Study of the Ecosystem of Circular and Smart Disposables in the Health Sector and Design of an Innovative Solution

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***Abstract*—The aim of this project is to develop a solution based on connected devices to enhance the management and recycling of disposable healthcare products.**

The quantities of plastic products used in healthcare activities, such as syringes, infusion bags, and surgical gloves, amounted to over €36 billion globally in 2020 and are expected to reach €55 billion by 2025, according to the Healthcare Plastics Recycling Council. Most of these products are disposed of in landfills or through incineration, even though a significant portion is non-contaminated and thus recyclable. Connected device solutions have the potential to impact the value chain of these products by improving their handling while ensuring safety and process efficiency.

The initial step involves conducting a study on the areas where Internet of Things (IoT) technologies could enhance the handling of healthcare-related products. This includes aspects such as inventory management, smart waste bins, waste management, and monitoring the sterilization conditions of equipment. Subsequently, you are tasked with designing and implementing a concrete solution based on connected devices that addresses one of the identified areas.

***Index Terms*—Internet of Things (IoT) in Healthcare,Innovative Approaches to Medical Waste,Connected Healthcare Solutions,Medical Waste Management**

Contents

I. Introduction:

In the ever-evolving landscape of healthcare sustainability and technological advancement, the management of disposables within the health sector has become a critical issue. We can distinguish two main problems. First, the quantities of hazardous and infectious healthcare waste generated from improved patient care keeps increasing ; its cost is estimated at 36 billion in 2020 globally and is expected to reach 55 billion in 2025, according to the Healthcare Plastics Recycling Council. The second critical problem are employees working in the healthcare sector along with handlers of waste, they are frequently exposed to the injuries and toxic effects of waste management from healthcare facilities, without forgetting the fact that they are human so an employee can throw an item in the wrong container and this will lower the accuracy of the recycling process.

Traditionally, in most healthcare centers it is healthcare providers, patients or caregivers, who generate waste, who are sorting medical waste into the adequate waste containers (bags, bins, needle boxes) and health facility managers must ensure an appropriate system for the separation, transport, and storage of waste.

Internet of things (IoT) can be defined as “a network of interconnected physical devices, vehicles, appliances, and other objects embedded with sensors, software, and network connectivity, enabling them to collect and exchange data” ; is being introduced among solutions to reduce the criticality of this issue.

Previous work has mostly focused on the first part of the problem, as most researchers came up with solutions about treatment, and disposal systems but neglected the collection part which can be very harmful for the employees working in these sectors considering that 15% of medical waste is retained as “dangerous” and can pose a number of health risks as 10% is Infectious and the 5% left are chemical and radioactive waste according to World Health Organization.

In our report, we will discuss the diffrent solutions proposed by researchers as some of them porposed solutions sort the waste and used RFID to monitor the waste inside the containers, while others focused on the transportation and treatment of it. We have noticed that none of them proposed a complete solution which will combine all phases of the timeline; this led us to propose a sollution that takes all of the phases in concideration focusing on treating the problem of collection as we want to reduce the interaction between employees and the healthcare waste which the most critical. The idea is about introducing smart bins that will help in sorting and categorizing the waste to decide how it’ll be treated and recycled ; we will also use RFID labes to track and monitor the waste when it is put into containers.

A. The Waste Timeline:

We are going to use this timeline as a reference in the whole report , as we will discuss in every part of it the waste from its creation till it is treated (recycled or landfilling) :

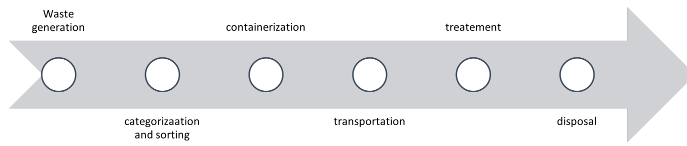

Figure 1: Timeline of a waste life cycle

1) Waste generation: Refers to the moment the item is used and needs to be thrown.

2) Categorisation and sorting: Refers to the collection and in house segregation.

3) Containerization: The waste generated is put into containers at a storage point.

4) Transportation: The waste is transported in specialized vehicles.

5) Treatment: Generated waste is treated and disposed in Common Biomedical Waste Treatment Facility.

6) Disposal: Refers to the recycling and landfiling.

II. Literature review:

Through the timeline previously exposed we came across multiple solutions and study of the question each with different outcomes and objectives we will review some of them that we judged relevent to our research.

A. Step 1 :Waste generation

In this step the differents approaches consist of preventing the generation of the waste therefore shortcutting the rest of the timline for exemple the work of [5]The Concept introduces the use of inorganic nanoclusters (NCs) with tailored features on nanofiber surfaces to impart intrinsic bactericidal and antiviral properties. To achieve complete sterilization, nanofibers are modified with photothermally efficient nanoparticles (NPs) for light-assisted on-demand photothermal disinfection. Plasmonic NPs, known for their photothermal effect, offer a novel approach to thermal disinfection.

The ultimate goal is to enable on-demand thermal disinfection of face masks through controlled temperature elevation using suitable light sources. The nanotechnology-assisted disinfection, combined with the mechanical robustness of nanofibers, allows for multiple utilizations of non-disposable masks. The multifunctional masks, acting as moisture pumps, enhance comfort by dissipating humidity. This innovative cascade-like mechanism represents a paradigm shift in reusable and personalized PPE, ensuring comfort, high filtration, low humidity, intrinsic antiviral activity, and on-demand light-triggered disinfection.

B. Step 2 :Categorization and sorting

Various approaches have been proposed at this part of the timeline. First we have Surinder Gopalrao Wawale and co-workers [6] came with a very plausible study which suggests that trash from every area of the healthcare facility (HCF) is gathered, divided manually into different colored bags (black, red, yellow, blue, and white), and then transported to BMW storage facilities in the basement or on the HCF property, and a fuzzy-based system categorizes it in terms of four parameters (Cost generator, Health risk, Bio/Non-bio-degradable, Environmental effect) According to the category, the hidden layer (HL) in the fuzzy chooses the appropriate process. In their paper, only five processes are taken into consideration which are Autoclaving , Microwaving Incineration, Sharp materials disposal, Radioactive waste. But it can extend to nine if required. After getting the input from the fuzzy system.

This research [1] treats the process of automating waste sorting at first, the researchers studied how waist storing is done manually by analyzing the cognitive and sensorimotor characteristics of tasks that are strongly repetitive in the process. They then tried to develop a software to assist operators inspired by the manual way. They use touchscreen monitors to view waste on a conveyor belt in top-down static images. To maintain collective workload management, the software allows operators to temporarily take on tasks assigned to others, enhancing flexibility. The software also considers an anticipation strategy, providing alerts about upcoming work and live video of waste approaching the operator's station. This aids in better preparation.

Brindha. S and her team [3], proposed an automatic medical waste segregation system by using sensors which works as it follows ; the waste is sorted using a conveyor belt, motor, micro controller, and sensors. The inductive proximity sensor detects metal waste, which is then pushed into a metal waste bin. If not metallic, the conveyor sensor determines if the waste is wet or dry. If wet, the belt is turned off, and the waste is pushed into a wet waste bin. If not, the waste is pushed into a dry waste bin.

With the aid of MATLAB, Manikandan.R. and Ramya.R [9] offered a solution utilizing embedded system technology. Robots, ultrasonic sensors, image processing, zigbee, and human-machine interfaces are used here. Using an ultrasonic sensor, the robot separates the waste into two categories: biodegradable waste and nonbiodegradable waste. The most crucial piece of equipment is image processing, which is acquired via a camera that takes the picture and then compares it with preset images.Consequently, the wastes are directed to the appropriate bins.

C. Step 3 :Containerization

Interestingly, the most innovative method for tracking BMW in the HCF is through the implementation of RFID system that tracks the indoor garbage present in the waste bins in the HCF premises. Surinder Gopalrao Wawale and co-workers [6] proposed an automatic system that helps in identifying, storing, and retrieving important data via wireless communication channels between electromagnetic wave (EMW), transmitters, and receivers; by using an IoT server to track the waste by labeling the bags with RFID tags, monitoring and tracking the real-time movements, temperature, and humidity of the waste generated by healthcare centers can be done through this system.

Hao Liu, Zhong Yao [8] RFID solution's primary goal is to find solutions for waste-related issues including loading, weighing, concentration, and classification by collecting medical waste from various departments, classifing it, and packaging it according to the classification standards. After pasting the RFID electronic tag and weighing, the RFID read-write device records waste category, source, and weight on the package.

The RFID labelling of waste has been considered by Ankur Chauhan Ankur Chauhan et al [4] as an important method to track waste. As ithelps in generating the information about waste in terms of its quantity, location, travel time, storage, and final disposal. It also assists in preventing any unlawful activities which can be conducted by waste disposal firms and hospitals to gain at the cost of public and social health.

D. Step 4 :Transport

Surinder Gopalrao Wawale and co-workers [6] developped a system which consists of a GPS that is able to track the capabilities thereby enabling it to monitor the waste more easily starting from the point of their generation, collection, transportation, and disposal.

Ankur Chauhan et al [4] used GPS and GIS to enable a vehicle with cameras to monitor the movement of a waste collection vehicle and its different transfer locations. Since the healthcare waste disposal business is not exactly a profit-making business, to save cost, many firms tend to violate the guidelines on waste disposal. As a result, such firms dispose of their waste at the municipal solid waste sites, rivers, and other illegal dumping grounds.

In their article Hao Liu, Zhong Yao [8] medical waste from hospitals is transported to waste treatment plants according to a scheduled program. Each vehicle is equipped with RFID tags, recording specific information like vehicle category, unit, lines, license, plate number, driver, contact information, and date. The data is synchronized with waste management centers and plants, and real-time tracking of vehicle trajectories is done using GPS.

E. Step 5,6 :Treatement and Disposal

In thier research Ankur Chauhan et al [4] suggests that as the truck arrives at the disposal plant, an RFID reader reads the vehicle's electronic tag information and matches it to the waste management system. The truck is allowed to unload and is then stored temporarily according to the waste category. The RFID reader then checks the data with the waste management system, allowing the waste to be disposed of and updating the data accordingly. They [4] also mentioned The chimneys of the healthcare waste disposal plants generate toxic and harmful gas emissions; the lack of understanding of the effect of these emissions by the waste disposal firms and as environmental bodies do not pay much attention to this important aspect, they usually decide on a particular height to release the emissions into the atmosphere, polluting the environment even more. Hence, to prevent this negligence and irregularity, the mounting of digital devices is required on a chimney, providing information on the presence of toxins in the emissions, their requirement for treatment.

The next method introduces an IoT-based smart recycling machine for personal protective equipment (PPE) disposal proposed by [7]aims to conduct a feasibility study on recycling method to design an IoT-based smart recycling machine for collecting and sterilising the waste. This system utilizes IoT for control, monitoring, and logistics optimization in recycling centers. It integrates IoT functions for communication, allowing real-time monitoring of critical parameters inside and outside the machine by technicians. Three sterilization methods suitable for the smart recycling machine are outlined:

1) Heat Sterilization
   - Dry heat: Uses hot air with less efficiency.
   - Steam sterilization: Incorporates water vapor and pressure, widely used in healthcare for enhanced efficiency.
2) Photocatalytic Disinfection
   - Utilizes photocatalysts, like titanium dioxide, activated by light energy for decontamination and sterilization.
3) Ultraviolet (UV) Light – UVC
   - UVC light (253.7 nm wavelength) is effective for sterilization by destroying DNA and RNA of microorganisms.
   - Non-contact sterilization method suitable for waste PPE pre-treatment.

The article [7] underscores the significance of a non-contact sterilization method, proposing UVC light as a potential solution. It references studies on the survival of the COVID-19 virus on surfaces, emphasizing the need for advanced sterilization methods in PPE waste management .

F. Upgrade by automation after waste creation :

To initially reduce the life cycle of medical waste, it is advantageous to eliminate manual sorting and categorizing steps and replace them with an automated process. A method extensively explored and acknowledged within the scientific community involves the automation of procedures through the application of machine learning and deep learning techniques. This approach is exemplified in the study conducted by [11], which specifically focuses on a subset of medical waste that constitutes a substantial, if not the entirety, of the spectrum of existing medical waste.

The study Zhou et al. [11] addresses the challenges in classifying medical waste (MW) due to variations in classification across countries. It emphasizes that textile materials, particularly gauzes and bandages, constitute a significant portion of overall MW, followed by plastic products,they Zhou et al. [11] then shift focus to the classification of hazardous and common MW, identifying eight specific types for study. These include textile materials like gauze, plastic items such as gloves and infusion bags, and sharp objects like needles. The concluding statement highlights the potential for improving the efficiency and safety of MW classification through image analysis, given the diverse shapes of the selected objects.

They Zhou et al. [11] highlight various deep learning techniques, underscoring the diversity of architectures such as Convolutional Neural Networks (CNNs), AlexNet, VGG, GoogLeNet, ResNet, and ResNeXt. These advancements showcase the richness of approaches in the field of deep learning, illustrating how these models have evolved over time. Furthermore, they assert that the intensive use of these techniques makes sense, especially in the context of medical waste classification, where the task is primarily based on visual features extracted from images. In summary, resorting to deep learning models is justified due to their adaptability and effectiveness in addressing complex problems related to image analysis, which is particularly relevant in the domain of medical waste classification.

To further enhance the practical application of deep learning techniques, once the abstract classification is achieved, it is crucial to mechanize the sorting and categorization processes, as elucidated by the propositions of [10] and their embedded system that involves training a model, specifically utilizing the AlexNet architecture, with a large dataset to classify detected objects. The trained model is then used for predicting the type of object based on images captured during the detection process.

As for the hardware component, the central operating module is a Raspberry Pi4, which receives signals from an IR sensor and transmits signals to the Pi camera and servo motors. A USB light is used for constant illumination inside the input bin, where the image of the thrown object is captured. The placement of components, such as the IR sensor, Pi camera, USB light, and Raspberry Pi, is visually detailed in the provided annex[10].

A medical waste classification system based on OpenCV and SSD-MobileNet was proposed in [2] the system is divided into two parts: locating objects by OpenCV and recognizing objects by SSD-MobileNet. Prior to differentiating the binarized current frame from the binarized background frame, the system uses OpenCV to binarize both the acquired background frame and the current frame. Therefore, using the image's mean pixel value following the background subtraction algorithm, the system can determine whether medical waste needs to be identified in the current frame. The system resumes using the current frame if there is no medical waste. In the event that medical waste is present, closed operation is used to improve the image features and locate the waste within the frame. Finally, SSD-MobileNet obtains the recognition results.

III. Proposed Solution and design:

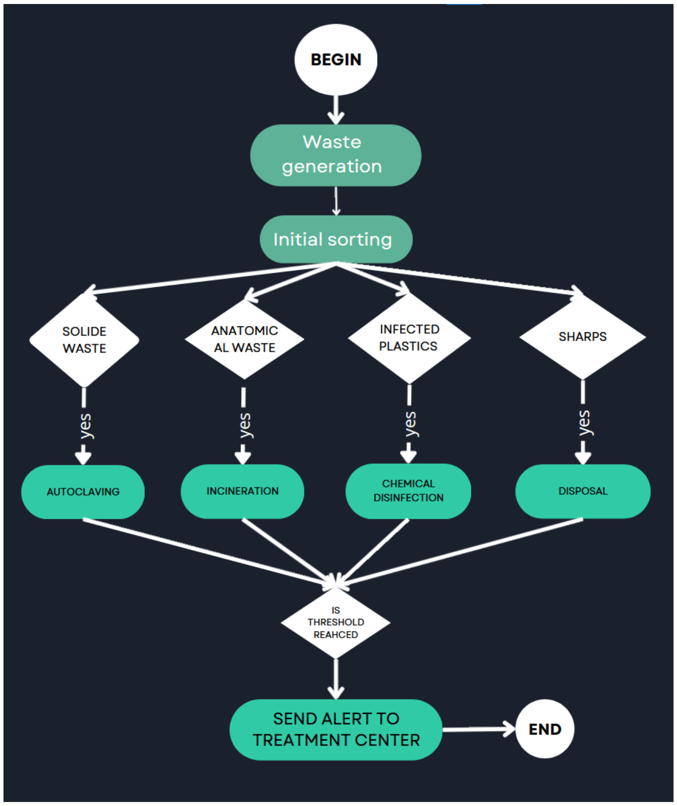

Figure 2: flow chart of the solution

Our proposed solution aims to enhance the entire waste management timeline for disposable healthcare products through merging the different solutions across the lifecycle of the waste. We envision a comprehensive system that addresses waste from its generation to its treatment at specialized centers. The proposed workflow is as follows:

- **Initial Collection:** Waste is initially disposed of without sorting into specific bins.
- **Smart Bin Implementation:** We will develop a specialized bin equipped with cameras that capture images of the items thrown into it. These images are then processed by the AI sorting system powered by machine learning algorithms. The AI system analyzes the images, categorizes the waste, and determines the appropriate treatment method.
- **Sorting:** Each discarded material is then directed to a specific container associated with a treatment method, which is continuously monitored.
- **Container Threshold Alert:** When a container reaches a predefined quantity threshold, an alert is sent to our system. This prompts us to contact the associated treatment center, enabling them to dispatch specialized vehicles to collect the waste.

This solution aligns with the broader objective of our project, which is to utilize connected devices to revolutionize the management and recycling of disposable healthcare products. The healthcare industry generates vast quantities of plastic waste, contributing to environmental challenges.

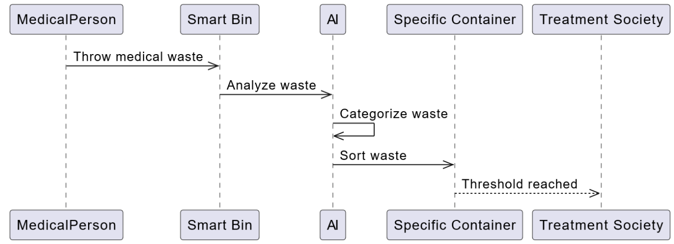

Figure 3: UML sequence diagram of the solution

By implementing IoT technologies, we aim to improve the efficiency and safety of the entire process.

The fundamental objectives of our system In contrast to previous research that often focused on treatment and disposal, our solution encompasses all phases of the timeline, and minimizes human interaction while preserving or enhancing the quality of waste sorting, logistics, and the optimization of the lifecycle of medical waste. Our system aims to automate the process of separating different types of waste, thereby reducing dependence on human intervention. By implementing advanced technologies such as automated sorting, we seek to enhance operational efficiency, ensure regulatory compliance, and minimize the environmental impact associated with medical waste management. This integrated approach also aims to optimize the logistics of medical waste transportation, considering the specific characteristics of each waste type and adhering to prevailing regulatory requirements. Our commitment to continuous improvement is supported by real-time monitoring of system performance, enabling constant adaptation to achieve our objectives.

IV. Performance Metrics: Enhancing Efficiency and Sustainability

In evaluating the effectiveness of our proposed waste management solution, we focus on three key performance indicators (KPIs) crucial to achieving our objectives: Accuracy, Precision, and Economic Gain.

A. Accuracy

- **Definition:** Accuracy measures the correctness of waste categorization and treatment determined by our AI sorting system.
- **Importance:** Ensuring accurate waste categorization is fundamental to the success of our solution. It minimizes the risk of improper treatment and enhances overall process reliability.
- **Evaluation:** We will assess accuracy through systematic comparisons of AI system classifications against established waste treatment standards, continuously refining our algorithms to optimize accuracy.

B. Precision

- **Definition:** Precision measures the consistency and reliability of our system in categorizing waste correctly over multiple iterations.

- **Importance:** Consistency is paramount in waste management. High precision ensures that our system reliably categorizes waste types, reducing the likelihood of errors and streamlining the overall process.
- **Evaluation:** Precision will be monitored through repeated trials, with a focus on the system's ability to consistently categorize waste materials correctly across various conditions.

C. Economic Gain

- **Definition:** Economic gain evaluates the cost-effectiveness and efficiency improvements achieved through the implementation of our waste management solution.
- **Importance:** Beyond environmental benefits, our solution aims to bring economic advantages by reducing operational costs, optimizing logistics, and minimizing the need for manual intervention.
- **Evaluation:** We will conduct a comprehensive cost-benefit analysis, considering factors such as operational efficiency, waste treatment savings, and potential revenue generation from optimized recycling processes.

In focusing on these KPIs, we ensure that our proposed solution not only meets environmental goals but also delivers tangible improvements in accuracy, precision, and economic efficiency, reflecting our commitment to a sustainable and efficient waste management system. Our dedication to continuous monitoring and refinement underscores our pursuit of excellence in achieving these KPIs.

V. Conclusion

In conclusion, this project aims to address comprehensively the growing challenge of managing disposable healthcare products by implementing an innovative solution based on connected devices. Faced with the anticipated increase in quantities of plastic waste in the healthcare sector, projected to rise from 36 billion dollars in 2020 to an estimated 55 billion dollars by 2025, it becomes imperative to adopt innovative approaches to minimize environmental impact and enhance process efficiency.

Our solution relies on leveraging the Internet of Things (IoT) to optimize the management of various aspects related to medical waste, including inventory, smart waste bins, waste management, and monitoring the sterilization conditions of equipment. By specifically focusing on the collection phase, we have developed smart bins capable of sorting and categorizing waste, thereby reducing the risks of employee exposure to toxic effects while improving the accuracy of the recycling process.

IoT technologies provide a unique opportunity to transform the value chain of disposable healthcare products by introducing solutions that not only strengthen environmental sustainability but also enhance the safety of healthcare workers. By harnessing the benefits offered by RFID labels for waste monitoring and tracking, our comprehensive approach aims to fill a significant gap in previous research, providing a complete solution that encompasses all phases of the process, from generation to final waste management.

Ultimately, by adopting our proposal of smart bins and RFID tracking, we aspire to contribute significantly to reducing risks for healthcare sector employees while promoting a more sustainable and efficient approach to managing disposable healthcare products on a global scale. This project represents a major advancement in the convergence of technology, environmental sustainability, and worker safety, underscoring the crucial importance of innovation in the field of medical waste management.

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