

Life Cycle Impact Assessment of Microalgae and Synthetic Astaxanthin Pigments

Beate ZLAUGOTNE^{1*}, Fabian Andres DIAZ SANCHEZ², Jelena PUBULE³,
Dagnija BLUMBERGA⁴

^{1–4}*Institute of Energy Systems and Environment, Riga Technical University, Āzenes iela 12/1, Riga, LV-1048, Latvia*

Abstract – The marketability of fish depends on the visual appearance of the fish, so the feed ingredient pigment contributes to the nutritional value and visual appearance of the product. The benefits of a natural pigment derived from microalgae are the ecological benefits, as the culture can fix carbon and release oxygen. The economic aspect is a benefit of synthetic pigments. The Life Cycle Assessment (LCA) method was used to determine the environmental impact of natural and synthetic pigments. The results obtained from the LCA are expressed according to the impact categories defined by the Product Environmental Footprint Category Rules (PEFCR). A sensitivity analysis was also carried out comparing the environmental impacts of electricity generated with hydropower or using a field mix from Norway for the natural pigment. The total single score value for natural pigment is 1.17E+01 mPt and the largest impact is from sodium nitrate and electricity. The sensitivity analysis results for electricity from the country mix is 1.82E+01 mPt. The total single score value for synthetic pigment is 8.24E–01 mPt, with the largest impact from methanol. Synthetic pigments have a lower environmental impact than natural pigments, but a sensitivity analysis shows that the environmental impact can be reduced by choosing an alternative to electricity. It should be noted that the comparison presented represents a general comparison of alternatives, as the input data is derived from a literature review.

Keywords – Astaxanthin; fish feed; LCA; microalgae pigment; synthetic pigment; sustainability.

1. INTRODUCTION

Global food production and consumption dynamics have evolved rapidly in recent decades, including fish consumption worldwide [1]. The rapid development of the industry has a positive impact on socio-economic indicators, but the impact of the industry on the environment and sustainability is causing concern for the industry [2]. Feed is one of the key elements in the aquaculture industry to achieve sustainability [3]. Sustainability is a balance between environmental, economic and social development [4]. Problems with the environment have slowly and steadily developed from previous generations and the time has come when society must live more sustainably to preserve and rejuvenate the environment [5].

Fish cannot synthesize the pigment by themselves, so it is absorbed from the diet [6]. Pigments give fish an attractive colour and astaxanthin is a red pigment which increases salmon marketability due to the appearance of the fish [7]–[9]. Also, astaxanthin pigment has high antioxidant activity and is an important dietary component for adequate growth and

* Corresponding author.
E-mail address: beate.zlaugotne@rtu.lv

reproduction [7]–[9]. Under stressful conditions, astaxanthin production can be increased, as plants containing the pigment help improve stress response processes in animals [10].

Most pigments on the market are chemically synthesised pigments [11]. Synthetic astaxanthin has a lower price and a more complex production than natural astaxanthin in terms of production and cost [12]. Other advantages of synthetic astaxanthin are low antioxidant activity and high availability of synthetic astaxanthin, but the disadvantage is the use of hazardous chemical reagents, hence high environmental impact and not sustainable and renewable [13].

Microalgae are considered a potential source of valuable nutrients such as pigments, proteins, carbohydrates and lipid molecules [14]. Astaxanthin pigment can be obtained from a variety of microalgae species, but most of the astaxanthin pigment is obtained from the microalgae *Chlorella zofingiensis* or *Haematococcus pluvialis*, while *Chlorella sorokiniana*, *Tetraselmis* sp. and *Scenedesmus* sp. are minor producers of astaxanthin pigment [12]. The use of microalgae in aquaculture brings economic benefits and also creates ecological benefits, as microalgae culture can capture carbon and release oxygen, thus large-scale pigment production from microalgae can be considered a greenhouse mitigation process [15]. Other advantages of natural pigments include low environmental impact, sustainability and renewability, but disadvantages include the expensive biorefining process and production, the short lifetime of the bio-product and the low availability of natural astaxanthin, as well as the space and time-consuming cultivation of *H. pluvialis* [13].

The Product Environmental Footprint Categorization Regulations (PEFCR) are designed to allow the comparison of products from the same industry. The PEFCR of feed production has 18 categories that describe the impact on the environment, which is determined using a Life Cycle Assessment (LCA). The LCA carried out an environmental impact assessment of three different photobioreactor technologies used to produce astaxanthin from *Haematococcus pluvialis*, with energy consumption as the most influential factor, although the technologies have different technical solutions and productivity [16]. Another LCA is an environmental impact assessment, which compares extraction methods to extract astaxanthin from *Haematococcus pluvialis* microalgae, and the more sustainable method is the one with a higher yield, lower cost, fast turnaround time and medium environmental impact [17].

The study aims to carry out an environmental impact assessment and to compare a natural pigment and a synthetic pigment. LCA was used and environmental impacts were determined according to the impact categories defined by PEFCR. The study also includes an analysis of the sensitivity of the natural pigment when the type of electricity is changed and how this affects the environmental impact.

2. METHODS

LCA consist of goal and scope, inventory, impact assessment and interpretation results in interpretation, which are carried out by ISO 14040 [18] and ISO 14044 [19]. The used software is *SimaPro 9.4*.

2.1. Goal and scope

The scope of the study includes the evaluation of pigment that can be used in fish feed. The astaxanthin pigment alternatives are natural pigments from microalgae culture *Haematococcus Pluvialis* and synthetic pigments. Functional Unit in this LCA study is 1 kg of pigment.

2.2. System boundary

In this case, LCA is “cradle to gate” and used data from the literature review. In Fig. 1.is system boundaries for boundaries for natural pigment and data is from literature review [20]. In Fig. 2 is system boundaries for synthetic pigment and data is from literature review [21].

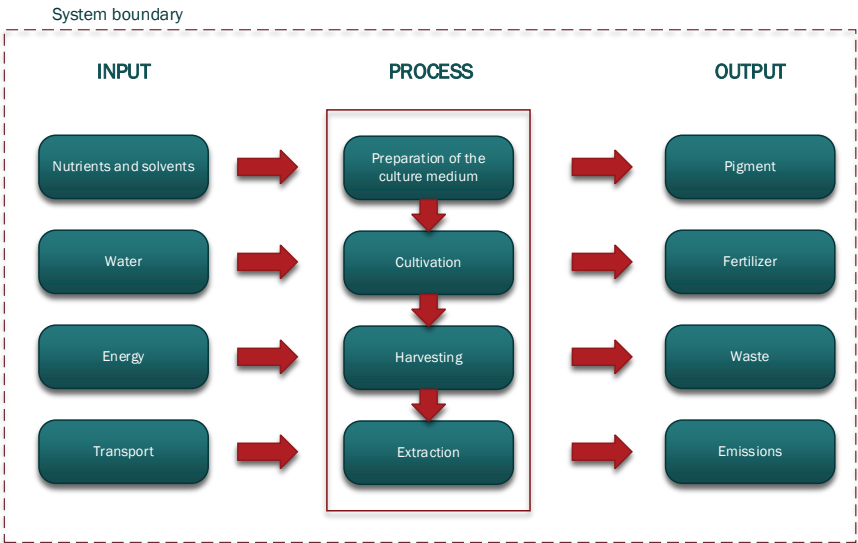


Fig. 1. System boundaries for the cradle-to-gate for microalgae pigment [20].

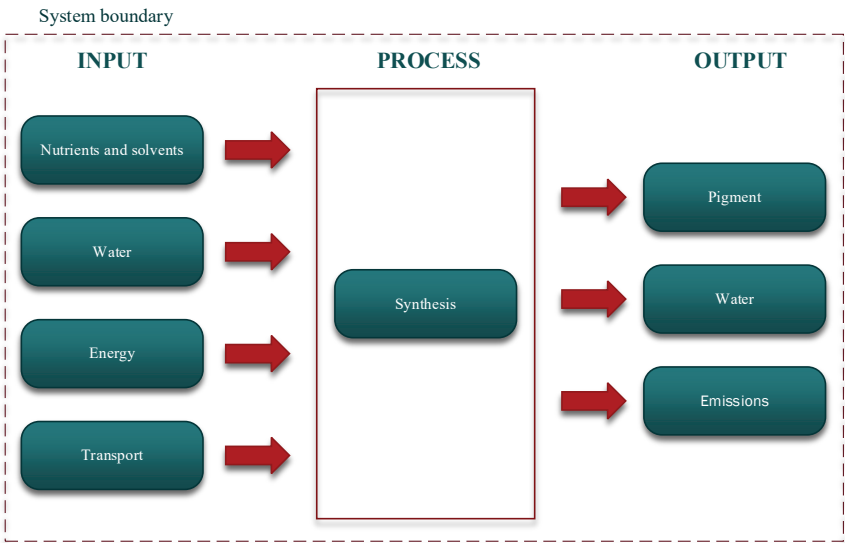


Fig. 2. System boundaries for synthetic pigment [21].

2.3. Life cycle stages

Life cycle stages consist of – the production of feed ingredients, transport of feed ingredients to the feed mill and feed production phases. The life cycle inventory energy and material inputs and outputs are quantified from literature analysis and available data in the *Ecoinvent v3.8* database.

The used data is from a literature review, but the assumption was made, that pigment is produced in Norway. Data in *SimaPro* were modelled to Norway or Europe and used energy – electricity is from hydropower, but as input data is used hydropower from France. As excluded processes, in this case, were packaging process because in literature review data about packaging were not found.

2.4. Life Cycle Inventory Data

Table 1 and Table 2 are inventory data for pigment alternatives from the literature. Mostly chemicals are used for Preparation of the culture medium phase. Data is collected for all production phases and in model is used market input values – transport is already taken into account and is recommended to be used in cases where specific data is not known. The input and output data are from the literature, so it is possible that the authors of the literature did not provide a complete accounting of the data.

TABLE 1. LCI FOR NATURAL PIGMENT [20]

Description	Amount	Unit
Input		
NaNO ₃	5.581	kg
CaCl ₂	0.364	kg
MgSO ₄	1.684	kg
NaCl	0.149	kg
C ₆ H ₈ O ₇	0.036	kg
Na ₂ CO ₃	0.597	kg
H ₃ BO ₃	0.017	kg
ZnSO ₄	0.001	kg
FeCl ₃	0.004	kg
MnCl ₂	0.012	kg
Biomass	0.021	kg
River/rain water	0.983	m ³
Air (excluding CO ₂)	543.4	t
CO ₂	0.325	t
Co-solvent (fish/vegetable oil)	5.838	kg
Electricity	2477.95	kWh
Output		
Nitrogen-rich fertiliser	0.539	kg
Phosphorous-rich fertiliser	0.353	kg
Air (excluding CO ₂)	543.4	t
CO ₂	0.3	t
NaNO ₃	0.111	kg
CaCl ₂	0.005	kg
MgSO ₄	0.024	kg
NaCl	0.002	kg
C ₆ H ₈ O ₇	0.0005	kg

Na ₂ CO ₃	0.008	kg
H ₃ BO ₃	0.0003	kg
ZnSO ₄	0.00001	kg
FeCl ₃	0.00005	kg
MnCl ₂	0.0002	kg
Products		
Microalgae pigment	1	kg

TABLE 2. LCI FOR SYNTHETIC PIGMENT [21]

Description	Amount	Unit
Input		
Phosphonium salt	2.83	kg
Aldehyde	0.35	kg
Methanol	7.91	kg
Solution of sodium methoxide	0.39	kg
Water	10	kg
Electricity	43.36	kWh
Products		
Synthetic pigment	1	kg

2.5. Life Cycle Impact Assessment

In *SimaPro 9.4* software used EF 3.0 method, which makes impact assessment according to PEFCR assessment categories.

3. RESULTS

LCA results for microalgae and synthetic pigment from characterization are shown in Table 3, it depicts impact score per environmental category.

TABLE 3. CHARACTERIZATION RESULTS

Impact category	Unit	Microalgae pigment	Synthetic pigment
Climate change	kg CO ₂ eq	3.35E+02	7.19E+00
Climate change – Biogenic	kg CO ₂ eq	6.30E–02	9.94E–03
Climate change – Land use and LU change	kg CO ₂ eq	4.00E–02	4.30E–03
Ozone depletion	kg CFC ₁₁ eq	5.48E–06	2.10E–06
Human toxicity, cancer	CTUh	4.96E–08	3.45E–09
Human toxicity, non-cancer	CTUh	5.37E–07	5.90E–08
Particulate matter	disease inc.	3.22E–06	1.90E–07
Ionising radiation	kBq U ₂₃₅ eq	3.11E+00	2.48E–01
Photochemical ozone formation	kg NMVOC eq	1.78E–01	2.43E–02
Acidification	mol H ⁺ eq	2.41E–01	3.01E–02
Eutrophication, terrestrial	mol N eq	6.47E–01	6.27E–02

Eutrophication, freshwater	kg P eq	1.02E-02	1.00E-03
Eutrophication, marine	kg N eq	7.07E-02	5.90E-03
Ecotoxicity, freshwater	CTUe	5.10E+02	1.38E+02
Land use	Pt	8.86E+02	3.07E+01
Water use	m ³ depriv.	2.39E+01	2.71E+00
Resource use, minerals and metals	kg Sb eq	3.23E-04	3.70E-05
Resource use, fossils	MJ	4.23E+02	2.84E+02

Fig. 3 shows weighted results for microalgae and syntenic pigment, expressed in mPt value. Pt is the unit of the eco-indicator, and 1 Pt is representative of one thousand of the annual environmental loads of an average European citizen.

Fig. 3 also shows weighted results for natural pigment production in impact category. For microalgae pigment very large impact is to climate change impact category, but for synthetic pigment the largest impact is to resource use fossils impact category.

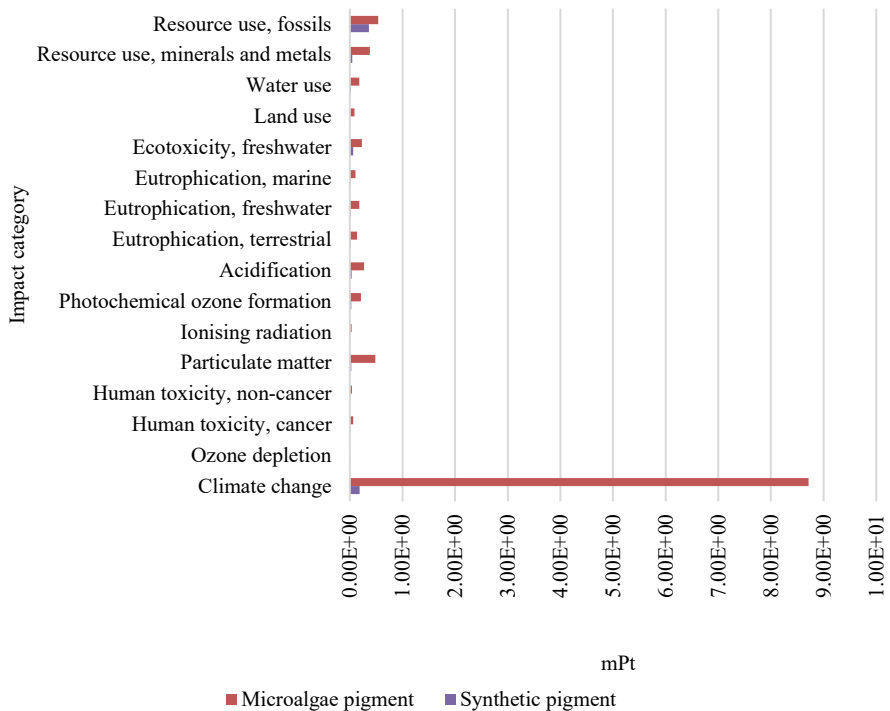


Fig. 3. Weighted results of microalgae and synthetic pigment for impact categories.

The total impact value for microalgae and synthetic pigment is presented in Fig. 4.

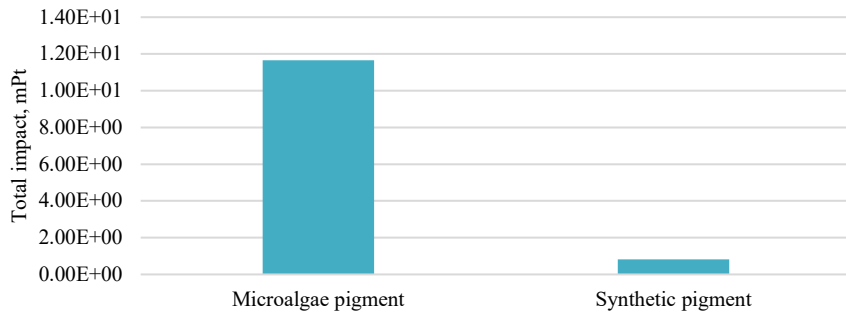


Fig. 4. Total impact for microalgae and synthetic pigment.

Fig. 5 and Fig. 6 illustrate contribution networks to identify environmental hotspots for pigment alternatives. Largest impact comes from sodium nitrate and electricity for microalgae pigment and for synthetic pigment largest impact is from methanol.

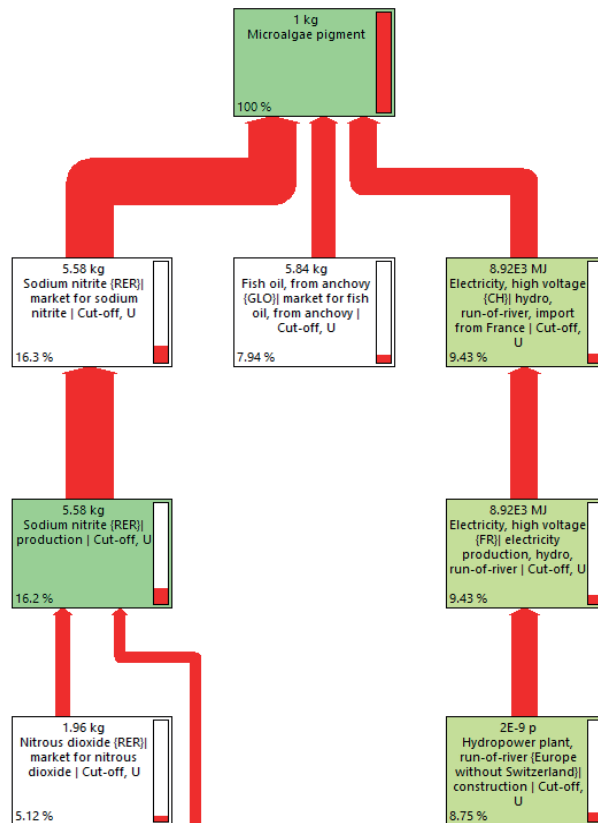


Fig. 5. Tree diagram for microalgae pigment.

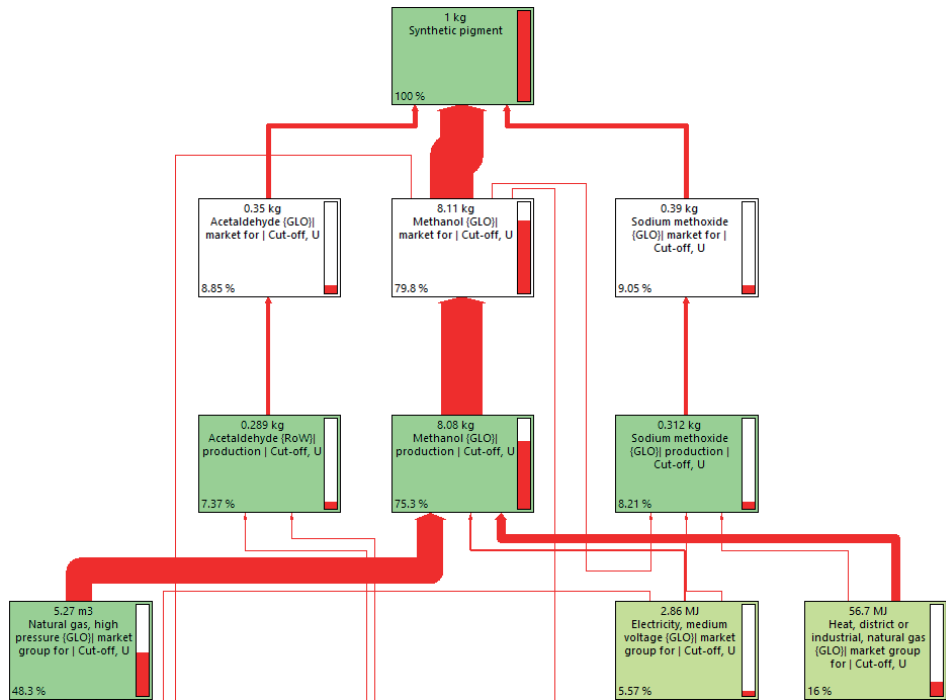


Fig. 6. Tree diagram for synthetic pigment.

3.1. Sensitivity analysis

A sensitivity analysis is performed for microalgae pigment. In this sensitivity analysis, changes were made only to electricity because it is second largest impact contributor. In original, electricity was produced by hydropower, but in sensitivity analysis, it will be compared by a country mix from Norway.

Fig. 7 depicts weighted results for microalgae pigment production in impact category. There is quite a difference in sensitivity analysis results. The largest difference in results is to impact category resource use minerals and metals and the impact category of climate change. Total impact result is $1.17\text{E}+01$ mPt for microalgae pigment using hydropower electricity, but for microalgae pigment using country mix electricity is $1.82\text{E}+01$ mPt.

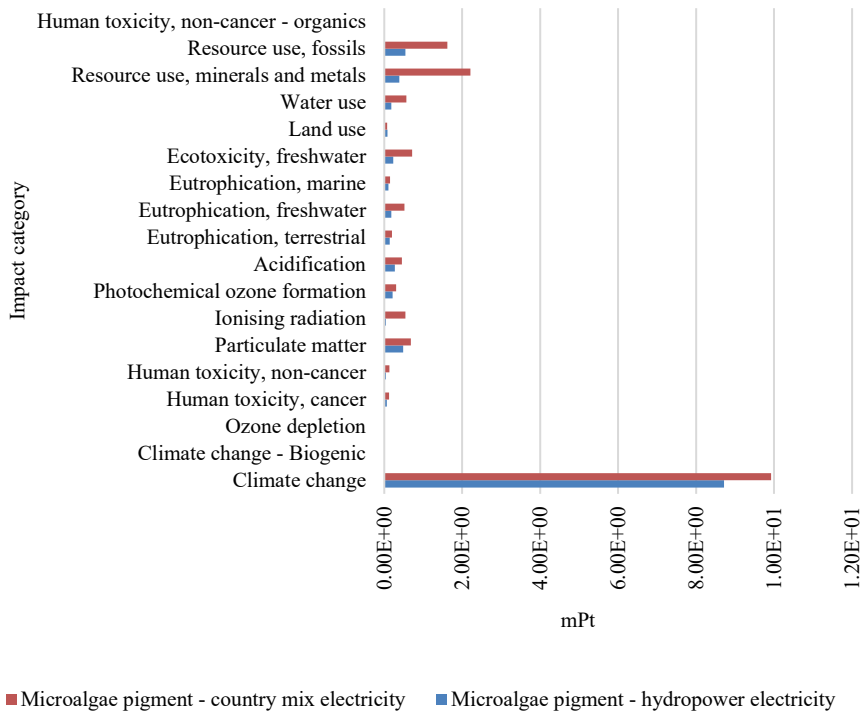


Fig. 7. Natural pigment weighted results for impact categories for hydropower electricity and country mix electricity.

4. CONCLUSION

An LCA study has been carried out for natural and synthetic pigments. The LCA study used data from the literature review. The document presents the results for the Functional Unit – 1 kg of pigment. From PEFCR most relevant impact categories are Climate change, Particulate matter, Acidification, Land use, Eutrophication terrestrial and Water use. Of course, the (marine) biodiversity impact category can also be determined with additional methods, but the results of this LCA study are according to PEFCR.

The total single score value for Microalgae pigment is $1.17\text{E}+01$ mPt, and the most significant impact is from sodium nitrate. The sensitivity analysis results for electricity from the country mix is $1.82\text{E}+01$ mPt. The total single score value for synthetic pigment is $8.24\text{E}-01$ mPt. The most significant impact is from methanol.

There are many differences between microalgae and synthetic pigments. Synthetic pigment is more economical than microalgae pigment, but microalgae pigment is sustainable and renewable, whereas synthetic pigment is not [22]. Microalgae pigment is more environmentally friendly because it uses natural resources, but the production of synthetic pigment uses different types of chemicals [22]. However, pigments will continue to be used because the product's visual appearance attracts buyers. Microalgae pigment production continues to develop, which means that the use of microalgae pigment could increase and thus become more economically viable as the problem of efficient production is solved.

ACKNOWLEDGEMENT

The research has been supported within the framework of the European Regional Development Fund project No. 1.1.1.5/17/I/002 “Integrated national level measures for strengthening interest representations for research and development of Latvia as part of European Research Area” by funding project No. 23-11.17e/21/165 “Non-Food Organic Resources-based feeds optimised for salmon until post-smolt stages” (NON-Fôr).

REFERENCES

- [1] Santeramo F. G. *et al.* Emerging trends in European food, diets and food industry. *Food Res. Int.* 2018;104:39–47. <https://doi.org/10.1016/j.foodres.2017.10.039>
- [2] Valenti W. C., Kimpara J. M., Preto B. de L., Moraes-Valenti P. Indicators of sustainability to assess aquaculture systems. *Ecol. Indic.* 2018;88:402–413. <https://doi.org/10.1016/j.ecolind.2017.12.068>
- [3] Campanati C., Willer D., Schubert J., Aldridge D. C. Sustainable Intensification of Aquaculture through Nutrient Recycling and Circular Economies: More Fish, Less Waste, Blue Growth. *Rev. Fish. Sci. Aquac.* 2022;30(2):143–169. <https://doi.org/10.1080/23308249.2021.1897520>
- [4] Bohvalovs G., Kirsanovs V., Blumberga A., Blumberga D. Bioeconomy Sustainability Index: A Fuzzy Cognitive Mapping Approach. *Environmental and Climate Technologies* 2022;26(1):1257–1267. <https://doi.org/10.2478/rtuect-2022-0095>
- [5] Akūlova L., Bukina A., Martinsone Ž. Environmental Management Challenges and Possible Solutions Regarding Chemical Pollution Caused by Households in Latvia: A Qualitative Pilot Study. *Environmental and Climate Technologies* 2020;24(3):534–544. <https://doi.org/10.2478/rtuect-2020-0122>
- [6] Idenyi J. N., Eya J. C., Nwankwegu A. S., Nwoba E. G. Aquaculture sustainability through alternative dietary ingredients: Microalgal value-added products. *Eng. Microbiol.* 2022;2(4):100049. <https://doi.org/10.1016/j.engmic.2022.100049>
- [7] Nagappan S. *et al.* Potential of microalgae as a sustainable feed ingredient for aquaculture. *J. Biotechnol.* 2021;341:1–20. <https://doi.org/10.1016/j.jbiotec.2021.09.003>
- [8] Yao Q., Ma J., Chen X., Zhao G., Zang J. A natural strategy for astaxanthin stabilization and color regulation: Interaction with proteins. *Food Chem.* 2022;402:134343. <https://doi.org/10.1016/j.foodchem.2022.134343>
- [9] Tuan Harith Z., Mohd Sukri S., Remlee N. F. S., Mohd Sabir F. N., Zakaria N. N. A. Effects of dietary astaxanthin enrichment on enhancing the colour and growth of red tilapia, *Oreochromis* sp. *Aquac. Fish.* 2022. <https://doi.org/10.1016/j.aaf.2022.06.001>
- [10] Raza S. H. A., *et al.* Beneficial effects and health benefits of Astaxanthin molecules on animal production: A review. *Res. Vet. Sci.* 2021;138:69–78. <https://doi.org/10.1016/j.rvsc.2021.05.023>
- [11] Patel A. K., *et al.* Algae as an emerging source of bioactive pigments. *Bioresour. Technol.* 2022;351:126910. <https://doi.org/10.1016/j.biortech.2022.126910>
- [12] Patel A. K., *et al.* Recent advancements in astaxanthin production from microalgae: A review. *Bioresour. Technol.* 2022;364:128030. <https://doi.org/10.1016/j.biortech.2022.128030>
- [13] Khoo K. S., *et al.* Recent advances in biorefinery of astaxanthin from *Haematococcus pluvialis*. *Bioresour. Technol.* 2019;288:121606. <https://doi.org/10.1016/j.biortech.2019.121606>
- [14] Silva S. C., Ferreira I. C. F. R., Dias M. M., Barreiro M. F. Review and Industry and Market Trend Analysis. *Molecules* 2020;25:3406:1–23. <https://doi.org/10.3390/molecules25153406>
- [15] Lu Q., Li H., Zou Y., Liu H., Yang L. Astaxanthin as a microalgal metabolite for aquaculture: A review on the synthetic mechanisms, production techniques, and practical application. *Algal Res.* 2020;54:102178. <https://doi.org/10.1016/j.algal.2020.102178>
- [16] Onorato C., Rösch C. Comparative life cycle assessment of astaxanthin production with *Haematococcus pluvialis* in different photobioreactor technologies. *Algal Res.* 2020;50:102005, 2020. <https://doi.org/10.1016/j.algal.2020.102005>
- [17] Papadaki S. G., Kyriakopoulou K. E., Krokida M. K. Life cycle analysis of microalgae extraction techniques. *Chem. Eng. Trans.* 2016;52:1039–1044. doi: 10.3303/CET1652174
- [18] ISO. ISO 14040: Environmental management – Life cycle assessment – Principles and framework. 2006.
- [19] ISO. ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines. 2006.
- [20] Pérez-López P., *et al.* Life cycle assessment of the production of the red antioxidant carotenoid astaxanthin by microalgae: From lab to pilot scale. *J. Clean. Prod.* 2014;64:332–344. <https://doi.org/10.1016/j.jclepro.2013.07.011>
- [21] Jeevanandam J., Choudhary V., Selvam J. D., Danquah M. K. The Bioeconomy of Production of Microalgal Pigments. In: Jacob-Lopes, E., Queiroz, M., Zepka, L. (eds) *Pigments from Microalgae Handbook*. Springer, Cham, 2020. https://doi.org/10.1007/978-3-030-50971-2_14
- [22] Kumar S., Kumar R., Kumari A., Panwar A. Astaxanthin: A super antioxidant from microalgae and its therapeutic potential. *J. Basic Microbiol.* 2022;62(9):1064–1082. <https://doi.org/10.1002/jobm.202100391>