Life Cycle Assessment of Medical Product Plastic Packaging at UVA Hospital

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Abstract

The United States is the world's highest plastic waste generator,[1,2] with approximately 292 million tons of waste per year, 18% being plastic.[3,4] The US healthcare industry contributes a significant amount of waste to landfills every year. Within each healthcare facility, the majority of equipment, tools, and materials are individually encased in plastic packaging, yet there is limited recycling infrastructure for this subset of hospital waste. This paper assesses the environmental impacts of plastic packaging at the UVA (University of Virginia) hospital to then inform their sustainability efforts. With a scope of low density polyethylene (LDPE) plastic packaging, a cradle-to-grave Life Cycle Assessment (LCA) was conducted to measure the resulting Global Warming Potential (GWP), electricity usage, and water consumption. In order to conduct this analysis, this study gathered a dataset of local packaging use, conducted a spectrometry material composition analysis, and researched existing literature LCA impact values. The result is an environmental impact summary of 14 pieces of hospital plastic packaging from 2021-2023 for the UVA hospital. The calculated impact came out to GWP of 96,274.57 kg CO_2 eq, electricity usage of 2.7 million MJ, 2.17 million liters of water consumption, and 14,600 kg of waste landfilled. The findings highlight the hidden environmental impact of individual plastic packaging for each hospital item. In order to relieve UVA hospital's environmental impact due to this waste stream, we propose three behavior changes and recommend the hospital provide estimated impact results for these changes. These changes include the reduction of excess hospital product use, implementation of a UVA recycling stream for clean plastic packaging, and a recommendation for hospital supply manufacturers to use recycled plastic in packaging production.

Keywords: Life Cycle Assessment (LCA), healthcare sustainability, operating room waste, environmental impact

Introduction

National Geographic considers the plastic pollution problem to be one of the most pressing issues of today, especially because the United States is the world's highest plastic waste generator.[1,2] As of 2018, the United States of America generated approximately 292 million tons of waste per year, 18% of which is plastic.[3,4] Plastic pollution is a hypernym for environmental subjects like ocean pollution, soil leaching, microplastics, and decreasing landfill space. A reason for this overwhelming pollution is the high prevalence of plastic combined with low recycling rates. Although many plastics are recyclable, approximately 91% are landfilled[1], leading researchers to predict U.S. landfills to be at capacity by 2080.[5] Plastic reduction practices, like reusing and recycling, must improve to prevent landfills from overflowing which will also decrease the impacts of plastic pollution.

An area that requires research into plastic waste impact is the US healthcare system. The healthcare industry is the second biggest contributor to U.S. national waste, generating approximately 6 million tons, or 8%, of the total annual U.S. waste.[6] A study conducted at Stanford University estimates that hospitals in the U.S. generate approximately 33.8 pounds of healthcare waste per day per patient.[7] Using this metric and UVA hospital's patients per day data,[7,8] we calculated that the UVA hospital creates approximately four thousand tons of waste each year which is approximately equivalent to the weight of 1,900 SUVs. Although the amount of waste generated per patient has been researched, there is limited literature on the composition of this waste creation. In order to better understand what waste is commonly created in the hospital, our team shadowed an anesthesiologist in the UVA hospital General Operating Room unit (OR).

We found that healthcare waste consists of single-use tools and materials, surgical gloves, and patient gowns and sheets, materials contaminated by blood and bodily fluids, like sharps and used gauze. One commonality for all materials was that each of these single-use supplies is contained within packaging, typically plastic. The reason for this packaging is to ensure sterility to limit contamination that could hurt a patient. We believe that the plastic packaging found on all products in the hospital has a large, unmeasured environmental impact. Prior to surgery, medical supplies are taken out of their sterile packaging and placed within the surgery field while their packaging is thrown away. From our shadowing, we see this plastic packaging disposal as a large contributor to the hospital's landfilling activities, despite its recycling potential as clean plastic. Although UVA has a strict focus on sustainability, there are no guidelines present for reducing the hospital's environmental impact. In order to establish guidelines, the hospital must first quantify its current waste disposal impact. With the quantification as a benchmark, UVA hospital would then need expertise on steps to reduce waste creation and build a robust recycling system from the ground up. Therefore, the goal of this project is to perform a waste audit of UVA hospital's plastic packaging waste generation by utilizing LCA methodology to show the impact plastic packaging waste has on the environment and recommend practices to reduce this impact.

Specific Aims

Aim 1: Track the use and disposal of plastic packaging within the hospital to assess material circularity

[A] Interview hospital staff regarding current disposal methods for plastic packaging. Determine whether a uniform disposal system exists, what organization is responsible for the disposal process, and material usage prior to disposal.
[B] Discuss the end of use disposal process for plastic packaging with facilities management personnel.

Aim 2: Conduct a Life Cycle Assessment (LCA) on collected plastic packaging from the UVA hospital

[A] Collect plastic packaging of at least three different plastic materials from the Director of Facilities Management. Determine type of plastic and material properties using spectroscopy.
[B] Collect material impact data from various historic LCAs. Compile into an LCA for collected packaging using openLCA software, seeking to understand the environmental impact of packaging hospital items in plastic.
[C] Complete a Life Cycle Assessment (LCA) determining the environmental footprint of the plastic packaging.

Aim 3: Comparison and proposition of plastic packaging findings and implementation

[A] Conduct a sensitivity analysis to scale data collected from LCA to UVA hospital using purchase history.
[B] Determine UVA Hospital economic and environmental impact from plastic packaging waste. Establish implementation strategies based upon impacts.
[C] Compile findings of plastic packaging into a LCA paper and subsequent memo to be presented to UVA hospital staff to provide recommendations for immediate and systematic implementation. This recommendation will create change through quantitative reporting, excess waste reduction, and greater environmental sustainability.

Life Cycle Assessment (LCA) Goal Statement

An LCA is a systematic analysis of the environmental impact of a product's entire life. The goal of this LCA is to quantify and understand the environmental impact of medical product packaging to inform sustainable actions within the UVA hospital. This LCA will be conducted using a functional unit of purchasing history over three years of selected medical waste packaging for the UVA hospital. This assumes each purchased product is used. Items of interest were identified by shadowing in the UVA hospital, then their packages were collected and weighed. Purchasing history of the cost and usage of the selected medical products over a three-year period was received from hospital value management personnel. A complication in the analysis is the lack of plastic composition identification as most packages observed had no label. The plastic packaging material composition was identified utilizing wavelength spectroscopy. The combination of these data points informed the environmental impact of the plastic packaging waste through Global Warming Potential (GWP), electricity usage, and water consumption. The scope of this LCA includes production, shipping, use, and disposal as shown in Figure 1. The results from this cradle-to-grave LCA analysis aims to inform UVA hospital staff, medical product manufacturers, and recyclers of the environmental impact of plastic packaging, encouraging these parties to engage in efforts to reduce and recycle this waste.

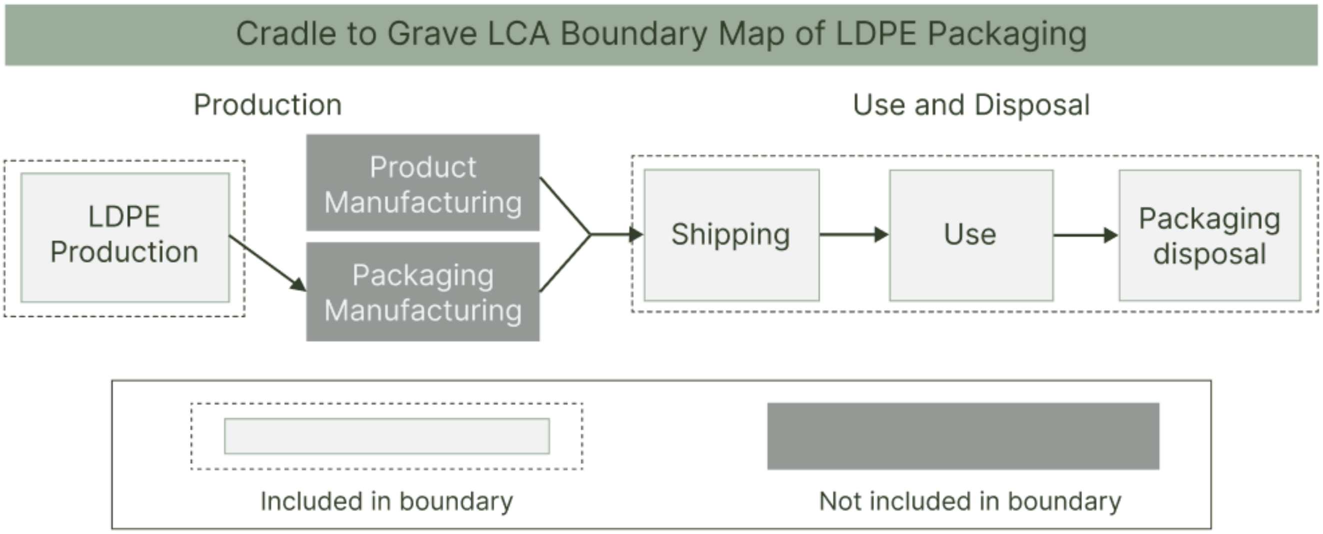

Fig. 1. Cradle-to-Grave LCA boundary map for LDPE packaging. Map includes material production (fossil fuel collection, refinement, etc.), shipping, use in hospital, and disposal of packaging. Both product and packaging manufacturing are not included within our boundary because accurate data is not available within the literature.

Methods

Exploration of Waste in the Hospital

The UVA hospital has a volunteer organization, the Medical Equipment Recovery of Clean Inventory (MERCI) program, that collects and distributes expired, clean, unopened, and unused medical equipment that would otherwise go to landfill. We shadowed a MERCI volunteer to understand the quantity and variety of medical waste at UVA. By observing medical waste from the hospital at large, we were able to select our waste stream of interest: medical plastic packaging. To then see the products that contribute to the plastic packaging problem we shadowed Dr. Matthew Meyer, an anesthesiologist, and Alex Foley, a sales representative for Stryker Sustainability. These customer discovery experiences allowed us to determine products commonly used in the OR that are encased in plastic packaging. The products chosen are a representative sample of UVA hospital's OR but are not indicative of every product found in the UVA hospital. Further work is needed to analyze every product in the hospital. Our selected product sample aims to serve as an initial investigation to test our plastic packaging hypothesis.

Packaging Collection & Weighing

To quantify the environmental impact of plastic packaging waste at the UVA hospital, we first collected examples of clean plastic packaging waste from the OR and MERCI. With this collection, we numbered the individual items and weighed the packaging to understand how much plastic is used in packaging per item. Figure 2 provides a visualization of our collected packages based upon their physical qualities. There were numerous types of packaging collected ranging from hard plastic, to thin film plastic. Table 1 presents a summary of the weight collection with brand and product names to contextualize each item. The full table of 19 items is in Table S1. Item numbers in this table refer to the packages labeled in Figure 2.

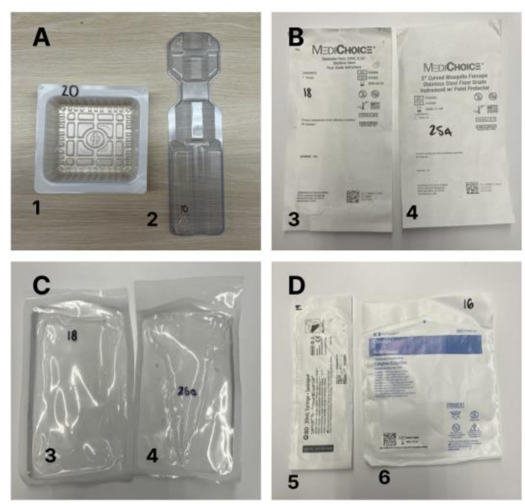

Fig. 2. Images of different kinds of hospital packaging. Depicted are (A) hard plastic, (B) thicker, tactile paper, (C) thin flimsy plastic, and (D) thin, silky plastic. Number labels correspond to specific items in Tables 1 and 2.

Purchase History

After collecting and weighing our prospective packaging, we requested the purchase history of products we selected from the hospital's value management department. The purchase history consists of the data of our selected

Table 1. Summarized identification of 6 collected hospital products and their packaging weight, in grams. Complete table available as Table S1.

Item Number	Brand Name	Product Name	Package Weight (g)	Item Number	Brand Name	Product Name	Package Weight (g)
1	Covidien	Gauze sponges	10.36	4	MediChoice	5" Forceps	5.38
2	Unknown	Surgical clamp	61.91	5	BD	30 mL syringe	3.59
3	MediChoice	4.75" Iris scissor	5.03	6	Covidien	Devon needle counter	7.8

Table 2. Summarized purchase history of 6 collected hospital products. Complete table available as Table S2.

Item Number	Brand Name	Product Name	Units Purchased	Total Cost ($)	Item Number	Brand Name	Product Name	Units Purchased	Total Cost ($)
1	Covidien	Gauze sponges	2,539,630	$38,094	4	MediChoice	5" Forceps	20,783	$35,680
2	Unknown	Surgical clamp	14,182	$15,884	5	BD	30 mL syringe	540,308	$151,286
3	MediChoice	4.75" Iris scissor	78,241	$101,693	6	Covidien	Devon needle counter	1,736	$1,892

products for the entirety of the hospital, not just the OR. This data includes the name of each product and its corresponding cost and number of purchases for 2021 through 2023. Unit size varied from cases of products to individual tools, so all units and costs were converted to represent the individual products. A summary of the cumulative data is shown in Table 2, the full table of 19 items is in Table S2.

After receiving the three-year purchase history for these products (our functional unit) and calculating the cumulative economic impact on the hospital, we shifted our concentration to focus on products with the most usage over the three-year period. We do not use the data for products whose packaging we did not have the weights of, nor the products that had low cost or units purchased. Since these products are not as commonly used, they are less likely to make an impact on the overall environmental cost of the hospital. With total usage and individual package weight, we can calculate the total plastic used in packaging over 3 years for our selected instruments in the UVA hospital. To calculate the environmental impact of this packaging, we need to convert our weight of plastic to the midpoint impact metrics of interest: GWP, electricity, and water usage.

Literature Review: LCA Data on Plastic Packaging

In order to convert from product usage to environmental impact, we needed the GWP, electricity usage, and water consumption values for 1kg of plastic. These values are calculated by organizations like the American Chemistry Council who have the resources to audit data from manufacturers, shipping companies, and landfill facilities. We do not have these tools or resources available to calculate these values ourselves, so we research values for plastic's impact found in prior LCAs. Our LCA boundary of plastic packaging includes plastic production, shipping, use, and disposal, but does not include product or packaging manufacturing because this data does not exist in literature. Thus, we were interested in the GWP, electricity usage, and water consumption associated with common types of plastic packaging to calculate the environmental impact of plastic packaging usage in the UVA hospital. We compiled data for polypropylene (PP), low density polyethylene (LDPE), high density polyethylene (HDPE), and polyethylene (PET). The results of this literature review are summarized in Table 3.

Table 3. Environmental impact values (GWP, electricity usage, and water consumption) for different plastic materials. Bracketed numbers correspond to source number in References.

Plastic Material	GWP per 1 kg (kg CO2 eq)	Electricity Usage (MJ)	Water Consumption (L)
PP	3.5 [9]	74.1 [9]	9.13 [10]
LDPE	2.79 [11]	78.3 [9]	63.02 [11]
Tyvek (HDPE)	10.1 [12]	12.97 [13]	57.7 [12]
PET(E)	3.29 [14]	63.83 [15]	17.25 [14]

Material Composition Analysis

The packaging we collected was not labeled with the specific plastic material number, thus material composition analysis was necessary to accurately perform our analysis. We worked with a Materials Science PhD student at UVA to identify the composition of plastic packaging by conducting wavelength spectroscopy. The technique used was Fourier Transform Infrared (FT-IR) spectrometry, which sends infrared radiation into a material with some being absorbed and some passing through.[16] This radiation is converted into rotational or vibrational electricity, which is picked up by the machine sensor converting the electricity into wavelengths. The wavelength measurements produced for the plastic packaging were compared to a library of material wavelengths and matched to the closest material composition. We measured the wavelengths of 6 different pieces of plastic packaging, with the majority being composed of LDPE, though the hit rates — accuracy to library wavelengths — varied. An example wavelength graph is shown in Figure 3. Table 4 displays the hospital products that were analyzed by FT-IR, displaying what material they were composed of, and if the hit rate was high enough to accurately determine material composition. Because the spectroscopy analysis showed that a majority of the packaging products were LDPE, we assumed that all collected plastic packaging was composed of 100% LDPE for our mathematical calculations. Further work is needed to see the complete range of plastic that the packaging consisted of, not just the assumption of LDPE.

Table 4. Plastic packaging material composition and hit/miss determination based upon wavelength spectroscopy library comparison.

Brand	Product Name	Plastic Material	Hit/ Miss
MediChoice	4.75" Iris scissor	LDPE	Hit
Covidien	Shiley intubating stylet	LDPE	Hit
Ansell Gammex	Non-latex surgical gloves	LDPE	Hit
Arrow	Arterial catheterization kit	LDPE	Hit
BD	EZ Scrub	LDPE	Hit
CareFusion	Bacterial/viral filter	PE	Miss

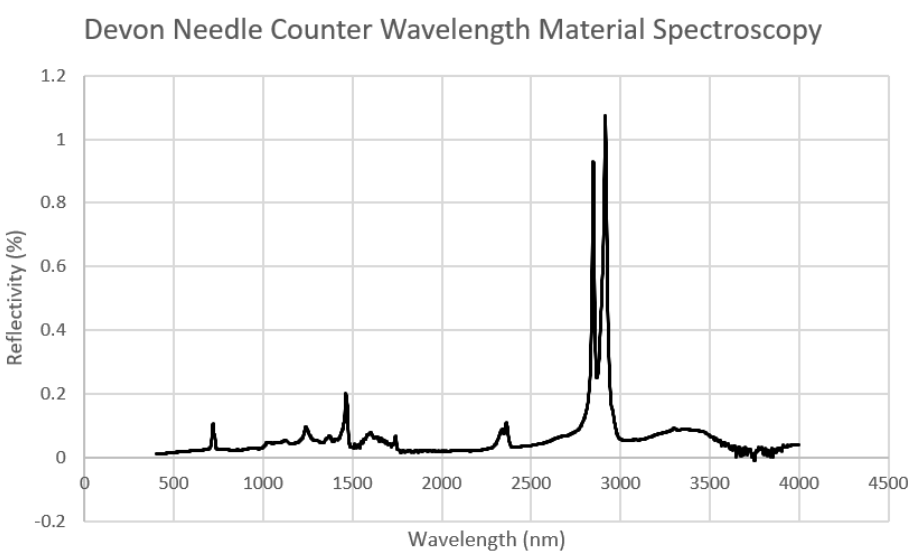

Figure 3. Wavelength material composition spectroscopy of Devon needle counter packaging. Peaks presented in this graph were compared against the material composition library whereby the closest match of wavelength peaks determined the material composition with a certain degree of accuracy (hit rate).

Literature Review of LDPE Impact Values

Following spectroscopy and wavelength analysis, we narrowed the scope of our LCA literature review to collect data only on LDPE. A cradle-to-gate analysis calculates environmental impact of a product from mineral extraction to end use excluding disposal while a cradle-to-grave analysis includes disposal as well. Our project aims to first investigate the environmental impact of the production of plastic packaging then our analysis includes disposal for the three impact categories mentioned above, but not all LCAs contain all of these elements. Different LCAs seek to argue different messages, and though containing information about the desired plastic, present their data in an incomplete way. The final argument is either without all three chosen impact values, in a convoluted manner, or falsely claim cradle-to-grave status. Also, many of the LCAs reference the same sources and databases, revealing that the data given is being rehashed in different forms across an assortment of LCAs. Table 5 summarizes the scope and components of LCAs we reviewed.

Table 6 shows the values we selected from literature compared to the information held within the packaging film, low density polyethylene {GLO}| market for | Cut-off, S - Copied from Ecoinvent stream of the agribalyse database on openLCA. These values were selected for the analyses' transparency of the functional unit and well formulated and defined process of calculation. openLCA is a free open source LCA software. The impact of LDPE film was determined using the ReCiPe 2016 Midpoint (H) impact category.

Table 5. Main characteristics and scopes of the LCAs of LDPE in literature. Filled boxes indicate processes included in the scope of the study.

Title of LCA Study	Cradle-to-Gate or Cradle-to-Grave	GWP (kg CO2 eq)	Electricity Usage (MJ)	Water Consumption (L)
A comparative cradle-to-grave life cycle assessment of single-use plastic shopping bags and various alternatives available in South Africa [17]	Cradle-to-Grave	13.28		7.04
Environmental Impact Assessment of Low-Density Polyethylene and Polyethylene Terephthalate Containers Using a Life Cycle Assessment Technique [18]	Cradle-to-Grave	2.97	100.23	
Cradle-to-Gate Life Cycle Analysis of Low-Density Polyethylene (LDPE) Resin [19]	Cradle-to-Gate	1.93		11.55
Streamlined Cradle-To-Grave Life Cycle Assessment of Cardia Biohybrid™ Products [9]	Cradle-to-Grave	2.6	78.3	
Life cycle greenhouse gas emissions and energy use of polylactic acid, bio-derived polyethylene, and fossil-derived polyethylene [13]	Cradle-to-Gate	2.9	79	
Comparative environmental life cycle assessment of PET/LDPE, MONO PET and MONO PE films [11]	Cradle-to-Grave	2.79		63.02
High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE), Linear Low-density Polyethylene (LLDPE) [20]	Cradle-to-Gate	1.87	82.9	12.2

Table 6. Comparison of LDPE environmental impact values between literature and openLCA database.

	GWP (kg CO_2 eq)	Electricity Usage (MJ)	Water Consumption (L)
Literature	2.79 [11]	78.3 [9]	63.02 [11]
openLCA	3.03	3.47	40.45

Table 7. Summary data of use, cost, and weight of 14 items of collected hospital products over three years, 2021-2023. Full table available as Table S3.

Brand Name	Product Name	Use over 3 Years	Cost per Use	Cost Over 3 years	Packaging and Label Weight (g)
CareFusion	Bacterial/viral filter	225,645	$0.75	$169,233.75	1.87
Ansell Gammex	Non-latex surgical gloves	448,281	$1.16	$521,982.60	2.82
CardinalHealth	Surgical gown	182,914	$1.96	$358,511.44	12.97
...	...	...	...	...	...
14 items		**4,595,256**		**$1,813,941.24**	

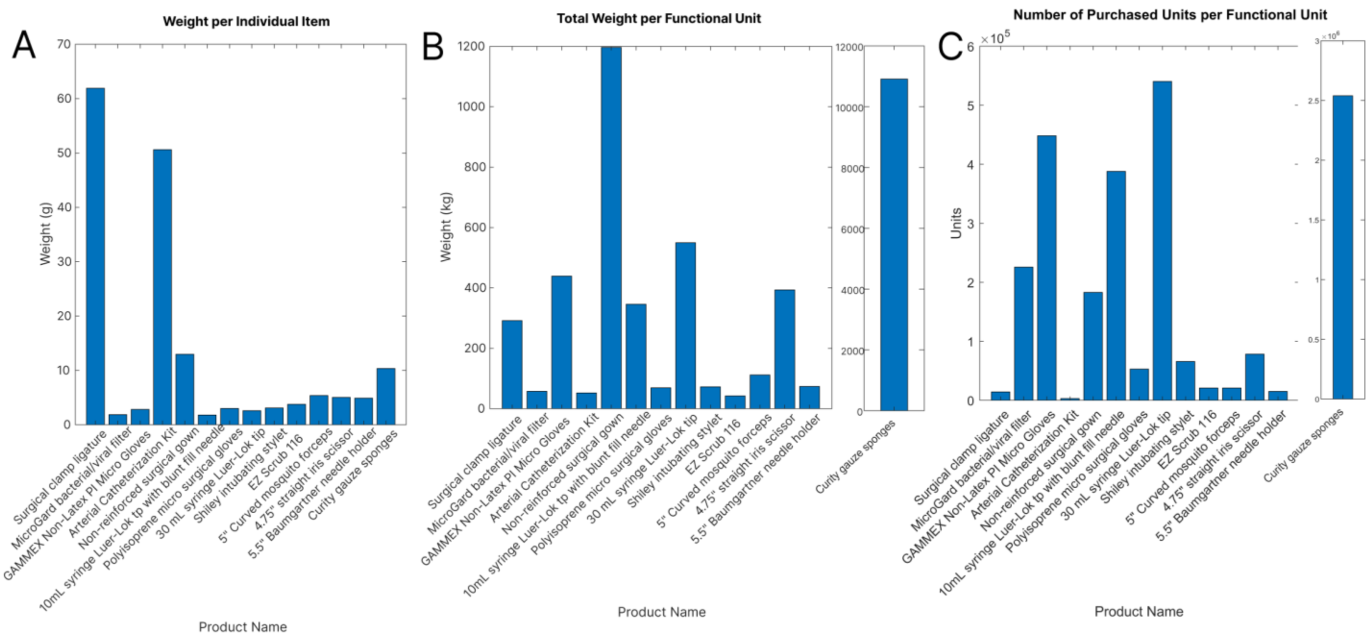

Figure 4. (A) The weight of each individual item's packaging in grams. The surgical clamp ligature plastic and arterial catheterization kit packaging weigh substantially more than the other packaging samples. **(B)** The weight of each individual item was multiplied by the number of uses within the years 2021-2023. The Curity gauze sponges (rightmost bar) contribute ten times more than any other item. **(C)** The number of units purchased (synonymous with amount used).

Results

We performed a cradle-to-grave Life Cycle Inventory Analysis (LCIA) for the 14 products collected from UVA hospital and their use over three years (2021-2023). Using the literature values shown in Table 6, each product was individually analyzed for its impact in reference to GWP, electricity usage, and water consumption, as well as cumulatively.

Impact Equations

We developed and used an equation to quantify the GWP impact of the collected plastic packaging from the UVA hospital. This equation measures for the GWP of a single item (GWP), in kg CO_2 eq, based upon the item's weight, individual units purchased within the time frame of 3 years, and material composition.

$$GWP = WP\sum_{j=1}^{J} GWP_j C_j \text{ kg CO}_2 \text{ eq}$$

Equation 1. Equation to calculate item GWP.

The weight of the item (W) was measured by a scale, in kilograms. UVA hospital value management provided the amount purchased per year (P) over the course of 2021-2023, in U.S. dollars ($). The GWP of the material (GWP_j) was provided by values in literature, in kg CO_2 eq. The composition of the material in product (C_j), in %, was yielded via the material composition spectroscopy.
The same formula was applied to electricity usage and water consumption.

$$E = WP\sum_{j=1}^{J} E_j C_j \text{ MJ}$$

Equation 2. Equation to calculate electricity usage.

$$W = WP\sum_{j=1}^{J} W_j C_j \text{ L}$$

Equation 3. Equation to calculate water consumption.

Where E and W being the electricity usage and water consumption of a single item. E_j and W_j are electricity usage and water consumption values per material provided from literature. We assumed material composition was 100% LDPE, so C_j was 1 for all calculations.

Plastic Packaging Impact

Using the GWP, electricity usage, and water consumption values found in literature (Table 6), these impact metrics over 3 years were calculated using the above equations for each plastic packaging collected from the hospital. These

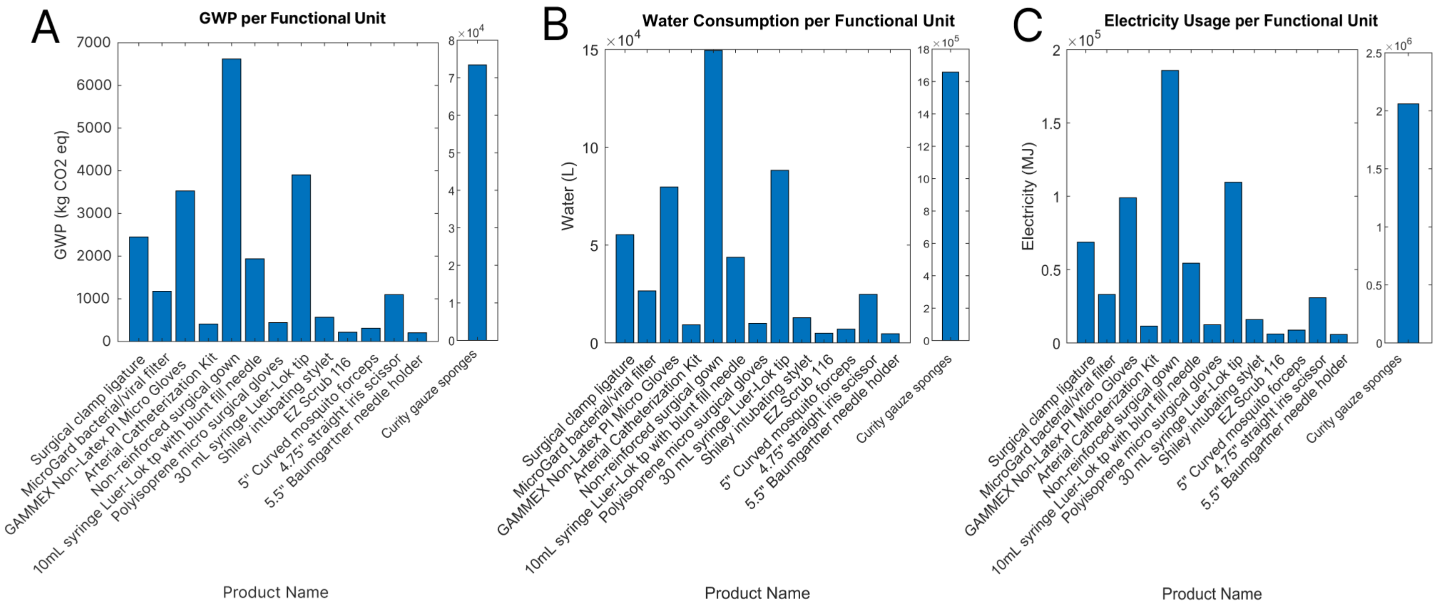

Figure 5. (A) GWP, in kg CO_2 eq, for each product per functional unit. **(B)** Electricity usage, in MJ, for each product per functional unit. **(C)** Water consumption, in liters, for each product per functional unit.

Product Name	GWP (kg CO_2 eq)	Energy Usage (MJ)	Water Consumption (L)	Weight (kg)
CareFusion bacterial/viral filter	1,177.26	33,039.17	26,591.68	57.73
Non-latex surgical gloves	3,526.99	98,983.13	79,666.89	439.2
Surgical gown	6,618.98	185,758.5	149,508.31	1,198.83
...	...	...	...	...
TOTAL IMPACT OF 14 ITEMS	**96,274.57**	**2,701,898.96**	**2,174,631.83**	**14,611.01**

Table 8. Summary of environmental impact as calculated by Equations 1, 2, and 3 for 14 individual items. Corresponding cumulative weights are shown in the right column. The data for all 14 items is shown in Table S4.

values were compiled to create a total impact of 96,274.57 kg CO_2 eq, 2,701,898.96 MJ, and 2,174,631,83 L, for GWP, electricity usage, and water consumption, respectively. The plastic packaging weights measured were multiplied by the total number of individual items purchased over the course of three years, yielding a total medical plastic packaging waste weight of 14,611.01 kg (Table 8). These total impact results are aggregated from the environmental impact per functional unit, purchasing history at UVA from 2021-2023, for each product. On an individual analysis, gauze sponges were used a thousand-fold more than any other product. This usage out scales the y-axis in comparison to the other packaging, as seen in Figure 5.

Table 9 presents the financial and geospatial impacts of plastic packaging taking up landfill space. The cost of

Table 9. Cost and landfill space lost for each collected product assuming LDPE cost ($1.16/kg) and density (0.92 g/cm^3). Cost and landfill data for each item is available in Table S5.

Product Name	Cost of Material Lost ($)	Volume in landfill (m^3)	Total weight (kg)
CareFusion bacterial/viral filter	95.25	0.06	57.73
Non-latex surgical gloves	724.68	0.48	439.2
Surgical gown	1,978.07	1.3	1,198.83
...	...	...	...
TOTAL IMPACT OF 14 ITEMS	**24,108.17**	**15.88**	**14,611.01**

material lost adds the cost of LDPE, \$1.16/kg,[21] and of landfill space, \$0.49/kg,[22] multiplied by the total weight of the plastic packaging purchased. The volume of waste in landfill was calculated from mass divided by density, with the density of LDPE being 0.92 g/cm^3. This yielded a total of \$24,108.17 worth of raw LDPE lost in the production cycle, and 5.55 m^3 landfill space occupied.

Analysis

Following the LCA calculations, we were able to identify the large issue that is hospital product packaging. This study aims to reduce UVA hospital's environmental impact for this waste stream, and thus we aim to estimate the impact potential of three recommendation cases. We explore the potential impact from the mitigation of unnecessary disposal of unused medical waste and the establishment of a recycling program within the hospital. We also quantified the impact of using recycled versus virgin materials in manufacturing to inform environmental impact potential in creating plastic packaging for hospital waste. This data will seek to inform manufacturers, the UVA hospital staff, and recyclers.

Identification and Reduction of Excess Waste

In a study completed within the UVA Health system, Mount Sinai Health System, and Meharry Medical College, researchers observed and measured the wasted usage of single-use, sterile surgical supplies (SUSSS) during 44 pediatric surgeries.[23] Their goal was to collect data on SUSSS that are opened, but unused during surgery, and identify most commonly wasted products and their costs.

We consider the needless disposal of unused hospital waste to be "fluff". Reducing the amount of medical waste "fluff", or the number of materials that are opened, unused, and wasted, can significantly decrease the hospital's environmental impact. Meyer et al. quantifies the amount of fluff to be 26% of all products opened for surgery.[23] With our results, we estimate that by removing excess use to reduce our sample's plastic waste weight by 26%, UVA hospital can reduce 25,000 kg CO_2 eq from the current sample GWP. This incremental reduction can be viewed in Figure 6.

A large reason for the waste observed in the OR is the existence of pre-made packs of commonly used products. Within the OR at UVA hospital, OR packs are created with a predetermined number of products prior to surgeries. From Meyer, et al., "preparation for the high probability events that may not happen, or low probability catastrophes that need immediate intervention". Systemically, the proposed 26% reduction of plastic packaging waste could

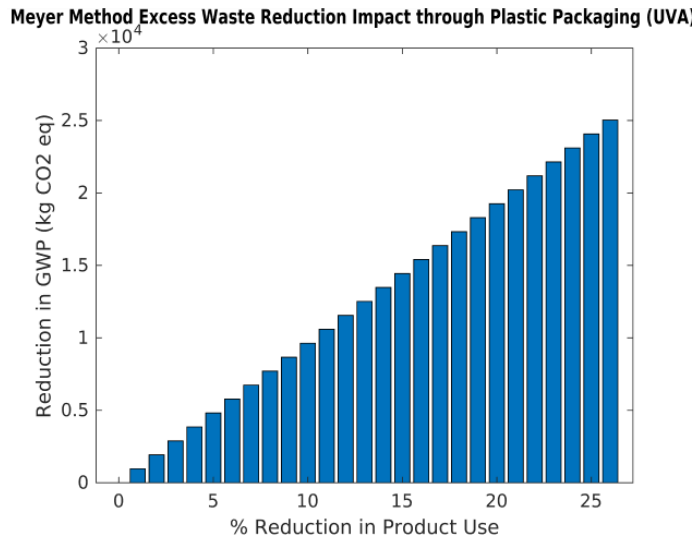

Figure 6. Reduction in GWP per percent reduction in product usage. 25,000 kg CO_2 eq could be saved through reduction of excess waste.

be implemented through decreasing the number of total products within the OR pack. This method, however, would require more of a burden of labor to those who are involved in the surgery, either estimating what additional materials need to be acquired external to the OR pack prior to surgery and collecting them or opening sterile products during surgery. In order to reduce the materials used, Meyer et al. proposed several possible interventions including: more frequent revision of preference lists, withholding of materials from sterile field until needed, notification and transparency of surgical supply cost, and waste education for hospital employees.[23]

UVA Hospital's Recycling Impact Potential

UVA hospital does not currently have an established recycling program because of the prioritization of patient health and safety over sustainability. To implement a hospital-wide recycling program, the hospital should place recycling bins in high-traffic and convenient areas, provide unit-based training on proper recycling, and hire recycling program staffers to incentivize good recycling practices. The implementation of a plastic packaging recycling program could decrease the amount of clean plastic packaging waste UVA hospital contributes to the landfill by 100% in a dream scenario. In the state of Virginia, the total plastic recycling rate is 4% (calculations show LDPE recycling <1%)[24]; nationally, it is 2%.[25] Both of these values are much below Europe's LDPE recycling rate of 31%.[26] The diversion of the hospital's LDPE waste from the landfill would contribute to a higher state and national recycling rate. A 100% waste reduction, then, is likely not achievable, but we propose that by bolstering recycling in the UVA hospital, 30%, or 4,380 kg, of plastic packaging waste can be diverted.

Manufacturers: Use of Recycled LDPE in Hospital Packaging

Although the reduction of waste generation within the UVA hospital could amount to a significant decrease in the hospital's total environmental impact, more consequential change could be made through plastic manufacturing. Though plastic has become a staple of healthcare systems and removal of it altogether is infeasible, developing a circular economy approach for plastic provides sustainability potential. A circular economy proposes a make, use, recycle approach, where materials never go to waste.[27] Plastic packaging and medical product manufacturers can spearhead this initiative by designing plastic packaging, especially LDPE, to be more recyclable. Once recycled, manufacturers can use this recycled LDPE, instead of virgin LDPE, feeding into the system of the circular economy. We calculated the potential reduction of impact for our subset of plastic packaging using values found in literature for virgin and recycled LDPE, as seen in Table 10. The percent reduction was calculated by subtracting the recycled LDPE impact values divided by the virgin LDPE impact values from one. If recycled materials were used in manufacturing, GWP could be reduced by 40%, water consumption would be reduced by 90.5%, and electricity usage would be reduced by 92%, visualized in Figure 7. Plastic manufacturing modifications goes beyond the "fluff" of hospital waste reduction, but begins to incorporate a systemic change to a long rigid system.

Table 10. Comparison of LDPE environmental impact values between virgin and recycled LDPE.

	GWP (kg CO_2 eq)	Water usage (L/kg)	Energy Consumption (MJ/kg)
Virgin LDPE	2.79 [11]	63.02 [11]	78.3 [9]
Recycled LDPE	1.67 [28]	6 [28]	6 [28]

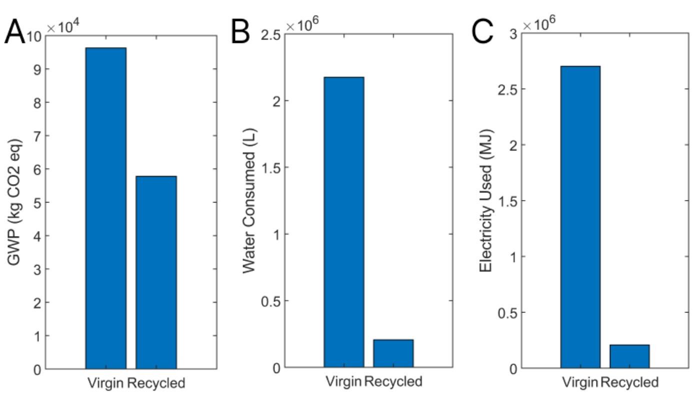

Figure 7. Comparison of the use of virgin and recycled LDPE in manufacturing for **(A)** GWP, **(B)** water consumption, and **(C)** electricity usage.

Discussion

The main goal of this study was to provide computational analyses to determine the environmental impact of UVA hospital's disposal of medical plastic packaging. This goal was achieved by conducting an impact assessment of LDPE packaging at UVA hospital usage over three years. Using LCA methodology, we calculated the environmental impacts of hospital plastic packaging at the UVA hospital from collection of use data, packaging weight, plastic composition, and LCA literature values. The three-year packaging use samples yielded a combined GWP of 96,274.57 kg CO_2 eq, electricity usage of 2.7 million MJ, water consumption of 2.17 million liters, and 14,600 kg of waste landfilled, assuming a 0% recycling rate. The UVA hospital contributes an estimated 5.3 m^3 of plastic packaging to the landfill per year <u>from these samples alone</u>. The results from this study represent a small portion of the total waste generated by UVA hospital over three years, despite their extremely large environmental impact.

After determining the environmental impact of our subset of plastic packaging, we explored potential avenues for impact reduction. By decreasing the number of materials that are opened, but not used during a procedure, the hospital could diminish its negative impact by approximately 26%. This reduction strategy, removal of "fluff", is a short-term solution that is both reasonable and impactful. Rather than opening an excessive number of materials and allowing them to be clean but not sterile, materials can be opened on an as needed basis in conjunction with a regular review of surgeons' preference cards to include only necessary materials. A more intensive, but effective effort could be made to establish a recycling program within the hospital, theoretically increasing the packaging recycling rate from 0% to 100%. A systemic change would need to be made for this program to be successful, including the additional employment of recycling staff, strategic placement of recycling containers in high-traffic, convenient, and decentralized locations, and education of all hospital staff on proper recycling practices. Rationally, a 100% recycling rate is infeasible to achieve, so we showed how a 30% increase in recycling rates would result in the diversion of 4,380 kilograms of plastic packaging over three years. At the production level, manufacturers should use recycled LDPE to create new plastic packaging, rather than virgin materials. The commitment to creating a circular economy of plastic waste would decrease the impact of plastic packaging as a whole by 40% of current GWP, 90.5% of water consumption, and 92% of electricity usage. Integrating systems of recycling and using recycled materials within UVA hospital, hospitals across the U.S., and manufacturing companies can reduce the environmental impact of plastic packaging. The results from the LCA provide incentive for change while our analysis offers actionable recommendations to guide sustainability efforts.

Limitations

Although this study was successful in quantifying the contribution of medical plastic packaging at UVA hospital, it was limited by being a single sample within the larger hospital. UVA hospital has thousands of different medical equipment that come in many shapes, sizes, and material types, with our sample being only a small portion of the environmental impact. We only interacted with waste in certain areas of UVA hospital (MERCI and in the OR), which likely influenced the products we selected as the most commonly used. Other units in the hospital may use items like syringes or gowns more than in the OR. Thus, the 19 products we collected, 14 of which we analyzed, does not represent the whole of all medical equipment, tools, and materials in the entire hospital. This LCA also focuses on one hospital, even though UVA hospital is not the sole contributor to healthcare waste and its environmental consequences. Expansion upon the hospital and product-specific limitations would further quantify the environmental impact of plastic packaging.

In addition to the limitation of sample size, this study is also limited by unknown material composition. After wavelength spectroscopy analysis was performed, we assumed that the plastic packaging that we had and were analyzing was composed of 100% LDPE. This assumption was made for the ease of calculation and general accuracy, but may not be precise. Because most medical packaging is not labeled as one specific type of plastic, they are likely to contain multiple plastic materials, even if in small amounts. The wavelength spectroscopy yielded wavelengths similar to those of LDPE within the material libraries, but did not have a 100% accurate hit rate. We hypothesize, then, that much of the packaging material is heterogeneous, containing multiple plastics, some in small amounts. Given the time and resource constraints of this study, we were unable to explore increasing the accuracy and precision of the wavelength spectroscopy that was performed.

A critical assumption made within the analysis was that the recycling rate for plastic packaging in UVA hospital was 0%. From what we observed while shadowing, this statement is true, however, our time observing in the OR may not reflect the practices of all hospital staff during each procedure or with every patient. Further research is needed in order to quantify, plan, and recommend changes for the UVA hospital recycling data.

The utilization of LCA values from openLCA does not represent the actual impact of the plastic packaging entirely. As stated in the literature review section, we were not able to collect impact values ourselves and relied on existing LCA literature. The transparent results from this study aim to serve as a basis for future LCAs in order to improve depth of existing literature.

Future Work

The work done in this study serves as the first step for a much larger network of sustainability research within healthcare. Based on the sample size limitations of this study, future research should expand the waste audit outside of the 14 samples we analyzed to all products in the OR and all products in the entirety of UVA hospital. This work can be expanded further to include all of the UVA Health system, all healthcare facilities in the state of Virginia, and every hospital in the U.S. The inclusion of more products and more facilities bolsters the authority of the results found in this study and their implications. By including all products, the environmental impact of healthcare waste will be more accurately represented in the LCA. Similarly, the inclusion of specific environmental impact values from the manufacturing and shipping processes would yield results more accurate to the existing processes and impacts. Furthermore, more rigorous work should be done within the material composition exploration to best represent the impact of each packaging unit. Though we assumed each package was composed of 100% LDPE, this is likely inaccurate. The inclusion of multiple materials analyzed using wavelength spectroscopy within the impact equations would produce more precise results.

Aside from refined computational approaches and larger sample sizes, future work should take actionable steps towards systemic changes based upon these LCA results, analyses, and recommendations. We recommended that the UVA hospital can reduce their environmental impact by decreasing unnecessary waste and establishing a recycling program in-house. These recommendations should be implemented and optimized within the hospital. With the proper recycling of plastic packaging, repurposed materials can be used to create different products, for medical or domestic use. Expanding the scope of this project beyond hospitals, but to industries across the country starts to acknowledge the true scope of the environmental problem in the U.S.

End Matter

Author Contributions and Notes

Anne Clements, Margaret Weber, and Davis Young all contributed equally to the conducted LCA. Zackary Landsman advised all work.

Conflicts of Interest

The authors declare no conflict of interest.

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Supplemental Materials

Item Number	Brand Name	Product Name	Package Weight (g)	Item Number	Brand Name	Product Name	Package Weight (g)
	Samco Bio-Tite	Sterile specimen container	3.53	6	Covidien	Devon needle counter	7.8
2	Unknown	Surgical clamp	61.91		Ansell PremierPro	Micro surgical gloves	3
	CareFusion	Bacterial/viral filter	1.87	5	BD	30 mL syringe	3.59
	VBMax	Bacterial/viral filter	2.41	1	Covidien	Gauze sponges	10.36
	CardinalHealth	Suction tubing	10.77		Covidien	Shiley intubating stylet	3.1
	Ansell Gammex	Non-latex surgical gloves	2.82		BD	EZ Scrub	3.76
	Arrow	Arterial catheterization kit	50.61	4	MediChoice	5” Forceps	5.38
	CardinalHealth	Surgical gown	12.97	3	MediChoice	4.75” Iris scissor	5.03
	BD	10 mL syringe	1.79		MediChoice	5.5” Needle holder	4.9
	Unknown	Mop cap	4.04*				

Supplementary Table 1. Identification of all 19 collected hospital products and their packaging weight in grams. Expansion upon summary data in Table 1. Item numbers correspond to the items in Figure 2.
* Packaging was not available for this item, so the weight value is for the product only.

Item Number	Brand Name	Product Name	Units Purchased	Total Cost	Item Number	Brand Name	Product Name	Units Purchased	Total Cost
	Samco Bio-Tite	Sterile specimen container	4,500*	$518.2	6	Covidien	Devon needle counter	1,736	$1,892
2	Unknown	Surgical clamp	14,182	$15,884		Ansell PremierPro	Micro surgical gloves	52,836	$61,290
	CareFusion	Bacterial/viral filter	225,645	$169,234	5	BD	30 mL syringe	540,308	$151,286
	VBMax	Bacterial/viral filter	900*	$787	1	Covidien	Gauze sponges	2,539,630	$38,094
	CardinalHealth	Suction tubing	2,610*	$1,438		Covidien	Shiley intubating stylet	65,735	$118,980
	Ansell Gammex	Non-latex surgical gloves	448,281**	$521,983		BD	EZ Scrub	20,790	$8,268
	Arrow	Arterial catheterization kit	2,895	$118,116	4	MediChoice	5” Forceps	20,783	$35,680
	CardinalHealth	Surgical gown	182,914	$358,511	3	MediChoice	4.75” Iris scissor	78,241	$101,693
	BD	10 mL syringe	387,968	$89,233		MediChoice	5.5” Needle holder	15,048	$25,690
	Unknown	Mop cap	83,800	$5,548					

Supplementary Table 2. Purchase history of all 19 collected hospital products. Expansion upon summary data in Table 2.
* The 2021 and 2022 data were not available, so the 2023 data was multiplied by 3.
** Data for 3 different sizes of gloves was available. To simplify calculations, their usage and cost were combined under one item name, size unspecified.

Brand Name	Product Name	Use over 3 Years	Cost per Use	Cost Over 3 years	Packaging and Label Weight (g)
Unknown	Surgical clamp	14,182	$1.12	$15,883.84	61.91
CareFusion	Bacterial/viral filter	225,645	$0.75	$169,233.75	1.87
Ansell Gammex	Non-latex surgical gloves	448,281	$1.16	$521,982.60	2.82
Arrow	Arterial catheterization kit	2,895	$40.80	$118,116	50.61
CardinalHealth	Surgical gown	182,914	$1.96	$358,511.44	12.97
BD	10 mL syringe	387,968	$0.23	$89,232.64	1.79
Ansell PremierPro	Micro surgical gloves	52,836	$1.16	$61,289.76	3
BD	30 mL syringe	540,308	$0.28	$151,286.24	2.59
Covidien	Gauze sponges	2,539,630	$0.015	$38,094.45	10.36
Covidien	Intubating stylet	65,735	$1.81	$118,980.35	3.1
BD	EZ Scrub	20,790	$0.3976	$8,267.49	3.76
MediChoice	5” Forceps	20,783	$1.7168	$35,680.25	5.38
MediChoice	4.75” Iris Scissor	78,241	$1.2999	$101,692.48	5.03
Sklar Sterile	5.5” Needle holder	15,048	$1.7072	$25,689.95	4.9

Supplementary Table 3. Cumulative data of purchase history and weight for 14 items selected for analysis, including packaging weight, units purchased, cost per unit, and total cost from 2021-2023. Expansion of summary data in Table 7.

Product Name	GWP (kg CO_2 eq)	Energy Usage (MJ)	Water Consumption (L)	Weight (kg)
Surgical clamp	2,449.64	68,748	55,332.04	291.78
CareFusion bacterial/viral filter	1,177.26	33,039.17	26,591.68	57.73
Non-latex surgical gloves	3,526.99	98,983.13	79,666.89	439.2
Arterial catheterization kit	408.78	11,472.2	9,233.44	52.28
Surgical gown	6,618.98	185,758.5	149,508.31	1,198.83
10 mL syringe	1,937.55	54,376.43	43,765.04	346
Micro surgical gloves	442.24	12,411.18	9,989.17	69.24
30 mL syringe	3,904.32	109,572.84	88,190.04	549.8
Gauze sponges	73,406.48	2,060,117.38	1,658,091.92	1,0912.11
Intubating stylet	568.54	15,955.86	12,842.12	72.53
EZ Scrub	218.10	6,120.74	4,926.3	42.41
5” Forceps	311.96	8,754.92	7,046.43	111.81
4.75” Iris Scissor	1,098.01	30,815.14	24,801.66	393.55
5.5” Needle holder	205.72	5,773.47	4,646.79	73.74
TOTAL IMPACT	**96,274.57**	**2,701,898.96**	**2,174,631.83**	**14,611.01**

Supplementary Table 4. Environmental impact as calculated by Equations 1, 2, and 3 for 14 individual items. Corresponding cumulative weights are shown in the right column. The values for all 14 products over 3 years are combined in the lowest row entitled Total Impact. Expansion upon Table 8.

Product Name	Cost of Material Lost ($)	Volume in landfill (m^3)	Total weight (kg)
Surgical clamp	481.44	0.32	291.78
CareFusion bacterial/viral filter	95.25	0.06	57.73
Non-latex surgical gloves	724.68	0.48	439.2
Arterial catheterization kit	86.26	0.06	52.28
Surgical gown	1,978.07	1.3	1,198.83
10 mL syringe	570.90	0.38	346
Micro surgical gloves	114.25	0.08	69.24
30 mL syringe	907.17	0.60	549.8
Gauze sponges	18,004.98	11.9	10,912.11
Intubating stylet	119.67	0.08	72.53
EZ Scrub	69.98	0.05	42.41
5” Forceps	184.49	0.12	111.81
4.75” Iris Scissor	649.36	0.43	393.55
5.5” Needle holder	121.67	0.08	73.74
TOTAL IMPACT	**24,108.17**	**15.88**	**14,611.01**

Supplementary Table 5. Cost and landfill space lost for each collected product assuming LDPE cost ($1.16/kg) and density (0.92 g/cm^3). Expansion upon Table 9.