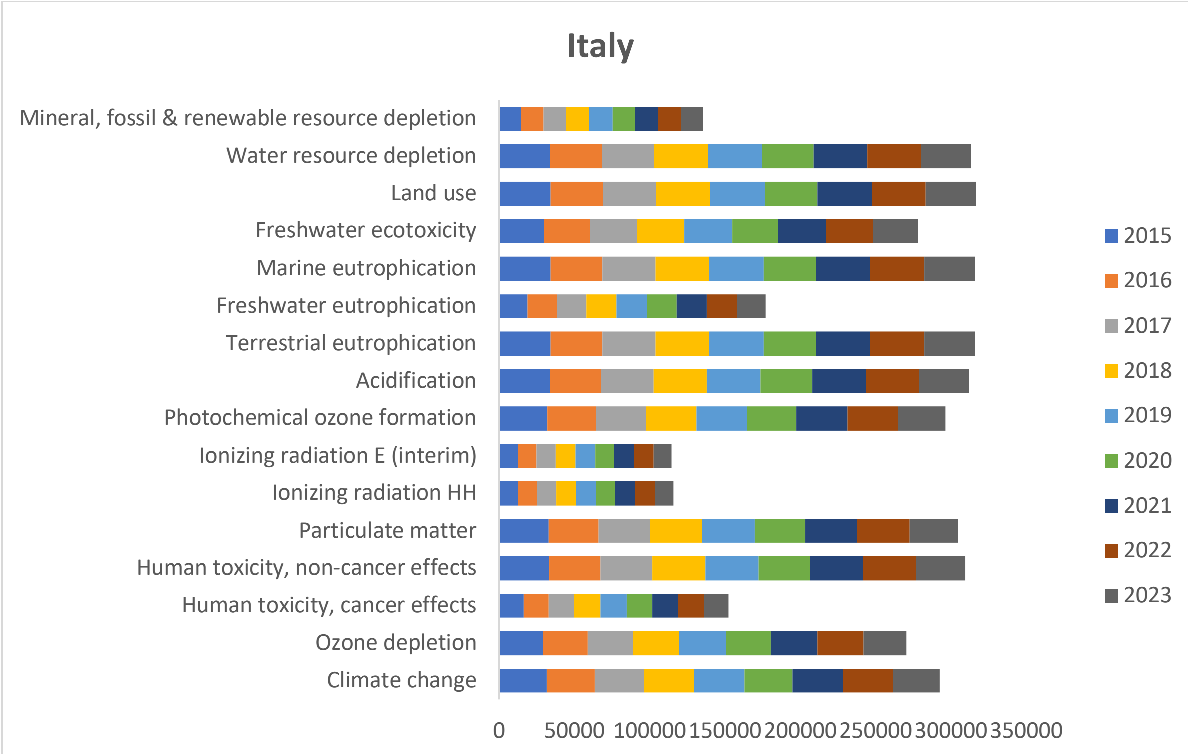


Figure 4-15 Impact Reduction Due to RFID tagging of milk in Italy 2015-2023 ('000 tons)

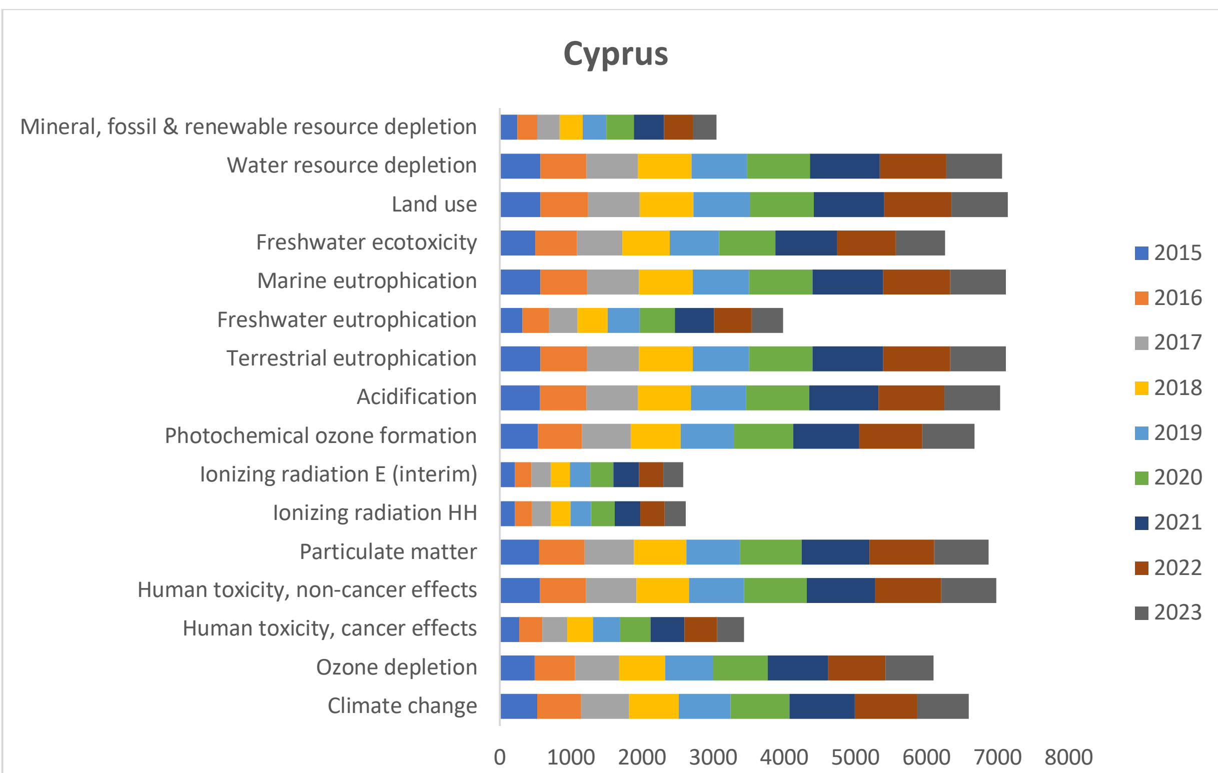


Figure 4-16 Impact Reduction Due to RFID tagging of milk in Cyprus 2015-2023 ('000 tons)

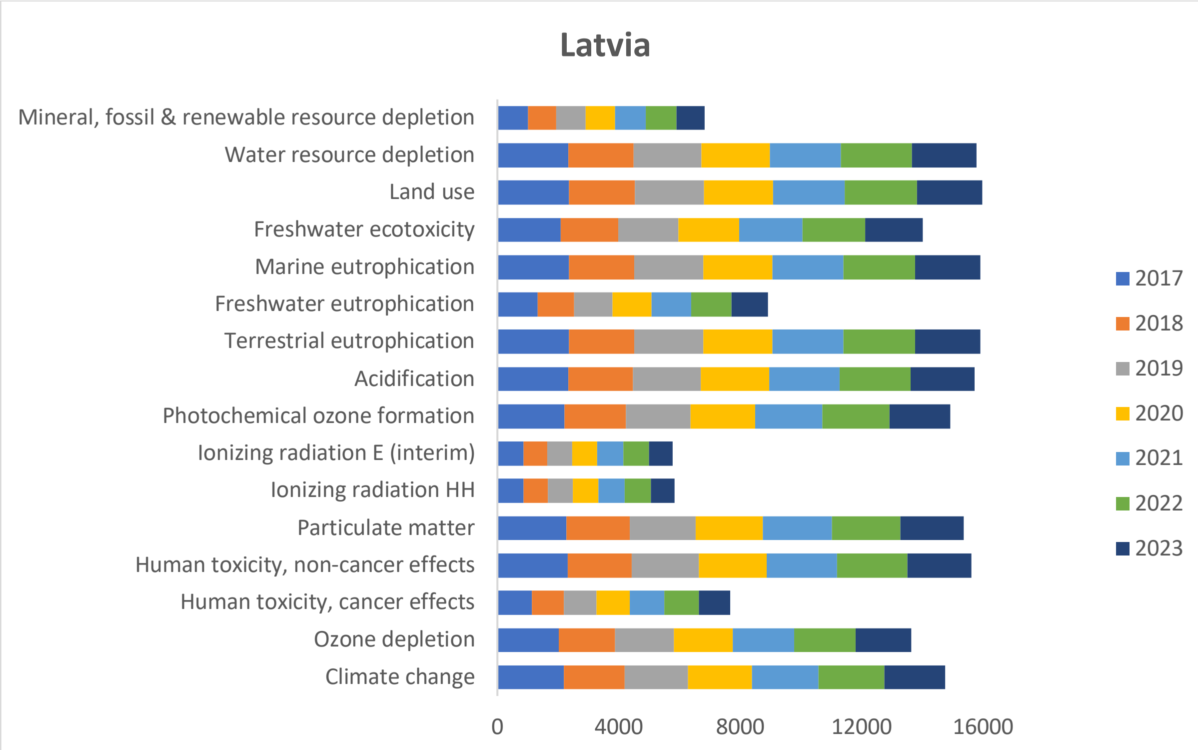


Figure 4-17 Impact Reduction Due to RFID tagging of milk in Latvia 2015-2023 ('000 tons)

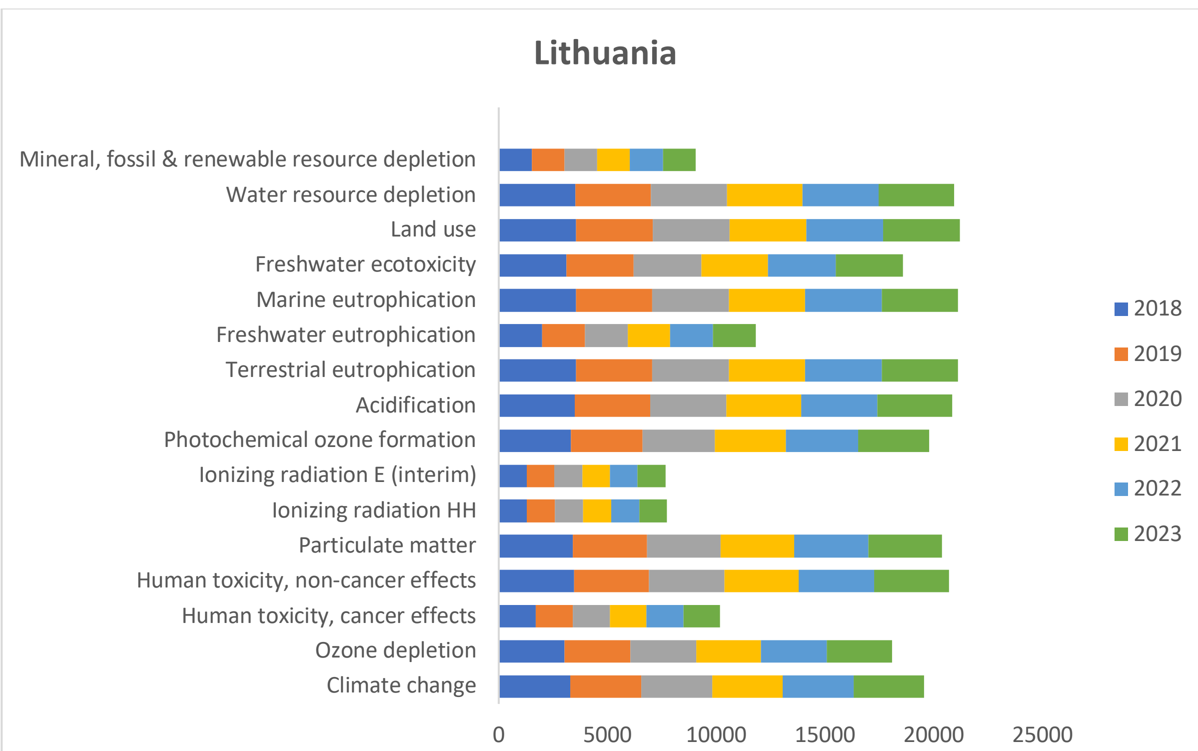


Figure 4-18 Impact Reduction Due to RFID tagging of milk in Lithuania 2015-2023 ('000 tons)

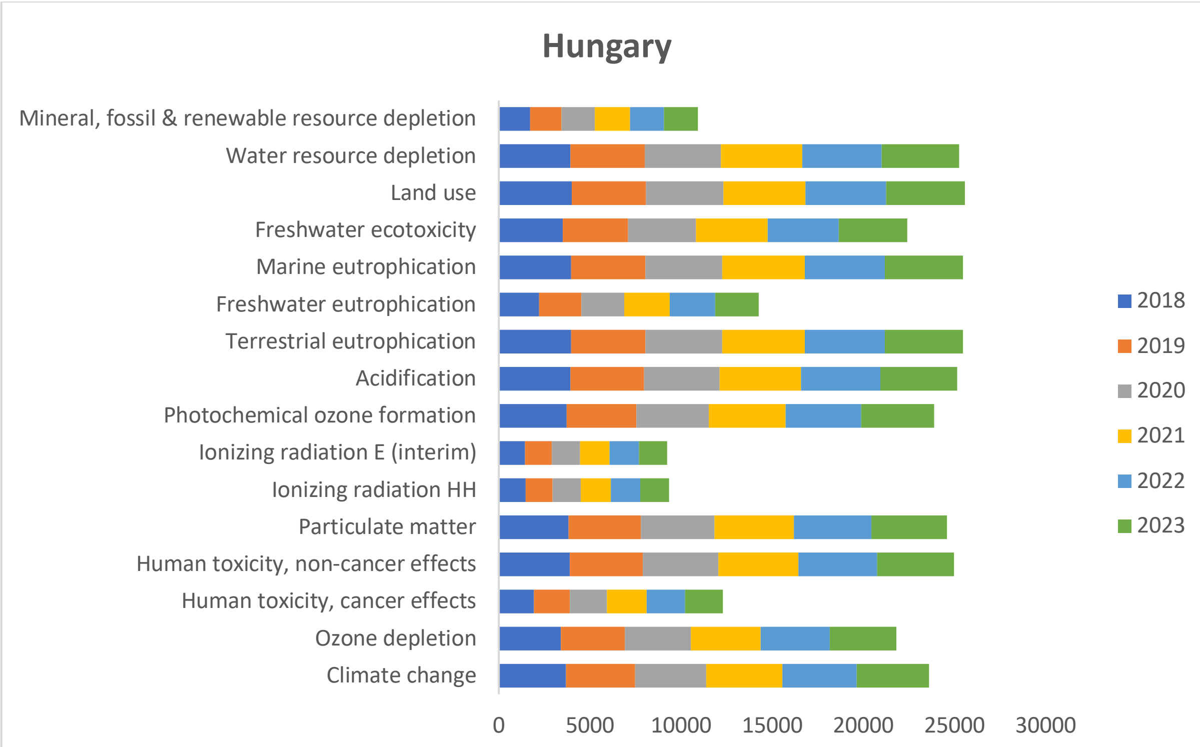


Figure 4-19 Impact Reduction Due to RFID tagging of milk in Hungary 2015-2023 ('000 tons)

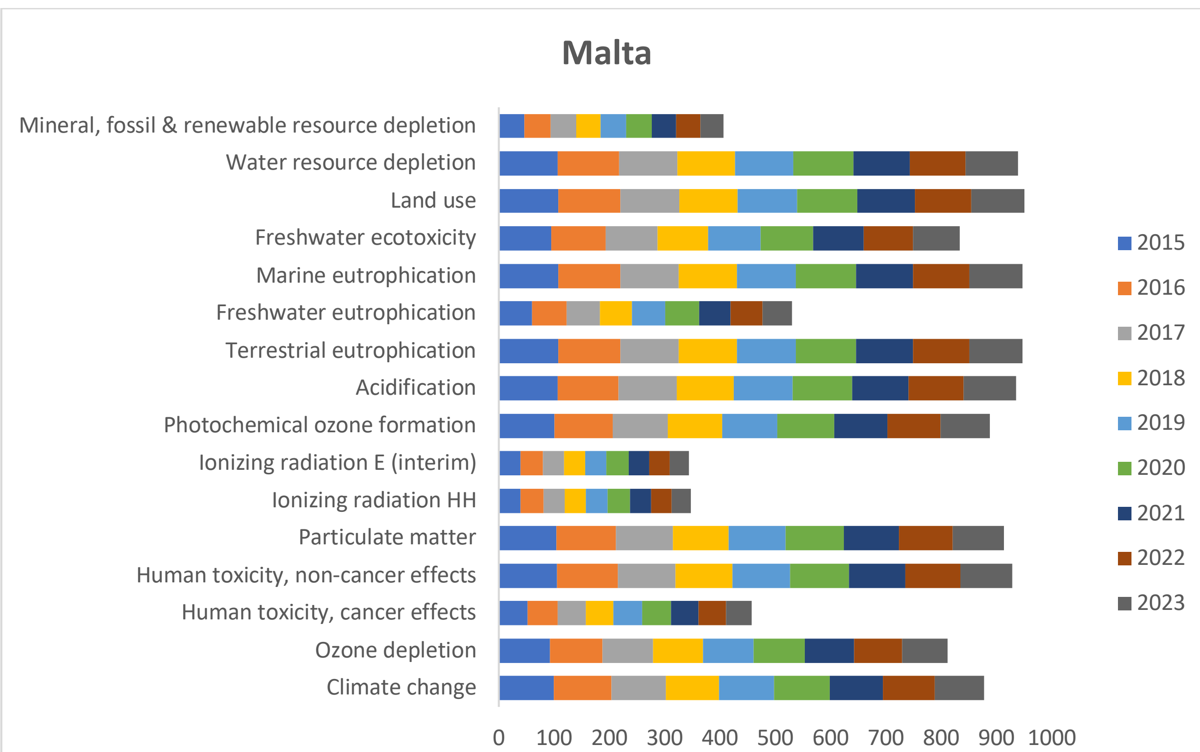


Figure 4-20 Impact Reduction Due to RFID tagging of milk in Malta 2015-2023 ('000 tons)

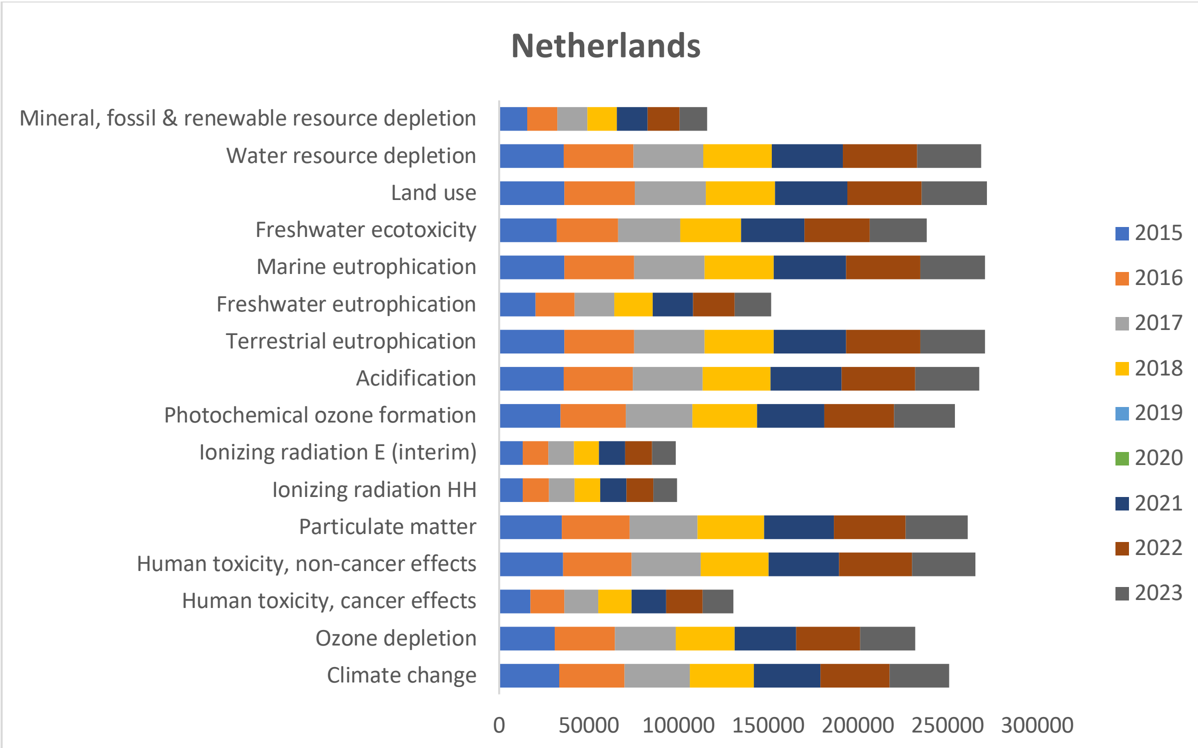


Figure 4-21 Impact Reduction Due to RFID tagging of milk in Netherlands 2015-2023 ('000 tons)

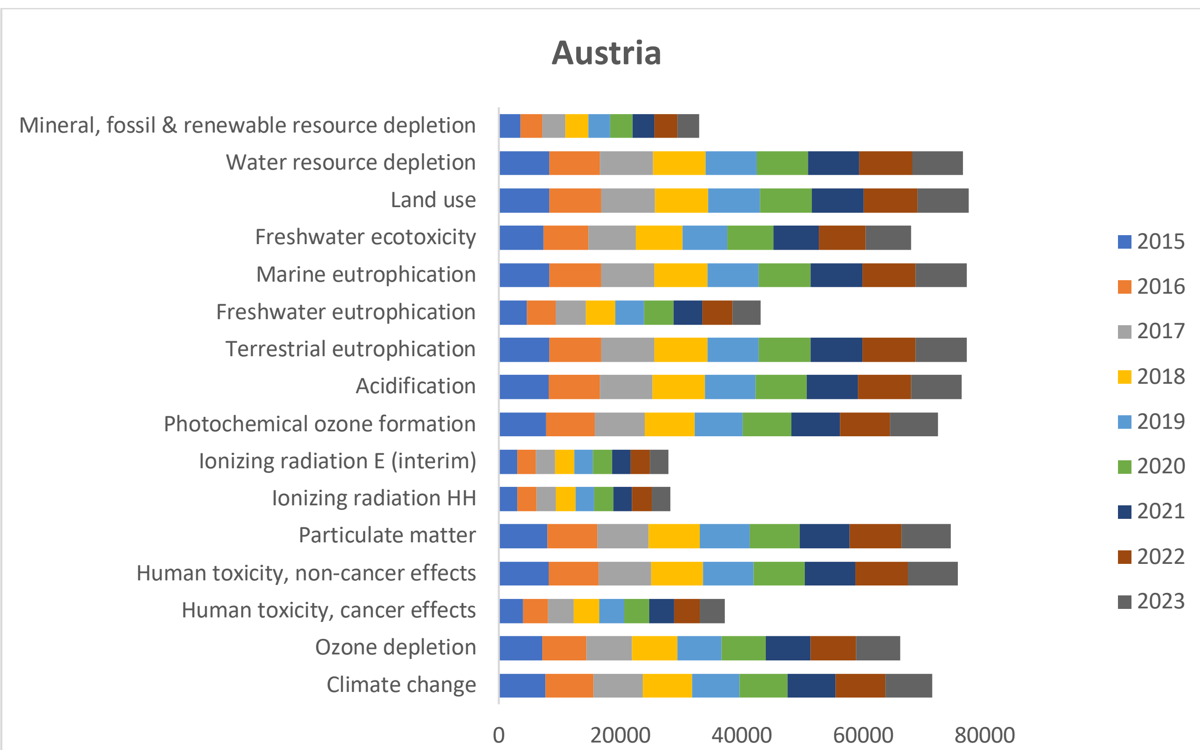


Figure 4-22 Impact Reduction Due to RFID tagging of milk in Austria 2015-2023 ('000 tons)

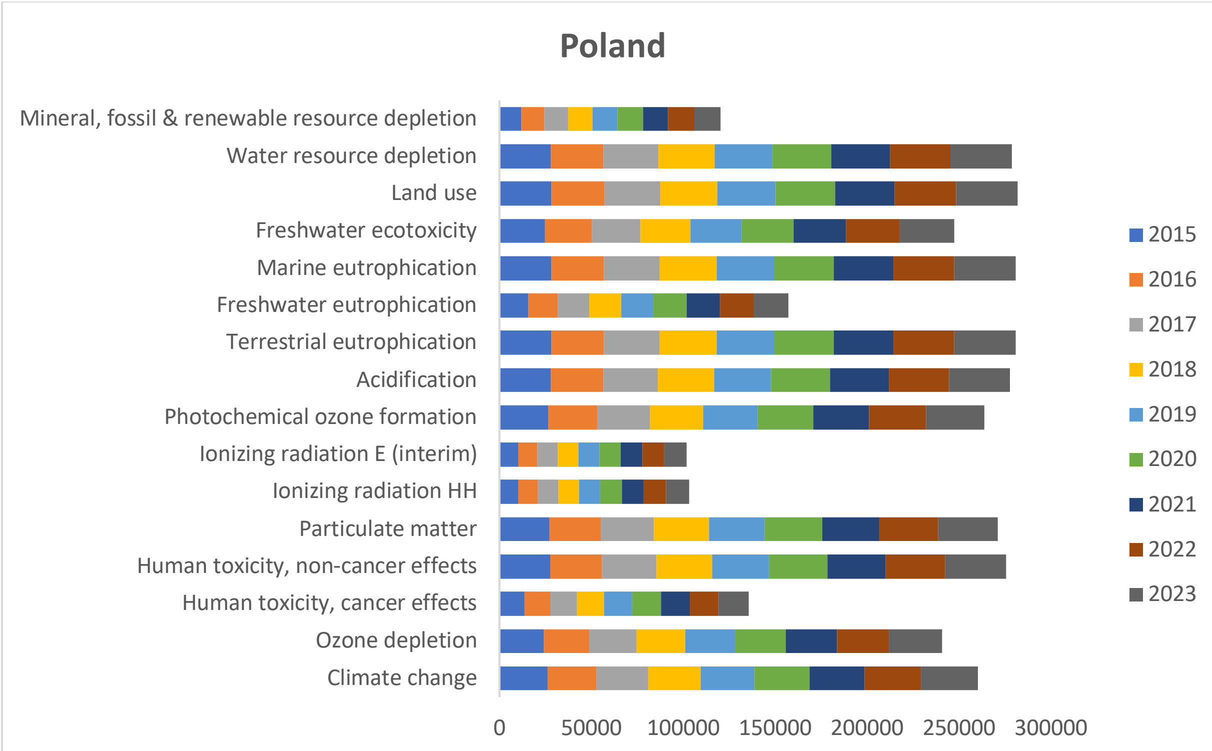


Figure 4-23 Impact Reduction Due to RFID tagging of milk in Poland 2015-2023 ('000 tons)

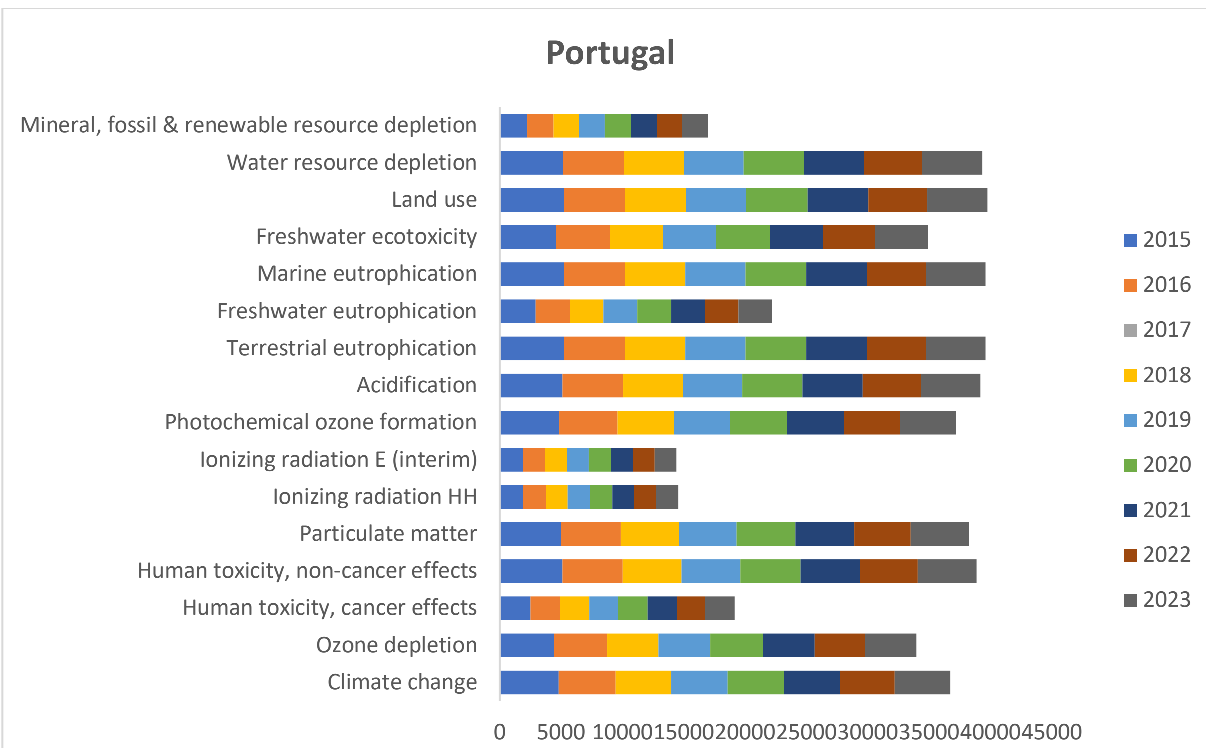


Figure 4-24 Impact Reduction Due to RFID tagging of milk in Portugal 2015-2023 ('000 tons)

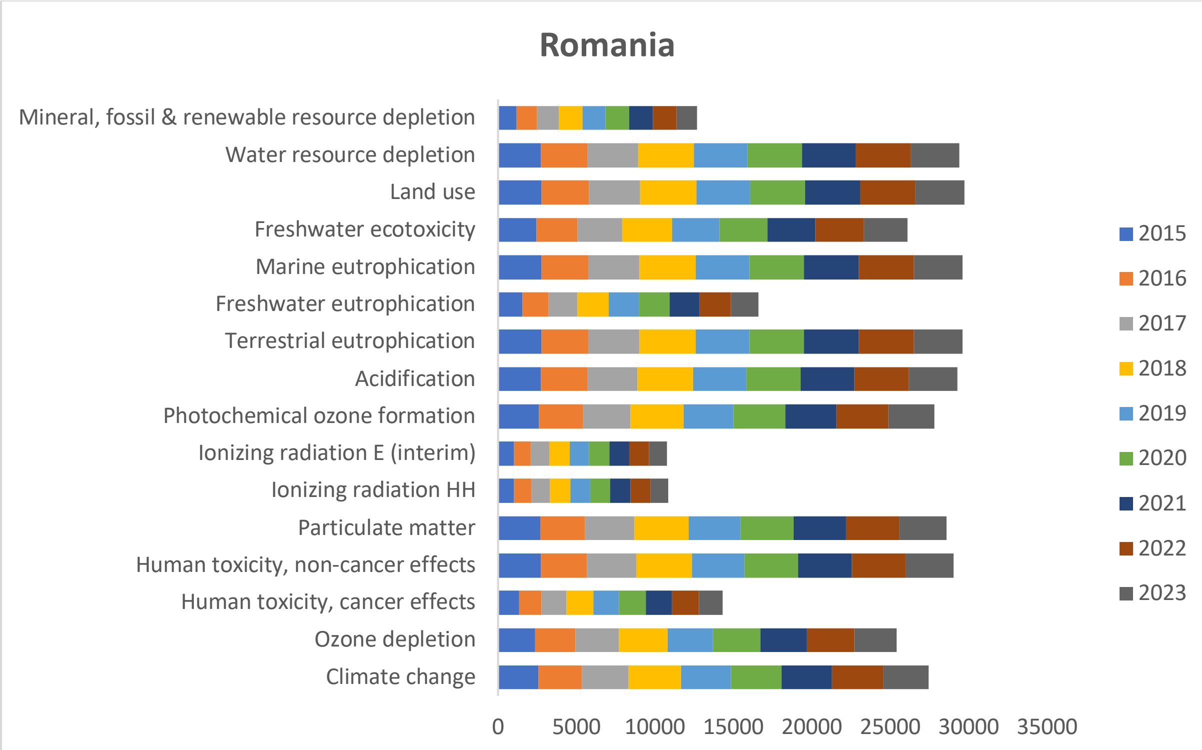


Figure 4-25 Impact Reduction Due to RFID tagging of milk in Romania 2015-2023 ('000 tons)

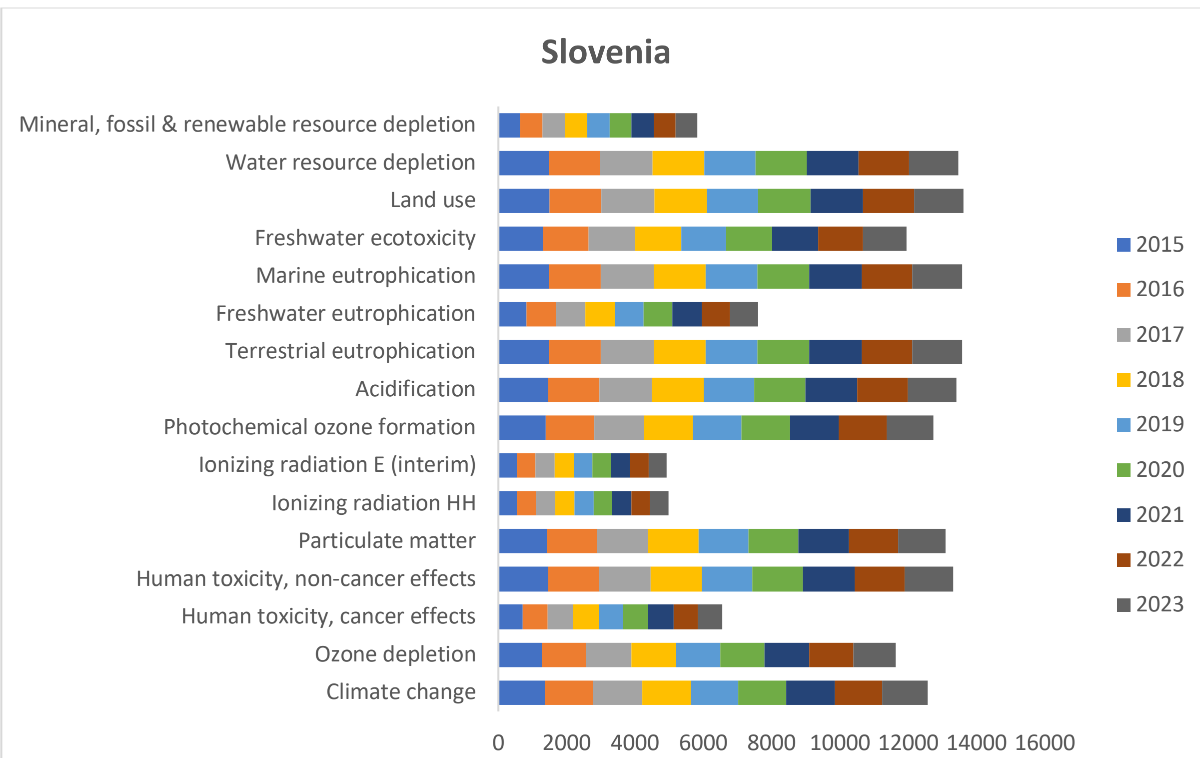


Figure 4-26 Impact Reduction Due to RFID tagging of milk in Slovenia 2015-2023 ('000 tons)

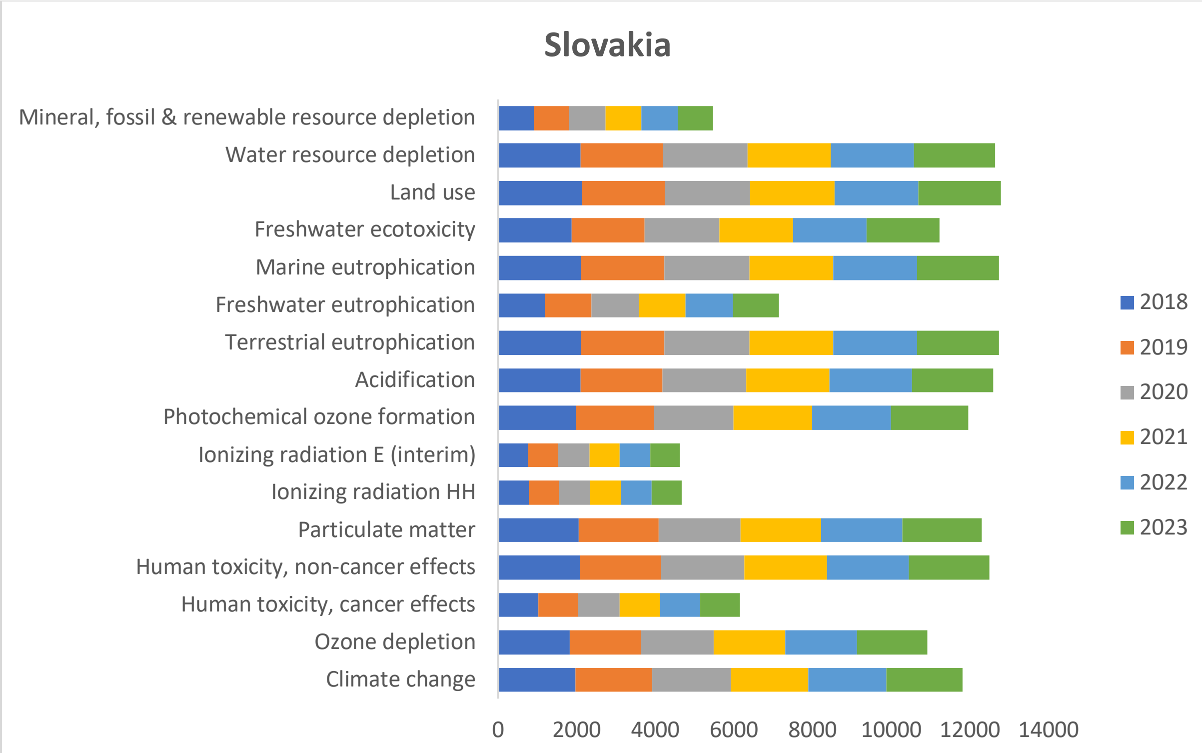


Figure 4-27 Impact Reduction Due to RFID tagging of milk in Slovakia 2015-2023 ('000 tons)

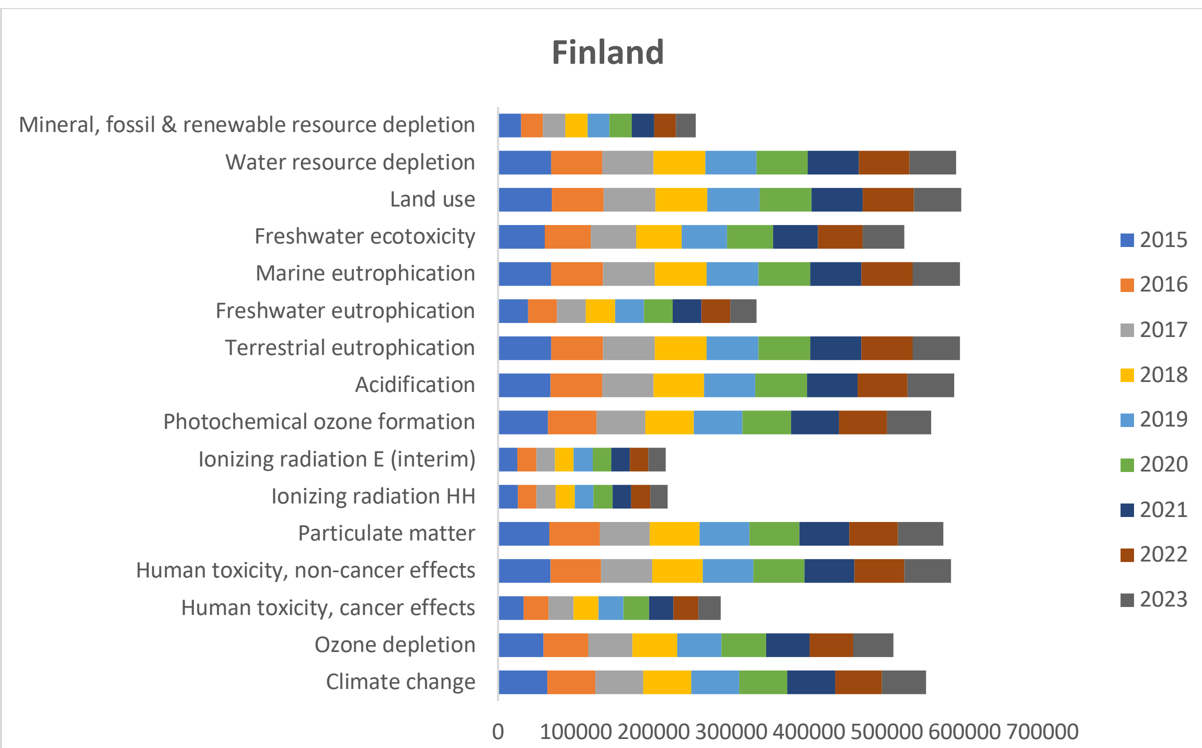


Figure 4-28 Impact Reduction Due to RFID tagging of milk in Finland 2015-2023 ('000 tons)

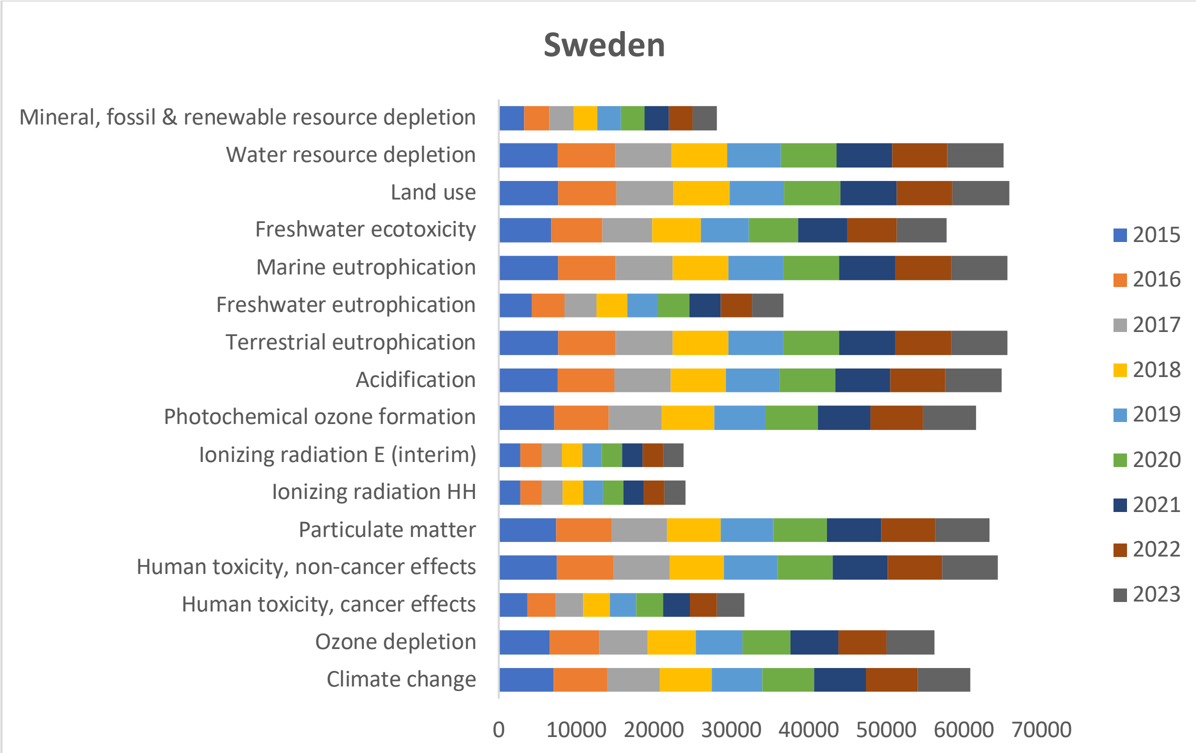


Figure 4-29 Impact Reduction Due to RFID tagging of milk in Sweden 2015-2023 ('000 tons)

The figure 4-30 displays the climate change impact, across the EU-27 countries. Germany exhibit the highest impact, both reaching nearly 80 Mt, significantly surpassing other nations. Finland and France follow, each with impacts between approximately 60 Mt. The Netherlands, Italy, and Poland follow, each with impacts between approximately 30 Mt. A middle group including the Republic of Ireland, Denmark, Belgium, Austria, and Sweden shows moderate impacts ranging from about 10 Mt to 25 Mt. The remaining countries, including Romania, Estonia, Bulgaria, Lithuania and the Czech Republic show much lower impacts, under 10 Mt. Some countries with unspecified data, exhibit negligible climate change impacts according to the chart. This data indicates substantial variability in climate change impacts achieved through RFID tagging of fresh milk across the EU-27, with certain countries contributing disproportionately higher levels.

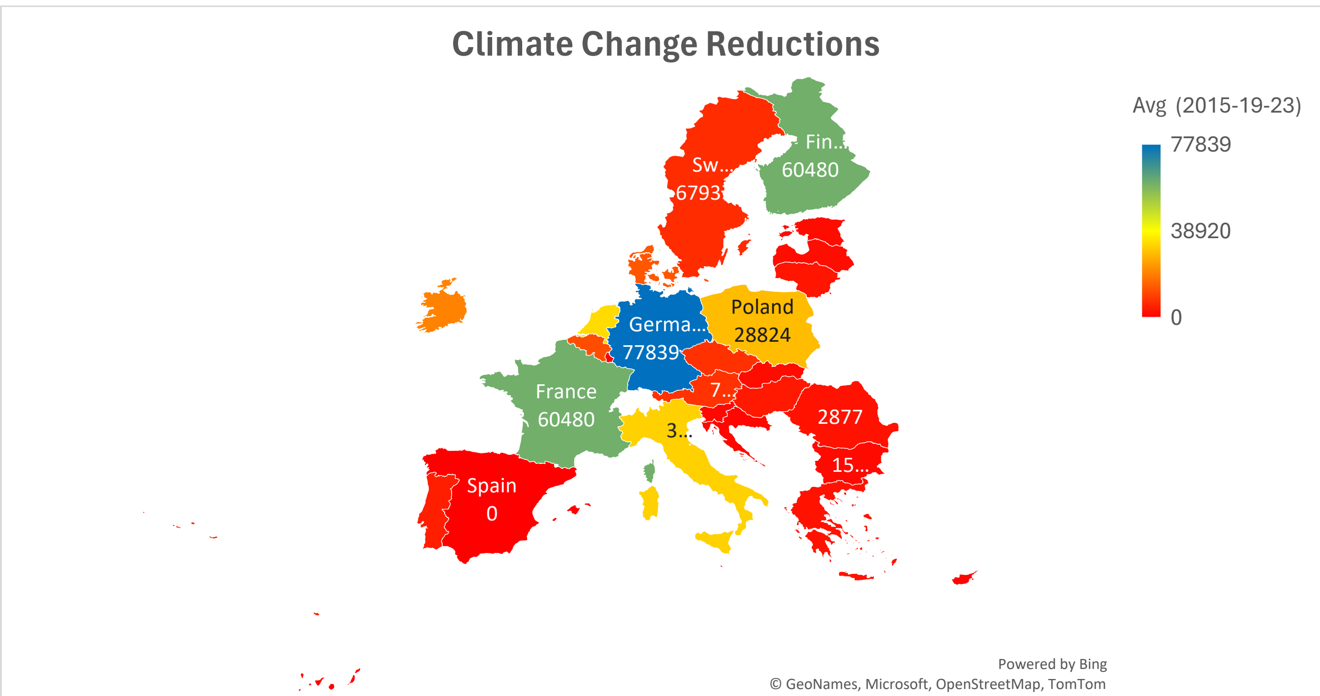


Figure 4-30 Climate change reductions due to RFID tagging of fresh milk across EU-27 ('000 tons)

The map, as shown in figure 4-31, illustrates the average particulate matter reductions across Europe from 2015 to 2023. Germany leads with the highest reduction of 81 Mt, marked in dark blue, indicating significant progress in air quality improvement. France and Finland also show substantial reductions of 63 Mt units each, highlighted in green. Poland, marked in yellow, has a moderate reduction of 30 Mt. Other notable reductions include Sweden with 7,076 (000 tons) and Romania with 2,997 (000 tons). However, several countries, including Spain and regions in Eastern Europe, show minimal to no reductions, indicated in red, with Spain notably achieving zero reduction. This data underscores the variability in particulate matter reduction efforts achieved through RFID tagging of fresh milk across Europe, with some countries making significant strides while others lag.

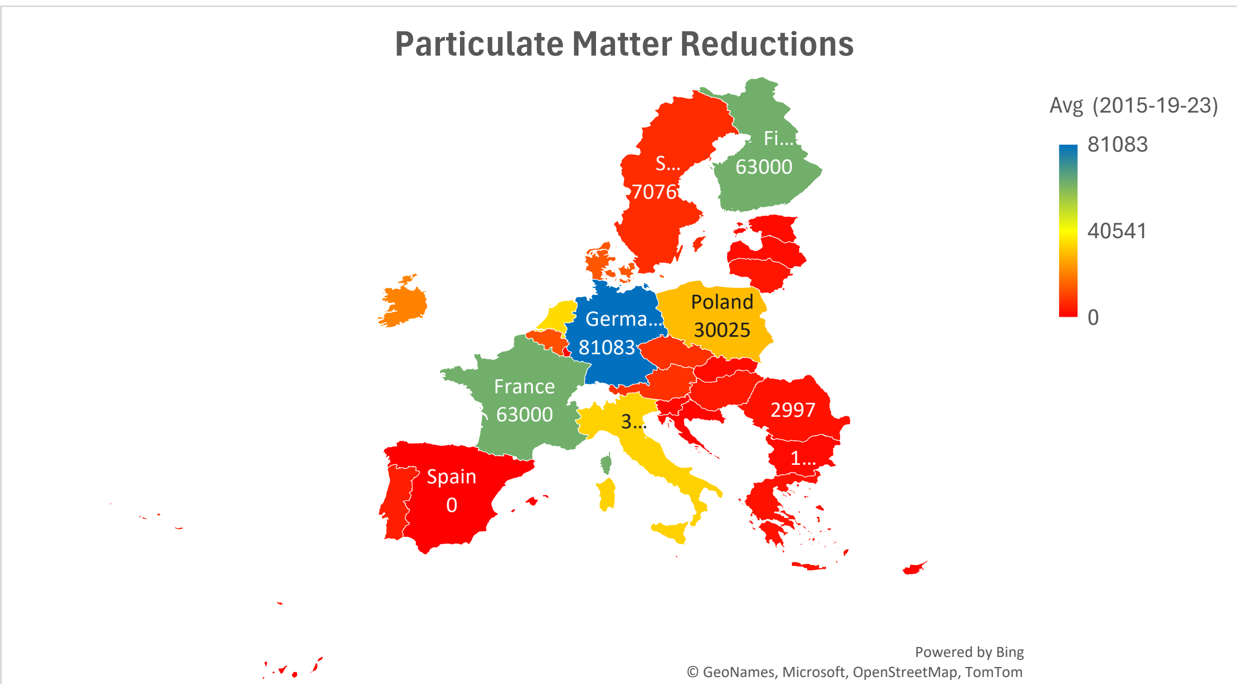


Figure 4-31 Particulate matter reductions due to RFID tagging of fresh milk across EU-27 ('000 tons)

The map, as shown in figure 4-32, illustrates the average land use reductions across Europe from 2015 to 2023. Germany leads with the highest reduction of 81 Mt, marked in dark blue, indicating significant progress in air quality improvement. France and Finland also show substantial reductions of around 65 Mt each, highlighted in green. Poland, marked in yellow, has a moderate reduction of 31 Mt. Other notable reductions include Sweden with 7359 (000 tons) and Romania with 3117 (000 tons). However, several countries, including Spain and regions in Eastern Europe, show minimal to no reductions, indicated in red, with Spain notably achieving zero reduction. This data underscores the variability in particulate matter reduction efforts achieved through RFID tagging of fresh milk across Europe, with some countries making significant strides while others lag.

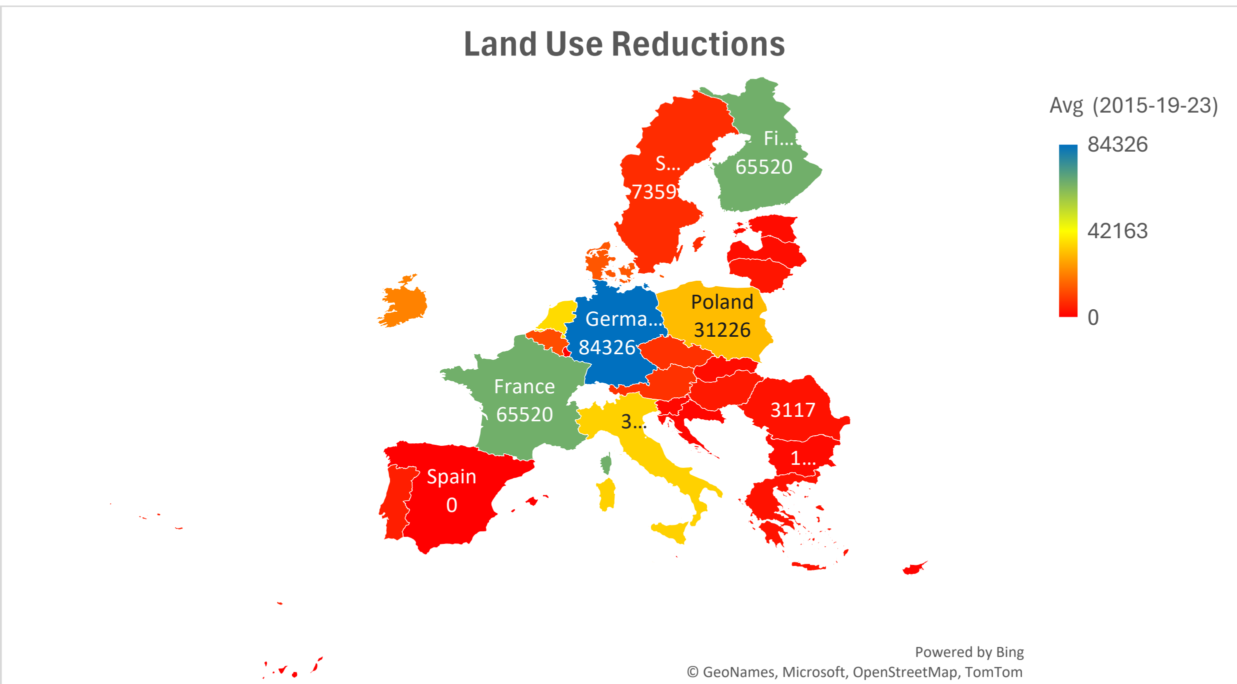


Figure 4-32 Land use reductions due to RFID tagging of fresh milk across EU-27 ('000 tons)

The figure 4-33 displays the water resource depletion reductions, across the EU-27 countries average values between 2015 to 2023. Germany exhibit the highest impact, both reaching nearly 80 Mt, significantly surpassing other nations. Finland and France follow, each with impacts between approximately 60 Mt. The Netherlands, Italy, and Poland follow, each with impacts between approximately 30 Mt. A middle group including the Republic of Ireland, Denmark, Belgium, Austria, and Sweden shows moderate impacts ranging from about 10 Mt to 25 Mt. The remaining countries, including Romania, Estonia, Bulgaria, Lithuania and the Czech Republic show much lower impacts, under 10 Mt. Some countries with unspecified data, exhibit negligible climate change impacts according to the chart. This data indicates substantial variability in climate change impacts achieved through RFID tagging of fresh milk across the EU-27, with certain countries contributing disproportionately higher levels.

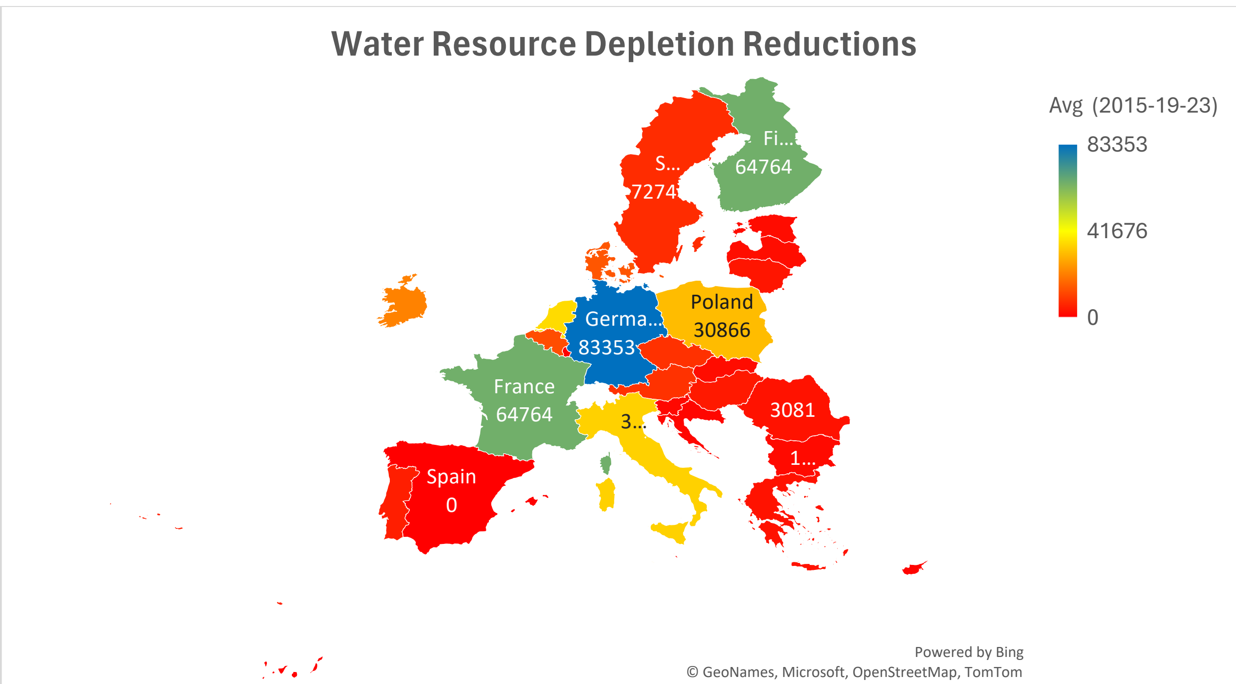


Figure 4-33 Water resource depletion reductions due to RFID tagging of fresh milk across EU-27 ('000 tons)

By 2035, milk production in the EU-27 is projected to decrease by an average of 0.2% per year, driven by sustainability demands, stringent environmental policies, and a shrinking dairy herd. Yield growth will slow to 0.9% annually, reflecting diminished impacts from past productivity improvements (EU AGRICULTURAL OUTLOOK). So, total milk production in 2035 in EU-27 is estimated to 147 million tons considering the factors contributing to declining production over the years. Hence, the environmental reductions obtained across each category in the EU-27 due to RFID tagging of fresh milk by 2035 is shown in figure in 4-34.

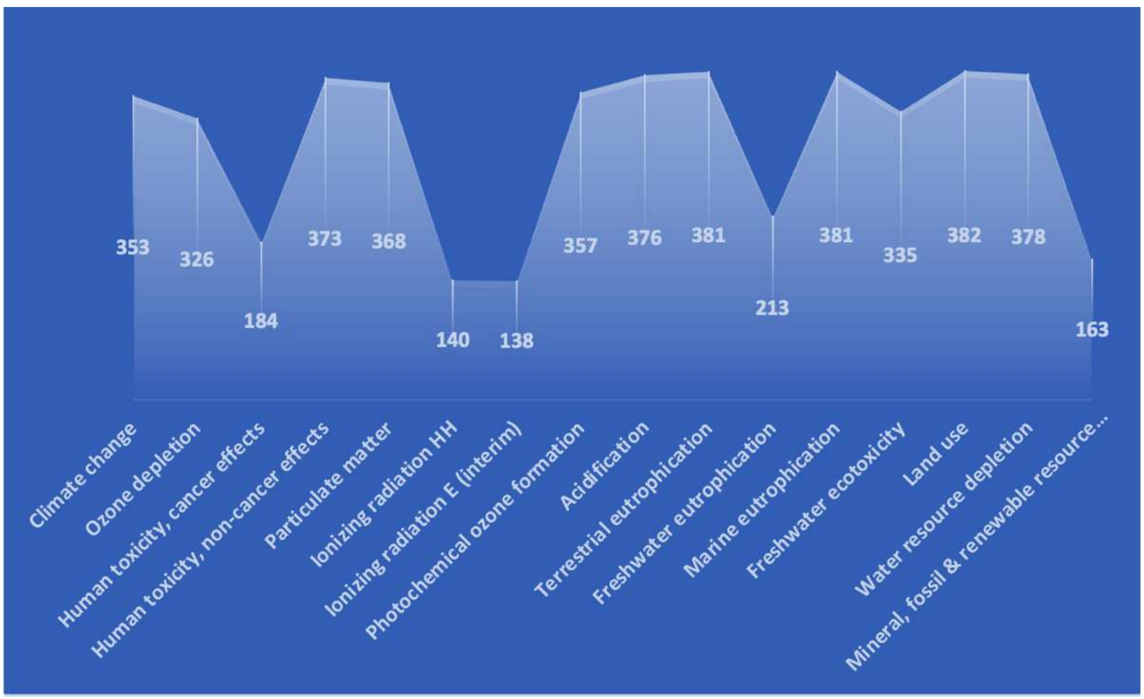


Figure 4-34 Reduction due to RFID tag in EU-27 countries, in 2035 (Mt)

5 DISCUSSION

5.1 OVERALL FINDINGS

The implementation of RFID technology in the milk supply chain has led to significant environmental benefits across various impact categories. The 2.6% of the total amount of milk produced in the EU can be saved through RFID tagging. The most notable reductions are observed in climate change, terrestrial eutrophication, land use, acidification, human toxicity (non-cancer effects), particulate matter, and water resource depletion. On average, the environmental benefits surpass the impacts by more than five times, highlighting the net positive outcome of RFID implementation. Specific reductions include a 2.40% decrease in CO2 equivalent emissions and substantial decreases in climate change, ozone depletion, human toxicity (non-cancer effects), and particulate matter, each exceeding 2%. Germany, France, Finland, Italy, Netherlands and Poland are the countries in the EU exhibiting higher impact reductions, approximately 80-30 Mt with the implementation of RFID tagging of fresh milk. In future, with the implementation of RFID technology to milk, around 353-160 Mt environmental impact can be reduced. This comprehensive analysis underscores the potential of RFID technology to mitigate environmental harm and enhance sustainability goals across the EU milk supply chain.

Moreover, the study's data is based on estimations and approximations for future scenarios, lacking actual values for specific countries. This introduces a level of uncertainty in the findings, which is addressed through a Monte Carlo simulation to account for variability and enhance the robustness of the results.

5.2 CHALLENGES & LIMITATION

- **Technical Challenges**

A significant technical challenge in implementing RFID technology in the EU lies in its reliability within retail settings, where reading UHF tags near human bodies is hindered by the interference from the body's high-water content. Tags on items containing substantial amounts of liquid or metal also present difficulties, as liquids absorb signals and metals reflect them, impeding tag readability. Additional technical obstacles include limited read ranges, typically around 1 meter for low-frequency RFID systems and 3 to 4 meters for UHF systems, necessitating more reliable readers with extended operating ranges for widespread adoption (Zuo et al., 2022a). Ensuring read accuracy poses complexities, with RFID readers struggling to communicate effectively with tags oriented perpendicular to their antennas, potentially rendering some tagged objects undetectable.

- **Cost**

Cost remains a significant barrier to the widespread adoption of RFID technology, with passive tags costing between 5 to 10 cents each in large quantities, still considerably more expensive than traditional barcode labels. The cost of active tags, designed for high-value items, can soar up to $100 per tag, making it impractical for widespread use across retail items (Zuo et al., 2022a). Efforts to reduce costs focus on improving manufacturing technologies and increasing volume usage, potentially leading to broader adoption. However, the per-unit price heavily relies on the quantity purchased, with significant discounts achievable at higher volumes. Despite advancements, challenges persist, including the selection of substrates, conductive materials, and fabrication processes to lower overall costs. Despite the decreasing costs, electronic labels priced lowest per unit cost still pose challenges for industries with thin profit margins, such as retail. Consequently, many supermarkets, including industry giants, have hesitated to fully embrace RFID technology due to its high implementation costs and confidentiality considerations.

- **Recycling**

The recycling process of common materials like paper, glass, plastic, and metal can be adversely affected by components of RFID tags such as adhesives, computer chips, metal pieces from antennae, and conductive inks. For instance, copper used in antenna construction can alter the chemical and structural properties of recycled steel, rendering it unfit for its intended purposes. Similarly, metal contamination during plastic recycling, particularly in materials like PET and HDPE, poses challenges. To mitigate these issues, alternative adhesives, different metals for antenna construction, or the removal of tags before recycling can be considered. Embracing recyclable RFID tags not only contributes to environmental sustainability but also aids in reducing RFID tag costs.

- **Standardization**

The allocation of frequencies for RFID applications varies across countries due to individual regulations, leading to discrepancies in frequency usage. For instance, Europe and the United States utilize different frequencies for ultra high frequency RFID—868 MHz and 915 MHz, respectively (Kumar et al., n.d.). Consequently, tags operating at a specific frequency in one country may not be readable in another country using the same frequency for a different purpose. This lack of standardized frequency allocation globally hinders the widespread implementation of RFID technology across various applications.

- **Security and Privacy**

Concerns regarding privacy among consumers pose a significant obstacle to the widespread acceptance of RFID technology. Consumers are concerned about the potential for automatic tracking of their movements and purchasing patterns. To address these privacy concerns, the implementation of kill switches, which disable the RFID tag at the point of sale, can offer a solution. However, security remains a prominent challenge in the adoption of RFID technology. Unauthorized users may exploit. Despite the potential benefits of RFID in enhancing convenience and efficiency, ensuring the security and privacy of information remains paramount, especially in the context of the food supply chain where sensitive data is involved.

5.3 FUTURE PERSPECTIVE

The future perspective of RFID tagging of milk in the EU appears promising, with several potential benefits driving its adoption. As the EU continues to prioritize food safety, traceability, and sustainability, RFID technology can play a crucial role in enhancing the milk supply chain. RFID tagging can improve traceability from farm to consumer, ensuring quality control and rapid response to any contamination issues. It can also optimize inventory management, reducing waste and ensuring fresher products reach consumers. Moreover, the data collected through RFID systems can support more efficient logistics and distribution, lowering transportation emissions and contributing to climate goals. As regulatory pressures for transparency and sustainability increase, and as technology costs decrease, RFID adoption in the dairy industry is likely to expand, fostering a more efficient and environmentally friendly milk supply chain across the EU.

The future of RFID technology holds promise across various sectors, driven by the quest for enhanced functionality, reduced costs, and greater sustainability in the EU. Efforts in research and industry are poised to prioritize achieving 100% read rates akin to conventional barcode technology, enhancing the reliability of RFID tag readers, and seamlessly integrating RFID data collection with decision support tools. While current RFID tag readers typically exhibit reliability rates between 80% to 95%, there is a push towards achieving 100% reliability to accurately capture information from every tag (Zuo et al., 2022b). Accomplishing these goals requires proper tag placement, optimal pallet configuration, and ongoing research into low-cost RFID tags.

Another pivotal area of development lies in the widespread adoption of UHF RFID technology, offering benefits such as multi-object identification, strong penetration and large memory capacity, particularly in sectors like farm management, where each animal can be outfitted with an electronic label, enabling traceability management throughout the production process—from breeding to quarantine, processing, and sales—while effectively addressing food safety concerns. Additionally, there is a growing demand for environmentally friendly electronic devices, leading to extensive research into eco-friendly sensor materials (soluble conductors, degradable matrix polymers, degradable media, degradable insulators, and soluble semiconductors as viable alternatives) that reduce or eliminate the use of noble metals by mitigating environmental impacts.

Innovations in food tracking systems, exemplified by NutriSmart, highlight the integration of edible RFID technology to provide consumers with comprehensive nutritional information and supply chain traceability. Within the system, the Smart Plate features an RFID reader discreetly embedded in its base. This reader scans the edible RFID chip embedded within the food as shown in figure 5-1, capturing dietary data, and subsequently transmits it via Bluetooth to a computer for further analysis and monitoring (Blockchain and RFID— Traceability Technology in Agriculture). This integration underscores the importance of efficient, cost-effective methods for monitoring and tracking food within the global supply chain, facilitated by smart, interconnected edge frameworks leveraging IoT principles.

Figure 5-1: Eggs with edible RFID tag

The integration of intelligent tags onto objects requires them to be compact in size, necessitating novel approaches for seamless incorporation into various materials such as food packaging, the human body, and everyday objects, with future sensor tags expected to adopt multi-module systems mounted on diverse substrates. Given that the antenna and its integration currently constitute up to 50% of the total tag cost (Zou et al., 2014), innovative manufacturing processes, such as printed antennas and heterogeneous integration, offer facilitation for system miniaturization, cost reduction, and enhanced performance. Heterogeneous integration enables the assembly of silicon circuits and non-silicon materials on flexible substrates, incorporating sensors, antennas, displays, and IC chips. Chipless RFID technology, operating on the radar principle does not require ICs or communication protocols, eliminating the need for connections between ICs and antennas, further expands possibilities by embedding tag information into the electromagnetic signature of structures, enabling ultra-low-cost, fully printable tags. Biocompatible, conductive organic inks and dyes for RFID tag printing offers promising prospects for sustainable and versatile applications in food supply chain. Overall, the future trajectory of RFID design emphasizes a balance between advancing functionality, reducing costs, and embracing sustainability to pave the way for superior system solution.

6 CONCLUSION

By analyzing all the results we can conclude that RFID technology in the EU's milk supply chain has demonstrated substantial environmental benefits, significantly reducing various environmental impacts. Despite technical and cost-related challenges, the positive outcomes of RFID implementation underscore its potential to contribute to sustainability in milk production. The study's findings, supported by scenario and uncertainty analyses, provide valuable insights for strategic planning and policy-making, aiming to further enhance environmental sustainability in the dairy industry. The comprehensive assessment and robust data analysis suggest that while there are challenges to overcome, the overall impact of RFID technology is overwhelmingly positive, paving the way for broader adoption in the future for the EU milk supply chain.

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