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Research paper
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LIFE CYCLE ASSESSMENT OF BONE GRAFT MANUFACTURING

Abstract: *In this paper, an assessment of the negative environmental impact of the manufacturing of bone grafts was carried out under various environmental aspects. The environmental impact assessment was carried out using the standardised life cycle assessment method . The aim of the study is to quantify and identify the main challenges related to the negative environmental impact of the bone graft production phase. Various aspects were analyzed, including material consumption, energy consumption, emissions, waste and others. The results indicate that the greatest environmental impact is due to energy inputs and material consumption, which highlights opportunities to reduce the impact through material selection, improved energy efficiency and optimization of the manufacturing process.*

Keywords: *Life cycle assessment, Bone graft, Manufacturing*

1. Introduction

In recent decades, the development of bone tissue engineering technologies has significantly improved the possibilities of bone regeneration, with a particular focus on the use of different biomaterials and advanced manufacturing technologies. One of the latest approaches in this field is the application of CAD/CAM technologies for the precise production of bone grafts, as well as the use of additive manufacturing technologies such as 3D printing. These technologies enable the production of bone grafts with improved mechanical and biological properties, making them suitable for use in oral surgery and other medical fields (Gialain et al., 2019; Alghazzawi, 2016; Sun and Lal, 2002). Given the increasing interest in sustainability and reducing the negative impact on the environment during the production phase of biomaterials, life cycle assessment (LCA) is an important tool for analyzing and optimizing the environmental impact of these processes (Ranjan et al., 2020).

A large number of previous studies have looked at various aspects of bone tissue regeneration and bone grafts manufacturing. Gialain et al. (2019) investigated the application of CAD/CAM technology in the production of allogenic bone grafts for maxillofacial reconstruction using preoperative virtual planning. The results showed that high dimensional accuracy was achieved when milling freeze-dried allogenic bone blocks compared to the virtual model, with minimal deviations in height, width and length of the graft. Alghazzawi (2016) analyzed the advances in CAD/CAM technology considering the 3D scanning, design and manufacturing methods for dental prostheses as the new classifications of this technology. The results show that CAD/CAM technology offers advantages such as digital impressions and models, but its application is still considered expensive and requires highly skilled professionals.

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Sun and Lal (2002) investigated the development of computer technologies in tissue engineering, focusing on the application of CAD/CAM, rapid prototyping (RP) technologies and 3D reconstruction in tissue modelling and implantation. The main conclusions include the improvement of 3D visualization of anatomy through computed tomography (CT) and magnetic resonance imaging (MRI) scanning, which is crucial for the creation of physical biomodels and tissue structure analysis. Schlee and Rothamel (2013) explored the use of customized allogeneic bone blocks for alveolar defect augmentation, focusing on their precise production using CNC milling. CAD technology enables the design of grafts based on preoperative CT scans, achieving optimal adaptation to the patient's anatomy. Sokac et al. (2025) designed a fixture for locating and clamping porous blocks of biocompatible materials for machining on CNC machines. Verification was performed using finite element method (FEM) analysis, which showed low stress concentration and minimal dimensional deviations. The proposed design reduces the risk of material breakages and deformations, but it can be improved by adding modular elements for greater flexibility in processing blocks of various sizes. Blume et al. (2019) investigated the regeneration of large bone defects in the maxilla using CAD/CAM manufactured allogenic bone blocks. These blocks perfectly matched the geometry of the defect, had minimal resorption, and enabled the formation of a sufficient amount of new bone, allowing for the successful implantation of an implant. Azari and Nikzad (2009) researched the development of RP in dentistry, focusing on the layer-by-layer production of 3D models from CAD designs. RP technology is particularly useful in surgery and implantology, enabling the production of customized dental appliances with reduced costs and production time. Ghaderzadeh et al. (2023) explored the use of custom xenografts for mandibular augmentation and dental implantation. Using the FEM and graft simulation, they produced xenografts through micro-milling, with 3D printing for preoperative assessment of bone fit.

Some of the previous studies have examined the impact of bone graft production processes on the environment. Tajurahim et al. (2022) analysed the impact of 3D printed scaffolds for bone tissue engineering and found that the manufacturing process contributes 47.6% to the overall global warming potential (GWP), while material consumption accounts for 32.5%. Senusi et al. (2022) showed that raw material and energy consumption, particularly electricity and transportation, have the greatest impact, while optimizing production time and using renewable energy sources can reduce environmental negative impacts. Putra et al. (2023) explored sustainable raw material sources for additive manufacturing of bone-replacement biomaterials, emphasizing the importance of using renewable and recycled materials as solutions for sustainable development challenges.

In contrast to the previous studies, the aim of this research is to analyse the negative impact of the bone graft machining phase. The study identified key factors contributing to the negative impact on the environment through the life cycle phases, from material selection to final production. Using the LCA, energy consumption, material usage, harmful gas emissions, and waste production were analysed. The obtained results provide a better understanding of the environmental negative impact of the bone graft machining phase. Additionally, they offer guidelines for improving energy efficiency and reducing negative environmental effects.

2. Metodology

LCA enables the analysis of the environmental impact of a product or system throughout its entire life cycle. The process involves the collection of data on materials used, emissions, energy consumption, waste,

and other aspects. Based on this data, a quantitative assessment of the negative environmental impacts can be carried out, including greenhouse gas emissions, air pollution, and the consumption of natural resources. The primary goal of LCA is to provide objective information about the environmental profile of a product or system, identifying key issues and opening opportunities for improving sustainable development. Figure 1 shows the stages of LCA according to ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), which include: goal and scope definition, inventory analysis (Life Cycle Inventory - LCI), impact assessment (Life Cycle Impact Assessment - LCIA), and interpretation of results (Ranjan et al., 2020).

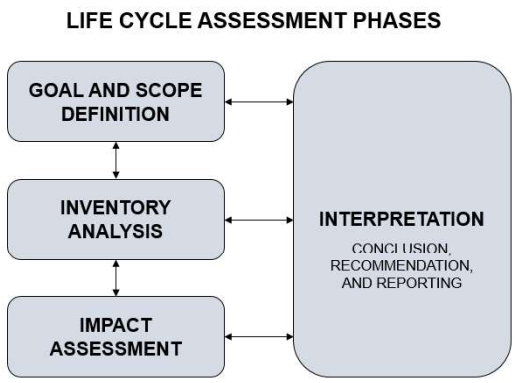

Figure 1. LCA phases

The goal and scope definition phase sets the framework for the entire analysis and determines the boundaries and scope of the study (Ranjan et al., 2020). The LCA of bone graft machining aims to assess the negative environmental impact of the bone graft machining process.

The functional unit for the LCA is the specifically produced bone graft weighting 25E-4 kg, which is used in medical and dental applications as a replacement for damaged bone parts. The bone graft is made from a porous block with 27% open porous microstructure. The porous block consists of a mineral matrix derived from bovine bone and enriched with biopolymers. It has a chemical structure and morphology similar to human bone (Sokac et al., 2025).

The CAD model (Figure 2) of the customized bone graft serves as the basis for its production. Due to the particularities of each individual patient, the CAD model has an irregular shape and complex geometry.

Figure 2. CAD model of the bone graft

The machining of the bone graft was performed on the dental CAD/CAM system CC Power (Figure 3).

Figure 3. CAD/CAM system CC Power

The machining was carried out in 6 operations, namely: rough milling (1st side), rough milling (2nd side), finish milling (1st side), finish milling (2nd side), profile milling, and milling of connectors. All tools used for machining were made of titanium. The coarse external machining

(both sides) was performed with a ball end mill with a tip diameter of 2 mm (Figure 4a), the fine external machining (both sides) was performed with a ball end mill with a tip diameter of 1 mm (Figure 4b), while the profile machining and connector milling were performed with a ball end mill with a tip diameter of 0.6 mm (Figure 4c).

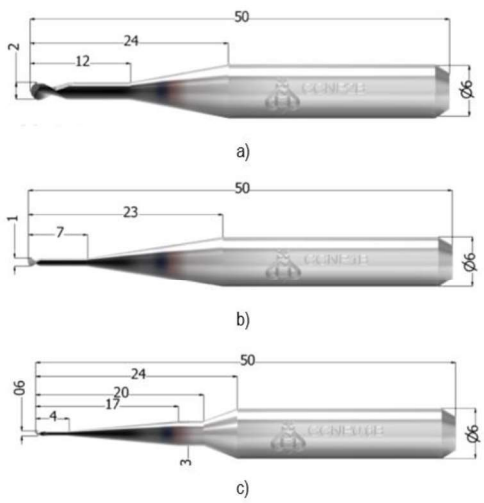

Figure 4. Cutting tools used for machining the bone graft

The machining conditions were defined based on the recommendations of the cutting tool manufacturer. The feed rate was varied depending on the operation, with 1200 mm/min for rough milling, 1000 mm/min for finish milling, 500 mm/min for profile milling, and 600 mm/min for connector milling. The cutting speed was constant at 1000 rpm for all operations (Sokac et al., 2025). The manufactured bone graft is shown in Figure 5.

For accurate and reliable LCA results, it is essential to clearly define the system boundaries. The system boundaries define the scope of the analysis and determine which stages of the life cycle will be included in the study. In the LCA of bone graft production, the system boundaries encompass all steps and activities related to the bone graft machining process, such as raw material, transport, storage and logistics, material and part production, and bone graft machining (Figure 6). The bone graft machining process is the foreground process, while all other activities are considered background processes. The use phase and end-of-life phase of the bone graft are not specifically considered, so they lie outside the system boundaries.

Figure 5. Manufactured bone graft

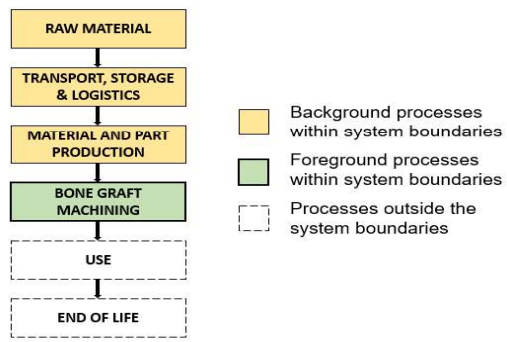

Figure 6. System boundaries

The limitations in the LCA analysis of bone graft production relate to variations in energy consumption during CNC machining, which can depend on numerous factors such as machining parameters, tool type, and material, potentially causing variability in the results. The analysis used an average energy consumption of 1.5 kWh for the CNC milling machine CC Power, based on available data on the energy consumption of this model under standard machining conditions. Another limitation is that the meat and bone meal LCI dataset was used as the graft material, as it closely resembles the bone graft in terms of its physical and

chemical characteristics.

The LCA analysis of bone graft machining was conducted using the OpenLCA software. The life cycle inventory of the bone graft encompasses all data and steps that enable a numerical representation of material and energy flows through the input and output stages of the life cycle. The Ecoinvent 3.7 Cut-off database (Wernet et al. 2016) was used for background data, providing information on energy and material flows throughout the different manufacturing stages. Table 1 shows the energy and material flows used for milling, which were included in the LCA analysis. Since milling of the bone graft is not specifically included in the Ecoinvent 3.7 Cut-off database as a separate activity, a specific inventory for this operation was created. The milling process for the bone graft was based on steel machining, with adjusted parameters for energy and material consumption.

Table 1. Input data from Ecoinvent 3.7 Cut-off database

Flow	Amount
Compressed air, 700 kPa gauge	1.28 m³
Electricity, low voltage	1.5 kWh
Energy and auxiliary inputs, Factory	4.41 kg
Lubricating oil	0.00382 kg
Factory	2.02E-09 Item(s)
Working machine, unspecified	0.000174 kg
Market for meat and bone	1 kg
Water, cooling, unspecified natural origin	0.01478 m³
Water, unspecified natural origin	0.001913 m³

Table 2 shows all the machining operations used in the bone graft production process, along with the amounts of material removed during each of these operations. The amount of material removed is crucial for accurately determining resource consumption, as well as for analyzing the negative environmental impact of each operation.

Table. 2. Amount of material removed during different milling operations

Operations	Amount of material removed (kg)
Rough milling (1st side)	26E-4
Rough milling (2nd side)	25E-4
Finish milling (1st side)	18E-4
Finish milling (2nd side)	17E-4
Profile milling	2.5E-4
Milling of connectors	5E-4

The LCIA was conducted using the ReCiPe method, which enables the identification and quantification of the potential negative impacts of a product or process on the environment. The impact categories according to ReCiPe considered in the study are: global warming potential (GWP) - kg CO_2 eq, fossil resource scarcity (FRS) - kg oil eq, freshwater eutrophication (FEP) - kg P eq, and terrestrial acidification (TAP) - kg SO_2eq.

The ReCiPe method includes two sets of impact categories: endpoint and midpoint, which are defined by the ISO 14040 standard. Midpoint impact categories reflect specific physical and chemical changes in the environment, while endpoint categories focus on their overall system impact and on the human system. This study performed an impact assessment at the midpoint, which allows for the quantification and evaluation of impacts on various factors throughout the life cycle of bone graft production.

3. Results and discussion

The LCIA results from ReCiPe method are presented in a graphical format. The graphical representation provides a clear and intuitive insight into the distribution and intensity of the impact of bone graft machining, categorized by key impact categories. Table 3 and Figure 7 present the results of the impact assessment of the bone graft milling operations on GWP, FEP, TAP, and FRS. The data shown relates to the defined functional unit, taking into account all relevant material and energy flows in the

analyzed process.

The results of the assessment clearly indicate variations in the environmental impact of different CNC machining operations on the bone graft. In all categories, rough machining operations have the dominant impact due to higher energy and material consumption, while fine machining and profile milling operations show significantly lower negative impacts. The largest contribution to GWP comes from rough machining, which can be explained by the higher electricity consumption due to more intensive machining regimes.

Table. 3. Results

Impact category		Reference unit	Rough milling (1st side)	Rough milling (2nd side)	Finish milling (1st side)	Finish milling (2nd side)	Profile milling	Milling of connectors
GWP	Energy and auxiliary input	1.18E+00	3.06E-03	2.94E-03	2.12E-03	2.00E-03	2.94E-04	5.89E-04
	Electricity	6.27E-01	1.63E-03	1.57E-03	1.13E-03	1.07E-03	1.57E-04	3.13E-04
	Factory	2.51E-01	6.54E-04	6.29E-04	4.53E-04	4.27E-04	6.29E-05	1.26E-04
	Compressed air	8.59E-02	2.23E-04	2.15E-04	1.55E-04	1.46E-04	2.15E-05	4.29E-05
	Waste mineral oil	8.45E-03	2.20E-05	2.11E-05	1.52E-05	1.44E-05	2.11E-06	4.23E-06
	Lubricating oil	4.72E-03	1.23E-05	1.18E-05	8.50E-06	8.02E-06	1.18E-06	2.36E-06
	Meat and bone meal	3.42E-03	8.89E-06	8.55E-06	6.16E-06	5.81E-06	8.55E-07	1.71E-06
	Machine	8.30E-04	2.16E-06	2.08E-06	1.49E-06	1.41E-06	2.08E-07	4.15E-07
	Waste mineral oil- CH	2.30E-04	5.98E-07	5.75E-07	4.14E-07	3.91E-07	5.75E-08	1.15E-07
FEP	Energy and auxiliary input	3.00E-04	7.50E-07	5.40E-07	5.10E-07	7.50E-08	1.50E-07	0.00E+00
	Electricity	6.20E-04	1.55E-06	1.12E-06	1.05E-06	1.55E-07	3.10E-07	0.00E+00
	Factory	6.05E-05	1.51E-07	1.09E-07	1.03E-07	1.51E-08	3.03E-08	0.00E+00
	Compressed air	8.50E-05	2.13E-07	1.53E-07	1.45E-07	2.13E-08	4.25E-08	0.00E+00
	Waste mineral oil	5.48E-07	1.37E-09	9.86E-10	9.32E-10	1.37E-10	2.74E-10	0.00E+00
	Lubricating oil	1.46E-06	3.65E-09	2.63E-09	2.48E-09	3.65E-10	7.30E-10	0.00E+00
	Meat and bone meal	2.50E-07	6.25E-10	4.50E-10	4.25E-10	6.25E-11	1.25E-10	0.00E+00
	Machine	1.06E-06	2.65E-09	1.91E-09	1.80E-09	2.65E-10	5.30E-10	0.00E+00
	Waste mineral oil- CH	1.49E-08	3.73E-11	2.68E-11	2.53E-11	3.73E-12	7.45E-12	0.00E+00
TAP	Energy and auxiliary input	1.73E-03	4.33E-06	3.11E-06	2.94E-06	4.33E-07	8.65E-07	0.00E+00
	Electricity	2.36E-03	5.90E-06	4.25E-06	4.01E-06	5.90E-07	1.18E-06	0.00E+00
	Factory	1.55E-03	3.88E-06	2.79E-06	2.64E-06	3.88E-07	7.75E-07	0.00E+00
	Compressed air	3.30E-04	8.25E-07	5.94E-07	5.61E-07	8.25E-08	1.65E-07	0.00E+00
	Waste mineral oil	4.58E-07	1.15E-09	8.24E-10	7.79E-10	1.15E-10	2.29E-10	0.00E+00
	Lubricating oil	2.29E-05	5.73E-08	4.12E-08	3.89E-08	5.73E-09	1.15E-08	0.00E+00
	Meat and bone meal	1.11E-05	2.77E-08	1.99E-08	1.88E-08	2.77E-09	5.54E-09	0.00E+00
	Machine	4.22E-06	1.06E-08	7.60E-09	7.17E-09	1.06E-09	2.11E-09	0.00E+00
	Waste mineral oil- CH	1.17E-08	2.93E-11	2.11E-11	1.99E-11	2.93E-12	5.85E-12	0.00E+00
FRS	Energy and auxiliary input	1.72E-01	4.48E-04	4.31E-04	3.10E-04	2.93E-04	4.31E-05	8.62E-05
	Electricity	1.68E-01	4.36E-04	4.19E-04	3.02E-04	2.85E-04	4.19E-05	8.39E-05
	Factory	7.68E-02	2.00E-04	1.92E-04	1.38E-04	1.30E-04	1.92E-05	3.84E-05
	Compressed air	2.29E-02	5.96E-05	5.74E-05	4.13E-05	3.90E-05	5.74E-06	1.15E-05
	Waste mineral oil	2.27E-07	5.90E-10	5.68E-10	4.09E-10	3.86E-10	5.68E-11	1.14E-10
	Lubricating oil	5.27E-03	1.37E-05	1.32E-05	9.49E-06	8.96E-06	1.32E-06	2.64E-06
	Meat and bone meal	1.19E-03	3.09E-06	2.98E-06	2.14E-06	2.02E-06	2.98E-07	5.95E-07
	Machine	2.10E-04	5.46E-07	5.25E-07	3.78E-07	3.57E-07	5.25E-08	1.05E-07
	Waste mineral oil- CH	5.15E-08	1.34E-10	1.29E-10	9.27E-11	8.76E-11	1.29E-11	2.58E-11

By reducing the intensity of machining, energy requirements decrease, leading to lower greenhouse gas emissions. A similar trend is observed in the FEP category, where operations with higher energy demands contribute significantly to freshwater eutrophication, while finer operations show a smaller negative impact. This is a result of emissions associated with electricity production and consumption during CNC machining, as well as the generation of by-products during machining. Operations that require a larger amount of electricity also have the highest impact on TAP and FRS. The results show that the most energy-demanding operations, such as rough machining, are key factors in shaping the overall environmental impact of the bone graft machining process. Optimizing machining parameters, such as reducing

machining time and improving the energy efficiency of the CNC machine, could significantly contribute to reducing overall emissions.

Figure 8 shows a comparative environmental impact of bone graft milling and steel milling on the categories GWP, FEP, TAP, and FRS, with results presented for processing 1 kg of material. The analysis shows that bone graft milling has a lower negative impact in all categories compared to steel milling, which can be explained by differences in the physical and mechanical properties of the two materials and the specifics of their machining processes.

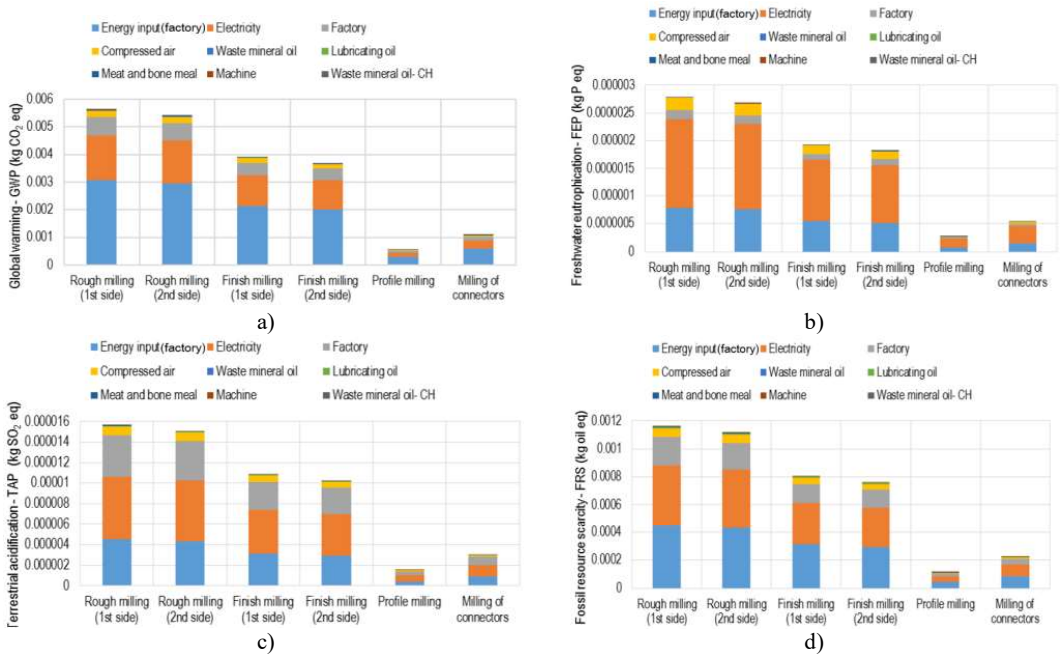

Figure 7. Impact of milling operations
a) GWP, b) FEP, c) TAP, d) FRS

Due to its lower density and hardness, the bone graft requires less intense machining parameters and lower energy consumption compared to steel, for which higher cutting forces and longer machining times are necessary to achieve the desired dimensions and surface quality. As a result, milling the bone graft produces significantly lower greenhouse gas emissions, as its energy requirements are lower.

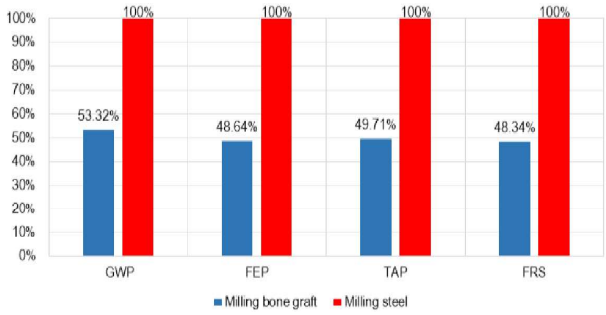

Figure 8. Comparison of the effects of milling steel and milling bone graft on GWP, FEP, TAP and FRS

A similar trend is observed in the FEP and TAP categories, where the lower resource consumption during bone graft processing is directly linked to a reduction in negative environmental impact. In contrast, steel processing requires more energy, cutting tools, and cooling fluids, resulting in increased emissions of pollutants. In the FRS category, this effect is also more pronounced during steel processing, as the demands for electrical energy and consumables are significantly higher than for bone graft processing. These results highlight the ecological advantages of bone graft processing over steel and point to the potential for reducing the ecological footprint through the optimization of processing regimes and energy efficiency.

Additionally, an important factor in considering the environmental impact of steel and bone graft processing is waste generation. During steel milling, metal shavings are produced, which require additional recycling or disposal processes, while the waste material from bone graft processing can have potential applications, for example, in biomedical research or regenerative medicine. This difference further contributes to the reduction of the overall environmental burden in bone graft processing compared to steel.

FRS is also more pronounced in steel processing, as the demands for electrical energy and consumables are significantly higher than for bone graft processing. The results emphasize the ecological benefits of bone graft processing over steel and suggest potential for reducing negative impacts through optimization of processing regimes and energy efficiency. Further optimization of processing parameters and the use of energy-efficient CNC systems could further reduce the ecological footprint of bone implant production, thereby improving sustainability and reducing environmental impact.

4. Conclusion

The study assessed the environmental impact of bone graft production using LCA with openLCA software. The ReCiPe method was employed to quantify the ecological footprint of the bone graft machining process through the analysis of key impact categories, including GWP, FRS, FEP, and TAP.

The results indicate that the largest contribution to the ecological footprint comes from energy consumption during CNC machining, with rough machining operations identified as the most intensive source of negative impacts. High electricity consumption in these operations leads to increased greenhouse gas emissions and a higher ecological burden across all analyzed impact categories. Finish milling and profile milling operations have significantly lower negative impacts, suggesting that optimizing machining regimes could be a key factor in reducing the overall ecological footprint of the process.

A comparison of the ecological impact of CNC machining of bone grafts and steel showed that bone grafts have a lower negative impact in all analyzed categories. This can be explained by the physical and mechanical properties of grafts, which require less energy for processing compared to metal materials. Additionally, the waste material from machining can be utilized in biomedical research, further reducing the ecological impact. Although the results are more favorable, energy and raw material consumption still present challenges for the sustainability and environmental acceptability of bone graft production.

Based on the conducted analysis, key recommendations can be made to reduce the ecological footprint of bone graft production processes. Increasing the energy efficiency of CNC machining, through optimization of machining regimes, can significantly reduce emissions and resource consumption. The use of renewable energy sources in production would reduce the negative impact

of electricity consumption. Additionally, waste reduction, through better material utilization and recycling, can contribute to minimizing ecological impact. Optimizing material selection, including the use of more environmentally friendly biomaterials, could improve the sustainability of the process.

The obtained results can serve as a foundation for future research focused on optimizing the processing of biomaterials and reducing the negative environmental impact. Future studies will focus on including the exploitation and end-of-life stages and applying more environmentally friendly biomaterials as well as advanced machining technologies for bone graft production.

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