# Life Cycle Assessment of Polymer-based Artificial Organs

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***Abstract*—Life cycle assessments of various polymer products have been carried out to reduce the environmental impact in manufacturing processes. However, there are a few cases where Life Cycle Assessment (LCA) has been conducted for artificial organs. In this study, LCA was conducted on three different types of polymer-based artificial organs: the esophagus, lungs, and liver to evaluate their environment impact. The LCA results for these artificial organs were considered in three scopes: the production of raw polymers, product molding, and incineration. The environmental impact ratio in the three scopes varied based on the type of artificial organ product. In particular, the environmental impact ratio with molding the polymer hollow fibers for the artificial lung was significantly high, representing an uncommon scenario. This paper explains that to efficiently reduce the environmental impact of a product's life cycle, it is important to identify the scope and processes with the greatest environmental impact from the LCA and prioritize their improvement.**

***Keywords—Life Cycle Assessment (LCA), artificial organs, polymer, biomaterial component;***

## I. INTRODUCTION

In recent years, various medical polymer materials have been developed, leading to their increased application in medical technologies. These medical polymers are categorized based on their specific medical applications, such as medical tubing and implantable artificial organs, or extraposition medical devices [1-5]. Primarily, petroleum-based polymers used for medical treatments are produced in large quantities and are subsequently incinerated after use to prevent secondary infections [6].

Recently, from the perspective of the sustainable development goals (SDGs), reducing the environmental impact of industrial products has become important. In industries such as automobiles [7], food [8], electrical appliances [9], and construction [10], LCA methods are used to calculate the overall environmental impact, including production, use, and recycling processes, and to propose environmentally friendly products. However, surprisingly, there are not many examples of LCA being carried out on medical polymer materials [11-14].

In this study, three types of artificial organs were studied: the esophagus [15-17], lung [18-25] and liver [26-29]. As a first step, their main types and the main polymers used in them were investigated [1-5]. In addition, some carbon dioxide ($CO_2$) emission intensity values of each medical polymer were mainly investigated from available database [30-33] and a few research papers [34, 35] to calculate LCA data. We studied the methodology to compare the LCA of petroleum-based polymers such as high-density polyethylene (HDPE) with plant-based polymers such as polylactic acid (PLA). In the LCA analysis covering the three processes of raw polymer production, molding, and incineration, the carbon neutrality of plant-based biomaterials was taken into accounts [11, 12].

According to the LCA estimation in the three processes, the total $CO_2$ emission of PLA is lower in most cases than petroleum-based polymers, making it a more environmentally friendly option. However, it is worth noting that in rare cases, when the environmental burden during molding is very high, it was suggested that the heavy plant-based cellulose with a high specific gravity will have a worse LCA result for the environment than the lightweight polypropylene (PP), even including the carbon neutral effect. Therefore, the overall environmental impact of the three processes varies depending on the type of artificial organ product, and it is important to identify the most effective process for reducing the environmental impact from the LCA results and prioritize improvements.

## 2. LCA METHOD FOR POLYMER-BASED ARTIFICIAL ORGANS

Fig.1 shows representative artificial organs prepared using various polymers [1-5,15-17, 22, 24, 27-29]. First, the main artificial organs and their types were investigated from references. The abbreviations of each polymer are as follows: polyethersulfone (PES), polymethyl methacrylate (PMMA), polyacrylonitrile (PAN), polyethylene (PE), polysulfone (PSU), polytetrafluoroetylene (PTFE), polymethylpentene (PMP), polyamide (PA), polyvinyl chloride (PVC), polyvinylidene chloride (PVDC), Flexible polyurethane foam (PUF), polyvinyl alcohol (PVA), polyurethane (PU). In this study, three types of artificial organs were studied: the esophagus, lung, and liver. Then, for each type, only one artificial organ product was selected for LCA [15, 16, 20-25, 27-29]. The structure, main polymer material, dimensions, volume, specific gravity and weight of each product were investigated [1-5. 15-29, 36-43].

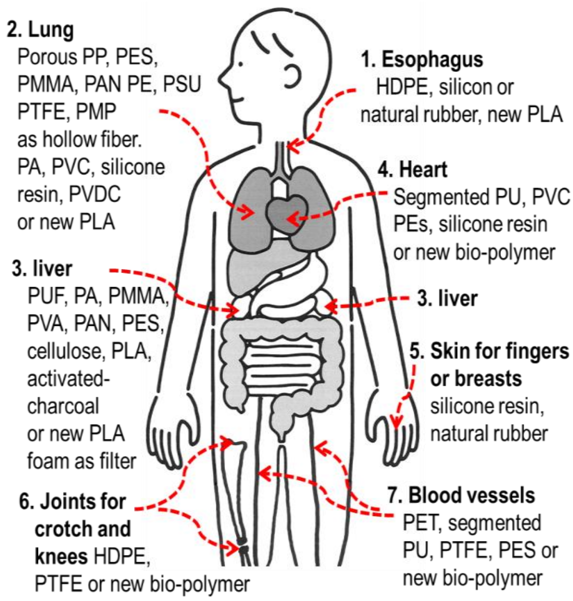


Fig.1. *Artificial organs prepared using polymers [1-5,15-17, 22, 24, 27-29].*

Next, a few petroleum-based polymer materials were selected as promising candidates for each product. General-purpose polymers derived from petroleum are inexpensive and highly durable and are widely used in artificial organs. However, plant-based -polymers are rarely used due to high cost and low durability. Bio-plant-based polymers were also considered as an alternative material that is more environmentally friendly than the petroleum-based polymers used in the target artificial organ products [5]. Furthermore, the $CO_2$ emission amount of each polymer was investigated from a commercially available database [29-32] and a few research papers [33, 34].

LCA is a technique for scientifically, quantitatively, and qualitatively assessing the overall environmental load of a product across all related processes (life cycle), from the gathering of resources for product manufacture all the way to product disposal.

Fig.2 shows the LCA scope of the artificial organs in this study [11, 12]. First, the $CO_2$ emission intensity of production in the raw material production process for each polymer was investigated. Next, the emission intensity of production in the process of molding artificial organ parts using each polymer raw material was investigated. Finally, the emission intensity of production in the process of incinerating artificial organ molded products made from each polymer material was investigated [29-34], Note that for bio-plant-based polymers, taking into accounts the carbon neutral effect, the $CO_2$ emission intensity in the incineration process was defined as zero. [11, 12].

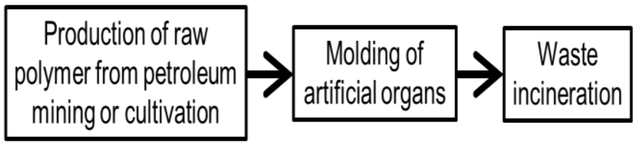


Fig.2. *Scope of LCA for artificial organs [11, 12].*

In the case of plant-based polymer, corn and wood are cultivated and harvested. Starch and cellulose are purified from these plants, and through reaction processing, they become PLA and fibers, which are used as raw materials for products. In the case of petroleum-based polymer, crude oil is extracted and refined. Naphtha is decomposed and polymerized to become PP and PE, which are used as raw materials for products.

The polymer molding product will be transported to market, used by a consumer, and disposed of as waste. Finally, the disposed polymer product will be recycled or incinerated. This is the life cycle of a polymer product which can be represented by processes shown in Fig.3

The total $CO_2$ emission per artificial organ product was calculated by multiplying the weight of each artificial organ product by the $CO_2$ emission intensity for each polymer process. The volume of each artificial organ product was defined as constant for each polymer. From these LCA results, the environmental impact of the life cycle of each artificial organ was considered.

### *2.1 Survey of artificial organs and setting scope of evaluation*

#### *2.1.1 Artificial esophagus*

This LCA was based on the artificial esophagus proposed by Osamu Ike et al. [15, 16]. This esophagus is made of silicone rubber, contains nylon mesh reinforcement, and has an outer wall covered with dried porcine collagen. This LCA only considered the base material, such as silicone rubber, which accounts for most of the weight of the artificial esophagus. The dimensions of the cylindrical artificial esophagus were defined as length 5 cm, outer diameter 2.7 cm, inner diameter 2.5 cm, and wall thickness 1 mm. Fig.4 shows the appearance of the artificial esophagus [15, 16].

Based on these dimensions, the volume of the artificial esophagus was defined as a constant 4.1 $cm^3$ regardless of the polymer material used.The polymeric materials commonly used in artificial esophagus are petroleum-based HDPE, silicone rubber, and natural rubber [1-3, 15-17]. We also envisioned plant-based PLA as an eco-material to replace HDPE in the future [5]. The LCA was performed for the cases in which each material was used in the artificial esophagus. Weight of artificial organ can be calculated from the specific gravity of each polymer. The specific gravity was defined as 0.96 for HDPE [36], 1.20 for silicone rubber [37], 0.92 for natural rubber [38], and 1.25 for PLA [39], based on references.

*Cultivation & harvesting for crops→Transport→Refining of starch, cellulose, etc.→Transport ↘
**Extraction of crude oil→Transport→Oil refining→Transport⇒ Production of polymer raw material, Granules →Transport →Molding of polymer product (using of polymer raw material) → Transport → Use & disposal of polymer product → Transport → Disposal (recycling, incineration)
Derivation from *bio plant or **petroleum.

Fig.3. *Processes for life cycle of polymer product.*

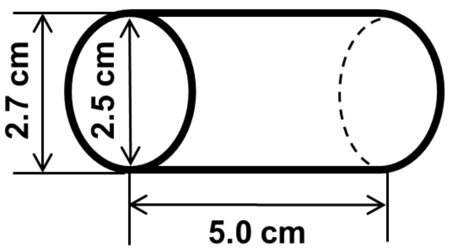


Fig.4. *Artificial esophagus [15, 16]. Drawn by author based on references.*

### *2.1.2 Artificial lung*

The Extracorporeal Membrane Oxygenation (ECMO) using hollow fibers is widely known as the main type of artificial lung. ECMO is a treatment using an extracorporeal circulation circuit that uses an artificial lung and a pump [18-20]. Most artificial lung products are made of hollow fibers with external perfusion type, which has little pressure loss. The oxygen flows inside the hollow fibers and venous blood flows outside, and oxygen is taken up into the blood by diffusion through the hollow fibers [19-24]. Fig.5 shows the appearance of the basic artificial lung that was the subject of this LCA [21, 22].

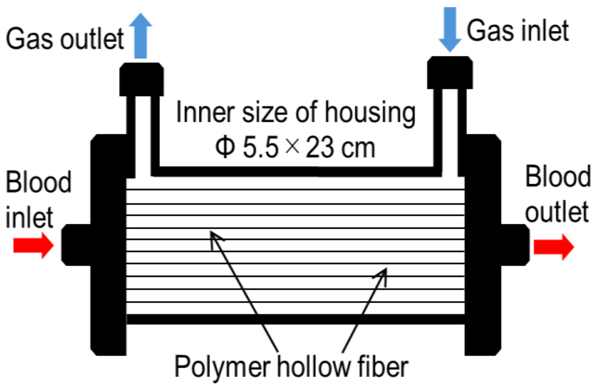


Fig.5. *Equivalent of Artificial lung [21, 22]. Drawn by author based on references.*

The artificial lung in this study was based on a Japanese patent from JMS Co Ltd. [21, 22]. In this LCA, the dimensions of one hollow fiber are defined as follows: inner diameter 200 μm, wall thickness 40 μm, length 23 cm, inner wall area 1.44 $cm^2$, and polymer volume 0.029 $mm^3$. The bundle of 13,850 hollow fibers in the holder has a total inner wall area of 2.0 $m^2$, and the total volume of the polymer material is defined as 0.40 $cm^3$ [20, 21, 23, 24]. We also assumed that plant-based PLA will be used as an eco-material for hollow fibers in the future. Polymer materials for hollow fibers used in oxygenators include petroleum-based PES, acetylcellulose, PMMA, PAN, polythene (PE), PSU, PTFE, PMP and porous PP is the most commonly using [3, 5, 22, 24]. The specific gravity was defined as 1.40 for PES [40], 0.91 for PP [41], 0.92 for cellulose [42], and 1.25 for PLA [39], based on the references.

### *2.1.3 Artificial liver*

There are few cases where artificial liver alone has saved a patient's life. Artificial livers are mostly used as a preparatory treatment before moving on to liver transplantation. Clinical trials of artificial livers using various systems are being conducted overseas. However, in Japan, although research on artificial livers is being conducted, it has not yet progressed to the clinical stage [26, 27]. The hybrid artificial liver developed by Kazumori Funatsu et al. was selected as the subject of this LCA [27-29]. Fig.6 shows the outline of the polymeric material of this artificial liver [28].

PUF is used as the base polymer of this artificial liver. A total of about 10 billion pig liver cells are filled into this foam material. Many ball-shaped micro-livers with a diameter of about 0.1 mm, composed of several hundred hepatocytes (100 g) from pig livers, are fixed in the pores of this open-cell foam polymer. The base polymer has about 640 capillary channels with a diameter of 1.5 mm through which blood flows. The total volume of this PUF is defined as 700 $cm^3$, not including the volume of the 640 blood channels. This artificial liver detoxifies harmful substances in the blood passing through it, also produces substances necessary for the body and supplies them to the blood. For patients who cannot receive liver transplants, it is hoped that an artificial liver with a blood purification function near that of the human liver will be developed [27-29].

We also anticipate using plant-based PLA as an eco-material for continuous foamed polymers in the future [44]. The apparent specific gravity of the foam material including pores was defined as 0.50 for PUF, based on references [32, 33]. The specific gravity of the foam was defined as 0.56, which is higher than that of PUF, since the specific gravity of PU is 1.12 [43] and that of PLA is 1.25 [39]. The LCA was performed on artificial livers using each polymer material.

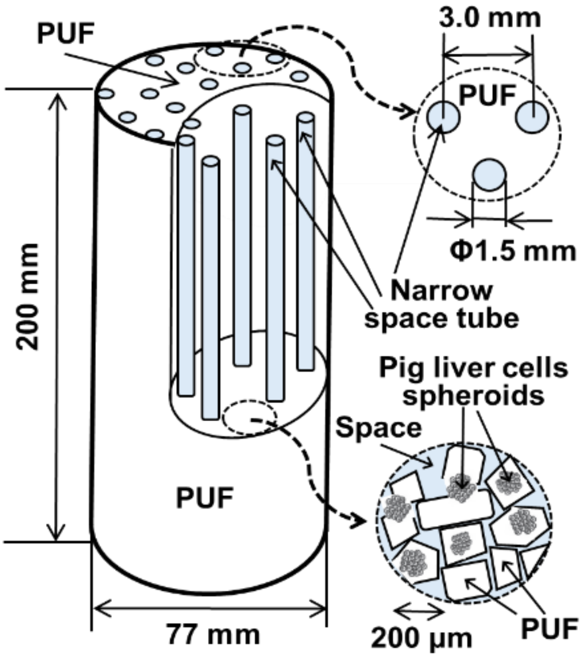


Fig.6. *Artificial liver [28]. Drawn by author based on references.*

### *2.2 Investigation and selection of polymers for artificial organs*

Table 1 shows the representative polymers derived petroleum and bio-plant-based for artificial organs and their $CO_2$ emission intensity values [1-5, 15-35].

Petroleum-based HDPE is used as a polymer for human organs in the esophagus, joints for crotch & knees, and inserts of thighbone units [1-5, 15-35]. Silicone rubber is used in the esophagus, heart, and skin of fingers and breasts [5, 15-17]. Porous PES [22, 25] and PP [3, 19, 22, 24] are petroleum-based polymers for hollow fiber membranes used in artificial lung to exchange carbon dioxide and oxygen in blood. The petroleum-based soft foamed polyurethane is being researched for use as a base material for blood purification in artificial livers. This polymer material is also used in cannulas for artificial kidneys [27-29].

Plant-based natural rubber is highly safe for the human body and has been used for artificial organs such as tubes such as the esophagus and heart, and skin [3]. Plant-based PLA is highly safe for human body, it is also used in medical materials such as dissolving sutures [1-3, 22, 24]. It is also used in drug delivery systems (DDS) [45]. Another example is its use in artificial nerves [46]. In the future, PLA is expected to be the most widely used biopolymer for various artificial organs such as the esophagus, liver, bones, and blood vessels [45]. Plant-based cellulose is being used as a hollow fiber filtration membrane in artificial lung or kidneys [1-3, 22, 24].

In addition, hollow fibers based on bio-cellulose are expected to be used as a replacement for the petroleum-based polymer PP mentioned above in artificial lung [3, 19, 22, 24]. In addition, research is also being conducted into using cellulose nanofibers in artificial organs [47].

### 2.3 *Investigation of $CO_2$ emission intensity of polymer products [11, 12, 30-35]*

The $CO_2$ emission intensity of each material was primarily taken from the Ecoinvent and GaBi databases. The emission intensity of European or German from both databases were primarily referenced, and their $CO_2$ emission intensity was averaged. However, for the productions of PLA raw materials, the average values for Europe and the United States were used.

First, we investigated the $CO_2$ emission intensities in the raw material production process for each polymer. Petroleum-based polymers are the process from oil mining to refining and polymerization reactions to the production of polymer raw materials. And biological plant-based polymers are the process from plant cultivation and harvesting to refining and polymerization reactions to the production of polymer raw materials. Most of the final products of polymer raw materials are in solid form. HDPE, PES, PP, PES, PP, and PLA products are granules for molding. However, the $CO_2$ emission intensity of PES production was not available in either database, it was taken from a research paper by Marvin Bachmann et al. [34]. Rubber products are in block form or granules [11, 12]. However, the final products of urethane raw materials are in two liquid forms: polyol and isocyanate [30, 31].

Next, we investigated the $CO_2$ emission intensity of production in the process of molding artificial organ parts using each polymer raw material. Extrusion molding and press molding are also molding methods using polymer granule raw materials. However, injection molding, which has excellent productivity, is the most widely used. In this LCA, we defined that the polymer parts of artificial organs are manufactured using injection molding. [11, 12]. Since there is no $CO_2$ emission intensity of production in the injection molding process for each polymer, we used the average value of three representative data sets in Europe: PP, PVC, and general values [30-33]. The emission intensity of molding hollow fibers such as PES and PP was referenced from a research paper by Pooja Yadav et al. [35]. This molding process involves mixing a polymer and a solvent to prepare a dope solution, and then spinning a hollow fiber membrane using a dedicated machine. The $CO_2$ emission intensity of hollow fiber molding is very high at 145 (kg-$CO_2$/kg), and the environmental impact is very large. In addition, the molding of polymer foam parts such as PUF was defined as foam molding in a metal mold using a liquid raw material [30, 31].

Finally, we investigated the $CO_2$ emission intensity of production during the incineration process of artificial organs made from each polymer material [30-

33]. Note that for bio-plant polymers, the $CO_2$ emission from the incineration process were defined as zero, is taking into the account carbon neutral effect [11, 12]. The $CO_2$ emission intensities were referenced from the Eco-Invent and GaBi databases. Whenever possible, the European or German versions of both databases were referenced, and the $CO_2$ emission per product were averaged.

TABLE 1. *$CO_2$ emission intensity of polymers derived petroleum and bio-plant for artificial organs [1-5, 15-35].*

| | Production Polymer (kg-$CO_2$/kg) | References | Molding (kg-$CO_2$/kg) | References | Incineration (kg-$CO_2$/kg) | References | Applications |
|---|---|---|---|---|---|---|---|
| **HDPE** | 1.57<br>1.35<br>**1.46** | Polyethylene production, high density, granulate, 2019, EU. [30, 31].<br>Polyethylene High Density Granulate (HDPE/PE-HD) Mix, 2019, GER.[32, 33].<br>**Mean value** | 0.935<br>3.85<br>2.23<br>**2.34** | Injection moulding, 2019, EU. [30, 31].<br>Polypropylene injection moulding part (PP), Polyvinylchloride Injection moulding part (PVC), 2019, EU.[32, 33].<br>**Mean value** | **2,92** | Treatment of waste polyethylene, open burning, 2019, world [30, 31]. | 1.Esophagus<br>5. Joints for crotch & kness /Insert of thighbone unit |
| **Silicon Rubber** | **1,46** | Synthetic rubber, 2019, EU. [30, 31]. | 0.283 | Extrusion, plastic pipes, 2019, EU. [30, 31]. | **3,16** | Treatment of waste rubber, unspecified, municipal incineration, 2019, EU. [30, 31]. | 1.Esophagus<br>4. Heart<br>6. Skin for fingers or breast |
| **PES Follow-fibes** | **13,4** | [34] | | | **2,5** | Waste treatment (plastics), 2019, GER. [32, 33] | 2. Lung |
| **PP Follow-fibes** | 1.66<br>1.67<br>**1.67** | Polypropylene production, granulate, 2019, EU. [30, 31].<br>Polypropylene granulate (PP), 2019, EU. [32, 33].<br>**Mean value** | 109<br>-181<br>**145** | Production hollow fibers using solvent [35].<br>**Mean value** | **2,46** | Treatment of waste polypropylene, open burning, 2019, world [30, 31]. | 2. Lung |
| **PUF** | 3.95<br>3.97<br>**3.96** | Toluene diisocyanate production 5.26×45% and polyol production 2.99×45%, 2019, EU. [30, 31].<br>Polyurethane (alcoholysis to polyol), 2019, GER. [32, 33].<br>**Mean value** | **0.26** | Polyurethane production, flexible foam, 2019, EU. [30, 31]. *Value of raw material including production was subtracted (4.22-3.96=0.26). | **2,26** | Treatment of waste polyurethane, open burning, 2019, world. [30, 31]. | 3. Liver |
| **PLA** | 3.29<br>2.18<br>**2.74** | Lactic acid production, 2019, EU., [30, 31].<br>Ingeo Polylactide (PLA) biopolymer production, 2019, US. [32, 33].<br>**Mean value** | 0.283<br>2.34<br>0.26 | Extrusion, plastic pipes, 2019, EU. [30, 31].<br>Injection moulding, Mean value above.<br>Same of PUF above. | | | 1.Esophagus<br>3. Liver<br>5. Joints for crotch & kness/Insert of thighbone unit<br>7. Blood vessele |
| **Natural Rubber** | 1.62<br>1.70<br>**1.66** | Seal production, 2019, GER & World, [30, 31].<br>**Mean value** | **2,34** | Injection moulding, mean value above. | **0** | **Carbon neutarl effect.** | 1.Esophagus<br>4. Heart<br>6. Skin for fingers or breasst |
| **Cellulosic Follow-fibers** | 3.15<br>3.70<br>**3.43** | Carboxymethyl cellulose production, powder, 2019, EU. & World, [30, 31].<br>**Mean value** | **145** | Production hollow fibers, mean value above | | | 2. Lung |
| **Imaginary Biopolymer (PLA) Foam** | **2,74** | PLA, mean value above. | **0,26** | Same of PUF above. | | | 3. Liver |

## 3. LCA RESULTS AND DISCUSSION

Table 2 shows the weight of the main polymeric material per product for each artificial organ and the LCA results [15, 16, 21, 22, 28]. For each organ, LCA was performed on petroleum-based and plant-based polymers and compared. In addition, for each polymer, the total $CO_2$ emission was estimated for the three processes of polymer production, molding, and incineration, and the total value was also calculated [11, 12].

### 3.1 *LCA of artificial esophagus*

Fig.7 shows the LCA results for the polymers in the artificial esophagus. First, in the polymer production process, PLA had the highest total $CO_2$ emission at 0.0141 (kg-$CO_2$/product). The values for the other materials were between 0.006 and 0.007 (kg-$CO_2$/product). Next, in the injection molding process, natural rubber had the lowest total $CO_2$ emission, at 0.00882 (kg-$CO_2$/product). This is because the specific gravity of material is low, and the weight per volume is also low. Finally, in the incineration process, HDPE had a total $CO_2$ emission of 0.0115 (kg-$CO_2$/product). In contrast, silicone rubber had a slightly higher emission of 0.0155 (kg-$CO_2$/product). As shown in Table 1, this is because when comparing this material with HDPE, the $CO_2$ emission intensity is slightly higher, and it has a higher specific gravity and is therefore heavier [36, 37].

The environmental impact of the incineration process of both petroleum-based polymers accounts for 43% to 45% of the total for the three processes. The total $CO_2$ emission values of the bio-plant-based polymers PLA and natural rubber were defined as zero, is taking into the account their carbon-neutral effect [11, 12].

It was reaffirmed that selecting materials with low specific gravity and weight is important in reducing the environmental impact in all processes. This is also possible that selecting polymers with high strength and durability and making thinner products will also reduce the environmental impact. Furthermore, as PLA currently poses a large environmental impact in the raw material production process, it is thought that research into improving production methods will be important in the future. It is due to the large amount of energy input during the many processes for PLA production, decomposition from starch, and fermentation and polymerization. Even in the molding stage, the environmental impact of PLA was greater than that of PP. In the case of PLA, this is due to the long takt time and the mold heating [11, 12].

### 3.2.1 *LCA of Artificial Lungs*

Fig.8 shows the LCA results for the polymers in the artificial lung. First, in the polymer production process, PES had the highest total $CO_2$ emission at 0.0075 (kg-$CO_2$/product). PP had the lowest $CO_2$ emission at 0.0006 (kg-$CO_2$/product), and cellulose had a value of 0.00206 (kg-$CO_2$/product). Next, in the hollow fiber molding process, cellulose had the highest total $CO_2$ emission at 0.087 (kg-$CO_2$/product), and PP had the lowest $CO_2$ emission at 0.052 (kg-$CO_2$/product.

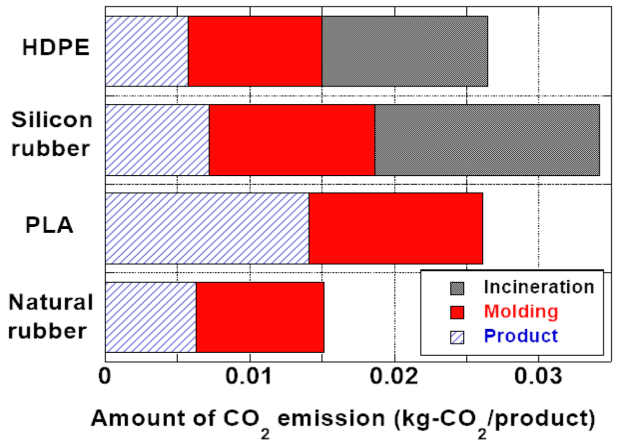


Fig.7. *LCA results of polymer artificial esophagus.*

TABLE 2. *LCA results of polymers for artificial organs derived petroleum and bio-plant [15, 16, 21, 22, 28].*

| Artificial Organs Volume ($cm^3$) | Polymer | Weight (g) | Polymer Production (kg-CO2/unit) | Molding (kg-CO2/unit) | Incineration (kg-CO2/unit) | Total (kg-CO2/unit) |
|---|---|---|---|---|---|---|
| 1.Esophagus 4.1 | HDPE | 3.94 | 0.00575 | 0.00922 | 0.0115 | 0.0265 |
| | Silicon Rubber | 4.92 | 0.00718 | 0.0115 | 0.0155 | 0.0342 |
| | PLA | 5.13 | 0.0141 | 0.012 | 0 | 0.0261 |
| | Natural Rubber | 3.77 | 0.00626 | 0.00882 | 0 | 0.0151 |
| 2. Lung 0.40 | PES Follow-fibers | 0.56 | 0.0075 | 0.0812 | 0.0014 | 0.0901 |
| | PP Follow-fibers | 0.36 | 0.0006 | 0.0522 | 0.000886 | 0.0537 |
| | Cellulosic Follow-fibers | 0.6 | 0.00206 | 0.087 | 0 | 0.0891 |
| 3. Liver 700 | Polyurethane Foam from petroleum | 35 | 0.139 | 0.0091 | 0.0791 | 0.227 |
| | Imaginary Biopolymer (PLA) Foam | 39.2 | 0.107 | 0.0102 | 0 | 0.117 |

PES had a value of 0.0812 (kg-$CO_2$/product), close to that of cellulose. This is due to the difference in specific gravity between the polymers, i.e., PP has a lower specific gravity, and the product is light in weight [40-42]. Finally, in the incineration process, the total $CO_2$ emission of PES was 0.0014 (kg-$CO_2$/product), slightly higher than that of PP. This is due to the material has a higher specific gravity and weight than PP, and that the $CO_2$ emission intensity of production is higher [40, 41]. Considering the carbon neutral effect, the total $CO_2$ emission of the biopolymer cellulose was defined as zero [11, 12].

The effect of reducing the environmental impact by improving other polymer production processes and changing to plant-based polymers is small. However, the PES polymer production process has a larger environmental impact than other polymers, it needs to be reduced. From the LCA results, the hollow fiber molding process uses a lot of organic solvents and electrical energy, the environmental impact is much larger than general-purpose injection molding [35]. Therefore, it is most important to develop a new method for forming polymer hollow fiber membranes to reduce the environmental impact. The hollow fiber membranes are used frequently because they have a small volume and a large membrane area compared to flat membranes [1, 3]. However, polymer flat membranes have a smaller environmental impact in the molding process than hollow fibers, it is important to consider expanding their use in the future. Because hollow fibers are lightweight, the proportion of the environmental impact from incineration was very small among the three processes. In the case of hollow fibers, the environmental impact in the entire process is very large for the molding process and only a small amount for the incineration process, the benefit of carbon neutrality using plant-based polymers is also low. This case of the product considered to be very rare.

3.3 *LCA of artificial liver*

Fig.9 shows the LCA results for the polymers in the artificial liver. First, in the polymer production process, the total $CO_2$ emission of PUF was high at 0.139 (kg-$CO_2$/product). In comparison, the amount of PLA was slightly lower at 0.107 (kg-$CO_2$/product). This is because, although PU is lighter than PLA, as shown in Table 1, the $CO_2$ emissions intensity of the raw polymer production process is large. Next, in the foam molding process, the total $CO_2$ emission of PUF was 0.0791 (kg-$CO_2$/product). The amount of PLA foam was slightly higher at 0.0102 (kg-$CO_2$/product). The environmental impact of this process for both is smaller than other processes. This is because PUF is a lighter and the $CO_2$ emission intensity of foam molding is smaller. In this LCA, the $CO_2$ emission intensity of PLA foam molding was defined as the same as that of PUF. On the other hand, Ricoh Co., Ltd. has also reported a foam molding technology for PLA using supercritical $CO_2$ [44], and it is conceivable that in this case the $CO_2$ emission intensity value will be a higher and the total emission will be larger. Finally, the total $CO_2$ emission of PUF in the incineration process was 0.0155 (kg-$CO_2$/product), accounting for 35% of the entire process. In consideration of the carbon neutral effect of biopolymer PLA, the total $CO_2$ emission was set to zero.

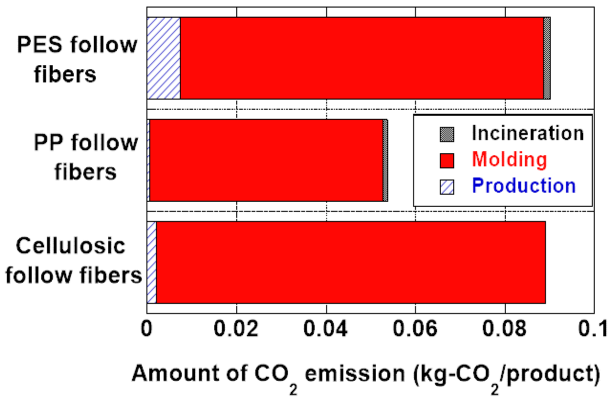


Fig.8. *LCA results of polymer artificial lung.*

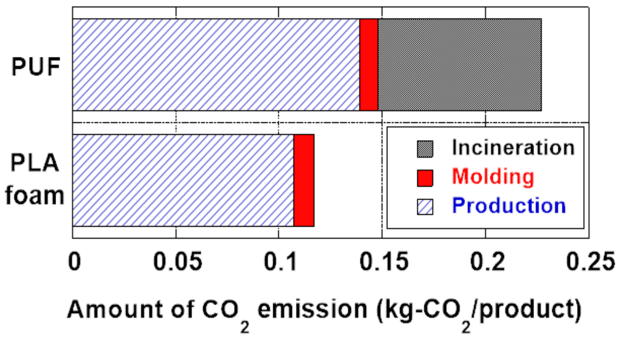


Fig.9. *LCA results of polymer artificial liver.*

## 4. CONCLUSIONS

LCA results of polymer artificial esophagus indicated that the total environmental impact of the three processes was the highest for petroleum-based silicone rubber at 0.0342 (kg-$CO_2$/product), followed by HDPE at 0.0265 (kg-$CO_2$/product). The plant-based polymers, which have a carbon-neutral effect, had a smaller environmental impact than both petroleum-based polymers. The $CO_2$ emission of PLA was 0.0261 (kg-$CO_2$/product). The value for natural rubber was the lowest at 0.0151 (kg-$CO_2$/product). For all polymers, the environmental impact of each process accounts for 20% to 60% of the total for the three processes. Therefore, it is expected that effective reductions in environmental impacts can be achieved by improving each process in the future. This LCA results of this shows that changing petroleum-based polymers to plant-based polymers or adding plant-based materials are effective methods for reducing the environmental impact in the incineration process.

LCA of polymer artificial lung indicated that the total environmental impact of the three processes was the highest for the petroleum-based PES hollow fiber at 0.0901 (kg-$CO_2$/product), followed by the bio-cellulose hollow fiber at 0.0891 (kg-$CO_2$/product). And the petroleum-based PP hollow fiber was the lowest at 0.0537 (kg-$CO_2$/product). For all polymers, the environmental impact of the hollow fiber molding process accounts for more than 90% of the total impact of the three processes. Therefore, in the future, the reduction of the environmental impact of the molding process should be the top priority for hollow fibers. The effect of reducing the environmental impact by improving other polymer production processes and changing to plant-based polymers is small. However, the PES polymer production process has a larger environmental impact than other polymers, it needs to be reduced. Because hollow fibers are lightweight, the proportion of the environmental impact from incineration was very small among the three processes.

LCA of polymer artificial liver indicated the total environmental impact of the three processes was large for petroleum-based PUF at 0.227 (kg-$CO_2$/product), and for plant-based PLA at 0.117 (kg-$CO_2$/product). In the total environmental impact of the three PUF processes, the raw material production process accounted for 61%, the incineration process for 35%, and the molding process for only 4%. In the total environmental impact of the three processes for PLA foam material, the raw material production process accounted for 91%, and the molding process accounted for only 9%. The results of this LCA show that the raw polymer production process has a large environmental impact for both polymers. Therefore, improvements in this process will be required in the future. In addition, the incineration process of petroleum-based polymers also has a large environmental impact, the development and widespread use of new plant-based polymer foam materials will be important in the future.

Depending on the type of artificial organ product, the ratio of the environmental impact of each of the three processes of polymer raw material manufacturing, product molding, and waste incineration varies. Therefore, for all polymer material products, including artificial organs, it is important to identify the most effective process for reducing the environmental impact from the LCA results and prioritize improvements.

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## REFERENCES

[1] Kimihiko Sato and Seiich Manabe, et al., “Application of Fibers to Artificial Organs”, Journal of the Textile Machinery Society of Japan, 31( 7 ), p.306-311 (1978),

[2] Eiichi Masuhara and Yoji Imai, “Organic polymer materials for artificial organs”, Journal of Medical Electronics and Bioengineering of Japan, 9 (6), p.38-43 (Dec.1971).

[3] Atsushi Takahara, “Medical Polymer Materials”, Polymer Materials Science 2008, Slides

from Takahara Laboratory, Kyushu University, Japan, accessed on 09/ 20/2024.

[4] Yoshito Ikada, "Artificial organs and polymer materials", Transactions of Japanese Society of Medical and Biological Engineering, (2), p. 15-22 (1990).

[5] "What are artificial organs?", website of Japanese society for artificial organs, https://www.jsao.org/public/what/, accessed on 09/ 20/2024.

[6] Shiv Bolan and Lokesh P Padhye et. al., "Review on distribution, fate, and management of potentially toxic elements in incinerated medical wastes", Environmental Pollution, 321(15), p.121080 (2023), https://www.sciencedirect.com/science/article/abs/pii/S0269749123000829, accessed on 09/ 20/2024.

[7] Keiichiro Sano and Keisuke Tomioka et al., "LCA study of automotive recycling: CO2 reduction by recycling of each material", Transactions of Society of Automotive Engineers of Japan, 49 (4), p. 845-848 (2016). https://www.jstage.jst.go.jp/article/jsaeronbun/49/4/49_20184470/_article/-char/ja/, accessed on 09/ 20/2024.

[8] Naoki Yoshikawa and Tomoya Matsuda, "Life cycle environmental and economic impact of a food waste recycling-farming system: a case study of organic vegetable farming in Japan". The International Journal of Life Cycle Assessment, 26, p963–976 (2021). https://doi.org/10.1007/s11367-021-01879-0, accessed on 09/ 20/2024.

[9] Anna Lewandowska and Przemysław Kurczewski et al., "Environmental Life Cycle Assessment of Refrigerator Modelled with Application of Various Electricity Mixes and Technologies", Energies, 14(17), 5350, p.1-17 (2021). https://doi.org/10.3390/en14175350, accessed on 09/ 20/2024.

[10] Yohei Endo and Hideki Takamura, "Evaluation of Life-Cycle Assessment Analysis: Application to Restoration Projects and New Construction in Alpine Climate, Japan", Sustainability, 13 (7), 3608, p.1-19 (2021). https://doi.org/10.3390/su13073608, accessed on 09/ 20/2024.

[11] Keiichiro Sano and Toru Aoki et al., "Study of life cycle assessment for medical eco-polymer materials", P3-19, Poster session 3, International Symposium on Biomedical Engineering (ISBE2023) & International Workshop on Nanodevice Technologies 2023 (IWNT2023), Satake memorial Hall, Hiroshima University (22nd Nov. 2023).

[12] Keiichiro Sano and Toru Aoki et al., "Life cycle assessment study of medical polymer materials",2023 Biomedical Engineering Joint Research Center Results Reporting Session, Poster Presentation, Tokyo Medical and Dental University (March 8, 2024).

[13] Ana Catarina Sousa, Veiga and Anabela Veiga, et al., "Assessment of the environmental impacts of medical devices: a review", Environ Dev Sustain 23, p.9641–9666 (2021). https://doi.org/10.1007/s10668-020-01086-1, accessed on 09/ 20/2024.

[14] Anna Schulte and Daniel Maga, et al., "Combining Life Cycle Assessment and Circularity Assessment to Analyze Environmental Impacts of the Medical Reproduction of Electrophysiology Catheters", Journal: Sustainability, 13 (898), P.1-22 (2021). https://www.mdpi.com/2071-1050/13/2/898, accessed on 09/ 20/2024.

[15] Osamu Ike and Yasuhiko Shimizu et al., "Experimental Studies on an Artificial Esophagus for the Purpose of Neoesophageal Epithelization Using a Collagen-Coated Silicone Tube", ASAIO Transactions 35 (3), p 226-228 (1989). https://pubmed.ncbi.nlm.nih.gov/2597450/, accessed on 09/ 20/2024.

[16] Osamu Ike and Yasuhiko Shimizu et al., "Study on collagen-coated silicone artificial esophagus for regeneration of the esophagus", The Japanese Journal of artificial organs, 18 (1), p.315-318 (1989). https://www.jstage.jst.go.jp/article/jsao1972/18/1/18_1_315/_pdf, accessed on 09/ 20/2024.

[17] Toru Ichikawa and Ken Shintani et al., "Development of mechatronic esophagus using thin straight fibers artificial muscles", Monthly journal of the Institute of Industrial Science, University of Tokyo 61 (2), p.135-138 (2009). https://www.jstage.jst.go.jp/article/seisankenkyu/61/2/61_2_135/_article/-char/ja/, accessed on 09/ 20/2024.

[18] "ECMO", website of Fujita Health University, http://fujita-accm.jp/outline/medical_guide/ecmo, accessed on 09/ 20/2024.

[19] "Artificial lung", website of Japanese society for artificial organs, https://www.jsao.org/public/what/what01/. accessed on 09/ 20/2024.

[20] "Artificial heart-lung machine", Glossary, website of Japanese Hospital, https://nippon-no-byoin.com/glossary/jnksps.html, accessed on 09/ 20/2024.

[21] JMS Co Ltd., "Hollow fiber membrane oxygenator", Japanese Patent Publication of JP4186113B2, p.1-11 (2008). https://patents.google.com/patent/JP4186113B2/en, accessed on 09/ 20/2024.

[22] JMS Co Ltd., "Blood processing equipment", Japanese Patent Publication of JP5347602B2, p.1-11 (2013). https://patents.google.com/patent/JP5347602B2/en, accessed on 09/ 20/2024.

[23] Terumo Corporation, "Artificial lung and artificial heart-lung circuit device", The World Intellectual Property Organization (WIPO), The Patent Cooperation Treaty (PCT), Patent Publication of WO2016052204A1, p.1-24 (2016). https://patents.google.com/patent/WO2016052204A1/en, accessed on 09/ 20/2024.

[24] Terumo Corporation, "Artificial lung and artificial lung/production method", The World Intellectual Property Organization (WIPO), The Patent Cooperation Treaty (PCT), Patent Publication of WO2016143752A1, p.1-59 (2016). https://patents.google.com/patent/WO2016143752A1/en, accessed on 09/ 20/2024.

[25] Lunhao Zhi and Siyu Li et al., "In-situ modified polyethersulfone oxygenation membrane with improved hemocompatibility and gas transfer efficiency". Journal of Membrane Science, 667, 121162, p.1-11, (2023). https://www.sciencedirect.com/science/article/pii/S0376738822009073?casa_token=rp4yHWjJ4ZsAAAAA:V2h8NmMweFySoF4JYSzQ5znzyZlVPCpBc0HgrLUaiLKOGEpuHH1K50Lsbjm0UXwD0zZox83fsOE, accessed on 09/ 20/2024.

[26] "Artificial liver", website of Japanese society for artificial organs, https://www.jsao.org/public/what/what04/, accessed on 09/ 20/2024.

[27] Ryoichi Sakiyama and Jyunji Fukuda, et al., "Development of hybrid artificial liver for clinical use", Journal of Japanese Society of Biorhelogy,15 (1), p. 14-25 (2001). https://www.jstage.jst.go.jp/article/jpnbr1987/15/1/15_14/_article/-char/ja/, accessed on 09/ 20/2024.

[28] Kazumori Funatsu, "Development of an artificial liver for the treatment of acute and chronic liver failure", website of the Khyushu University Museum, https://www.museum.kyushu-u.ac.jp/publications/PP/PP2002/05/05-j3.html, accessed on 09/ 20/2024.

[29] Hiroshi Mizumoto and Shunsuke Hayashi, et al., "Evaluation of a Hybrid Artificial Liver Module Based on a Spheroid Culture System of Embryonic Stem Cell-Derived Hepatic Cells", Cell Transplantation, 21, Issue 2-3, P.421-428 (2021). https://journals.sagepub.com/doi/full/10.3727/096368911X605321, accessed on 09/ 20/2024.

[30] Website of the ecoinvent database. https://ecoinvent.org/database/, accessed on 09/ 20/2024.

[31] ecoinvent 3.5, website of openLCA, https://www.openlca.org/ecoinvent-3-5/, accessed on 09/ 20/2024.

[32] LCA For Experts (formerly GaBi), website of shera, https://sphera.com/solutions/product-stewardship/life-cycle-assessment-software-and-data/lca-for-experts/, accessed on 09/ 20/2024.

[33] Sphera (GaBi), website of LCA Software, https://lca-software.org/sphera-gabi/, accessed on 09/ 20/2024.

[34] Marvin Bachmann and Annika Marxen, et al., "High performance, but low cost and environmental impact? Integrated techno-economic and life cycle assessment of polyoxazolidinone as a novel high-performance polymer", Green Chemistry, 24, p.9143-9156 (2022). https://pubs.rsc.org/en/content/articlehtml/2022/gc/d2gc02400d, accessed on 09/ 20/2024.

[35] Pooja Yadav and Norafiqah Ismail et al., "Assessment of the environmental impact of polymeric membrane/production", Journal of Membrane Science 622, 118987, p.1-8 (2021). https://www.diva-portal.org/smash/get/diva2:1515678/FULLTEXT01.pdf, accessed on 09/ 20/2024.

[36] High density polyethylene HDPE, Plastic Material: Density & Specific Gravity, website of Ji-Horng Plastic Co., Ltd. https://www.ji-horng.com/plastic-material-density-specific-gravity, accessed on 09/ 20/2024.

[37] Silicone rubber, website of Primasil Silicones, https://www.primasil.com/materials/general-purpose-silicone/, accessed on 09/ 20/2024.

[38] Natural rubber, website of Astlett Rubber Inc., https://astlettrubber.com/nr/index.html, accessed on 09/ 20/2024.

[39] Polylactide PLA, website of chemical Book, https://www.chemicalbook.com/ChemicalProductProperty_JP_CB2343615.htm, accessed on 09/ 20/2024.

[40] Polyethersulfone PES, website of Swicofil, https://www.swicofil.com/commerce/products/polyethersulfone/318/properties, accessed on 09/ 20/2024.

[41] Polypropylene PP, Polyolefins, website of PLASTICS EUROPE, https://plasticseurope.org/plastics-explained/a-large-family/polyolefins/#:~:text=PP%20(polypropylene)%3A%20The%20density,resistance%2C%20but%20less%20chemical%20resistance, accessed on 09/ 20/2024.

[42] Cellulose, website of PubChem, https://pubchem.ncbi.nlm.nih.gov/compound/Cellulose, accessed on 09/ 20/2024.

[43] Polyuretne PU (thermoplastic), Teknor Apex Laripur® LPR 8860EG, website of MatWeb, https://www.matweb.com/search/datasheet.aspx?matguid=5271f09a53834ddeaabe49d7dccd2371, accessed on 09/ 20/2024.

[44] "PLAiR – A New Material Made from Plants and Air", website of Ricoh Co., Ltd., https://www.ricoh.com/technology/tech/091_PLAiR, accessed on 09/ 20/2024.

[45] Yuichi Ohya, "Current status and new developments in biodegradable polymers", The Japanese Journal of Artificial Organs, 28(3), p. 582-

589 (1999). https://www.jstage.jst.go.jp/article/jsao1972/28/3/28_3_582/_article/-char/ja/, accessed on 09/ 20/2024.

[46] akuya Yokoi and Takuya Umemura et al., "Artificial organs: Peripheral nerve regeneration using hybrid artificial nerves and their application to adhesion prevention materials", The Japanese Journal of Artificial Organs, 47(3), p.185-188 (2018). https://www.jstage.jst.go.jp/article/jsao/47/3/47_185/_article/-char/ja/, accessed on 09/ 20/2024.

[47] Yuuki HATA, Takeshi SERIZAWA, "Application research of nanocellulose to artificial organs", 48 (3), p.182-185 (2019), The Japanese Journal of Artificial Organs, https://www.jstage.jst.go.jp/article/jsao/48/3/48_182/_article/-char/ja/, accessed on 09/ 20/2024.