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# Life Cycle Analysis (LCA) of Biorobotics: A Comprehensive Review on Environmental Impact and Sustainability

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**Abstract:** To the best of our knowledge, there is no comprehensive review on the environment and sustainability of biorobotics concerning the application of Life Cycle Analysis (LCA) to the life cycle and environmental impacts of biorobotic systems. This article has therefore reviewed and discussed the environmental impact and sustainability of bio-robotics applications. Sustainable issues in biorobotics, the combination of biological and mechanical, and electronic subsystems, create special opportunities and problems. The concept of LCA leverages an opportunity to evaluate the entire life cycle of a biorobot that includes the minerals extraction and manufacturing process, coupled with its operation, with end-of-life (EOL) disposal. Major considerations of the review entail the use of sustainable materials, energy consumption in the production process, and energy consumption and efficiency of the operation phase, as well as EOL management. A particular concern is paid to the intricacies of biological systems, data scarcity, and the necessity to use standardised LCA frameworks that would be specific to biorobots. In addition, the article reviews the future trends, such as data modelling, material development, and the strategy of a circular economy that can be implemented to enhance the sustainability of biorobots. The results provide support to the suggestion that LCA should be used in developing the biorobots in an approachable manner that is compatible with the sustainability objectives and reduces the amount of their environmental burden.

**Keywords:** Life Cycle Analysis (LCA); Sustainability; Biohybrids; Environmental Impact; Circular Economy; Sustainable Manufacturing

## 1. Introduction

Biorobotics is an interdisciplinary field that applies knowledge from the areas of biology, engineering, and robotics to develop systems that interact with or otherwise emulate biological organisms [1]. Such systems are sometimes called biorobots and are formed by combining biological tissues or organisms with mechanical or electronic parts to accomplish functionality that could not be accomplished by using either biological or mechanical systems alone. Biorobotics aims at coming up with robots that can effectively conduct tasks in complex but unstructured environments, and, at the same time, remain adaptable, efficient, and sustainable. Biorobotics applications are numerous, among them prosthetics, exoskeletons, surgical robots, and environmental monitors. The flexibility of the biorobotic system has triggered an opportunity in the fields of healthcare and agriculture, defence, in addition to the space exploration industries [2,3].

With the ongoing increases in technological solutions in the fields of materials science, bioscience engineering, and robotics, biorobots are increasingly savvy and able to easily combine both biology and mechanics. As an example, in order to create bio-hybrid actuators (based on muscle tissue, or neurons, etc.), the robot can be made to move in a lifelike manner and also make decisions like humans do. Equally, an advancing issue is the usage of biological layouts that tend to soft robotics, that is able to provide more flexible, adaptive, and convenient robots. The high rate of advancement in these technologies, however, comes with a serious challenge, especially regarding how sustainable and less environmentally taxing they can be. The issue of sustainability has been one of the key factors in the evolution of the current technologies, even in such spheres as robotics. Sustainability in biorobotics is the development of systems that not only work and perform efficiently but are also environmentally friendly. The environmental awareness of the problematic nature of the traditional robotic systems surrounding diminishing resources, using energy, and creating waste stresses the necessity of biorobots, which are less harmful to the environment. Moreover, biorobotics can help us in dealing with the issue of global sustainability due to bio-inspired designs that mimic the efficiency of biological organisms [4,5].

To make a real profit from these potential advantages, it is necessary to take into account the environmental effects of the biorobotic system throughout its life [6]. Whether that be through material selection and production, use, end-of-life recycling, or maintenance, there exist possibilities in every step of a biorobot's life to make decisions that will limit environmental degradation. In addition, biological elements introduced into the robotic systems, despite being innovative, introduce their challenges. The biorobot's biological parts can give rise to new issues regarding biodegradability, bio-compatibility, and waste utilization. Consequently, the creation of sustainable biorobots needs an integrated development that incorporates prudent planning, material selection, energy conservation and waste reduction schemes. This review aims to study the role of the analysis of the environmental impact of the biorobotic systems of the Life Cycle Analysis (LCA). LCA is a thorough tool applied in the evaluation of the environmental impact of a product or system after the product has been produced from raw materials extraction, manufacturing, operation, and disposal. Using LCA on biorobotics, researchers and engineers will have a good idea of how sustainable biorobots are and where improvements are possible, and on which fronts future designs should be based [7]. LCA could contribute to quantifying the environmental effects of the different stages of the life cycle of a biorobot, as well as the consumption of resources, the use of energy, the generation of wastes and emissions. Due to the complexity of biorobotic systems as such (a combination of the use of both biological and mechanical parts), LCA offers a set of new challenges and opportunities. The traditional robotic systems, which consist largely of synthetic materials, can be evaluated through agreed LCA techniques. Analysis of the incorporation of living tissues, cells, or biohybrids complicates, however, such systems should be discussed through the prism of biological processes, biodegradability, and biological safety. The goal of the review paper is to present an overview of current LCA applications to the issue of biorobots, elicit major challenges in this field, and explore how LCA methodologies can be developed and improved to be better applicable to the biorobotic systems [8].

Besides reviewing the existing LCA frameworks, this review will also review the environmental life cycle of biorobotic systems. The effects that the material selection process, energy use in production, and the business running of biorobots on the environment will be addressed. Additionally, the issues and the prospects dealing with the end-of-life (EOL) part of biorobots that touch on the subject matter of recycling, disposal, and biodegradability will be examined. The role of biorobots in a more sustainable future, such as minimising environmental damage with the help of efficient design, bio-inspired systems, and circular economy regulations, will be identified as a key target. This review has given a broad description of LCA where it has been applied to biorobotics, and thus will form a basis of additional study into the area of sustainability in designing biorobots. The conclusions that can be obtained using the insights provided by this review are aimed at helping researchers, engineers, and policymakers come up with a strategy to create environmentally responsible biorobots. The final aim is to see sustainability aspects incorporated in design, manufacture, and lifecycle of biorobots whereby the systems have a positive contribution towards the future of technology and the environment [9].

This paper has five major parts. The following section is a review of the Life Cycle Analysis (LCA) methodology and its steps involved, including the four stages and the most relevant indicators applied to the analysis of the environmental impacts. Based on this, the paper will then evaluate the use of LCA in the area of biorobotics, looking at existing frameworks and the specific issues raised by the use of biological parts. The third chapter deals with the environmental consequences of biorobots, specifically such aspects as material use, production process, and the use of energy in running. The fourth section treats the end-of-life (EOL) phase of biorobots that raises issues of disposal, recycling, and the circular economy. Then, the article finishes with conclusions in which the major issues related to the application of LCA to biorobotics are summarized, and the way forward is suggested for research and innovation endorsing sustainable bio-robotics design [10].

## 2. Life Cycle Analysis (LCA): Framework and Methodologies

### 2.1 Overview

Life cycle analysis (LCA) refers to a method followed to assess all the environmental effects of every phase in the life cycle of a product or system. It aims to measure the overall environmental load from cradle to grave when including all stages of extraction of raw material, production, transport, use, and end-of-life disposal or recycle process. LCA methodology is especially useful since it provides a thorough evaluation of the sustainability of the given product beyond the production stage, in terms of the raw materials that have been used during the process, the amount of energy consumed, the quality of the emissions and the number and type of waste materials at every level. Such an inclusive methodology is critical in ascertaining the actual environmental factor of a product, especially in a world where people are more focused on environmental advances and sustainability objectives. LCA usually consists of four different phases, which enable the researchers to view the environmental effects of a product or a system and interpret them correctly [11].

Goal definition and scope are the first step. This step determines the scope of LCA, i.e., what it is intended to achieve, including assessing the environmental impact of a product, comparing the alternatives, or knowing the places where improvement is possible in terms of sustainability. The goal also defines the functional unit, upon which comparison is made, which in the case of biorobotic prosthetic could be, e.g., "the ability to help walk 5 years." The scope is a limit of the analysis, which processes should be covered, and which system components should be under evaluation. It also makes sure that the system that will be analyzed can be well defined, and the LCA process can then take place in a clear-cut manner [12].

The second is Inventory Analysis, better known as Life Cycle Inventory (LCI). During this stage, all the inputs and outputs, which accompany the life cycle of the system, are measured. This comes in the form of identification and quantification of the raw material used in the production process, energy requirements at different stages, emissions, and the production of wastes. An objective is to make an elaborate listing of all inputs and outputs relating to the product life cycle. In the case of a biorobotic system, one would consider the resources that went into the manufacturing process, e.g., the metals, polymers, and biological media such as muscle cells or tissue cultures, as well as energy that was consumed during the manufacturing and operational processes. The second step is called the Impact Assessment step: it includes the assessment of possible environmental impacts of the resources used and emissions that were identified in the inventory analysis. Data tabulated in LCI is split into categories of impact, which include global warming potential (GWP), ozone depletion, impacts on human health and water and air pollution, as well as resource depletion. As an example, a biorobotic prosthesis may have an impact assessment based on the production of materials used in the prosthetic and their contribution to carbon emissions or simply the toxicity and effect on the user when the biorobotic materials degrade or are discarded [13].

The last stage is the Interpretation, where the results of the LCI, as well as the impact assessment, are discussed and applied to practical knowledge. This step assists in establishing some of the main areas in which environmental impact may be minimised or eliminated. Interpretation also involves assessing the reliability of the information and use of sensitivity analysis to assess how the findings can be impacted when there is varying input data. It could also include the act of drawing suggestions that are meant to redesign or change production processes to increase sustainability.

## 2.2 Challenges in Applying LCA to Biorobotics

There are some special issues in the application of LCA to biorobotics because of the combination of traditional mechanical and electronic components and biological parts [14]. Nevertheless, the original LCA techniques have already been successfully used in systems containing solely synthetic materials and mechanical structures, but biorobotics (feasible in tours containing biological tissues and biohybrids) needs a different approach to adequately evaluate the environmental consequences. The main issue in the use of LCA in the biorobotics field is that the biohybrid is complex. Biorobots are usually combinations of biological parts (muscles, cells or even alive organisms) with mechanical devices (motors, actuators and others). These biohybrids could grow, self-repair, or naturally degrade; thus, it is hard to have as much certainty about the life cycle of these biohybrid systems as it is about fully synthetic systems. Biological systems are dynamic, and they undergo changes in the long run and therefore, assessing the behaviour of a biological system is difficult in the long run. A more sustainable result can be achieved or repaired, but rather challenging to model in LCA models traditionally concerned with inert, non-living materials [15].

The other issue is that the biological systems are variable. Biological components do not act in a homogenous fashion, since they are influenced by a wide variety of factors, including environmental conditions, nutrition, and health of biological material. e.g., as in the rate of growth of cultured muscle cells employed in biorobots, this might vary with temperature, moisture, and the make-up of the growing medium. This non-consistency hinders the standardisation of data, resulting in the high uncertainty of LCA outputs. As opposed to synthetic materials, biological systems tend to exhibit variances in performance across a set of conditions, making the accurate assessment of the impacts even more problematic [16].

Moreover, the limited amount of data poses a considerable barrier to LCA application in biorobotics. In the case of traditional robotics, there are well-defined material and environmental impact data available to LCA practitioners on materials such as metals, plastics, and even electronic components. The information that can be seen of biological parts, like the environmental effect of creating muscle tissue or other biological cells, is, however, scarce. Less is known and documented about the environmental impact of the production and maintenance of biological components during the life cycle of those components, along with the energy and material inputs. This inability to provide data complicates the possibility of performing a comprehensive LCA of biorobotic systems. Also, the biorobotic end-of-life (EOL) poses specific challenges. Retirement of the typical robotics device, the end-of-life (EOL) stage in the traditional robotics industry is usually recycling or disposing of electronic parts and metals, where there are systems and rules that have been created. But the end-of-life of biorobots, possibly with biodegradable biological materials or biohybrids, is more complicated. Biodegradation may deforest, or expend energy in natural environments, and produce emissions, although biological constituents may, after the process of biodegradation. Furthermore, not all of the biological substances are easily compostable or broken down in a manner safe to the environment, and special attention should be paid to the process of disposal and the effects it has [17].

### 2.3 Existing LCA Methodologies in Robotics and Their Applicability to Bio robotics

LCA has gained extensive use with regard to traditional robotics, these practices must be adapted so as to accommodate the distinctive nature of biorobotic systems. The existing frameworks of LCA applied in the context of robotics are usually concerned with the effects of the manufacturing processes on the environment, battery choice, and energy consumption. To illustrate, research findings have demonstrated that the biggest environmental influence in conventional robotics is in the manufacturing of metals, plastic substances, and the energy-demanding manufacturing procedures incurred in the generation of robotic parts. These models and frameworks usually assume a strict separation of components and materials, which is not possible in the case of biological ones. In the case of biorobotics, the time-tested LCA frameworks will have to be modified with respect to the growing, living, and self-healing properties of living and biological parts. Although some advancements have been achieved in changing LCA approaches to biohybrids (e.g., including information about the cultivation of biological cells or tissues and corresponding with their degradation with time), LCA practices are not fully developed yet. More research is being done to tighten these models and even incorporate them more with the available LCA model employed in conventional robotics [18,19,20].

Further interest had developed in the use of sustainability models based on biological systems, e.g., in bio-inspired robotics, where the aim is to achieve resource efficiency and sustainability in the natural world. Other researchers have focused on how natural principles like the utilization of massless material or the optimization of energy consumption would apply to the creation of robotic systems. Nevertheless, these bioinspired strategies have not yet taken into account the bio-distinct lifecycle implications of biomaterials and assimilation into an artificially made framework. Further development in this field will probably entail additional assimilation of LCA appraisals, which will involve biological lifecycle features and integration of the complexity of biohybrid systems as far as robotics is concerned.

Consequently, novel and specific LCA frameworks applicable to biorobotics are required that would be able to compensate for the environmental effects of biological parts in full and consider the variability and dynamics of biological systems, as well as to merge them with the more traditional parts of robotics. With the aid of such structures, the sustainable development of biorobots can be given much better guidance, and the effect these robots can have on the environment can be evaluated more accurately and in more detail.

To summarize, LCA has become an effective solution when it comes to the assessment of the ecological soundness of the biorobotic systems; nonetheless, implementing it in biorobotics has also brought along a variety of difficulties. As well as their connections with the biological aspect, the differing nature and uncertainty of biological systems, the fact that there is less data available, and the complexity surrounding end-of-life issues, among many other factors, all complicate analysis of LCA in the case of biorobotics compared to standard robotic systems. As the research in this direction evolves, we must clarify and modify the methodologies of LCA in an attempt to include these biological considerations so that we can achieve more sustainable and environmentally friendly uses of biorobots [21].

## 3. Environmental Impact of Biorobots: Material Use, Manufacturing, and Operation

### 3.1 Materials and Sustainability

The choice of materials is actually the key component to any robotic system, as well as sustainability, but in the scenario of a biorobot, it is of even more value, as it incorporates biological parts as well as manmade materials. The type of material has a direct effect on the environmental impact at different phases of product life, such as during production, use, and disposal. In the case of biorobots, sustainable material choices include taking into account the environmental impact of materials, where the impacts are analyzed as the extraction of the resources, manufacturing procedures, and the decommissioning process. The main materials of traditional robotics can be regarded as metals, plastics, and electronics that all have significant environmental impacts because their production requires a lot of energy and irreversible extraction of resources. On the contrary, biorobotics aims at lessening this effect and thus using bio-based materials and biodegradable materials.

Bio-based materials refer to forms of materials that are obtained using renewable biological sources, which include: cellulose, bio-based materials and plant fibres. The materials are far less environmentally demanding as compared to their counterparts, which are the usual petroleum-based plastics. To give an example, polylactic acid (PLA), as a biodegradable polymer originating in corn starch or sugarcane, is commonly used in sustainable robotics and has been suggested to be used in biorobots. Such bio-based materials as PLA and others decrease the dependence on fossil fuels and can be recycled by natural means minimizing long-term waste deposition [22].

In contrast, biodegradable materials are developed in such a way that they break down into non-toxic materials with the passage of time, and this aspect supports a better reduction of complicated processes involved in recycling, and also the resulting waste is minimized. Biorobots, in particular external parts, made of bio-degradable materials, may be a required attribute in minimizing the ecological cost at the end-of-life stage of the biorobot. Recent innovations of materials such as bio-based composites, hydrogel-based material, etc., are just a few examples of biodegradable versions that have also been actively explored with regard to use in robotics. Nevertheless, there are a couple of trade-offs related to the environmental benefits of these materials. Although biopolymers would provide a less petrochemical-intensive dependency, there is a possibility that they might need a considerable agricultural contribution and demand water and energy as well. Also, the bio-based production has the potential to cause land-use change, which can cause an unforeseen environmental impact, including habitat loss or greenhouse gas emissions. Moreover, the biological part of biorobots may lead to problems in their biodegradation whenever the design and use are close. Components such as biodegradable ones may fall in the category of being worn out extremely fast in operation or underperforming [23].

Another level of complexity is due to the integration of a biological tissue (muscle cells, neurons, or plant cells in the case of actuators in the biorobots). When incorporated as an actuator or energy source, these biological materials have the advantage of being readily self-repaired and adaptable, as would be the case in nature when using natural biological processes. Nevertheless, they could bring some difficulties connected with production (cultivation), their ethical origin, and sustainability. Thus, to ensure sustainability, it is extremely important to design biorobots using an optimal combination of artificial and organic components [24].

### 3.2 Energy Use in Manufacturing

The energy required in the manufacturing of biorobotic systems is very important in defining the effects of such systems on the environment. In conventional robotics, collision occurs mostly in the process of metals (e.g., aluminium, steel), and plastics extracting, treating, and manufacturing that require huge volumes of energy. The changes in materials used, however, create dynamic shifts in the manufacturing procedures as a result of the addition of the biological component in the biorobots [25].

The energy that is used to manufacture biorobots may be divided into several steps:

**Energy costs associated with the extraction and processing of raw materials:** In the case that the biorobots have bio-based materials, the energy cost incurred in the production of these materials is less compared to traditional metals and plastics. But where biological materials are grown or harvested, e.g., plant fibre or cultured cells, the energy-demanding aspect depends on the production scale of the grown or harvested materials. To give an example, the tissue engineering processes (e.g., muscle cells grown in culture) entail controlled conditions, replenishment of nutrients, and temperature control, which all use energy [26].

**Fabrication of Biological Parts:** Efforts on the fabrication of biological parts, bio cultured cells, or biohybrid actuators may require large amounts of energy. As an example, the growth of muscle tissue or keeping biological systems under control in bioreactors has to be well-monitored, controlled, and fed with nutrients. This manufacturing is usually energy-intensive when compared with classical methods of synthetic material manufacturing, like injection moulding or 3D printing [27].

**Combination of synthetic with biological materials:** We encounter further problems when we combine biological elements with mechanical ones. These hybrid systems might need special processing, fine manufacturing plans, and sterilization procedures that devour energy. Bio-hybrid systems will need special techniques and technologies to combine living biological systems with synthetic electronics (e.g., sensors, processors, actuators), and these techniques and technologies can take up to the same amount of energy as it does to produce traditional robots. Although this is a challenge, innovations in green manufacturing methods are becoming a reality in order to save power used in the manufacture of biorobots. An example is three-dimensional bio printing that has the potential to create a biologically active printed product, such as biological tissues, using a layered approach with control of structure and material application, potentially minimizing waste and energy usage. Also, scientists are investigating bio-manufacturing, where materials are produced by biological organisms or mechanisms, as a potentially low-energy alternative to currently made synthetic materials. Rather than degrading its concerns about sustainability, biorobot development must focus on energy-efficient manufacturing procedures. The attempts to optimise the usage of energy when producing biohybrids, e.g., by providing the tissue culturing with optimal conditions or using energy-efficient processes in manufacturing centres, will be necessary to ensure these all-positive effects on the environment [28].

### 3.3 Operational Energy Efficiency

As soon as a biorobot is produced, the energy used in the course of its functioning becomes a decisive factor in the total environmental impact. To be sustainable, biorobots, more so those that are long-term or continuous, must be energy efficient. An example is that of a biorobotic prosthetic limb, a robot intended to be used in the medical field, or an agricultural robot, which will require that it must be able to work reliably over long periods, and with a minimal amount of energy utilized. The efficiency of the energy used in the operation of biorobots is also a factor of the design of the robotic system and how it is combined with the biological ones. As an illustration, biohybrid actuators constructed of living tissue or cells boast the benefit of relying upon biological phenomena of motion, which may need less energy input than their more conventional counterparts, their motors and actuators. Biochemical processes that can generate power are present in biological systems (e.g. ATP hydrolysis) and are very efficient within biological organisms. Such biohybrid systems can also substantially ease the total energy requirement of the biorobots with respect to traditional robots with only electrical or mechanical actuators [29].

Bio-inspired energy harvesting is another way of mitigating operational energy efficiency in biorobots. Living things have developed ways to extract energy from the surrounding environment, and through the mechanisms they use, biorobots can become more energy efficient. As another example, piezoelectric materials (which produce electricity as they undergo mechanical deformation) could also be used to produce energy in the biorobots as they move, or could use external forces to obtain energy. Also, showing that biorobots used outdoors (e.g. agricultural robots, environmental monitoring systems, etc.) can have their power topped off or even fully charged via solar panels.

Moreover, the scientists are examining the possibility of a bioelectronic system which enables biorobots to classify biochemical energy into electrical energy, as biological organisms, as well as muscles in them, produce motor power. The usage of biological sources of power in robotic systems will make these machines more energy-efficient to operate, and, by extension, increase the amount of time that the machine will survive without the necessity to be recharged regularly.

Regardless of these developments, the trade-off between the effectiveness of biological components and the performance of the entire system is one of the issues. Although biohybrids may have the potential to lower energy requirements, their power may not be adequate to support the demands of more compartmentalized or high-achieving robotic structures. Thus, there is a need to optimize the energy usage in both living and mechanical systems in such a way that would not sacrifice the performance of the biorobot but would make it operationally efficient. Finally, operational energy efficiency is of biorobots an important element of environmental sustainability. It is in principle possible that biorobots consume less energy than traditional robotic systems, as the approach integrates bio-inspired actuators and bioenergy harvesting, as well as energy-efficient designs. With further research, breakthroughs in biohybrid technologies and energy capture processes will significantly contribute to enhancing the sustainability of biorobots in a range of undertakings.

In short, the environmental impact of biorobots depends on several factors, such as the materials, energy consumed in the bid to create it, and the efficiency with which the biorobot operates. One way to minimize the ecological footprint of biorobots is through sustainable choices of materials used to construct biorobots, including using bio-based materials as well as materials that are biodegradable. Also, projects on energy optimization at the manufacturing and operations level, by efficient production processes and bio-inspired energy extraction technologies, will play a role in the sustainability of biorobotic systems in the long run. With the further advance of technology, it would be more and more practical to create with the help of biorobots, energy-efficient technologies that have little effect on the environment [30,31].

## 4. End-of-Life (EOL) and Circular Economy in Biorobotics

### 4.1 Disposal and Recycling

The End-of-Life (EOL) segment of a product life cycle is that point in time when the product becomes no longer used and can be disposed of, recycled/or repurposed. In conventional robotic systems, EOL takes into account such practices as recycling of materials such as metals, plastic, and electronics. These processes, however, are complicated by the activities of biological components inside biorobots since biological components are easily degraded in a special environment with different ways of degrading biological material into synthetic ones. It is quite important to address these issues already during the EOL phase so that the biorobots can be properly disposed of or recycled in a responsible way to limit the impact on the environment.

A major issue of the EOL of biorobots is the biodegradability of biological components. Biorobots can utilize biological materials, e.g., muscle cells, plant tissues, or cultured organisms, which over a period of time may break down due to natural processes. Although this biodegradability may be beneficial in more ways because it reduces waste and pilling of the waste in the landfills, it creates some difficulties in controlled biodegradation. It is possible that the biological materials will be destroyed in unpredictable ways that are almost impossible to overcome in comparison to the synthetic materials, which can just take a long period to be destroyed and can be recycled or given another alternative. As an example, biohybrid elements of a biorobot or muscle tissue might disintegrate rapidly in the surroundings and cause the emission of organic junk, which may be toxic or challenging to prevent.

The problem of recycling is more evident, especially in focusing on hybrid systems, which consist of both synthetic and biological elements. Conventional recycling techniques that usually have the ability to deal with metals, plastic, and electronics cannot recycle biological elements. As a case in point, removing the useful components, such as the metals, out of the biorobot, and at the same time maintaining the biotic sections neatly, poses a big challenge. Further, the biological elements incorporated can equally make the process of disassembly hard. A bio robot can be very expensive to have the biological materials managed in special facilities to dispose of it, but a robot made of metals and plastics can be processed relatively easily in normal recycling locations. The other worthy factor is the hazardous or toxic consequences of some biological elements at the expiration of their existence. Take an example, biorobots are products of engineered tissue/cells which have the potential of environmental and health hazards in case they carry toxic substances due to degradation. Additional studies should be done on the need to provide biological materials used in the robotics field with characteristics that they are non-toxic, readily biodegradable, and do not emit toxins as they degrade. Guidelines and standards of EOL management need to be created, which would take into consideration the peculiarities of the properties of biological components incorporated into biorobots [32,33].

The waste management of the biorobots also has environmental effects on the pollution that can ensue because of incorrect disposal of biological and synthetic components. One of such risks is that they might end up emitting greenhouse gases, polluting water or damaging local ecologies in case biohybrid systems are disposed in an incorrect way. Consequently, the processes of EOL in application to biorobots should be designed to take special care of the life cycle effect on either biological or synthetic material, responsible disposal, environment pollution and safe recycling routes.

### 4.2 Circular Economy

A Circular Economy refers to an economic structure that devises ways of reducing waste and maximising use of available resources. In a circular economy, it is designed to make goods in such a way that they will last longer, be reused and recycled instead of what is used to be known as the take-make-dispose model. This is aimed at preserving the value of products, materials, and resources within the economy as long as possible through the reduction of waste, repairing, and reusing resources. In the case of biorobotics, the best way to implement a circular economy approach is by creating a design approach that can allow parts to be disassembled, repaired, or repurposed once the systems are at the end of their lifecycle. It may be especially complex, considering the hybridity of biorobots; however, the possibilities of minimizing their total impact on the environment by recycling more of the biological material and synthetic components are also opened up. Some measures of facilitating a circular economy in biorobotics are:

**Design For Disassembly:**

- An important concept of a circular economy is making sure that the products are designed in a way that they are disassembled into their small parts with ease once their useful life is over. In conventional robotics, by this is usually implied the design of robots with modular hardware- usually motors, sensors, and frames that can be serviced easily, used multiple times, or even recycled.
- In case of biorobots, the concern is how to make biological parts removable, replaceable or regenerable at will. As an example, a biohybrid system, based on muscle tissues or actuators made of plants, should be constructed in such a way that the biological part may be replaced or regenerated without having the whole robot to be thrown away. Investing in the reusability of biological tissues, e.g. usage of culturable and harvestable cells or the construction of biohybrids with exchangeable biological components, can help make the design of biorobots more circular.

Disassembly and repurposing could be made possible by modularisation of biological parts: e.g., through standardised biohybrid-actuators or engineered tissue muscles which can be replaced with others, such that not all biorobot components require complete disposal [34].

**Recycling and Reuse of Materials:**

Material recovery in the context of biorobotics, material recovery is the process of discovering potential ways to reclaim and repurpose the saleable contents that the system utilizes, especially metals, electronics, and, in some applications, biomaterials. For example, the commonly used synthetic materials, such as metals and plastics used in biorobots, can be recycled much the same way as traditional robotics. Nevertheless, the peculiar difficulties of retrieving bio-material have their chance to seek out new ways of extraction and reuse of organic compounds. As an extemporary, scientists can consider the possibility of developing biofriendly sensors that would either biodegrade or be reutilized once their biological components. In addition, the waste produced in the manufacturing of biological components may also be dealt with by means of recycling or reuse. Other biotechnological applications or products can use the waste biological tissue growing products, like the culture media or cultures, so that this waste does not accumulate in the whole system [35].

**Design: Bio-based and Biodegradable:**

- A decisive aspect of transitioning toward circularity in terms of biorobotics should be to invest in biodegradable and bio-based materials. As explained above, the bio-based resources produced by renewable sources such as plant fibres, biopolymers, and, in fact, biological cells (e.g., muscle tissue) have a higher chance of biodegrading safely and naturally once the lifecycle belongs to it.
- Once a biorobot is created using mostly biodegradable parts, circularity can be easily achieved since the product will naturally decompose into non-toxic substances and will not form part of global pollution. A major way in which biorobots in the circular economy can be minimised would be through research on biodegradable composites and plant-based materials.

**Regeneration and Repurposing of Biological Components:**

- Regeneration or reuse of biological pieces is another futuristic plan in the circular economy of biorobots. Biological parts of biorobots, e.g. tissues and cells, could, in contrast to conventional machines, be reproducible and thus have a perpetual life.
- Biorobots may have the potential to undergo a process of self-repairing or feedback/resetting - self-restoring whereby the regeneration of biohybrids or regrowth of muscle tissues would provide an option to extend the active part of their lifespan by many-fold. Studies in this field may allow cutting down the necessity of thorough replacements of biological elements, and the system will be more sustainable in the long perspective.

The second option will be to take biological waste (e.g. wrecked biological tissue or cells) and generate new robots based on the concept of closed-loop systems. This kind of recycling would facilitate the regenerative utilization of organic materials in the circular economy model.

The fabrication of a circular economy model into biorobotics also demands new design methodologies, materials, and practices that permit disassembly, recycling, and safe destruction of synthetic and biological materials. The design should be such that it can be easily disassembled and materials recovered as well, and another design being made biodegradable can help to eliminate wastes and help in environmental awareness, in addition to increasing the functionality of the systems. With the increase in advanced biorobots that introduce biological parts, the challenge will consist of focusing on how to incorporate regenerative systems and create sustainable approaches to handling biological as well as synthetic material at the end of life. Adopting such approaches, biorobotics will be able to achieve a more sustainable future where it will be possible to reduce waste, conserve resources, and become environmentally responsible [36].

## 5. Challenges and Future Directions

### 5.1 Challenges in LCA for Biorobotics

Certainly, the deployment of Life Cycle Analysis (LCA) to biorobotics is an emerging field of study, and a number of particular and important challenges are present. Such difficulties are due partly to the complexity of the problem of incorporating biological systems into more conventional robotic systems, and partly to the comparatively early state of the field of bio-robotic technology. Some of the major challenges are as follows:

**Data Gaps**

The unavailability of quality and extensive data is among the main problems when it comes to implementing LCA in biorobotics. In the case of traditional robotics, there is a heavy amount of data on materials, manufacturing processes, the amount of energy consumed and waste generated. The data is the result of years of study and practice, and this is why the life cycle assessments can be done rather accurately. The picture is more complicated, however, when biological parts are used in the systems of robots. The biological materials, e.g. muscle tissues, cells or biohybrids, possess a very versatile quality in their variety, growth conditions and application within the robotic system.To take an example, the growth of muscle cells or plant-based material to make biorobots can be highly different due to various elements, including nutrients available, growth media and environmental factors. Consequently, valid and consistent biological component data during its lifecycle is not usually presentable. This data gap poses a problem to the LCI (Life Cycle Inventory) stage of LCA, where one cannot accurately measure the overall impact of the biorobots on the environment. Moreover, the end-of-life (EOL) of both biorobots, in general, and those with a mixture of biological and synthetic parts, in particular, are poorly supported by data. The loss of biological materials, e.g., muscle tissue or cultured cells, is extremely locally specific and easy to model. The environmental effects of the EOL stage (the biodegradability, the possibility of emission of harmful by-products, or recycling works) are not well enough known, which further complicates the LCA [37].

**Deficiency of Standardization**

The other major issue of LCA in the accountability of biorobotics is the absence of standard methods. Conventional LCA approaches have a rich history lined up; however, such frameworks cannot be applied directly when it comes to biorobotic systems, as they are far more complex and involve bio-entities. Biorobots possess both installations, mechanical and biological installations, and these two aspects involve the combination of data and approaches connected to different disciplines and sectors, such as robotics, biology, material science, and environmental engineering, among others.

Such inconsistency in the implementation process of LCA regarding biorobots may result in varied findings. The introduction of biological systems into LCA has no standardized method; additional complexity is added to it because it may be difficult to draw parallels between various biorobotic systems or evaluate the overall sustainability of the latter. Consequently, it is difficult to establish a unified series of quantitative values in order to evaluate the environmental impact made by the biorobots in various applications, e.g., in prosthesis, exoskeleton, or independent robots in eco-monitoring.

In addition, there is the complexity caused by the fluctuation in biological elements. The decomposition of biological tissues, reactions with synthetic ones, and the possible environmental consequences of the decomposition or disposal should be considered carefully. These considerations do not fit well into classical LCA but rather compound the need to develop a specific LCA framework to support bio robotics [38].

**Complex Biosystems**

The factors that make biological systems unique add more difficulties when brought into biorobotics since biological materials are highly complex and dynamic. In contrast, biological systems, unlike synthetic components, grow, self-repair and degrade, which are affected by various parameters including temperature, humidity and availability of nutrients. The question of how long the biorobots will survive or how they will affect the environment at large is yet to be precisely estimated, due to this biological variability, particularly in the operational and EOL stages.As an example, biohybrid actuators, based on biological materials, such as muscle tissue or neurons, could display performance degradation over time as a result of biological processes, such as tissue fatigue/metabolic constraints, or immune system reaction. These make it difficult to determine long-lasting energy consumption, material requirement, and environmental implications. The fluctuation in the working of biological parts contributes to the overall uncertainty of LCA as a whole.

Also, there are ethical, environmental, and regulatory issues when it comes to sourcing biological components. Our tissues and plant-based bio systems present potential possibilities in sourcing biological materials without the need to get them responsibly through their producing process, being sustainable and ethical. Moreover, there is a possibility that the moral issue of including living organisms in robots could lead to some regulatory issues regarding the safety of using living cells, organisms, or GMOs, which can pose a challenge to the ecosystem of the planet [39].

### 5.2 Future Research Directions

In order to deal with the above challenges to improve the biorobotics field, there are a few future research directions that are essential in enhancing LCA methodologies, data modelling, and material innovation.

**Better LCA methods**

It is important to develop better LCA methods, which work specifically with the biorobots. Given that conventional LCA frameworks cannot be used directly to model a biohybrid, attention is immediately needed to design tailored LCA instruments capable of sufficiently evaluating the environmental effects of biological and artificial components in a biorobot. Within these new frameworks, there should be:

- **Dynamic simulation of biological materials:** Biological materials are dynamic (i.e., they may grow, self-repair, or degrade), and the models used in LCA must consider this through dynamic simulation. This would enable us to model the life cycle of biohybrids more accurately, along with energy, material and resource demands during their growth and operation.

Biohybrids end-of-life: Future LCA approaches should contain special recommendations and methodology to consider the end-of-life stage of biorobots, particularly in connection with their biological parts and degradation or biodegradation. This comes in knowing how the biological components will react with natural environments once disposed of, and their safe breakdown or the prospects of recycling them.

- **Multidisciplinary integration:** The LCA models must also incorporate information across different academic disciplines (biological sciences, material engineering, robotics, and environmental science) as biorobots cut across all these disciplines. It will entail the integration of specialists of these disciplines so as to develop standard, cross-disciplinary LCA practices of bio robotics [40].

**Improved Data Modelling and Data Collection**

Data gaps exist right now, and there is an urgent requirement to enhance the data collection and modelling procedure in regard to biorobots. This will include the development of new datasets but also the enhancement of the resolution of the study of existing data, focusing on biological elements. There is potential for research in the following directions:

- **Bio-tracking databases:** To determine the correct amount of environmental impact of biorobots, scientists must develop comprehensive databases that trace the environmental impact of biological materials (e.g., muscle cells, plant-based materials, and biohybrid materials) in their entire lifespan. This would cover their production, energy consumption, emissions and waste both in the manufacturing and operating phases.
- More sophisticated modelling processes: The researchers could be able to generate simulation models able to estimate the behaviour of biological systems under different environmental situations, which would assist in considering such variables as tissue growth, the rate of degradation, and the changes in performance over time. It would make it possible to make improved energy usage, materials, and waste predictions of biorobots throughout their complete life cycle.

The life cycle databases of biohybrids: As the biological systems are diverse, it will be relevant to develop a dedicated LCI databases that encompass biohybrids with details on their growing and material separation and the life cycle impacts of the biological components. These databases will help conduct more reliable LCA studies because a form of standarization in data concerning biohybrids will exist [41].

**Sustainable Material Development**

Biorobot sustainability is another area of research where sustainable materials will be created. As it has been argued earlier, natural and bio-based, and biodegradable materials have the potential they minimize the environmental effects of biorobots. But they have not been widely used in robotics yet. The research directions that have to be pursued in the future include:

- **Bio-based polymer composites:** There is a need to develop durable and high-performance polymers that are bio-based, which could be used instead of the use of traditional synthetic plastics and metals in robotic systems. They must also be biodegradable or recyclable: they must not waste after their life cycle due to creating a part in environmental pollution.

Biohybrid performance: Improving the performance of biohybrids, e.g. tissue-engineered muscle or neural systems, in order to make them more efficient and long-lasting, will play a key role in making biorobots more sustainable. It may include improving tissue engineering, making biohybrids more robust and maximizing how biohybrids are combined with synthetic materials.

- **Self-healing and regenerative material:** Research on materials that are capable of repairing or regenerating may lead to a decrease in waste moving forward because biorobots could last longer. As an example, self-healing biohybrids may fix themselves so that they no longer require a repair outside their bodies to reduce resources expended and robots' lifetime usage.

Summarizing the paper, the problem of biorobotics in the application of LCA methods can be significantly related to data shortage, the limitation of biological systems, and the lack of standardization. Nevertheless, the ability to reduce these challenges by the use of better LCA frameworks, enhanced data modelling, and even the creation of sustainable materials presents promising prospects of improvements to the sustainability of biorobots. With the possible solutions to these challenges, there is a path to a new future, where robots are resourceful, efficient, and environmentally friendly and sustainable in the developed field of bio robotics [42,43].

## 6. Conclusions

In summary, Life Cycle Analysis (LCA) is a vital system to determine the environmental impact of biorobots, and it can provide information on how sustainable are systems incorporating biological elements with conventional robot technologies. The emergence of biorobotics poses a special set of issues and opportunities to LCA as such systems are made to be more complex with living tissues, cells and biohybrids. By using the methodology of LCA, the environmental effects of biorobots can be more thoroughly discussed within all the cycles that these robots have, starting with raw material acquisition and ending with the disposal of these robots. The use of bio-based and biodegradable materials in biorobotics can be the key to deepening the ecological footprint of such systems. Through proper choices of materials and rational design of energy usage in production and exploitation, there is a possibility to produce biorobots that would be more sustainable, would not demand so many resources in fabrication and operation, and would not leave numerous wastes behind. Nonetheless, there are major issues to overcome, such as the correct representation of the biological parts in modelling, data relative shortages, and the adjustment of LCA procedures in terms of the complexity of biohybrids.

As a conclusion, it is essential to sharpen up LCA frameworks based on specifically designed biorobotics, mostly dynamic modelling of biological systems, improved data gathering, and innovation of sustainable materials. The identified advances will enable filling the existing knowledge gaps and enable a broader and standardized assessment of the environmental effects of biorobots. Moreover, further improvement of the sustainability of biorobots can be done through the development of the circular economy principles, e.g., designing to disassemble, waste material recovery, etc., so that biorobots help to create a more sustainable world. With biorobots becoming increasingly advanced and significant in an array of fields, such as healthcare, agriculture, and environmental monitoring services, their capacity to perform efficient and sustainable tasks will be of the highest priority. Thus, it can be concluded that the applied and ongoing research and implementation of LCA will prove essential in terms of informing the responsible construction and implementation of the biorobots, which will assist in coordinating the development of the technology with the overall aims of sustainability on a global scale and ecological accountability. With such endeavours, biorobotics can be not only another industrial revolution, but also make a difference on the planet, heralding a greener and environment-savvy future.

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