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LIFE CYCLE ASSESSMENT OF NANOFIBER PRODUCTION OBTAINED BY BIOMASS NANOSPHERES FROM *MICROALGAL*

AVALIAÇÃO DO CICLO DE VIDA DA PRODUÇÃO DE NANOFIBRAS OBTIDAS POR NANOESFERAS DE BIOMASSA MICROALGAL

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ABSTRACT

Microalgae are rapidly being employed in carbon fixation due to their benefits over other crops for energy needs, such as high photosynthetic efficiency, massive biomass production and rapid development. Spirulina maxima is a microalgae whose production is based on cultivation with favorable growing conditions. Within the Life Cycle Analysis, the steps that fed into the Impact 2002 system included assembly and cultivation, production and characterization of nanochitosan, flocculation of biomass with nanochitosan, filtration, drying, production and characterization of the nanosphere, and obtaining the microalgae filter. The production stages were evaluated regarding the environmental impacts that could be caused. To evaluate these processes, Life Cycle Analysis (LCA) was applied using SimaPro software version 8.5 and Ecoinvent 3 database with the "Impact 2002+" impact method from the Swiss Federal Institute of Technology. Characterization and normalization data were considered. The impact categories that stood out the most in relation to the release of particulates into the atmosphere by carrying out the steps are carcinogenic, non-carcinogenic, inorganic breathables, depletion of the ozone layer, organic breathables, global warming, non-renewable energy. Within the category of carcinogens (Kg C_2H_3Cl eq), there is a total of 1.81 kg C_2H_3Cl eq of released particulates, for non-carcinogens a total of 3.91 Kg C_2H_3Cl eq of released particulates, inorganic breathables have a total of 0 0418 kg of particulates released during the stages, for the category of damage and destruction of the ozone layer, expressed there is a total of 1.35 E-6 divided between the stages, the organic breathables totaled 0.00771, for the global warming category expressed in kg CO_2 eq we have a total of 24.1 and within the non-renewable energy category we have a total of 352 MJ. As a final result, after evaluating the main categories of risks present during the LCA process, the main category of environmental impact was "Damage to human health". The result obtained is due to the high consumption of electricity.

Keywords: Nanoscience, Energy, Enviromental Impact, Bioremediation, Natural Fibers.

RESUMO

As microalgas estão sendo rapidamente empregadas na fixação de carbono devido aos seus benefícios sobre outras culturas para necessidades energéticas, como alta eficiência fotossintética, produção massiva de

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biomassa e rápido desenvolvimento. A Spirulina maxima é uma microalga cuja produção se baseia no cultivo com condições favoráveis de crescimento. Dentro da Análise do Ciclo de Vida, as etapas que alimentaram o sistema Impact 2002 incluíram montagem e cultivo, produção e caracterização de nanoquitosana, floculação de biomassa com nanoquitosana, filtração, secagem, produção e caracterização da nanoesfera e obtenção do filtro de microalgas. As etapas de produção foram avaliadas quanto aos impactos ambientais que poderiam ser causados. Para avaliar esses processos, a Análise do Ciclo de Vida (LCA) foi aplicada usando o software SimaPro versão 8.5 e o banco de dados Ecoinvent 3 com o método de impacto "Impact 2002+" do Swiss Federal Institute of Technology. Dados de caracterização e normalização foram considerados. As categorias de impacto que mais se destacaram com relação a liberação de particulados na atmosfera através da realização das etapas são: carcinogênicos, não carcinogênicos, respiráveis inorgânicos, destruição da camada de ozônio, respiráveis orgânicos, aquecimento global, energia não renovável. Dentro da categoria de carcinogênicos (Kg C_2H_3Cl eq), tem-se um total de 1,81 kg C_2H_3Cl eq particulados liberados, para os não carcinogênicos um total de 3,91 Kg C_2H_3Cl eq de particulados liberados, respiráveis inorgânicos tem um total de 0,0418 kg de particulados liberados durante a realização das etapas, para a categoria de danos e destruição da camada de ozônio, expresso tem-se um total de 1,35 E-6 dividido entre as etapas, os respiráveis orgânicos totalizaram 0,00771, para a categoria de aquecimento global expresso em kg CO2 eq temos um total de 24,1 e dentro da categoria de energia não renovável temos um total 352 MJ. Como resultado final, após avaliação dentro das principais categorias de riscos presentes durante o processo de ACV, a principal categoria de impacto ambiental foi "Dano à saúde humana". O resultado obtido se deve ao alto consumo de energia elétrica.

Palavras-chave: *Nanociências, Energia, Impacto Ambiental, Biorremediação, Fibras Naturais.*

INTRODUÇÃO

Life Cycle Assessment - LCA is a technique for evaluating environmental aspects and potential impacts associated with a product system through Compiling an inventory of inputs and emissions in the production system; Potential assessment of environmental impacts associated with inputs and emissions; Interpretation of the results of the inventory analysis and the phases of the impact analysis concerning the objectives of the study (ABNT NBR ISO 14040, 2009).

These analyzes are carried out by several authors to evaluate the impact of microalgae production, focusing on sustainable products developed from biomass such as biodiesel, biomethane, limonene, ethanol, phycocyanin, protein, aviation fuel, chlorophyll, β-carotenoid, polyphenols (LI *et al.*, 2011) including (nano)biotechnological materials, as it is a technology of great interest for filtration applications. It is understood, within this market, that the smaller the diameter, the greater the particle retention characteristics of the filter medium. Research continues to improve extrusion equipment and develop new polymers to produce fibers of ever-smaller diameters. There are a few alternatives to biosustainable polymers used to obtain a better composition, shape, flow, and retention of particles in filtration processes.

In Israel, *Spirulinas* are used to treat water with industrial and domestic waste, according to Cuesta and Serrano (2006). In London, tertiary waters from *spirulina* cultivation are used to produce biomass and purify it for other uses.

Microalgae contain valuable chemical substances and molecular compounds used in the production of green plastics, green cleaning products, detergents, and biodegradable and non-toxic polymers and sold at a price compatible with petroleum products, collaborating with the environment and, at the same time, with the health of populations (SIMÕES *et al.*, 2019).

Every product causes some impact on the environment, not only when discarded but throughout its life cycle. Starting with raw material extraction, transmitting pollution, waste, and emissions to the environment. Aiming to reduce the impacts, the Life Cycle Analysis is a study based on a broad product database intended for research (ROBLES JUNIOR and BONELLI, 2006).

LCA categorized four distinct phases, which are: 1) objectives and scope; 2) inventory analysis; 3) impact assessment, and 4) Results from interpretation. All steps are interconnected and communicate with each other until it is possible to generate valuable information for specific applications:

1) objective and scope in this phase are the main reason for conducting the study, its breadth and limits, the functional unit, the methodology, and the procedures necessary to guarantee the quality of the study, and that should be adopted and defined, according to Schmidt (2008).

2) Life Cycle Inventory Analysis (LCIA) involves data collection and calculation procedures to quantify inputs and outputs, or elementary flows, relevant to a product system, according to Ferreira (2004). Qualitative and quantitative data for inclusion in inventory is a must for each process unit included within the system to reduce time consumption and costs of life cycle study. Data collection should answer the proposed questions.

3) LCIA is a phase targeted at determining the significance of potential environmental impacts (3), from the life cycle inventory analysis. This process involves associating inventory data with specific environmental impacts to understand them (FERREIRA, 2004).

4) Life Cycle Interpretation (LCI) is the phase of the LCA in which findings of the inventory analysis and impact assessment are combined with the defined objective and scope to reach conclusions and recommendations (ISO 14044, 2009).

An example of how LCA studies can help in decision-making regarding the implementation of technologies with less environmental impact is the study by Jorqueira *et al.* (2009). A comparative study of energy consumption of the life cycle between the microalgae cultivation systems in open ponds, flat plate photobioreactors, and those with horizontal tubular plates, concluded that the first one's present higher energy production than the other options.

Life Cycle Assessment (LCA) is a tool that considers and quantifies the consumption of resources and the impacts environmental factors associated with a product or process during its life cycle (BOULLAY *et al.*, 2011), collaborating for a better assessment of overall performance and contributions for different stages of the life cycle, thus allowing identifying opportunities to improve the environment and of the global performance of the systems (BENETTO *et al.*, 2009).

Since the 19th century, algal cultures have been studied worldwide. Since the mid-20th century, in Brazil. Microalgae can be cultivated in controlled environments for commercial purposes, especially for biochemical compound extraction such as polyunsaturated fatty acids, dyes, and enzymes (BOROWITZKA, 1994 apud DERNER, 2006).

In this context, the present study aimed to carry out the LCA of the cultivation process of Spirulina maxima on a laboratory scale in a closed growth system to produce a water filter with nanotechnological characteristics. This work also aims to assess the environmental sustainability of the entire filter production process, identify the aspects responsible for most of the impacts, and propose strategies to mitigate these impacts.

MATERIALS AND METHODS

Microalgae have several applications; the LCA has defined the function of the microalgae would be to supply biomass to obtain microalgae filters. The functional unit (reference flow) established was the production of 1 kg of *Spirulina maxima* microalgae biomass. The parameter data of each process were fed into SimaPro 8.5 to obtain the microalgae biomass until the end, with the production of the microalgal filter (LOURENÇO, 2006; ANTONI *et al.*, 2007).

The method chosen was the "Impact 2002+", characterizing the inventory results in fourteen impact categories correlated to at least one of the four damage categories (JOLLIET *et al.*, 2003). The "Impact 2002+" dataset covers a wide range of effects on the environment. Inputs referring to water use were quantified, for example, in cubic meters (m^3), and inputs referring to products in kilograms (kg) of material. For energy consumption, inputs were quantified in (kWh). Outputs related to atmospheric emissions throughout the life cycle were quantified in kg of gas emitted to the atmosphere.

The system under study is located in Santa Maria, State of Rio Grande do Sul, Brazil. The data present in the ACV were all collected at the Nanotechnology Laboratory belonging to the Franciscan University. Data were included in the "Impact 2002+" method in collaboration with the University of Santa Cruz do Sul (UNISC). The production process, delimited by the study, started with the culture in BG 11 medium of *Spirulina maxima* strains, coming from the Food Technology Laboratory of the Federal University of Santa Maria/RS, with a volume of 5 L in PET bottles in a controlled environment, artificial lighting, and constant aeration.

The cultures were carried out in an environment with a temperature of 24 ºC, humidity around 60%, luminosity with an alternating photoperiod of 14/10h, light/dark, T8 red lamps of 40 W, initial pH around 9.3, being cultivated for 16 days.

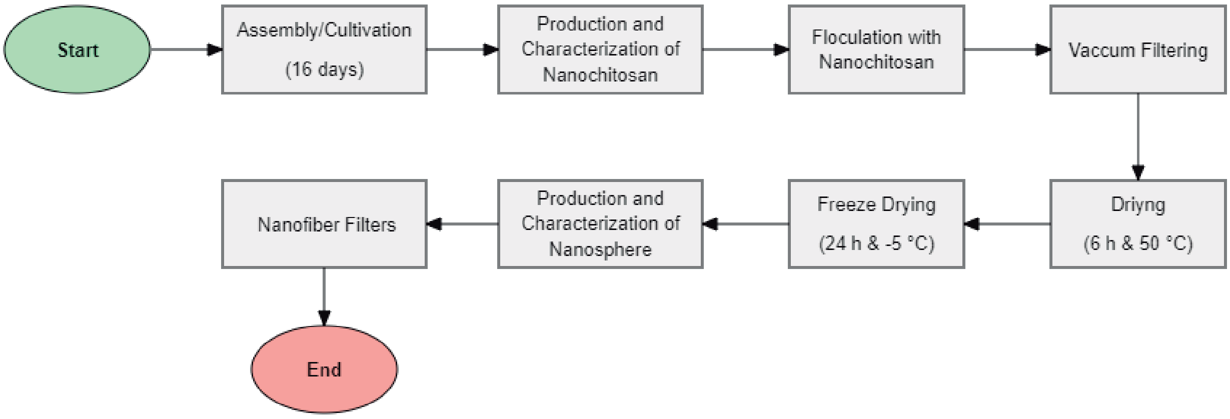
After cell counting was performed by optical microscopy, the biomass was flocculated with chitosan nanoparticles and vacuum filtration, where the wet microalgal biomass was removed. The solution was filtered through microfiber fabric, and then taken to an oven for 6 h at a temperature of 50 °C to perform drying.

After the drying procedure, the biomass was manually milled in a porcelain crucible, and sieved with a mesh diameter of 45 µm to separate larger granules.

The resulting biomass of this process was stored for later use in the preparation of nanospheres to be used in the making of the microalgal filter.

The scope of the analysis, where the steps considered for this study are delimited (production chain with a reference flow of 1 kg of biomass, to establish a functional unit of 5 L of cultivation, aiming at the production of a filter), are presented in Figure 1, according to the flowchart below.

Figure 1 - Flowchart of the process steps.



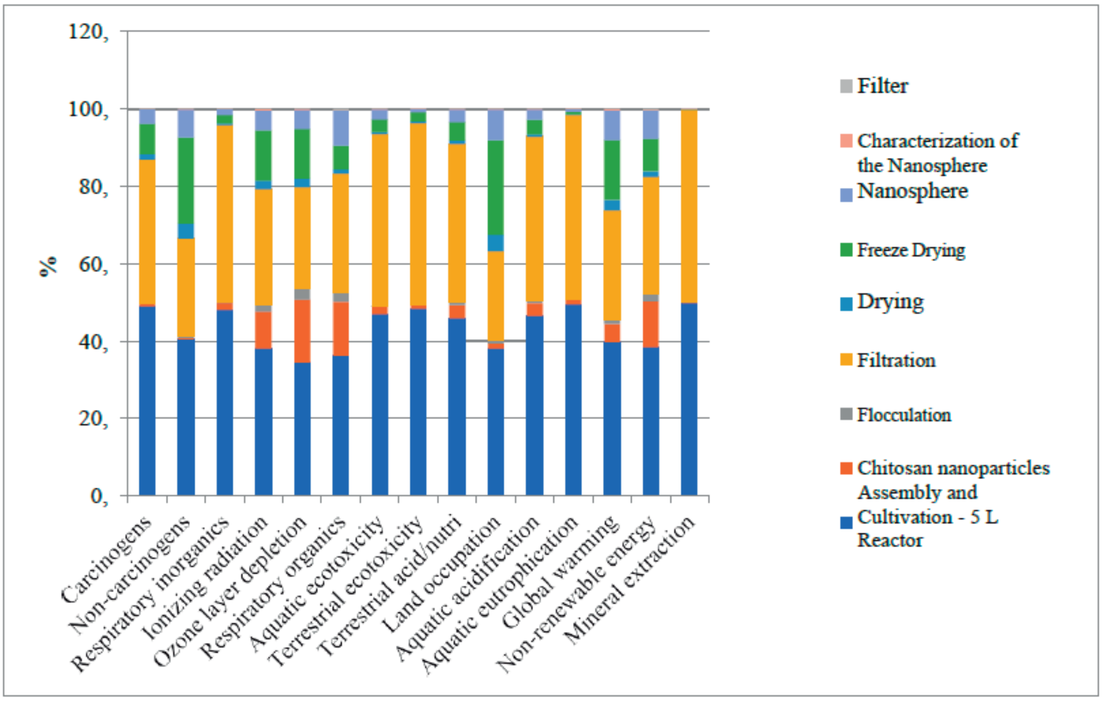
Source: Author's Construction

For these steps, the "Impact 2002+" method evaluated 15 impact indicators: carcinogenic, non-carcinogenic, inorganic respirable, ionizing radiation, ozone layer depletion, organic respiratory, aquatic ecotoxicity, terrestrial ecotoxicity, soil acidity, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, and mineral extraction.

RESULTS E DISCUSSIONS

The first results found in the LCA, illustrated in Figure 2, show the evaluations of the steps performed in this work, according to the impact indicators, according to the "Impact 2002+" method.

Figure 2 - Characterization of Impacts



Source: "Impact 2002+"

The impact categories that stood out the most regarding the release of particulates into the atmosphere through the completion of the steps are carcinogenic, non-carcinogenic, inorganic respirable, ozone layer depletion, organic respirable, global warming, and non-renewable energy.

Within the category of carcinogens (Kg C_2H_3Cl eq), which are particulates released into the atmosphere, we have a total of 1.81 kg C_2H_3Cl eq particulates released, where we can find about 0.887 kg of particulates released during the assembly of the closed system and cultivation; preparation and characterization of chitosan nanoparticles released the equivalent of 0.00994 kg; flocculation process 0.00517 kg, filtration 0.672 kg, drying 0.0245 kg, lyophilization 0.143 kg, nanosphere preparation 0.0674 kg, nanosphere characterization 0.000912 kg and filter production 0.00175 kg.

The release of carcinogenic particulates expresses the effects of transmitted emissions of carcinogenic substances supplied to the air, water, and soil, being it. Any chemical, physical or biological agent that can cause cancer. Examples of chemical carcinogens: substances in tobacco, certain chemical solvents. Examples of physical carcinogens are ultraviolet radiation and radioactivity (SENAI, 2003).

For non-carcinogenic we have a total of 3.91 Kg C_2H_3Cl eq of particulates released divided between: closed system assembly and cultivation 1.58, chitosan nanoparticles 0.0114, flocculation 0.0242, filtration 0.983, drying 0.15, lyophilization 0.87, nanosphere 0.281, nanosphere characterization 0.0045, filter 0.00379.

Inorganic Breathable (Express the effects caused by the emissions of inorganic substances such as particulate matter, sulfur, and nitrogen oxides to the atmosphere), are expressed in PM 2.5 eq (fine particulate matter, are a type of inhalable particles, with a smaller diameter at 2.5 μm) and constitute an element of atmospheric pollution) has a total of 0.0418 kg of particulates released during the performance of the steps: assembly and cultivation 0.0201, chitosan nanoparticles 0.000738, flocculation 0.000135, filtration 0.0191, drying 0.000164, lyophilization 0.000952, nanosphere 0.000582, nanosphere characterization, $3E^{-5}$, filter $1.94\ E^{-5}$. The suspended particles are responsible for a high number of phenomena from the meteorological point of view. They behave like condensation nuclei, favoring the formation of clouds and modifying the microclimate of some regions. From a sanitary point of view, they are responsible for acid mists production, which represents a danger for people affected by chronic bronchial diseases. It exerts a pernicious influence on the vegetation, as it is deposited on the leaves, hindering the normal development of many biological activities (photosynthesis and respiration) (SENAI, 2003).

For the category of damage and destruction of the ozone layer, expressed in Kg CFC-11eq, we have a total of $1.35\ E^{-6}$ divided between the stages: assembly and cultivation $4.66\ E^{-7}$; chitosan $2,2\ E^{-7}$ nanoparticles; flocculation $3.75\ E^{-8}$; filtration $3.56\ E^{-7}$; drying $2.99\ E^{-8}$; lyophilization $1.74\ E^{-7}$, nanosphere $6.64\ E^{-8}$; characterization of the nanosphere $2.67\ E^{-9}$ and filter $7.61\ E^{-10}$.

The ozone layer constitutes a "natural solar shield" as it filters harmful ultraviolet (UV) rays from the sun before they can reach the surface and cause harm to humans and other life forms. (WWF, 2015) The ozone layer constitutes a "natural solar shield" as it filters harmful ultraviolet (UV) rays from the sun before they can reach the surface and cause harm to humans and other life forms (WWF, 2015). With the damage, UV rays manage to reach the Earth and thus reduce the quality of life of humans, animals, and plants, harming their growth and health (MMA, 2015).

Respirable organic (Kg C_2H_4 eq), characterized by the emission of organic pollutants into the air, being them volatile organic compounds or particulate matter, we have a total of 0.00771 divided between the steps: assembly and cultivation 0.0028; 0.00107 chitosan nanoparticles; flocculation 0.000173; filtration 0.00238; drying $8.21\ E^{-5}$; lyophilization 0.000477, nanosphere 0.00069; characterization of the $1.14E^{-5}$ nanosphere and $2.86E^{-5}$ filter.

For the global warming category expressed in kg CO_2 eq (equivalent indicator). We have a total of 24.1, divided between the stages: assembly and cultivation 9.57; chitosan 1,12 nanoparticles; flocculation 0.264; filtration 6.81; drying 0.642; lyophilization 3.73, nanosphere 1.85; characterization of the nanosphere 0.0443 and filter 0.0399. During the analysis, it may be that no CO_2 is emitted into the atmosphere, but it is an indicator of release and global warming. It can be highlighted that the CO_2 used during photosynthesis is listed as CO_2eq in the climate change category. The capture of CO_2 by microalgae is not a simple study. It is necessary to evaluate the photosynthetic efficiency to know the fixation capacity (KHAN *et al.*, 2009).

According to Khan *et al.* (2009), Ahmad *et al.* (2011), and Kumar *et al.* (2011), 1 kg of dry biomass produced by microalgae requires about 1.8 kilograms of CO_2. Khan *et al.* (2009) also emphasize an efficiency for CO_2 fixation of 10-50 times greater than terrestrial plants.

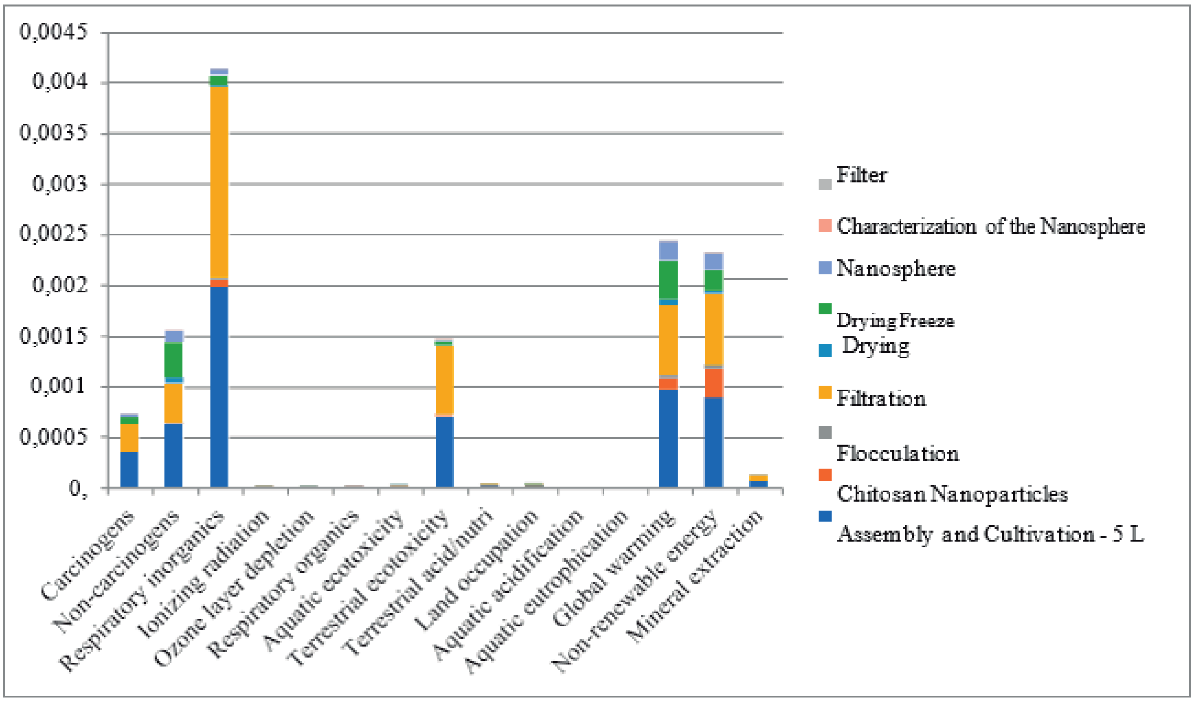
Within the non-renewable energy category, we have a total of 352 MJ, and the following data are available: assembly and cultivation 135 MJ; chitosan nanoparticles 41.9 MJ; flocculation 7.05 MJ; 106 MJ filtration; drying 5.12 MJ; lyophilization 29.8MJ; nanosphere 25.5 MJ; characterization of the nanosphere 0.648 MJ and filter 0.958 MJ.

The energy consumption present in the process has an unfavorable character for the environment, generating impacts and depletion of natural resources. Mitigating environmental impacts and, in particular, energy consumption, managing the use of solvents, and water management present challenges and opportunities, in some cases requiring solutions at the local level (GOUVEIA *et al.*, 2017).

Figure 3 shows the normalization profile of the risk categories present during the LCA process, noticing that the stages of assembly, cultivation, and filtration were the ones that significantly influenced the process. Among all the categories presented in the chart, the ones that stood out the most: were carcinogenic, non-carcinogenic, inorganic respiratory, terrestrial ecotoxicity, global warming, non-renewable energy, and mineral extraction.

The normalization step is conducted after the characterization of the damage and aims at the adequacy of the information for the procedure of weighting (SOUSA, 2008). It also allows the establishment of references of magnitude for each category considered, making it possible to visualize which impacts caused by the studied product are significant or negligible compared to the consequence of the reference area (BAUMANN; TILLMAN, 2004).

Figure 3 - Standardization profile of risk categories present during the LCA process



Source: "Impact 2002+"

Observing the data in figure 3 in the assembly/cultivation, filtration and lyophilization, due to the use of electric energy, there was a massive action within the categories of damages. On a smaller scale, there is an impact on the production of the filter. It is worth noting that the impact contribution is in the category of inorganic respiratory.

The use of microalgae goes beyond the various forms of contribution to the mitigation of water and air pollution, the production of microalgae must be carried out purely. The selection of biomass recovery technology is fundamental for the economic viability of production and includes filtration among the processes (LIMA *et al.*, 2016).

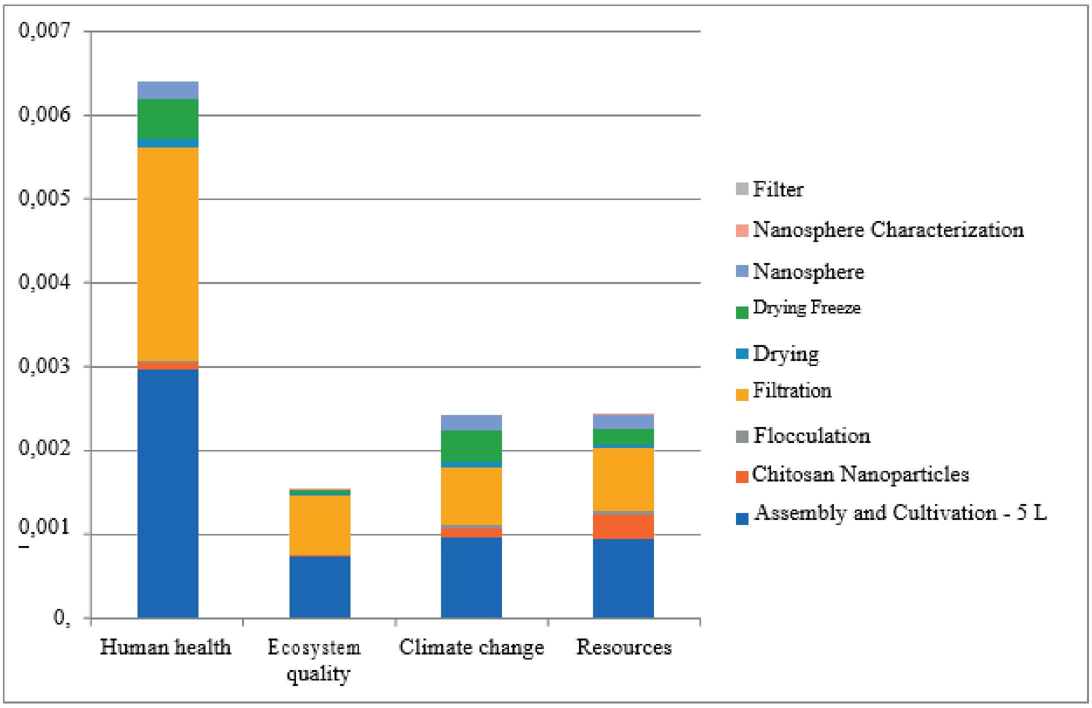
Also, in the cultivation stage, instead of using a closed system, a system built on uneven terrain would not be necessary to use a pump to drive the cultivation medium, reducing the impact of the use of electric energy due to having light bulbs fluorescent. Another alternative to reduce this impact would be to evaluate the possibility of using solar energy and develop new evaluation scenarios with this condition (LIMA *et al.*, 2016).

Studies have compared crops energetically and environmentally cultivations in open and closed systems of hypothetical operation. He concluded that cultivations in tubular photobioreactors consume significantly more energy than cultivation in open ponds (STEPHENSON *et al.*, 2010).

Microalgae can be manipulated to increase biomass productivity as well as produce other compounds of interest to improve various aspects of production responsible for economic or environmental impacts. Cleaner technologies that use flue gas as a source of inorganic carbon and wastewater as a culture medium, for example, reduce environmental impacts. Because of LCA, there are tools for identifying the best technological paths for microalgae production at the required scale. (LI *et al.*, 2011).

Figure 4 shows the results referring to the grouping of impact categories: human health, ecosystem quality, climate change, and resources.

Figure 4 - Grouping profile of the main risk categories present during the LCA process



Source: "Impact 2002+"

When examining the long-term life cycle impacts, one can see a comparison of the damage categories' results for the analyzed scenarios. The Human Health category of damage includes the science that an individual can be harmed either by reducing the time of life for early death or by reducing, temporarily or permanently, some of the organism's vital functions. The following steps were the most important in this category: system assembly, cultivation, flocculation, filtration, chitosan nanoparticles, lyophilization, and nanosphere.

The input that contributed the most to this result was electric energy, mainly in the carcinogenic and non-carcinogenic category, grouped in "Damage to Human Health" due to the life cycle of electric energy production being a process that is known to generate environmental impacts (LIMA *et al.*, 2016).

In the Ecosystem Quality damage category (PDF-*Potentially Disappeared Fraction indicator*), results equivalent to the following steps are also observed: system assembly, cultivation, filtration, chitosan nanoparticles, lyophilization, and nanosphere characterization (CLARENS *et al.*, 2010).

Climate Change expresses global warming caused by greenhouse gases in kilograms of CO_2 equivalent. System assembly, cultivation, production, flocculation, filtration, lyophilization, drying, and characterization of chitosan nanoparticles and nanosphere are all included in this category.

The Natural Resources damage category relates to natural resources and fossil fuels. This category includes activities: system assembly, cultivation, production, and characterization of chitosan nanoparticles, flocculation, filtration, drying, lyophilization, nanosphere, and filter.

Studies point out that the life cycle impacts on algae cultivation are sensitive to several inputs, such as the availability of renewable sources of nutrients and CO_2. In contrast, the model is generally insensitive to the availability of water and sunlight to reduce the impacts of algae cultivation to make it competitive with terrestrial crops producers will have to use some specific waste. as raw material in the production process (CLARENS *et al*., 2010).

Mitigating environmental impacts, especially energy consumption, presents both challenges and opportunities, where many can only be addressed at the local level.

Founding in the processes carried out and, in the methods, compared that the stage of assembling the cultivation and filtration stood out in terms of energy consumption, which was an impacting element, presenting high relevance in the categories of impacts.

According to the *US Energy Information Administration's* (EIA) projections published in the *International Energy Outlook* 2010 article, total global consumption of commercialized energy will increase by 49% by 2035. The study shows that, among energy sources, renewable will have the fastest growth in consumption in the period, reaching 2.6% per year. The upward trend in oil prices, concern about the environmental impacts of the use of fossil fuels, as well as strong government incentives to increase the use of renewable energies in many countries justify the prospects for the expansion of renewable sources worldwide (AEO, 2021).

CONCLUSIONS

The ACV analysis revealed that the filter made with a nanosphere of biomass flocculated with nanochitosan met the expectations of the paper's objective in terms of filtration and resistance tests during and after filtration, which is a positive.

But it was also possible to notice that the stages of system assembly, cultivation, filtration of microalgal biomass, and lyophilization must be reviewed and replaced by the relation to energy demand.

As can be seen, energy consumption harms the environment, resulting in impacts and depletion of natural resources. Because this impact was also efficient during the cultivation stage, fluorescent lamps could replace natural lighting or solar panels, and adjustments in the biomass production process like having this process in an open environment, mitigating and improving the results.

Through the information obtained from the LCA, it was identified which inputs or processes are impactful. In addition, the results confirm the potential of microalgae as an energy source but demonstrate the need to reduce the use of electrical energy.

Furthermore, a method for obtaining nanofibers was demonstrated in this work to create a new filter for water bioremediation that proves effective for the initially proposed goal: potability and microorganism retention.

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