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Materials Science Toolkit for Carbon Footprint Assessment: A Case Study for Endoscopic Accessories of Common Use

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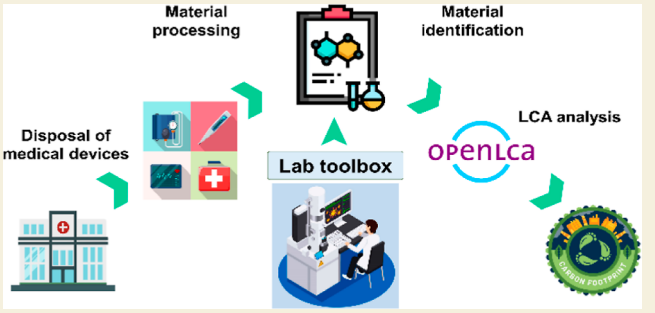
ABSTRACT: Ironically, healthcare systems are key agents in respiratory-related diseases and estimated deaths because of the high impact of their greenhouse gas emissions, along with industry, transportation, and housing. Based on safety requirements, hospitals and related services use an extensive number of consumables, most of which end up incinerated at the end of their life cycle. A thorough assessment of the carbon footprint of such devices typically requires knowing precise information about the manufacturing process, which is rarely available in detail because of the many materials, pieces, and steps involved during the fabrication. Yet, the tools most often used for determining the environmental impact of consumer goods require a bunch of parameters, mainly based on the material composition of the device. Here, we report a basic set of analytical methods that provide the information required by the software OpenLCA to calculate the main outcome related to environmental impact, greenhouse gas emissions. Through thermogravimetry, calorimetry, infrared spectroscopy, and elemental analysis, we proved that obtaining relevant data for the calculator in the exemplifying case of endoscopy tooling or accessories is possible. This routine procedure opens the door to a broader, more accurate analysis of the environmental impact of everyday work at hospital services, offering potential alternatives to minimize it.



KEYWORDS: *endoscopy accessories, materials characterization, carbon footprint, life cycle assessment, toolkit*

1. INTRODUCTION

In recent years, climate change has become one of the most important challenges facing humanity, and the threat of global warming poses serious risks to people around the world, with human activities being the main culprit.[1]

Carbon dioxide (CO_2) is one of the most important greenhouse gases (GHG), and it is released into the atmosphere due to human activities, such as the burning of fossil fuels as well as natural processes like volcanic eruptions and respiration.[2−5] Approximately 95% of scientists and climate experts believe that human activities have significantly altered the earth's atmosphere, causing global warming.[6] GHG generally absorbs a certain amount of energy in a way that protects the environment from extreme cold, but the important contribution of GHG to global warming must be addressed as temperatures continue to rise.[5,6]

In this general background, healthcare represents about 5% of global environmental impact, with a tendency to increase monotonically.[7−10] In Italy's healthcare system, the top three highest-generating departments of hazardous waste were anesthetics (5.96 kg·day^{-1}·bed^{-1}), pediatric and intensive care (3.37·kg·day^{-1}·bed^{-1}), and gastroenterology-digestive endoscopy (3.09 kg·day^{-1}·bed^{-1}).[11] According to Lenzen et al.,[7] interventions to reduce the effect of contamination in hospitals should focus on reducing waste (avoiding unnecessary plastics and reducing single-use items and drugs) and reducing pollution (especially anesthetic gases and asthma inhaler propellants, as well as transport).

Most healthcare waste is nonhazardous, potentially recyclable waste. If the waste content is not examined, a significant percentage of nonhazardous waste may not be adequately treated, increasing the cost.[11] The legislation of the majority of the countries includes safeguarding the environment, reducing wastefulness, and looking for the most efficient and cost-effective waste treatment.[12] Vaccari et al.[11] showed that, although there is a positive correlation between healthcare expenditure and waste derivative, the example of Germany

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indicates that waste management can be dramatically decoupled from everyday expenses at hospital facilities. In fact, the healthcare industry faces many challenges, but one particular characteristic of this sector is its slow adaptation to the sustainability movement. The main reason for this lack of focus on sustainability has been the prioritization of patient safety above all other considerations.[13] MacNeill et al.[14] presented a framework for constructing environmentally sustainable health systems, where they conclude that the race to net zero health-care emissions is not simply a climate change mitigation strategy but rather the capstone of a societal transition toward health and wellbeing for all. This framework is based on three principals: to reduce demand for health services, to match the supply of health services to demand, and to reduce emissions from the supply of health services, optimizing the efficiency and environmental performance of care delivery.

To reduce the environmental emissions of healthcare procedures, healthcare providers must implement a combination of approaches, including minimizing materials, maximizing instrument reuse, and single-use device reprocessing.[15] The first step is an assessment of the sources of emissions and target intervention strategies. Thiel et al.[15] used a hybrid environmental life cycle assessment framework to estimate laparoscopic surgery's greenhouse gas (GHG) emissions. They found that the most significant carbon footprint savings came from selecting specific anesthetic gases and minimizing the materials used. Consequently, they proposed energy-related interventions, such as moving away from heat-trapping anesthetic gases, maximizing reuse, and recycling surgical waste. They showed that the carbon footprint of an average laparoscopic hysterectomy could be reduced by up to 80%. Recycling alone does very little to reduce the environmental footprint.

Healthcare systems have increasingly turned toward the use of disposable medical equipment in an attempt to reduce the transmission of infections. However, the use of disposable instruments leads to an increase in solid waste with a negative environmental impact. Sustainability-related research in the healthcare sector has mainly focused on recycling and its benefits for gas emission reduction. In this sense, research has shown that many healthcare centers have started to get involved with the Go Green initiative, while some have already taken action using reusable medical products. For example, an experiment conducted by scientists on disposable and reusable laryngeal mask airways found that the reusable mask was a more effective and affordable option compared to the disposable ones, which increased the waste management workload.[13] On the other hand, Donahue et al.[16] compared the carbon footprints of single-use and reusable vaginal specula. They concluded that using reusable, instead of single-use, vaginal specula could reduce up to 75% of GHG emissions and even more solid waste, considering the same number of examinations. In some cases, reusable endoscopes are combined with disposable attachments, as in the case of single-use duodenoscopes, where the level of disinfection is higher than in reprocessed duodenoscopes with currently available cleansing methods.[17] However, the cost and environmental footprint remain the biggest obstacles to disseminating single-use duodenoscopes. Hernandez et al.[18] found that using a single-use duodenoscope consumed energy and released CO_2 around 20 times more than using a reusable duodenoscope. Most of the impact of the single-use duodenoscope effects came from its production, which accounts for 96% of energy consumption and greenhouse gas emissions. Although the difficulties in reprocessing reusable duodenoscopes have moved to the utilization of single-use ones, essential questions around their usability, cost, and environmental impact remain unsolved.[19]

The environmental impact of gastrointestinal endoscopy is widely recognized.[19−22] An endoscopy unit that performs 40 endoscopies daily generates approximately 241.4 tons of CO_2eq annually, which is 7% of total emissions due to consumables, that is, around 16 tons of CO_2eq[23] In the U.S., the GHG production related to endoscopic procedures was estimated to be 85,768 t of CO_2eq annually.[21] Interventions to make endoscopy more sustainable are urgent to minimize our carbon footprint and avoid the worst consequences of climate change. The European Union has recently enhanced waste management strategies toward a circular economy.[24] One of the proposed objectives is to reduce the amount of incinerated waste, reduce packaging to the strictly necessary level, and use environmentally friendly materials.

Endoscopy procedures are essential in preventing, diagnosing, and treating gastrointestinal (G.I.) diseases.[25] Besides environmental issues, the main concern must be the safety of the patients. Spaulding classification describes the potential risk of infection caused by a device in contact with a patient, where reusable medical devices that come into contact only with the skin and mucosa are defined as noncritical devices and must undergo cleaning and disinfection but do not need to be sterile.[25] However, most flexible endoscopes used in G.I. endoscopy are classified as semicritical devices because they meet intact mucous membranes and do not ordinarily penetrate sterile tissue. Endoscopic accessories that penetrate the mucosal barrier (e.g., biopsy forceps, guidewires, polypectomy snares, and hemoclips) are classified as critical devices and must be sterile at the point of use. Single-use devices should not be reprocessed at any time.

Among endoscopic accessories, we selected three of the most commonly used ones (biopsy forceps, polypectomy snares, and hemostatic clips) from 3 different manufacturers. These instruments are responsible for 15% of total CO_2eq emissions from consumables.[26] Polypectomy snares are commonly used in endoscopic resection for treating G.I. polyps. The endoscopist selects the polypectomy snare according to the procedure and the lesion characteristics. They can be oval-shaped, hexagonal-shaped, or rounded.[27] Biopsy forceps are the most frequently used accessories in G.I. endoscopy to take biopsy samples.[28] Reusable and disposable biopsy forceps are available for use. As they have similar shapes and sizes in cups, they have equivalent performance regarding specimen size, histological depth, and so forth.[29] Hemoclips are used for endoscopic clip placement within the G.I. tract. They are indicated for any G.I. bleeding to achieve hemostasis by occluding the bleeding vessel without additional tissue damage. Closure of mucosal defects or perforations after endoscopic resection is another important application to consider.[30]

In recent years, concerns regarding endoscopy-associated infections have increased commercial interest in disposable endoscopes. For therapeutic procedures, most accessories are also single-use, are not recyclable, and are disposed of via incineration. At present, it is impossible to estimate the carbon footprint of single-use consumables unless manufacturers declare it.[21]

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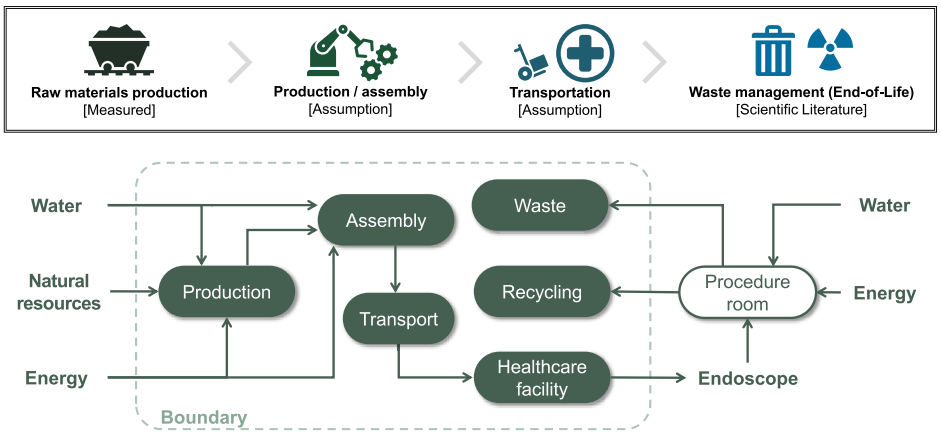

Figure 1. Phases assessed in the life cycle of the accessories and product system flowchart.

Life cycle assessment (LCA) is a technique to evaluate the environmental emissions associated with the production and consumption of products or processes.[31] The evaluation embraces the entire life cycle, from extraction to manufacturing, transportation, and distribution. It also considers the use, reuse, recycling, and final disposal in such cases. LCA typically occurs in four steps. The first phase is a description of the goal and scope. The second phase, inventory analysis, compiles inputs and outputs for each process in the life cycle. In the third phase, life cycle impact assessment, emissions, and resources are grouped according to their impact categories and converted to common impact units (such as CO_2 equivalent emissions) to make them comparable. The final phase is the interpretation of the impact assessment results in order to answer the objectives of the study.[32] LCA has been conducted in many fields, from industry to agriculture.[32] Information provided by LCA enables the determination of the biggest impact-reduction potentials, and it could contribute to the prioritization of management efforts. Moreover, LCA is particularly suited.[32]

The health area has been used to measure the environmental impact of products or processes, among others, in dentistry,[33,34] surgery,[15,35] vaginal specula,[16] or pharmaceutical products.[36,37] Leiden et al.[38] investigated the environmental impact of a reusable and disposable surgery instrument set for lumbar fusion surgeries with the implantation of four screws and two rods. An LCA was conducted, and five impact categories and one single score indicator were used. The environmental impact of the disposable system was significantly lower in all studied impact categories and in the single-score indicator. The main reason for this is the high environmental impact of the steam sterilization process in hospitals and the large size of the reusable surgery instrument set. This study also highlighted the significance of the uncertainty in the production phase of disposable instruments, which indicates the importance of a toolkit for an accurate determination of this phase.

In this paper, we disclose a new procedure to evaluate the carbon footprint of different endoscopic accessories, even when their materials are unclear or unknown. The procedure consists of breaking them down into their components and using the knowledge obtained in a material science laboratory to determine the composition of the parts, correspondingly unveiling information about the assembly and manufacturing process as well. Using LCA software to calculate the carbon footprint made it possible to understand the environmental impact better and compare various endoscopic accessories from different suppliers.

2. EXPERIMENTAL/METHODS

2.1. Materials

The commercial accessories analyzed in this paper are three polypectomy snares, named S1, S2, and S3; two hemoclips, named H1 and H2; and three forceps, named F1, F2, and F3. S1, H1, and F1 were manufactured by Olympus; S2, H2, and F2 were manufactured by Boston Scientific; and S3 and F3 were manufactured by Cook Medical.

2.2. Sample Preparation

Each of the accessories was cut and disassembled into pieces of different materials. Then, samples for the characterization were prepared, with one sample for each material composing each of the eight accessories. Samples were classified according to their function and composition after the first visual survey.

2.3. Characterization Techniques

The composition of the metallic parts was examined with a field emission scanning electron microscope (FESEM, ZEISS Ultra-55) at 30 kV, 500 pA, where X-ray microanalysis mapping was performed with an energy-dispersive X-ray spectrometer (EDS) from Oxford Instruments attached to the FESEM. The exposure time for data acquisition was set at 4 min for each sample.

The composition of the polymeric parts was determined using three techniques: differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), and Fourier-transformed infrared spectroscopy (FTIR). DSC measurements were carried out with a PerkinElmer DSC 8000 under a flowing nitrogen (N_2) atmosphere. The mass of the samples was between 5 and 10 mg. A single cooling and two heating thermograms were recorded from −80 to 240 °C at 20 °C·min^{-1}. Samples at room temperature were heated to 240 °C, then cooled to −80 °C to avoid thermal history, and reheated again to 240 °C. It was possible to obtain the melting temperature, T_m, and the glass transition temperature, T_g, from the second heating thermogram.

TGA measurements were performed on a T.A. Instruments SDT-Q600 system. TGA tests were carried out in alumina crucibles in which samples of weight between 5 and 10 mg were heated from 30 to 800 °C at a heating rate of 10 °C·min^{-1}. TGA experiments were performed using a nitrogen flow of 20 mL·min^{-1} in order to avoid thermo-oxidative reduction. The decomposition temperature, T_d, was obtained from the temperature of the peaks in the derivative curves.

Fourier-transformed infrared spectroscopy in the attenuated reflection mode (ATR-FTIR) was performed by using a Bruker Alpha I spectrometer with a wavenumber range from 4000 to 400 cm^{-1}, 24 scans, and a resolution of 4 cm^{-1}.

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2.4. Life Cycle Analysis

Life cycle assessment was conducted on Open LCA free software, version 1.11, using the Environmental Footprint v3.0 method (included in the openLCA LCIA pack v2.2.1) and the Ecoinvent v3.8.1 database.[39] For this study, the only impact category evaluated was GWP100, referred to here as the "carbon footprint", and used to compare the different endoscopy accessories. It was selected as the mainstream indicator of the anthropogenic environmental impact for the general public. The four main phases of the life cycle of this type of devices were analyzed according to ISO 14040 (Figure 1), considering one finished product as the functional unit, packaging included. As for the functions of the different systems, accessories from the same family (snares, hemoclips, or forceps) share the same surgical purpose. The different families are also comparable between them since they have a similar shape and mass, and they all must be used through the working channel of a much heavier endoscope, as represented in the flowchart in Figure 1.

The characterization of the previous section led us to determine the composition and weight of the raw materials for each part of the different accessories. This enabled us to select an array of processes from the OpenLCA inventory to be assigned to every accessory, along with the corresponding mass, instead of assuming that the whole device is made of a single material. Each process covered cradle-to-gate steps of the transformation of natural resources into specific components ready to be assembled (e.g., polymer rods and metal wires) and allowed to discriminate the geographical location. Some factors from the rest of the phases were impossible to determine, and, in these cases, data were obtained from the literature (secondary data) or based on assumptions from our expertise, as shown in Figure 2. Based on general industry and manufacturer information, several assumptions were made to estimate the production, assembly, and transportation carbon emissions of the endoscopic tools and materials. For instance, even though the operations needed for accessory manufacturing and assembly are not trivial, typical values of 0.2 kg CO_2eq·device^{-1} are calculated for disposable ancillary medical devices[40] or rigid enclosures.[41] The items would be transported from the producer locations to the Hospital la Fe in Spain (Valencia) by a cargo ship for transoceanic routes and a diesel truck for continental ones. More precisely, the following assumptions were made based on each company's production site: Olympus factory is located in Vietnam (Hó Ch Minh, 14.000 km freight container ship), Boston Scientific is located in Costa Rica (San José, 800 km diesel lorry +8000 km freight container ship), and Cook Medical is located in the U.S. (Indiana, 2000 km diesel lorry +6000 km freight container ship). Waste management of biomedical tools generally included high-temperature incineration, followed by landfill disposal or on-site burial of incombustible residues (typically metals and ashes). The carbon footprint effect of this process was estimated at 2.408 kg CO_2eq·kg^{-1} for plastics[42,43] and 1.074 kg CO_2eq·kg^{-1} for nonplastics.[44]

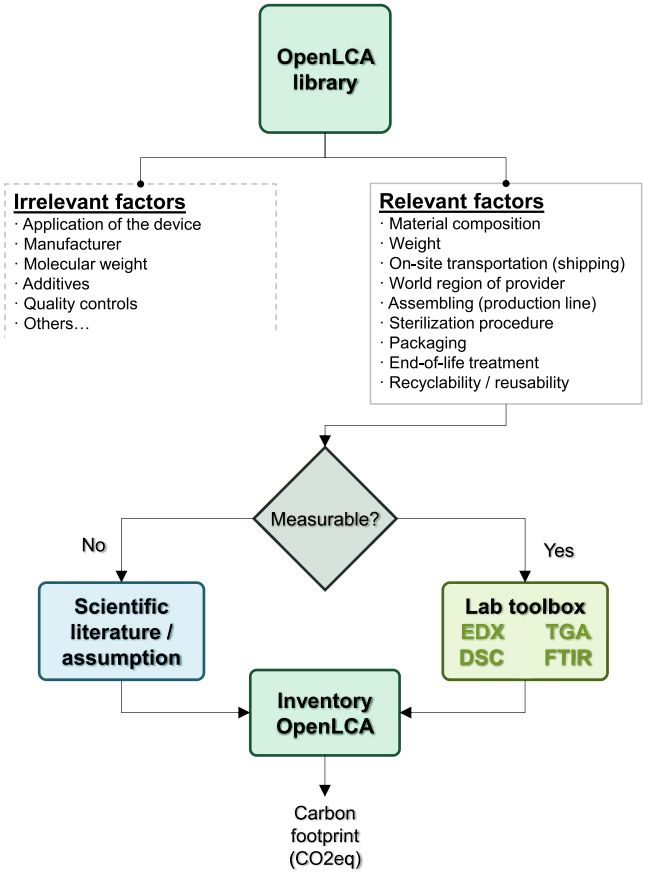

Figure 2. Decision-making criteria followed in this work were to obtain the input data (inventory) for OpenLCA calculations.

3. RESULTS AND DISCUSSION

3.1. Main Composition of Selected Single-Use Endoscopic Tools

Table 1 summarizes the weight distribution of the most commonly used single-use endoscopic accessories at the Digestive Endoscopy Unit of the La Fe Hospital, Valencia, Spain. Figure 3 shows the percentages of polymer and metal for each accessory. In the case of forceps, a high presence (around or over 50%) of metallic materials is observed. This is because this is a particular tool where metallic elements are needed to obtain adequate tissue samples from the patient for further analysis. On the other hand, polymeric materials prevail in the material distribution of snares (the percentage is higher than 85% in all cases), with the handle being their heaviest component. Hemoclips present a mixed distribution, depending on the manufacturer.

All of the accessories are appropriately packaged before use. While the packaging and handle could be recycled, the endoscopic accessory (including wiring and tubing) could not, as it is in contact with the patient's tissues and should be considered a critical device and, therefore, subjected to incineration. This is the reason that led us to separate the analysis of all the accessories into three main parts: packaging, handle, and wiring and tubing. Figure 4 shows the percentage of mass of each of these three parts for each device. It is worth noting that the packaging represented percentages higher than 20% in most of the cases. Besides, the percentage of packaging plus handle was higher than 50% of the mass of the accessories, which is only lower than 50% for H2 (45.6%) and F1 (34.0%).

In this work, a toolkit of techniques of common use in material science has been determined and tested which reveal detailed information about the composition of medical devices, thereby narrowing the uncertainty of the corresponding mass of CO_2 equivalent emitted. Specifically, the designated techniques are SEM/EDX for metallic pieces and FTIR, TGA, and DSC for polymeric parts.

The DSC and TGA analyses were used to determine the thermal nature of the material analyzed, particularly the melting temperatures (T_m), glass transition temperature (T_g), and decomposition temperature (T_d) of polymers, which are specific to each polymer. They also provide the information needed to identify whether the sample is pure (one material made) or hybrid (presence of additives, several polymers, -blends-, or a composite). FTIR was used to determine the chemical profile of each sample, providing precise information

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Table 1. Mass Distribution in Polymeric and Metallic Materials and Number of Parts for Each of the Eight Accessories

	snares			hemoclips		forceps		
	S1	S2	S3	H1	H2	F1	F2	F3
m_{Total} (g)	64.59	52.10	52.92	56.97	85.64	74.51	54.62	74.32
$m_{polymer}$ (g)	55.55	45.20	45.56	49.93	39.49	35.06	33.94	40.53
m_{metal} (g)	9.04	6.91	7.36	7.03	45.95	39.44	20.68	33.79
$m_{packaging}$ (g)	17.12	13.37	11.80	13.35	20.03	9.86	13.16	11.44
m_{handle} (g)	25.66	18.67	26.21	33.20	19.00	15.48	16.04	25.36
m_{rest} (g)	21.81	20.07	14.91	10.42	46.61	49.16	25.42	37.52
number of parts	11	12	8	15	10	9	9	11

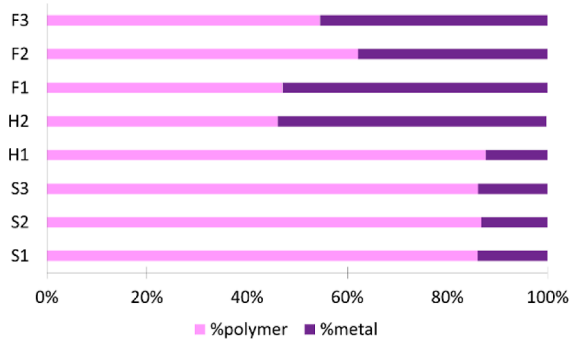

Figure 3. Percentage of polymeric and metallic materials for each accessory.

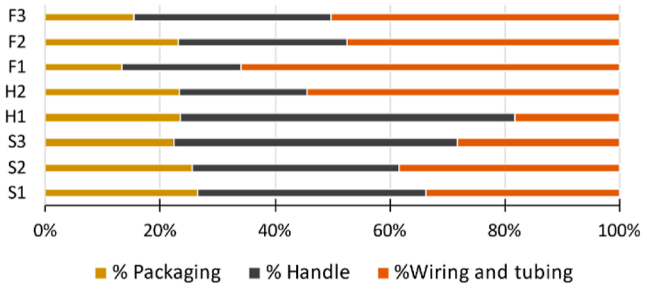

Figure 4. Percentage of packaging, handle, and wiring and tubing for each accessory.

about the composition of each polymeric sample. As an example, Figure 5 shows the datasheet for the material of the handle of the hemoclip H1. The material presented the following thermal characteristics: T_m of 214.99 °C, T_d of 427.87 °C, and no T_g. These data, when combined with the FTIR chemical profile, confirmed that the material was an acrylonitrile butadiene styrene (ABS) copolymer.

Once the characterization process of all the polymeric components of the different accessories, including packaging, was completed, the polymers were associated with polymeric families. Figure 6 shows the percentage of the polymeric

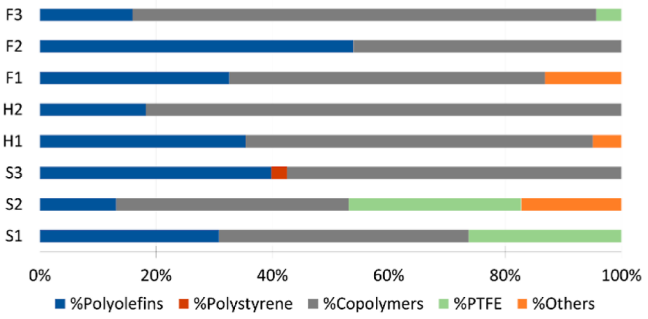

Figure 6. Percentage of polymeric families found in the analyzed accessories. Polyolefins (PE and PP), polystyrene (PS), copolymers (EVA and ABS), Teflon (PTFE), and others (PET and PDMS/Silicone).

families present in the analyzed accessories, such as polystyrene (PS) and polyolefins (PO), including polyethylene (PE) and polypropylene (PP), found in all the accessories. Copolymers such as ethylene-vinyl acetate (EVA) or acrylonitrile butadiene styrene (ABS) were also present and typically abundant in all the accessories. Some of them contained polytetrafluoro-

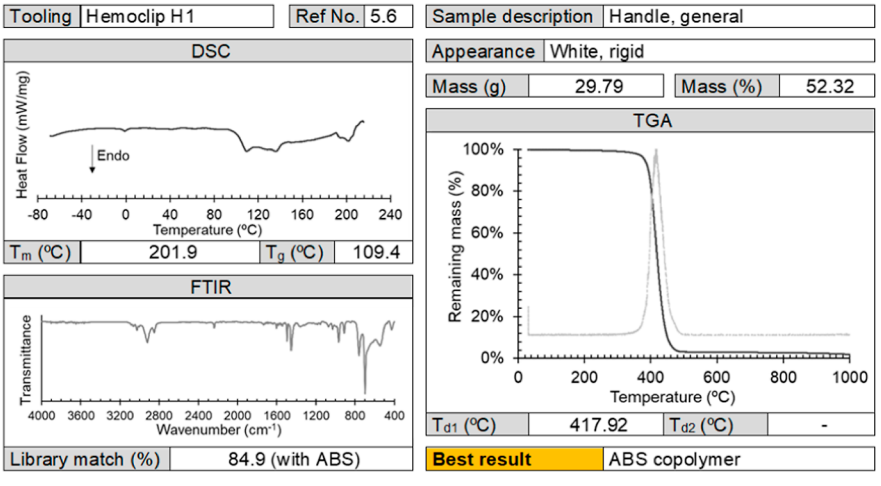

Figure 5. Example of datasheet of a polymeric material, the material of the handle of H1.

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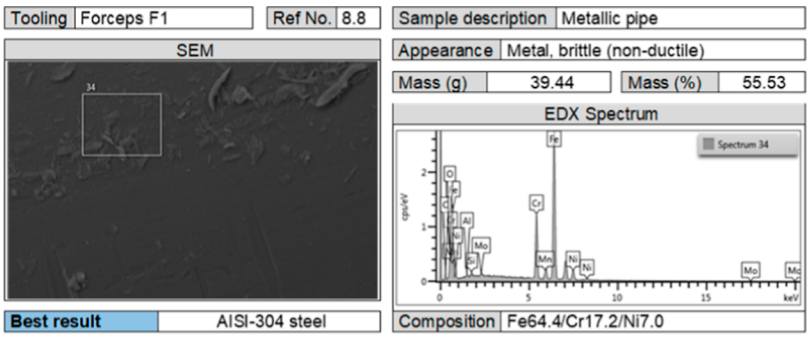

Figure 7. Example of the datasheet of a metallic material of forceps F1.

ethylene, or Teflon (PTFE). On occasion, some other polymers, such as polyethylene terephthalate (PET) or polydimethylsiloxane (PDMS), were also found in lower quantities for very specific components.

On the other hand, the techniques used to determine the composition of nonpolymeric materials were FESEM and EDX, since they are mostly metallic. Both techniques together provide information about the elemental composition of the sample, giving an atomic profile which, when analyzed, provides information to determine the nonpolymeric material nature. Figure 7 shows an example of the datasheet of the metallic pipe from forceps F1. It was obtained with the following atomic composition Fe64.4/Cr17.2/Ni7.0, most likely attributable to AISI 304 stainless steel (S.S.).

Most metal components are made of medical-grade stainless steel with different percentages of iron, chrome, and nickel. Apart from this, some nickel alloys and brass were found. Figure 8 presents the percentage of the different metallic families with respect to the metallic mass of the accessories.

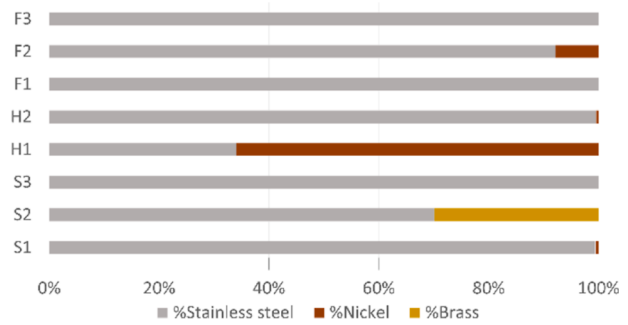

Figure 8. Percentage of the metallic families found in the analyzed accessories.

3.2. Raw Material Production Calculated from Analytical Techniques

Thanks to the combination of the classification and further characterization techniques mentioned above, the determination of all materials that compose each element becomes highly accurate. From Figure 2 can be established most of the relevant factors that are determined for further carbon footprint analysis (GWP100) such as material composition, weight, packaging, and, in some cases, end-of-life treatment. None of the carbon footprint determination studies nowadays possess this level of accuracy since they used to resort to third parties' information that may not be that accurate as the in situ analysis that we present in this work.[16,44] For instance, if we would identify the material of the handle of H1 device as LDPE from bibliography instead of ABS, as happening in some scientific publications,[45,46] its carbon footprint determination would vary around 6%. Once all determinations are completed, the outcomes can be introduced in OpenLCA software and proceeded to the carbon footprint determination.

3.3. Life Cycle Impact Assessment for Different Single-Use Endoscopic Parts

Figure 9 shows the carbon footprint of each endoscopic accessory. In detail, S1 has almost 40% more kg of CO_2eq than

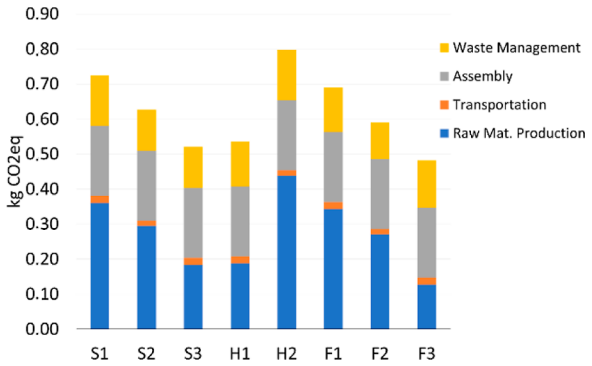

Figure 9. Carbon footprint assigned to each life cycle stage for each endoscopic accessory, obtained by an OpenLCA carbon footprint analysis.

S3, which are 0.72 and 0.52 kg CO_2eq, respectively. Regarding the forceps accessories, F1 contaminates 43% more than F3, with values of 0.69 and 0.48 kg CO_2eq. Hemoclips also present different carbon footprint values, such as 0.54 kg of CO_2eq in the case of H1 and 0.80 kg of CO_2eq for H2.

The raw material production phase is identified as the most important life cycle stage along with the waste management phase, incineration. Raw material production is responsible for 26 to 55% of the overall life cycle impact. The values of product assembly are in the range of 25−42% of the total global warming potential, which is consistent to accessories and more complex medical devices (15−18%,[40] but also to other products with several assembling steps, ∼15%[47]). Waste management's overall contribution falls between 18 and 28%. Transportation produces 0.02 kg of CO_2eq for each accessory except for S2, H2, and F2 with 0.015 kg of CO_2eq, both nearly negligible results, as compared to any of the other stages.

As for the limitations of the study, we acknowledge that the effect of the user manuals (made of paper mainly) was not considered. However, this only represents remarkable values for complex devices and equipment, being under 0.05 kg CO_2eq for easy-to-use accessories.[46] The sterilization techni-

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que has not been computed in the calculations either, but this was deliberate since it is supposed to be only meaningful in life cycle assessments of reusable medical devices.[38,45] The phase concerning the usage of the devices was intentionally disregarded (out of the boundary in Figure 1) since, as accessories, they are inherently subordinated to the use of other medical instruments (i.e., endoscopes). Even if a small fraction of this phase were attributed to every single brand and type of tooling, it would surely be distributed evenly between them, thus having a minor impact on the comparison.

Other environmental impact indicators were calculated and could have been disclosed for analysis, but we focused on the carbon footprint (GWP100) for simplicity, given the instructive, final-user orientation of the study. A sensitivity analysis to test different scenarios was not performed either, but our results and conclusions would benefit more from prospective work with detailed, surveyed data from the production phases. Finally, since we resorted to some data, which are estimations based on other sources or personal knowledge, the total carbon footprint may assume a certain uncertainty, but we think deviations from real values have been as narrowed down as possible in this case.

In the context of testing our toolkit on single-use endoscopic accessories, two main aspects arose. On one side, the carbon footprint of all devices studied is relatively high (0.48−0.80 kg CO_2eq·accessory^{-1}), representing ∼40% of the total consumables footprint for a single endoscopy[23] and especially considering that all of them are single-use and that they require an endoscope to be used, i.e., 2.1 kg additional CO_2eq·device^{-1}.[48]

Moreover, not only differences between types of accessories were significant but also between models for the same application, depending on the brand. The accessory with the highest impact was 39, 49, and 43% more contaminating than the least analyzed, for snares, hemoclips, and forceps, respectively. If this data were revealed in packages or catalogs, practitioners may decide over those accessories with a "greener" footprint, thus forcing manufacturers to refine the production lines or lobbying governments to consider the reuse of this tooling under safe and controlled conditions. For instance, in a previous study,[49] we proposed a "green mark" for the accessories (snares, hemoclips, and forceps) identifying the part of the accessories which could be recycled instead of treated as biomedical waste, as it has no contact with the patient; that intervention could save up to 27.44% of kg CO_2eq. While traditionally the carbon footprint has not been a driving factor for the design of medical devices in the industry, the differences revealed here and in other studies will likely become a pressure for competition. In this context, the toolkit developed here will contribute significantly to the cause.

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Notes

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ABBREVIATIONS

TGA, thermogravimetric analysis; DSC, differential scanning calorimetry; FTIR-ATR, Fourier-transformed infrared spectroscopy in the attenuated reflection mode; EDS, energy-dispersive X-ray spectroscopy; GHG, greenhouse gas; G.I., gastrointestinal; LCA, life cycle assessment, S1, 2, and 3, polypectomy snares 1, 2, and 3; H1 and 2, hemoclips 1 and 2; F1, 2 and 3, forceps 1, 2, and 3; FESEM, field emission scanning electron microscope; T_m, melting temperature; T_g, glass transition temperature; T_d, decomposition temperature; ABS, acrylonitrile butadiene styrene; PS, polystyrene; PO, polyolefins; PE, polyethylene; PP, polypropylene; EVA, ethylene-vinyl acetate; PTFE, polytetrafluoroethylene; PET, polyethylene terephthalate; PDMS, polydimethylsiloxane; SS, AISI 304 stainless steel; LDPE, low-density polyethylene

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