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An Organisational-Life Cycle Assessment Approach for Internet of Things Technologies Implementation in a Human Milk Bank

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Abstract: Human milk banks (HMB) are responsible for screening and recruiting milk donors with surplus milk to their own infant's needs, followed by transporting, heat-treating (pasteurising) and microbiologically confirming the donor human milk (DHM) is safe to issue to vulnerable infants. Maintaining the safety and quality of DHM are vital requirements in HMB operations. DHM must be maintained in ideal temperature conditions throughout the whole period—from expression until delivery. In this regard, monitoring technologies (e.g., sensors, Big Data and the Internet of Things) have become a viable solution to avoid food loss, allowing prompt corrective action. Therefore, this study aimed to understand the trade-offs between optimising DHM transportation and the environmental impact of implementing such technologies. The environmental performance was carried out through an Organisational Life Cycle Assessment (O-LCA). The electricity consumed during milk storage is the main driver for the environmental impacts in this organisation, responsible for up to 82% of the impacts in ionising radiation. The transportation stage and the treatment of discarded DHM were also relevant for ozone formation and marine eutrophication, respectively. Considering the strategy to integrate monitoring technologies to control the temperature conditions during transportation and the reduction of milk discarded by 3%, an environmental impact reduction can be also observed. In some categories, such as global warming, it could avoid around 863 kg of CO_2-eq per year. The sensitivity analysis showed that the impacts of the HMB depend highly on the transport distance. In addition, changing the transportation mode from motorcycles to drones or electric vehicles can affect the environmental performance of this organisation. Therefore, human milk transport logistics must be studied in a multidisciplinary way to encompass all possible impacts of these strategies.

Keywords: environmental analysis; human milk bank; IoT technologies; milk waste; organisational LCA

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1. Introduction

Human milk is a valuable resource that has been proven to protect infants from a wide range of infectious and non-infectious diseases [1–3]. However, for numerous reasons, there are circumstances in which mothers cannot lactate at all or provide sufficient breast milk to meet their infant's needs in the immediate postnatal period [4]. In these situations, donor human milk (DHM) is considered the best substitute, especially for vulnerable and sick infants [4–6].

Human milk banks (HMBs) play a vital role by recruiting donors, processing, storing, and supplying milk in a safe and controlled manner [7]. Maintaining the quality of DHM is essential [8]. The milk must be maintained in ideal temperature conditions throughout the whole period—from the point of expression until its delivery [8,9]. In this regard, modern digital technologies (e.g., sensors, Big Data and the Internet of Things) have become viable solutions for continuous quality monitoring [10,11]. Continuous monitoring and timely corrective action can preserve milk quality and prevent unnecessary milk wastage [12].

While these digital technologies can help preserve the cold chain for DHM, the production of these electronic technologies can contribute to adverse environmental impacts [13,14]. The long-term environmental impacts of IoT technologies are unknown, but a noticeable amount of energy is needed to support the production and operation of digital devices [15]. Therefore, it is important to look at the trade-off between the value of milk waste avoided and the additional environmental impacts created due to the production of digital technologies. Understanding this trade-off is the primary purpose of this paper.

Life-Cycle Assessment (LCA) is a common methodology to understand such questions and is frequently used as a decision-support tool by food corporations [16,17] and policymakers [18,19]. In addition, LCA enables the identification and quantification of critical hotspots and helps food companies to improve and minimise their environmental impacts through the optimisation of product management chains [20,21]. However, conducting a single-standing product LCA will only analyse a small part of the overall company. To address this issue, the Organisational Life Cycle Assessment (O-LCA) methodology set out in ISO/TS 14072 [22] is designed to assess the entire collection of goods and services of an organisation.

Therefore, this paper makes at least two contributions to the literature by carrying out the LCA. First, it uses a special case of LCA, namely O-LCA, for the analysis. Second, this is the first time the use of digital technologies to reduce DHM wastage is being evaluated using LCA. The paper is organised as follows. The theoretical background of LCA and O-LCA are discussed in the next section. The methodology of O-LCA is explained in detail in Section 3. Results are presented and discussed in Section 4. Additional sensitivity analyses are also performed in this section, including the case of using another digital technology, namely drones. Conclusions are presented in the last section.

2. Literature Review on O-LCA

Life cycle thinking has been applied to industry and politics during the past few years to comprehensively estimate product or services potential environmental impacts from cradle-to-grave [23,24]. It can help companies make their activities more environmentally friendly and less damaging to the environment [25]. In the recent decade, the knowledge of LCA methodology has progressed and evolved significantly [26]. Simultaneously, analysing potential environmental impacts on an organisational level is becoming increasingly attractive for a growing number of companies [27,28].

Although LCA was first created for product and service levels, there are still some limitations when expanding the unit of analysis at a whole organisational level. The main cause of this limitation is a lack of appropriate environmental data covering the entire portfolio of operations across the entire organisation [29]. As a result, academics have started investigating how to combine LCA with other methodologies to create a robust foundation for organisational decision-making [30–32].

To this extent, the UNEP/SETAC Life Cycle Initiative promoted the development of the organisational life cycle assessment. Through the "LCA for organisations" project, a guide paper was released in 2013 [33]. This provides instructions for conducting an O-LCA study containing references to current ISO standards and directives such as 14072

[22], 14040/44 [34,35], and 14001 [36]. It defines O-LCA as the "compilation and evaluation of the inputs, outputs, and potential environmental impacts of the activities associated with the organisation as a whole or portion thereof adopting a life cycle perspective" and aims to analyse the value chain of an organisation from the acquisition of the raw materials to its end-of-life through a multi-impact method, i.e., by taking into account a variety of environmental categories in order to prevent burden shifting [22]. The method is intended to be widely applied in different organisations, including, but not limited to, a sole trader, company, corporation, firm, enterprise, authority, partnership, charity or institution, or part or combination thereof, whether incorporated or not, public or private [22].

Most requirements and recommendations listed in ISO 14040/44 series standards for product LCA are equally appropriate for O-LCA. More specifically, the four-phase methodology used for product LCA is also used for the O-LCA implementation [22,35]. The fundamental distinctions between the two approaches refer to the scope and inventory phase, as the object under study. Furthermore, O-LCA should not be applied to compare different organisations or for corporate ranking, but rather to address improvements within the specific organisation [22].

Multiple organisational needs can be satisfied by this methodology: i) identification of environmental hotspots along the whole company; ii) environmental performance monitoring and management; iii) support for strategic decision-making; and iv) provide data for corporate sustainability reporting [33]. In general, O-LCA enables organisations to establish their sustainability strategies, enhances their operational activities, as well as supports the transition to more sustainable consumption and production models, towards a more resource-efficient and circular economy.

However, although interest in the LCA is growing quickly and significant explorative experiences are evolving, comprehensive and rigorous applications of O-LCA are not yet common practice, and further research is still required to comprehend how organisations should apply O-LCA. The most difficult aspects of an O-LCA study were found to be the classification of activities into direct, indirect upstream and downstream activities, producing the final report, evaluating the data quality and interpreting the results [29]. Therefore, offering solutions to these methodological issues will make method implementation easier, enabling environmental evaluations and impact reduction in different sectors. Moreover, no case applications have been published for non-profit associations, especially for HMBs.

3. Materials and Methods

3.1. General Rules for the Environmental Impact Assessment of Organisations

O-LCA follows the four-phase approach proposed by ISO 14040/44 for product LCA, including goal and scope definition, inventory, impact assessment and interpretation [34,35]. During the first phase of the analysis, the study motivation and the intended application are defined [22]. Particular attention must be paid to the scope phase since some features of the O-LCA differ from a conventional LCA procedure. The discrepancies are detailed below in accordance with the Guidance on Organisational Life Cycle Assessment [33]:

(i) It is necessary to disaggregate the reporting, i.e., the functional unit, into two components which correspond to description (reporting organisation) and quantification (reporting flow). All of the organisation's units and components shall be organised using either the control (financial or operational) or the equity share approach.

(ii) It is necessary to determine the reporting period (i.e., the specific period for which the organisation is being studied), as the results are only valid throughout that timeframe.

(iii) It is necessary to consider both direct and indirect emissions and resource utilisation in the system boundary. The first takes place within the reporting organisation, whereas the second occurs along the entire value chain associated with the organisation's operations.

(iv) It is necessary to include the resource consumption and emissions of the use and the end-of-life stages (i.e., waste disposal and treatment) of the products during the reporting period of a complete cradle-to-grave assessment. However, a cradle-to-gate perspective can be adopted if the organisation has no control over the use or end-of-life stages, eliminating the downstream phases.

The inventory phase describes the data collection procedures and the processing data relating to all inputs and outputs of the organisation considered [33]. It categorises them into activities following the organisation's value chain (direct activities, indirect upstream activities and indirect downstream activities) [22].

In the impact assessment, all inputs and outputs collected in the previous phase are converted into potential environmental impacts using specific characterisation factors [33]. The results of the impact categories taken into consideration are used to create a profile of the organisation's potential environmental impacts. Last, the interpretation phase requires a critical assessment of the result of an LCA study and allows us to derive conclusions and recommendations to support decision and communication strategies [22].

3.2. Description of the Case Study

The study focuses on one facility where the entire operations occur, the Hearts Milk Bank, located within the Rothamsted Institute in Hertfordshire. Hearts operates as part of the Human Milk Foundation (HMF), a charity dedicated to creating nationally equitable milk bank services. The mission of the charity is to support families facing feeding challenges in neonatal intensive care units through the provision of education and donor human milk (DHM), as well as where a bridge to a full milk supply is needed or lactation is not possible. Access to DHM is of particular importance for premature and very sick babies whose mothers temporarily or in the long term are not able to provide any or enough of their own milk. Hospital neonatal units are charged a fee to cover the milk bank's costs, but DHM and lactation support is provided free of charge to families who would not currently qualify on the National Health Service. The provision of the DHM is under the oversight of a healthcare professional.

HMBs play a vital role by recruiting donors, processing, storing and supplying donor milk to neonatal units and similar settings in a safe and controlled manner [7]. However, if the milk does not pass the rigorous microbiology tests both before and after pasteurisation, it is discarded [37]. The main factor involved in human milk wastage is microbiological contamination, which represents around 10–12% of donated milk being discarded currently [38,39].

Therefore, a strategy implemented in this particular HMB to ensure that the milk has remained in optimal conditions from the point of expression until fed to a vulnerable infant is to monitor the temperature and humidity during milk transportation using IoT technologies. For every journey, a sensor was installed to monitor the milk in the right condition of temperature and humidity. The sensors transmit the temperature/humidity information to a Big Data server, and alerts are sent when the temperature exceeds the acceptable limit. Detailed information on the monitoring system will be presented in the following sections.

3.3. Definition of Goal and Scope

The goal of the assessment is to assess the potential environmental impacts of a single research-focused UK HMB and the potential environmental savings due to implementing a monitoring system based on IoT technologies.

Table 1 summarises the main characteristics of the organisation analysed in this study. The reporting unit was defined as "human milk management during one year of HMB operation". The reporting flow is, therefore, 3936 L of human milk, which was the volume of human milk donated between January and December of 2021 (reference period).

Table 1. Organisational life cycle assessment characteristics.

Criteria	**Specific Features**
Reporting organisation	Human milk bank in the UK
Organisation size	Small size (<50 employees and volunteers)
Intention of application	Environmental performance assessment and improvement, identification of environmental hotspots, strategic management and control
Targeted audience	Disclosed to the public, including HMB associations, policymakers, funding sources and costumers
Reporting period	January–December 2021
Reporting unit	Human milk management during one year of operation
Reporting flow	3936 L of human milk
Consolidation method	Operational control
Experience-based pathway	Existing environmental assessment gate-to-gate (Pathway 2)
System boundary	Cradle-to-grave (excludes the recruitment, selection, approval, consent and education of milk donors and the milk defrosting and consumption by the recipients).
Data collection method	Top-down: direct activities data were collected through company interviews. Indirect upstream and downstream activities data were taken from Ecoinvent database.

The consolidation method applied was the total control over operational terms; i.e., the reporting organisation has full operational control on how the human milk is distributed to final consumers, used and disposed of. Under this approach, the organisation accounts for 100% of the impacts from units over which it has operational control. All activities and related life cycle processes of the reporting organisation were considered according to ISO/TS 14072. Four experience-based pathways are described in the UNEP/SETAC report [33] for conducting an O-LCA. The reporting organisation had initial environmental experience and information to perform a gate-to-gate analysis; therefore, it fits the "pathway 2".

Two scenarios were built to determine the effect of IoT technologies on monitoring/controlling the temperature and humidity during milk transportation on the environmental impacts of the HMB. Scenario A represents the baseline scenario and includes the processes associated with the HMB. Scenario B follows the same processes as scenario A but includes the IoT technologies used to monitor the transport conditions.

The system boundaries are illustrated in Figure 1 and follow a cradle-to-grave approach. The consolidation method applied allows the inclusion in the system boundaries the processes over which the organisation has the full authority to introduce and implement its operating policies at the operation. In this study, the processes include milk collection, storage, first transportation from the donor's home/hospital to the HMB, processing (screening, pasteurisation, packaging and storage), second transportation from the HMB to the hospital/recipient home and final treatment provided to all solid waste generated (landfill and recycling).

Scenario B also comprises digital sensors for measuring the specific parameters, the Big Data server and the human milk avoided. Both scenarios exclude the recruitment, selection, approval, consent and education of milk donors, the milk defrosting and consumption by the recipients, as well as the energy consumed by breast pumps and the freezers at donors' home/hospital. The use of containers to collect the milk was included in the boundaries, as they are provided by the HMB and are part of the bank's operational control.

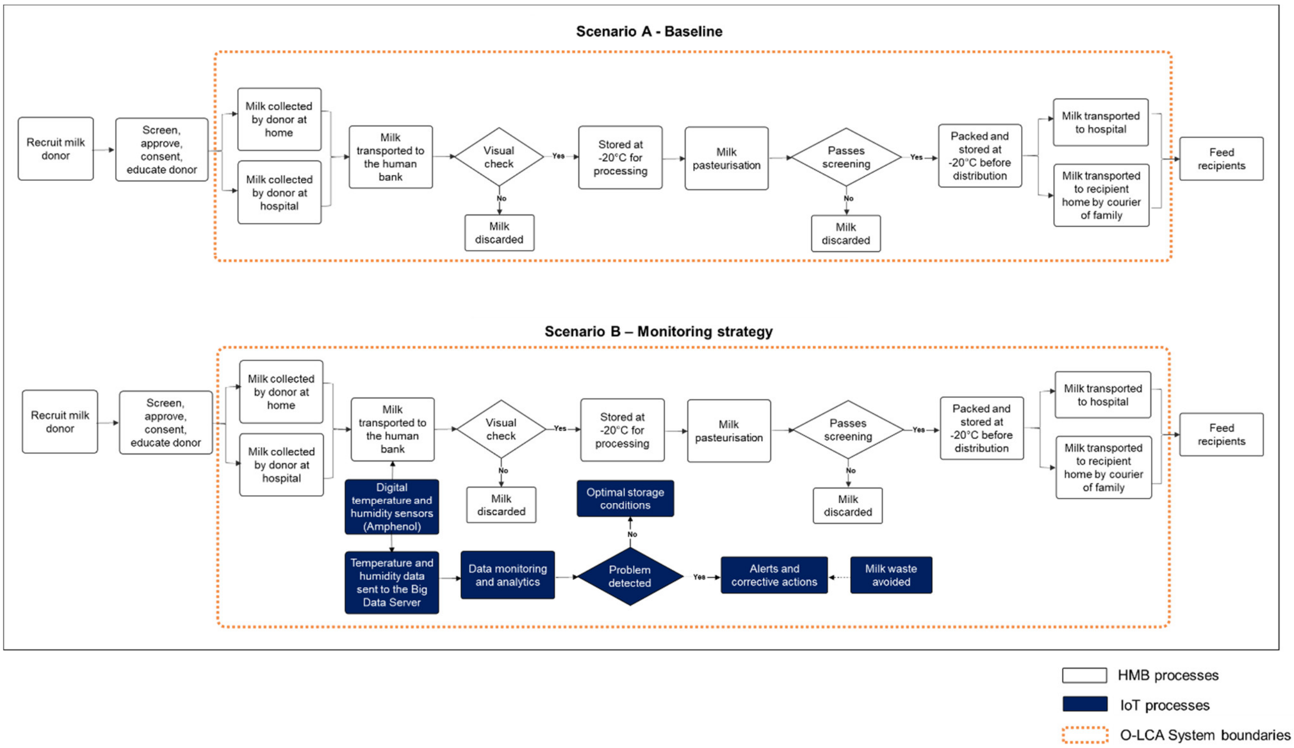

Figure 1. Schematic representation of the system boundaries. (**A**) refers to the baseline scenario, and (**B**) refers to the monitoring strategy implemented in the organisation.

3.4. Life Cycle Inventory

Data collection followed the recommendations for O-LCA provided by UNEP/SETAC [33]. According to its guidance, the system should include all inputs and outputs from direct and indirect activities. Direct activities represent the processes owned or controlled by the reporting organisation, while indirect activities are related to the consequences of the reporting organisation’s actions that occur at sites controlled by other organisations of the value chain. Figure 2 shows the inputs, outputs and direct and indirect activities under analysis.

In this study, the data collection method was defined as a top-down approach, that is, an inventory-oriented approach. It considers the reporting organisation as a whole and adds upstream models for all inputs of the organisation and downstream models for all outputs [33]. Therefore, specific data should be used for direct activities. There are two main methods to quantify the inventory for direct activities: direct measurement or calculation. In this study, direct quantification of all resources was systematically made by the reporting organisation, including a detailed list of all materials used and the energy consumed. Calculation procedures were used to quantify the indirect activities and required the use of activity data and consumption/emission factors.

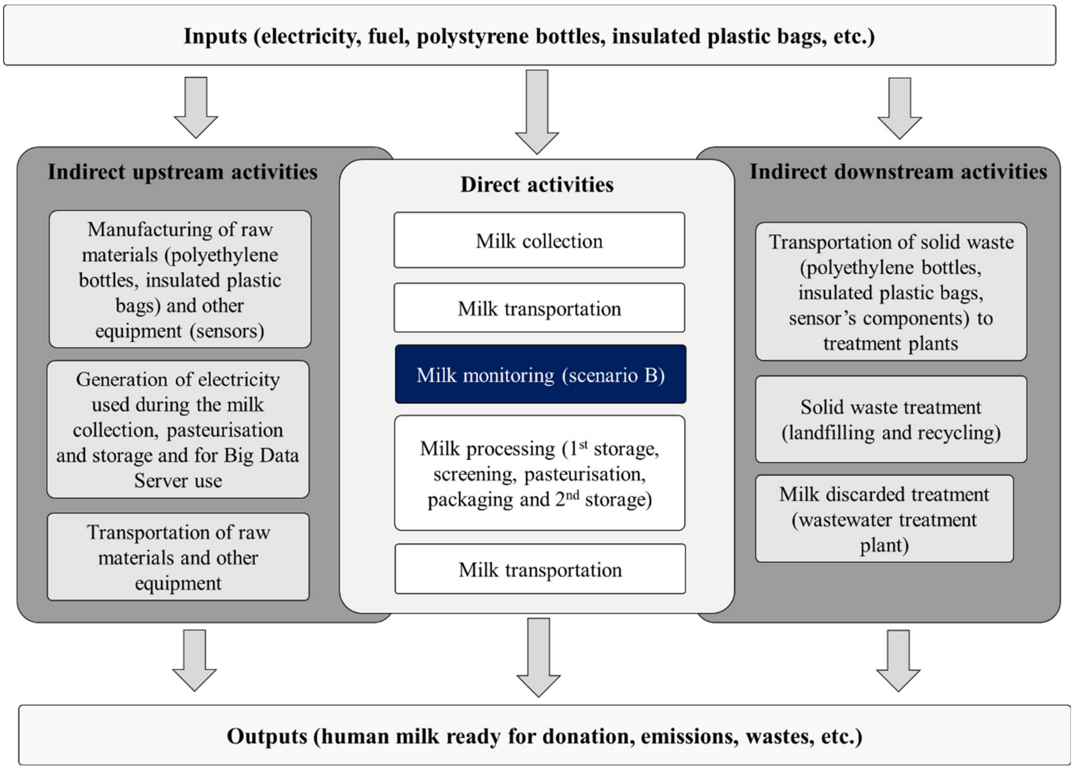

Figure 2. Inputs, outputs, and activities (direct and indirect) of the reporting organisation.

Direct activities include energy use, milk collection, processing (storage, screening, pasteurisation and packaging) and transportation. Indirect upstream activities include extraction and manufacturing of raw materials (e.g., polyethylene bottles and insulated plastic bags), generation of electricity and transportation of the raw material to the HMB. Indirect downstream activities are related to the transportation of solid waste to the final destination, solid waste treatment (landfilling and recycling) and treatment of discarded DHM. The life cycle inventory of direct activities (scenario A) can be found in Table 2.

3.4.1. Milk Collection

Breast milk is expressed manually or using electric or manual breast pumps. The milk is collected and stored in high-density polyethylene (HDPE) containers (free of bisphenol-A, bisphenol-S, DEHP and phthalates). The containers are single-use and are recycled after their end-of-life. The minimum volume required for donation is 2 litres per collection due to logistical limitations, maximising efficiency of milk bank processes and operational costs of donor recruitment. The total time to collect the minimum volume of milk required ranges from 3 days to 3 months, depending on the mother's circumstances and her physiology.

Donors are responsible for freezing and controlling the temperature while the milk is under their responsibility. The HMB provides donors with a standard domestic freezer thermometer to check the freezer's temperature and requires them to record the temperature daily. The HMB under study typically recruits 40–50 donors per month and serves approximately 4000 infants annually.

Table 2. Life cycle inventory of an HMB in the UK per reporting flow.

Unit Process	Value	Unit
Inputs		
Milk collection		
Polyethylene bottles	388	kg
1st transportation		
Diesel	1006	L
Insulated plastic bags	2.83	kg
Dry ice	5.62	kg
Milk processing		
Electricity consumption—1st storage	4795	kWh
Electricity consumption—pasteurisation	414	kWh
Electricity consumption—2nd storage	33,350	kWh
Polyethylene bottles	388	kg
2nd transportation		
Diesel	670	L
Insulated plastic bags	2.83	kg
Dry ice	5.62	kg
Outputs		
Products		
Human milk ready for donation	3361	L
Liquid wastes		
Human milk discarded	575	L
Solid wastes		
Polyethylene bottles	776	kg
Insulated plastic bags	5.67	kg
Air emissions (transportation)		
CO_2, fossil	3937	kg
CO, fossil	482	kg
CH_4, fossil	10.5	kg
NMVOCs	117	kg
N_2O	0.05	kg
NO_x	11.2	kg
SO_2	20.1	g
Particulates	1.59	kg

3.4.2. Milk Transportation

Donated milk is normally transported by blood bike motorcycle volunteers. Normally, between one and six volunteers make the transportations per day, totalling about 20 volunteers working at the HMB. The milk is transported using insulated and weather-resistant bags of three different sizes, small (30 × 25 cm), medium (35 × 35 cm) and big (70 × 35 cm). The durability of the bags was assumed to be 10 years and was considered that they are recycled after their end-of-life. The average amount of human milk transported per bag is 7 litres. The insulated bags can keep the milk frozen for up to 4 h. If the transport time is longer, it is necessary to use dry ice. It was assumed that 1% of the trips require the use of 1 kg of ice, although this is likely an overestimate.

The average transport distance during the first transportation (from donor/hospital to HMB) is around 50 miles, but it can achieve up to 100 miles per route. For calculation purposes, it was considered the average distance (mean: 75 miles). The second transportation mode (from the HMB to the hospital neonatal units/recipient home in the community) is also made by motorcycle volunteers, but the average distance is 50 miles. The diesel-related emissions to air during combustion were taken from Ecoinvent [40].

3.4.3. Milk Processing

The recently arrived frozen milk is unloaded, labelled for identification and transferred to freezers that maintain internal temperatures of at least −20 °C. Four medical-grade freezers (262 L capacity) and seven upright food-grade freezers (365 L capacity) are used to store the incoming milk, while three fridges (400 L capacity) are used for defrosting the milk at the HMB. The milk can be kept frozen for some weeks before the first screening. The electricity consumed by each medical freezer is equal to 2.2 kWh per day, while the food freezers consume around 12 kWh per day and the fridges 4.4 kWh. The milk is then defrosted, and the contents of 10 to 20 containers are pooled by being poured into stainless steel jugs and gently stirred before decanting into 50, 100, or 200 mL sterile containers. Samples from each batch are taken for microbiological analysis. Milk is not pooled between different donors.

After this process, the milk is pasteurised. The method involves heating the human milk at around 62.5 °C for at least 30 min. The HMB has two pasteurisers, which process up to 19 L of milk and consume 2 kWh per cycle. A sample from each batch is screened after pasteurisation for microbial contamination, and milk is discarded if microbiological thresholds are exceeded in accordance with the NICE Clinical Guideline [41]. The processed milk is frozen and stored in freezers with a cooling capacity of −25 °C. The milk is stored in polyethylene containers with different capacities (50–200 mL) depending on the final use (infants in hospital or recipients at home). The milk can be stored for up to 6 months after the date of the first expression until expiration, but it is typically used in less than 3 months.

Approximately 330 L of human milk were managed per month in the calendar year, but output from Hearts is increasing by approximately 40% year on year. The percentage of milk discarded monthly (considered unsuitable for consumption) ranged from 5.1% to 17.9% over the last year (mean: 11.7%; September 2021–August 2022), with the highest failure rates during the summer months (June–August).

3.4.4. Milk Monitoring (Scenario B—IoT Technologies Implementation)

A total of 12 sensors were installed to monitor the milk and ensure it remained in the right temperature and humidity condition. The Eagle datalogger (Digital Matter) was selected as the IoT platform, which formed the basis of the temperature and humidity monitoring system deployed in this human milk bank. The logger is an IP67-rated rugged cellular IoT device, supporting a range of inputs for various IoT applications. Each logger has four cell long-life power alkaline batteries, each with a capacity of 7800 mAh. Therefore, no other electricity or energy is required during the use phase.

Onboard, the logger contains a printed circuit board (PCB) with an array of sensor inputs, a GPS module and an accelerometer for geofencing and movement detection and is equipped with a cellular modem and sim card allowing the device to run on the IoT low-power LTE-M (CAT-M1) 4G network for data transmission. For sensing, the eagle was equipped with a T9602 temperature/relative humidity (T/RH; ± 2% RH, ± 0.5 °C, 0.01 °C resolution) sensor probe (Amphenol, Wallingford, Connecticut, USA).

The sensors used in this study were manufactured in South Africa, but most of the electronic components of the PCB were produced in China as well. The sensors were transported to the UK in a container ship as a whole component, and the batteries were also included. A freight lorry was used for transportation within the UK. Transport distances were calculated based on the distance from the production site to the HMB. The air emissions due to the combustion of diesel and heavy fuel oil during the sensor transportation were taken from Ecoinvent [40]. The electricity consumed during the manufacturing phase for mounting the PCBs and the sensors was taken from Chiew and Brunklaus [42].

The sensors were installed inside the bag of each volunteer blood biker making regular journeys. Installation of the sensor is performed manually, and no environmental burden was assumed. The life span of the sensor is around 10 years, depending on the environmental conditions [42]. According to the supplier, the batteries last about 4 years, considering one measurement every 20 min. However, in this study, the sensors measure the conditions every 2 min; therefore, it is estimated that the batteries will last about 5 months each.

For the end-of-life phase of the sensor's components, it was considered that the sensor housing, the copper cables, and the screws were recycled, while the PCB was reused, and the batteries and the antenna were sent to a landfill, as they cannot be recycled at this time. It was considered that 100% of the solid wastes reach the final disposal (regardless of the technique used). The sensors components were weighted, and the complete inventory data of raw materials, manufacturing, use and end-of-life were described in Table 3.

Table 3. Life cycle inventory of sensor manufacturing, transportation and use per single unit working one year.

Unit Process	Value	Unit
Inputs		
Raw materials		
Printed circuit board	1.576	g
Copper flexible cable	1.114	g
Antenna with ceramic tip metal probe	0.530	g
Alkaline batteries	219.2	g
Stainless steel screws	0.384	g
Housing top and bottom	6.746	g
Manufacturing		
Electricity	0.0044	kWh
Transportation		
Heavy fuel oil (container ship)	0.00062	L
Diesel (freight, lorry)	0.00024	L
Outputs		
Products		
Sensor	1	unit
Solid wastes		
Printed circuit board	1.576	g
Copper flexible cable	1.114	g
Antenna with ceramic tip metal probe	0.530	g
Alkaline batteries	219.2	g
Stainless steel screws	0.384	g
Housing top and bottom	6.746	g
Air emissions (transportation)		
CO_2, fossil	2.617	g
CO, fossil	0.002	g
CH_4, fossil	0.034	mg
NMVOCs	0.002	g
N_2O	0.134	mg
NO_x	0.047	g
SO_2	0.028	g
Particulates	0.004	g

The sensors measure the conditions and send the collected information to a Big Data server. The server sends alerts when the temperature exceeds the acceptable limit (above

−15 °C). The alert is sent via email or SMS to designated individuals at the HMB. The Big Data Server comprises one unit of computer equipment, a redundant power supply (1600 W), processors and storage drives. The estimated electricity consumption of the server is 1152 kWh per month. Each row of data generated per recording occupies around 87 bytes in the server. The sensors are configured to record data every 5 min while in a trip or every 12 h outside of a trip. The electricity consumption was allocated according to the use of the server space; i.e., 8.1% of the space in use was due to the sensors installed at the HMB. For the internet connection, the Ecoinvent database was used in the model. Whenever possible, regionalised datasets were used to model the foreground processes.

3.5. Life Cycle Impact Assessment

The life cycle impact assessment was mainly modelled using the software OpenLCA v1.10.3. The characterisation factors used in this study for the impact assessment are those of the ReCiPe 2016 method at the midpoint level following a hierarchical perspective [43]. The following environmental impact categories were included: global warming (GW), ozone formation–human health (OH), ozone formation–terrestrial ecosystems (OT), stratospheric ozone depletion (SOD), ionising radiation (IR), fine particulate matter formation (PM), freshwater eutrophication (FEu), marine eutrophication (MEu), freshwater ecotoxicity (FEc), marine ecotoxicity (MEc), terrestrial ecotoxicity (TEc), human carcinogenic toxicity (HTc), human non-carcinogenic toxicity (HTnc), terrestrial acidification (TA), fossil resource scarcity (FS) and water consumption (WC).

3.6. Sensitivity Analyses

Four sensitivity analyses were performed to understand the influence of some parameters on the environmental impact assessment results. A sensitivity analysis was made to assess the influence of the monitoring IoT technologies at the transportation stage on the milk waste avoided and, consequently, on the environmental impacts. At this moment it is not possible to estimate the exact amount of human milk wasted during the transportation stage, and the value used in this sensitivity analysis considers two hypothetical scenarios, where: (1) the IoT technologies avoided discarding 1% of human milk, and (2) 3% of human milk discarded due to transportation issues was prevented. The environmental burdens avoided were modelled through the system expansion by substitution [44]. Credit was given to scenario B for avoiding additional human milk production to cover the losses in scenario A and all related upstream activities, such as collection, transport and energy required to store and pasteurise the milk.

The second analysis evaluated the influence of transportation distances on the results. The assumed distances of the first transportation (from the donor’s home/hospital to the HMB) used in the baseline scenario are related to the average distance. The distances were changed to make the assessment more representative of other regions. Therefore, the transport distances were adjusted to the extreme values of the baseline distances (i.e., 50 and 100 miles).

Another sensitivity analysis assesses the influence of substituting motorcycle volunteers with delivery drones. Drones have found applications in many civil sector areas during the last decade. A drone is an aircraft without a human pilot on board whose flight is controlled either autonomously or under the remote control of a pilot on the ground or in another vehicle. Selecting this analysis was based on the Human Milk Foundation ambition to reduce reliance on fossil fuels for transportation purposes [45]. Ongoing projects aim to use drones to make 10% of the first and second transportation. In this scenario, the energy model used to determine the drone’s electricity consumption is based on the specifications of the Wingcopter 198 drone with 8 lift rotors [46]. The delivery includes flying at 18 km/h and descending to the delivery site with a payload of 5 L. The return trip is similar but without the payload. The drone has two Li-ion batteries of 814 Wh each, which allows a range of 75 km considering ideal conditions (no wind, sea level altitude, 15 °C air temperature) and ideal operation (ideal cruise speed, 20% battery reserve, standard payload form factor).

The last sensitivity analysis evaluates the substitution of 10% motorcycles for electric vehicles. In this scenario, the impact of the carried payload of human milk was also examined. Two scenarios were considered: (1) the electric vehicle transports 10 L per journey, and (2) 50 L of milk is transported per journey. The average energy consumption, 200 Wh/Km, was taken from EV [47] and is based on real-world values corrected for multiple versions of vehicles.

4. Results and Discussion

4.1. Environmental Impact Assessment and Hotspot Analysis

Figure 3 presents the relative contribution of each unit process to the total impact obtained for the baseline scenario (A). Human milk transportation is the main hotspot of six impact categories: global warming, ozone formation (human health and terrestrial ecosystems), terrestrial ecotoxicity, human non-carcinogenic toxicity and fossil resource scarcity. The contribution of first and second transportation combined represents 39.3–71.6% of the total impact in those categories. For global warming, carbon dioxide (CO_2) emitted from diesel combustion is the main contributor in this category. Other relevant emissions to consider during diesel combustion include non-methane volatile organic compounds (NMVOC) for ozone formation, zinc (Zn) and human non-carcinogenic toxicity and copper (Cu) for terrestrial ecotoxicity.

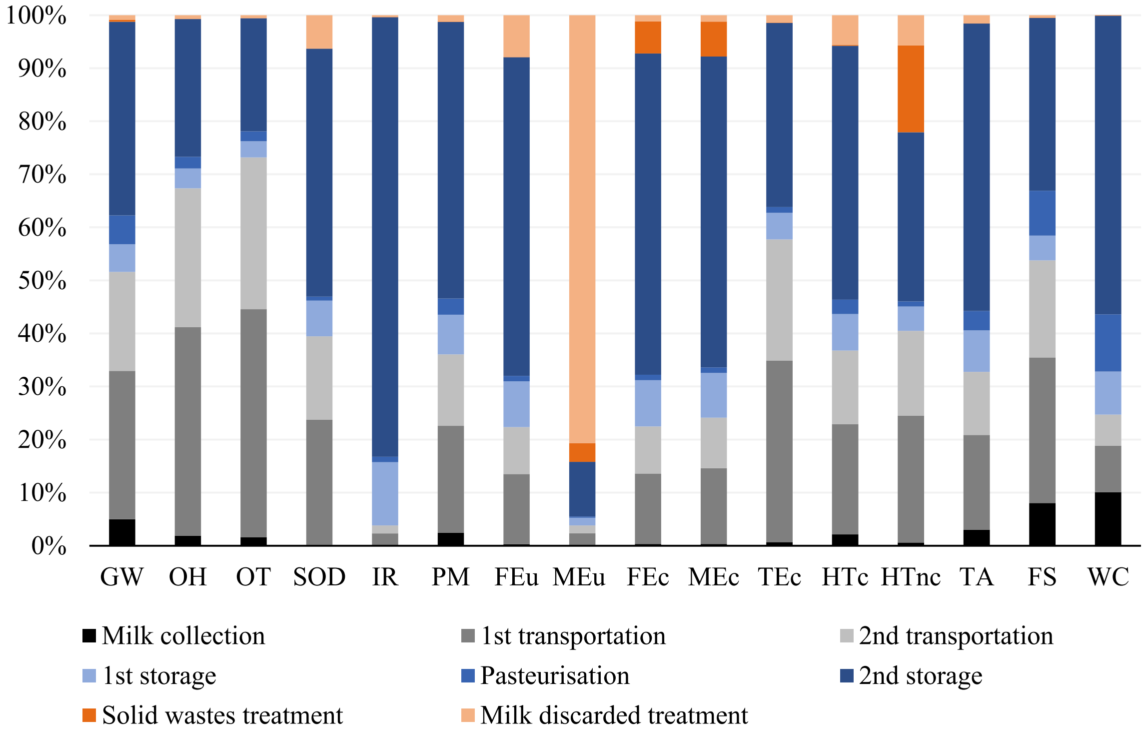

Figure 3. Relative contribution of each source to the total impact of the baseline scenario (A).

For ionising radiation, the electricity consumed during the second storage of human milk is the main hotspot (82% of the total impact), followed by the first storage (12%). The electricity consumed during milk storage is also relevant for stratospheric ozone depletion, fine particulate matter formation, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, terrestrial acidification and water consumption. Regarding marine eutrophication, the treatment of discarded milk represents

80.7% of the total impacts and was essentially due to the emissions of nitrate and ammonium to water.

Figure 4 presents the relative contribution of manufacturing, transportation and use for the total impact of the sensors used in this study. It was observed that batteries (manufacturing and use) are the main hotspot for the sensor life cycle, followed by the printed circuit board for all impact categories. The batteries represent 62–96% of the total impact, while PCB can achieve 3.5–36.6%. In this system, nitrogen oxide (NOx) is the main responsible for the impacts on ozone formation (human health and terrestrial ecosystems), while SO_2 is relevant for the impacts on fine particulate matter formation and terrestrial acidification. Copper (Cu) present during the batteries manufacturing is responsible for a great part of the impacts on ecotoxicity categories, including freshwater, marine and terrestrial, and Chromium VI is the most important contributor to the impact in the human carcinogenic toxicity category.

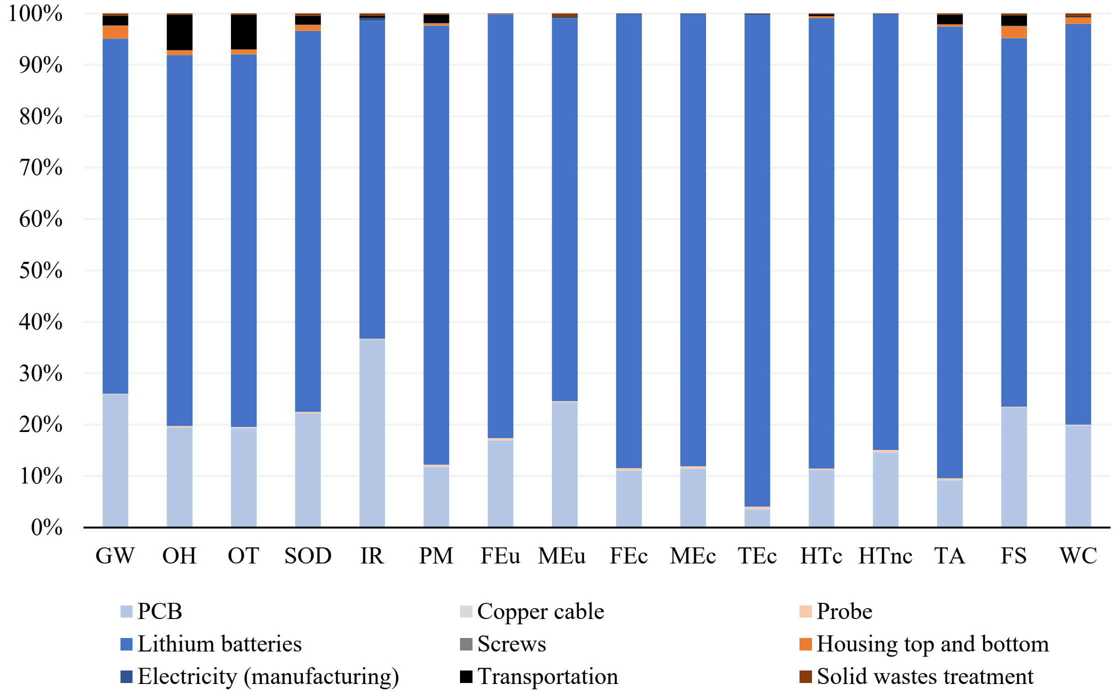

Figure 4. Relative contribution of each source to the total impact of sensors.

Figure 5 presents the IoT technologies' relative contribution to the HMB's total impacts regarding the potential milk avoided. Although integrating IoT technologies to monitor temperature/humidity conditions can have many advantages, the environmental implications of using these technologies have been scarcely debated. On one hand, these technologies substitute physical processes and may help avoid impacts, which Weber et al. [48] described as "moving bits instead of atoms". On the other hand, they use electronics, an impact-intensive technology. In addition, the energy consumption of electronic products is far from insignificant. Consequently, the environmental impacts these technologies help to avoid must be balanced with the environmental impacts they generate themselves, keeping in mind that these impacts may not be of the same nature and therefore lead to dilemmas. In Figure 5, it is possible to observe that this integration did not adversely affect the organisation in a significant way. The contribution of the IoT technologies implemented in this study, including 12 sensors and a Big Data server to store and control the data, achieved a maximum impact contribution of 2.3% for the freshwater ecotoxicity category.

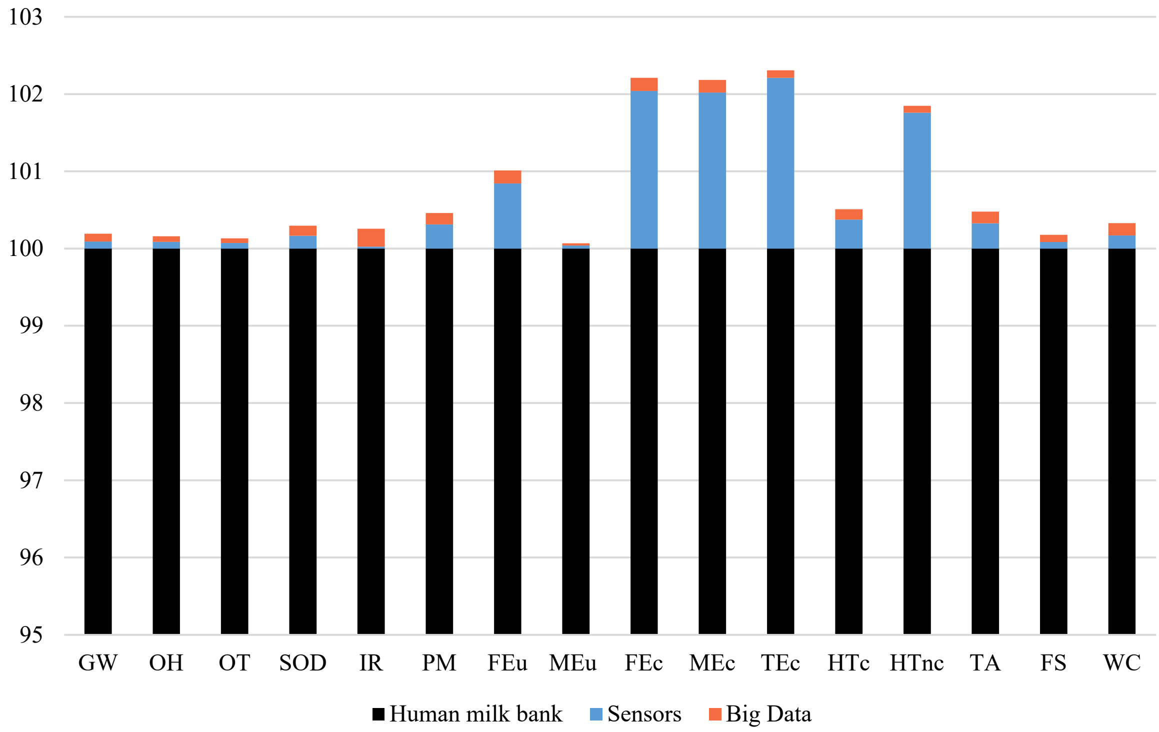

Figure 5. Relative contribution of each source to the total impact of the monitoring strategy scenario (B), disregarding the credits due to food waste avoided.

The main impact categories affected by the implementation of sensors are freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, human non-carcinogenic toxicity and freshwater eutrophication, especially due to the use of batteries as a source of energy. The common environmental side effects of metals mining to produce the batteries are increased salinity of rivers, contaminated soil and toxic waste, ground destabilisation and water and biodiversity loss [49]. The substitution of these batteries for more environmentally friendly alternatives can be a strategy to mitigate their associated impacts [50,51]. For about a decade, scientists and engineers have been developing sodium batteries, which replace the metals used in current batteries [52]. Another alternative can be supercapacitors and ultracapacitors. These devices offer advantages over batteries in lifetime, power density and resilience to temperature changes [53]. They also benefit from high immunity to shock and vibration. However, they can be high initial costs and provide low energy density [54].

The electricity consumed to store and control the data by the Big Data server contributed to a slight increase (<1%) in the impacts mainly for the following categories: ionising radiation, water consumption, fine particulate matter formation and freshwater eutrophication. However, a reduction in the environmental impact can be expected if human milk waste is avoided, which can equilibrate the additional impacts caused by the introduction of monitoring technologies. The surplus production of food to compensate in case of waste could cause a significant amount of environmental and social problems [55–57]. Therefore, it is recommended to use monitoring systems/technologies, such as the one proposed to avoid food waste and the environmental footprint associated with these wastes. The potential avoided impacts resulting from the decreased amount of milk waste discarded due to the implementation of IoT technologies are shown in Section 4.2.

4.2. Sensitivity Analysis

Table 4 presents the total impact obtained for the first sensitivity analysis, i.e., the influence of the monitoring IoT technologies on the environmental impacts considering 1–3% reduction in the total milk discarded. Figure 6 shows the percentage change based on the baseline scenario.

Table 4. Total results of the impact assessment associated with the baseline scenario (A) and the scenarios representing the implementation of monitoring technologies (B).

Impact Category	Unit	Scenario A	Scenario B (1% Waste Reduction)	Scenario B (3% Waste Reduction)
GW	kg CO_2 eq	30,749	30,501	29,886
OH	kg NOx eq	135	134	131
OT	kg NOx eq	166	165	161
SOD	kg CFC_{11} eq	0.0129	0.0128	0.0125
IR	kBq Co-60 eq	8489	8426	8256
PM	kg $PM_{2.5}$ eq	50.5	50.3	49.2
FEu	kg P eq	7.77	7.77	7.62
MEu	kg N eq	4.22	4.19	4.10
FEc	kg 1,4-DCB	2320	2348	2302
MEc	kg 1,4-DCB	2972	3007	2947
TEc	kg 1,4-DCB	103,960	105,318	103,239
HTc	kg 1,4-DCB	1112	1106	1084
HTnc	kg 1,4-DCB	27,857	28,094	27,536
TA	kg SO_2 eq	126	125	122
FS	kg oil eq	9037	8962	8781
WC	m^3	203	201	197

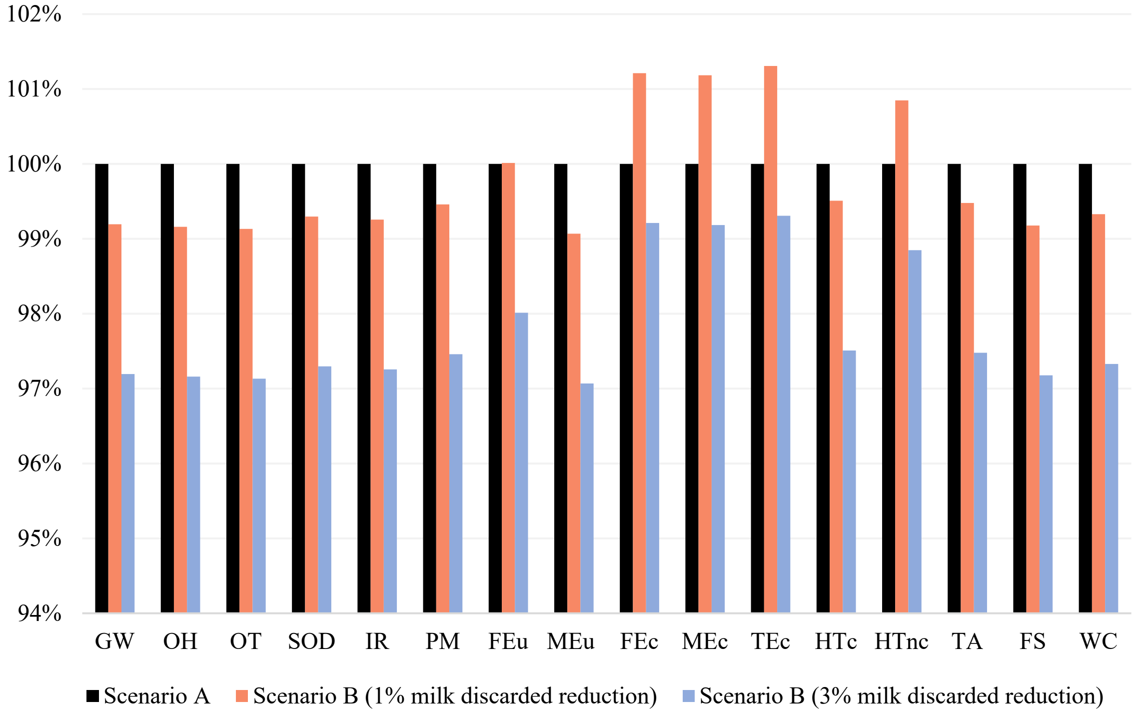

Figure 6. Results of the sensitivity analysis: effect of human milk discarded reduction.

A 1% reduction in discarded milk can decrease the environmental impacts from 0.5 to 0.9 % in some categories. Marine eutrophication and ozone formation were the impact categories more positively affected. However, this reduction is not sufficient to offset the impacts added to the system due to the implementation of IoT technologies in four categories: freshwater, marine and terrestrial ecotoxicity and human non-carcinogenic toxicity.

However, when milk discarded achieves a reduction of 3% in the second scenario, the impacts on the global warming category are reduced by 863 kg of CO_2-eq per year in this organisation. In this scenario, the control of the milk conditions proved to be relevant to the reduction of impacts related to air emissions and resource consumption. In this particular case, the recommended amount of human milk avoided should be at least 90.8 L per year in order to compensate for the additional impacts due to IoT technologies implementation.

Food waste is associated with different adverse effects on the environment [56,57]. When human milk food is discarded, all inputs used in processing, transporting, preparing and storing discarded milk are also wasted. The later the milk is wasted along the chain, the greater its environmental impact, because then we also need to take into consideration the energy and natural resources expended into each of those steps. In addition, the milk discarded that ends up in wastewater treatment plants produces a large amount of greenhouse gas emissions, which impact the environment [58,59]. Human milk management also involves steps that consume diesel and fossil fuels. For instance, transporting the human milk from the donor’s home/hospital to the HMB and then from the HMB to the hospital/recipient home needs diesel and other fuels; storing the milk in the freezers and pasteurising it also uses a large amount of electricity. Wasting fuel or electricity, both in the back and front end by wasting human milk, can have an impact on the environment and exacerbates the global warming crisis with its significant carbon dioxide emissions.

Reducing and preventing human milk waste can increase food security, foster productivity and economic efficiency, promote resource and energy conservation and decrease global warming. In this scenario, the additional production of food to compensate for these losses would not be necessary. Therefore, contributing to the reduction of all downstream impacts observed during human milk handling, including transportation, storage and pasteurisation. However, further assessment to quantify the precise amount of food waste avoided is recommended.

In the second analysis (Figure 7), the influence of transportation distances on the environmental impact results was evaluated. The transportation over larger distances results in higher consumption of diesel, increasing the emissions of carbon monoxide (CO), CO_2, SO_2, NOx, NMVOCs and others. These emissions are generated due to diesel combustion, which affects mainly the impact categories of global warming, ozone formation, terrestrial ecotoxicity and fossil resource scarcity. When the transport distance is changed by 25 miles, the net impact can vary by up to 14.3% in the ozone formation (terrestrial ecosystems) impact category. Therefore, the results show that human milk transportation depends highly on the transport distance, and the milk should be collected from donors located close to the HMB, and distribution should where possible be made to local hospitals in order to decrease the environmental impacts associated with transportation.

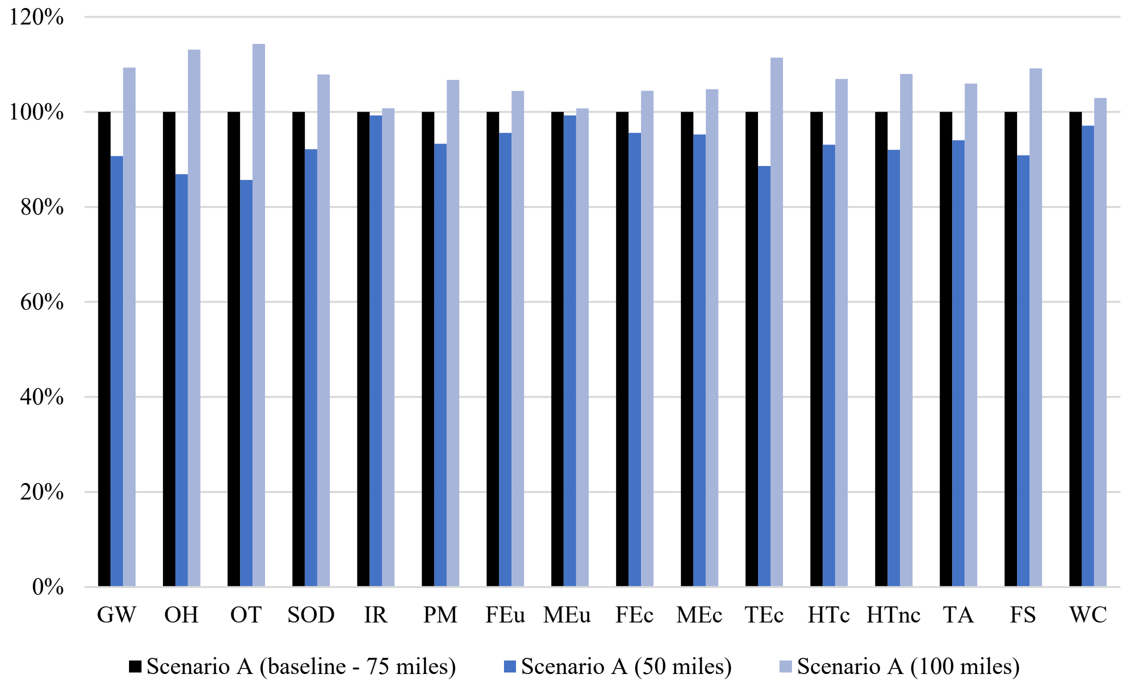

Figure 7. Results of the sensitivity analysis: effect of transportation distances.

An alternative is the introduction of more decentralised hubs, where local healthcare centres can be responsible for the collection, and the human milk bank acts as the principal organising centre supervising different branches. The creation of hubs has been designed to mitigate the impacts of having fewer milk banks and ones that collect and provide DHM over a wide area. This alternative is already in practice in this HMB. However, this study did not take into account the additional impacts associated with the creation of the additional facilities that would need to be established to allow for local collections and distributions, i.e., all the additional equipment and facility impacts and the extra staffing and other resources.

4.3. Employing Different Transport Modes in Place of Motorcycle Volunteers

The Human Milk Foundation is developing the use of drones for milk collection and delivery. While drones can substitute motorcycle volunteers in some cases, drones are sometimes the only option, especially in sparsely populated areas. Hence, an analysis of the impact of employing delivery drones has been carried out. Figure 8 shows the influence of substituting 10 % of motorcycle volunteers with delivery drones to transport human milk.

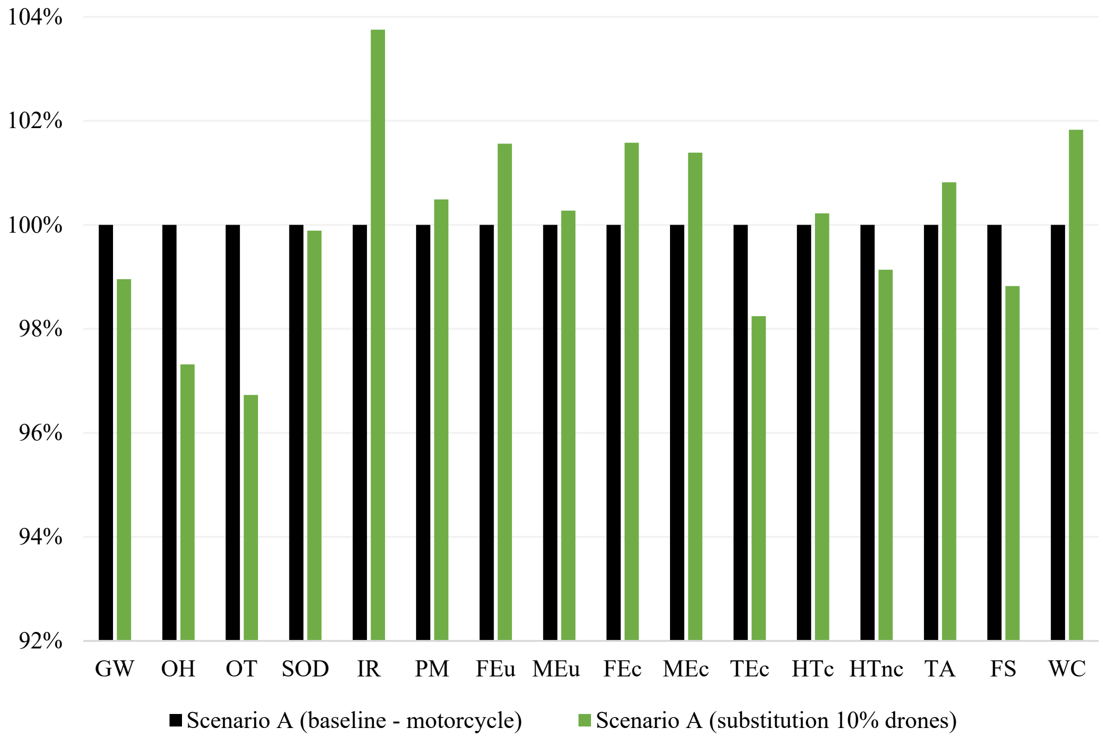

Figure 8. Results of the sensitivity analysis: effect of changing the transport mode to drones.

Effects on the environmental impacts were observed due to changes in the transportation mode. Effects on milk quality were not evaluated in this analysis. It was observed that the main categories positively affected by this substitution were global warming, ozone formation (human health and terrestrial ecosystems), terrestrial ecotoxicity, human non-carcinogenic toxicity and fossil resource scarcity. The substitution of 10% of motorcycles by drones achieved a reduction of 3.3% in ozone formation (terrestrial ecosystems). However, for other impact categories, such as ionising radiation, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity and water consumption, this change negatively affected the environmental performance of the organisation. For the ionising radiation impact category, the environmental impact increased by 3.8%, suggesting an environmental risk from using drones due to the high electricity consumption.

From an environmental perspective, there are pros and cons to using drones for delivery services. The main expected benefit for the environment is that, compared with many traditional methods of delivery using fossil fuel, drones could reduce CO_2 emissions locally as well as other air pollutants. However, although drones avoid environmental impacts from direct diesel combustion emissions, impacts relating to additional electricity production required by a drone-based logistics system may reduce or eliminate the benefits. The impacts depend on how local power is generated, e.g., using coal or natural gas, which emit carbon pollution, versus renewable resources such as wind or solar, which do not. In 2020, the electricity supplied in the UK came from 41% fossil-fuelled power (almost all from natural gas), 46.7% zero-carbon power (including 16.1% nuclear power and 30.6% from wind, solar and hydroelectricity) and imports [60]. As environmental impacts related to electricity consumption are intrinsically linked to the electricity mix supplied in the country, successive UK governments have outlined numerous commitments to reduce fossil-fuelled power. To the extent that more renewable energy sources such as wind and solar are used to generate electricity, the total greenhouse gases associated with the use of drones could be reduced. These results can serve as a precautionary note for policymakers planning to promote the use of delivery drones due to potential environmental impact reduction.

Among significant negative environmental effects, the threat to wildlife, especially birds, is another great concern. Beyond the apparent risk of collision, birds could be affected by the noise and stress caused by the frequent presence of drones in their habitat. To date, the consequences of excessive stress caused by drones on wildlife have not been studied systematically and are little understood. Other potential environmental risks include the wastes resulting from collisions and dropped cargo and the related responsibility for their disposal. Both factors might also result in resistance from society to the widespread use of delivery drones.

Figure 9 shows the influence of substituting 10% of motorcycles with electric vehicles to transport human milk. The results show that the environmental impacts of this substitution are highly dependent on the human milk payload transported. If the average amount of human milk transported per journey is around 50 L, it was observed a positive effect for all impact categories, except ionising radiation and water consumption. The maximum reduction was achieved in ozone formation (terrestrial ecosystems), which could avoid 2.7% of the impacts.

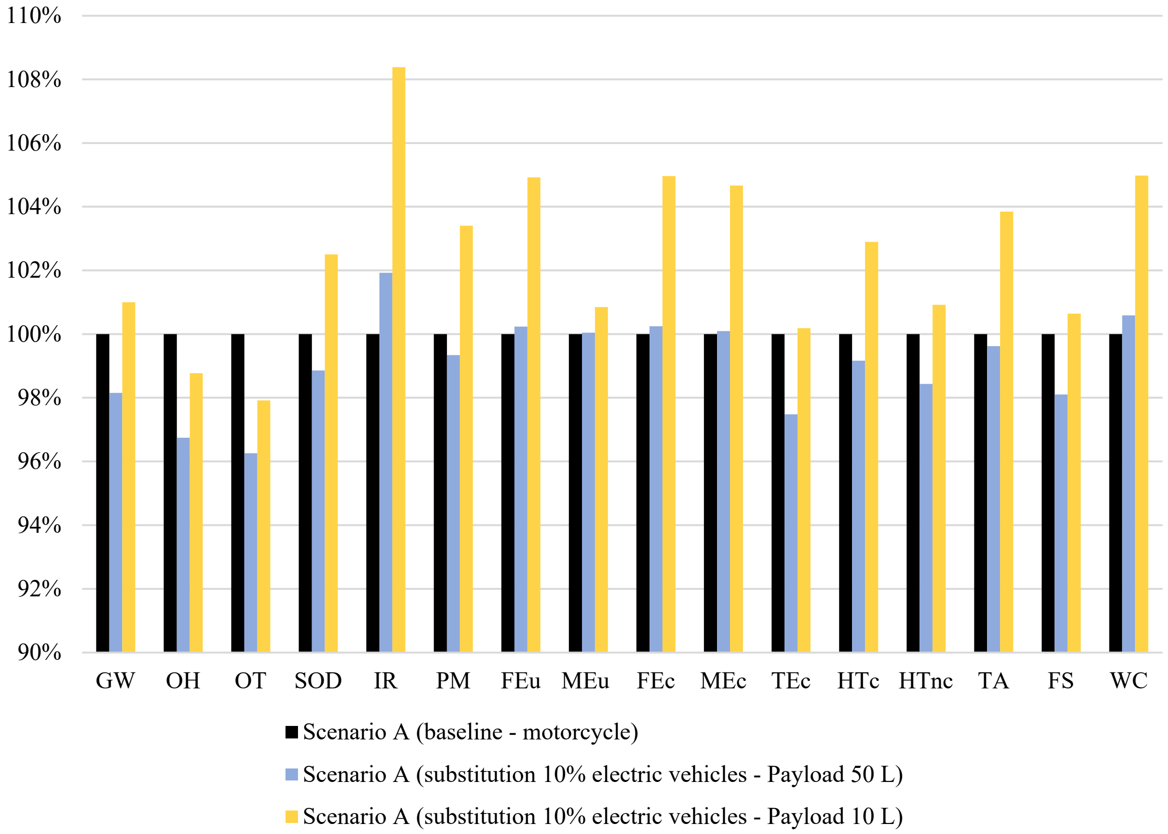

Figure 9. Results of the sensitivity analysis: effect of changing the transport mode to electric vehicles.

However, when less milk is transported per journey, and more trips are required, the environmental burden increases and a negative effect is observed for most of the impact categories. For example, the impact of ionising radiation would increase by 8.4% in this scenario. Therefore, the distribution of human milk using electric vehicles should be made transporting quantities of milk above 40 L to reduce the environmental impacts in most of the categories.

As mentioned above, battery production is an energy-intensive process. Vehicle cars rely on rechargeable batteries to run, which requires the use of energy-intensive materials such as cobalt and other metals. Producing electric vehicles leads to significantly more emissions than producing fossil fuel cars. Depending on the country of production, it can represent an additional 30 to 40% of production emissions [61].

In addition, the national electricity mix in most of the world is still powered by fossil fuels, such as coal or oil, and electric vehicles depend on that energy to get charged. The full benefits of electric vehicles will be achieved only after the electricity sources become renewable, and it might take several decades for that to happen [62]. Despite that, the local emissions per mile for electric vehicles are lower than vehicles with internal combustion engines [62], which highly affects the global warming category. However, other environmental categories should also be considered to make a more informed decision.

5. Conclusions

Quantitative estimates relating to the environmental performance of non-profit associations, such as HMBs, are crucial to provide a basis for further work on O-LCA. This methodology proved to be suitable for determining environmental impacts and savings of organisations, as the one analysed in this study, and equips decision-makers to understand the environmental performance of their companies through a comprehensive and science-based methodology.

In this study, the transportation of human milk was found as the main hotspot of this organisation for most impact categories, except ionising radiation and marine eutrophication. The electricity consumed during the second storage was the most significant contribution to the total impact of ionising radiation, while the treatment of discarded milk represented 80.7% of the impact for marine eutrophication. The strategy to integrate IoT technologies (sensors and Big Data server) to monitor temperature/humidity conditions did not adversely affect the organisation in a significant way. The batteries were responsible for a great part of the impacts of the sensors installed, followed by the printed circuit board. However, if the reduction in waste reaches 3%, then, the avoided environmental impacts resulting from this strategy could avoid 863 kg of CO_2-eq per year in the global warming category.

The sensitivity analysis regarding the influence of transport distance showed that the impacts of the HMB depend highly on the transport distance; the milk should be collected from donors located close to the HMB, and distribution should be made to local hospitals to decrease the environmental impacts associated with diesel combustion. The results of the sensitivity analysis also showed that changing part of the transportation mode from motorcycles to drones can positively affect some categories such as global warming, ozone formation, terrestrial ecotoxicity and fossil resource scarcity. However, for other impact categories, this change could result in environmental risk due to the high electricity consumption, especially for the ionising radiation impact category. Therefore, human milk logistics must be studied in a multidisciplinary way, addressing organisational, safety, economic, environmental and engineering aspects, before the transaction to a drone solution. Future studies could bring this approach to other sectors and companies. A similar analysis was performed considering the substitution by electric vehicles, and the results showed that the environmental impacts of this strategy are highly dependent on the amount of milk transported per journey. In order to reduce the environmental impacts, the amount of human milk that electric vehicles should transport in a single journey should be greater than 40 L.

While this is the first time the use of digital technologies for avoiding wasted human milk is evaluated using LCA, we are constrained by the availability of suitable data, which has limited our analysis and findings. For instance, the precise amount of food waste avoided due to IoT technologies implementation in this HMB is still under assessment, and further analysis is required. Despite these limitations, the results of this paper provide evidence of the sustainability benefits of modern digital technologies and bring out the value of investing in these technologies to support various needs of organisations. Future work should consider other difficulties associated with human milk waste, such as mothers' and donors' reduced knowledge of milk expression and saving, managerial challenges and socio-cultural and economic variables.

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Abbreviations

CFC, chlorofluorocarbons; CH4, methane; CO, carbon monoxide; Co, cobalt; CO2, carbon dioxide; Cu, copper; DCB, 1,4-dichlorobenzene; DEHP, Di(2-ethylhexyl)phthalate; DHM, donor human milk; FEc, freshwater ecotoxicity; FEu, freshwater eutrophication; FS, fossil resource scarcity; GW, Global warming; HMB, human milk banks; HTc, human carcinogenic toxicity; HTnc, human non-carcinogenic toxicity; IoT, Internet of Things; IR, ionising radiation; ISO, International Organization for Standardization; MEc, marine ecotoxicity; MEu, marine eutrophication; N_2O, Dinitrogen monoxide; NMVOCs, Non-methane volatile organic compound; NO_x, nitrogen oxides; OH, ozone formation—human health; O-LCA, Organisational Life Cycle Assessment; OT, ozone formation—terrestrial ecosystems; N, nitrogen; P, phosphorous; PCB, printed circuit board; PM, fine particulate matter formation; PM2.5, particulate matter with 2.5 m or less in diameter; SETAC, Society of Environmental Toxicology and Chemistry; SMS, short messaging service; SO2, sulphur dioxide; SOD, stratospheric ozone depletion; TA, terrestrial acidification, TEc, terrestrial ecotoxicity; TS, Technical Specifications; UNEP, United Nations Environment Programme; WC, water consumption; Zn, zinc.

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