Advanced Technologies for Bioeconomy: The Case of Microalgae Production

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Abstract

This article presents a meticulous examination of the global microalgae market, analyzing opportunities and prospects rooted in the scientific and technical interest in products derived from microalgae. The research systematically assesses the potential commercialization of these products across diverse regions worldwide, identifies the most promising microalgae strains, the product types themself, and their potential applications. An integral aspect of this research involves a forward-looking market forecast. The analysis of scientific and technical interest delves into publication activity, considering the yearly output of works in Scopus-indexed journals utilizing the main keyword "microalgae". This assessment is presented chronologically, categorically, and regionally, offering a nuanced perspective on the evolution of interest over time and in different geographical contexts. The commercialization potential is regionally scrutinized with a focus on key regions conducive to the development of microalgae-based products, namely the Americas (USA), Asia-Pacific (China, Japan), and Europe (Germany). This evaluation is interlinked with the prevailing market dynamics in each region, providing a holistic understanding of the market landscape.

This article contributes original insights derived from the analysis, offering a nuanced perspective on the microalgae market. It introduces a distinctive and informed viewpoint, enriching existing knowledge of microalgae markets. By categorizing the microalgae market based on applications, including nutraceuticals and pharmaceuticals, food and beverages, cosmetics, animal feed, and biofuels, the study identifies sectors exhibiting steady growth. Notably, each of these sectors contributes to the projected average annual growth rate of 6.8 % on the global microalgae market, forecasted to reach USD 2 billion by 2030. This growth trajectory emphasizes the growing importance and potential of microalgae-derived products in various industries and the importance of developing the bioeconomy as a whole.

Keywords: microalgae; market forecast; spirulina; chlorella; bioeconomy; global market; biomedicine; biotechnology; nutraceuticals; biofuel

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Introduction

Population growth together with urbanization and economic growth around the world is increasing the demand for food and energy resources, which in turn has a negative impact on the environment (Ramanauske et al., 2023). There are already serious environmental impacts such as depletion of energy and water resources, increased carbon dioxide emissions and pollution of water bodies (Moreira et al., 2023).

One of the possible ways to overcome the environmental crisis could be the application of the concept of circular economy. Realizing this, the developed countries of the world have already started their transition to circular economy, mainly focusing on the development of bioeconomy. Bioeconomy implies innovative use of sustainable renewable biological resources.

According to experts, the introduction of bioeconomy contributes to solving such important economic and environmental problems as depletion of natural resources, overuse of non-renewable resources, and climate change. The bioeconomy will also address challenges related to food security (Wydra, 2021; Machado Sierra et al., 2021; Ramírez et al., 2020; Parveen et al., 2023). Aimed at a global transition to a resource efficient and low carbon economy (Kuppan et al., 2023; Parveen et al., 2023), the bioeconomy has the potential to become a major new industry, displacing previous ones (Befort, 2020; Fernandez et al., 2021).

The Food and Agriculture Organization of the United Nations proposes to define bioeconomy as "knowledge-based production and use of biological resources, biological processes and principles of sustainable provision of goods and services in all sectors of the economy". Recently, the term "bioeconomy" has been increasingly used not only in science (Bugge et al., 2016), but also in management decisions at the state level (Pahun et al., 2018).

The European Commission (EC) expects the bioeconomic transition to have both environmental and socioeconomic benefits. Decisions on future biomass utilization pathways will strongly influence the characteristics of the future bioeconomy in terms of sustainability. (Asada et al., 2020). That said, according to (Bauer, 2018) there are various transformational pathways to transition to a bioeconomy and none of them are straightforward.

The concept of bioeconomy can be defined as an economy in which "the basic building blocks for materials, chemicals and energy are derived from renewable biological resources" (McCormick, Kautto, 2013). The use of biomass to replace synthetic products will have a positive impact on the environment and human health. For example, (Ahmad et al., 2021) reports that the concept of microalgae bioeconomy includes the use of algal biomass as an important component for the production of biofuels and other products using biorefineries. In the described example, biofuel production will be able to reduce CO2 emissions by 80%.

Microalgae are single-celled eukaryotic microscopic organisms capable of converting solar energy into chemical energy through photosynthesis. In addition, microalgae, also known as microphytes, produce about half of atmospheric oxygen and are able to utilize carbon dioxide for photoautotrophic growth. As the initial link in the food chain, microalgae provide energy to all trophic levels (Ponnuvel et al., 2023; Masojídek et al., 2023; Parveen et al., 2023; Chunzhuk et al., 2023).

Due to its rich energy content and high growth rate, research continues towards the development of technologies to enable the production of biofuels from microalgae (Hossain et al, 2019). Thus, microalgae-based fuels are environmentally friendly and have a high potential to fix carbon dioxide from the atmosphere (Onyeaka et al., 2021).

The use of bio-based packaging materials derived from various natural resources such as biomass, microorganisms or microalgae have shown high efficiency of packaging with improved physical characteristics (Kumar et al., 2022). Algae, including microalgae, provide a good alternative for natural production of many industrial products. In such production, the harm to the environment is significantly reduced. Microalgae are among the best among biomass-derived feedstocks for biopolymer production, while outperforming petroleum-based synthetic polymers. Microalgae-based biopolymer has improved mechanical properties compared to petroleum-based polymers. Thus, algae are potentially contributing to the bioeconomy leading to a circular bioeconomy on a global scale (Das et al., 2021).

According to (Khan et al., 2018; Fernandez et al., 2021) microalgae can be a rich source of carbon compounds that can be used in cosmetics, pharmaceuticals, and food supplements.

Microalgae are a rich source of carbohydrates (e.g., starch and glucose), proteins, fiber, essential acids, and vitamins B1, B2, B5, B6, B9, A, C, and E. Adding microalgae to human food has therapeutic effects on various health problems. For instance, eicosapentaenoic acid, a constituent of microalgae, promotes brain development in infants. Thus, in the context of global population growth, microalgae represent reliable substitutes for animal and plant products (Barkia et al., 2019; Garrido-Cardenas et al., 2018).

Studies in the field of medicine and pharmacology have reported high efficacy of microalgae in the prevention and treatment of many diseases of the immune, endocrine, digestive, cardiovascular and nervous systems of humans and animals. According to (Abeer et al., 2015) Spirulina Platensis and its extract have demonstrated therapeutic properties such as the ability to prevent cancer, reduce blood cholesterol levels, and provide protection against the harmful effects of radiation. Research in recent years shows that algae can also be used to target the biosynthesis of a range of compounds. For example, spirulina is capable of synthesizing iodine-containing

compounds of hormonal nature, such as thyroxine and triiodothyronine, which in turn are easily absorbed in the human body (Enzing et al., 2014).

In the pharmaceutical industry, microalgae are extensively used to produce capsule shells, diagnostic agents, vitamins, antibiotics, polyunsaturated fatty acids, and antibacterial substances. They are capable of producing toxins that block bacterial growth (Abu Zaid et al., 2015; Fernandez et al., 2021).

There is a wide range of commercial applications of algae in cosmetology because of its high content of oils, pigments, antioxidants (Kuldipsinh et al., 2023). Microalgae produce 15-100 times more oil per hectare than any other plants, and the negligible amount of lignin makes processing more efficient and easier (Maltsev et al., 2017).

In addition, the potential contribution of microalgae to emerging industries such as biomaterials, various agriculture related products, biofuel production and services such as wastewater and industrial gas treatment is described (Fernandez et al., 2021).

The global agricultural sector is actively adopting resource efficient animal husbandry and feeding technologies (Fernandez et al., 2021).

Feed enriched with microalgae biomass has a positive effect on animal physiology, improving the immune system of animals, reproductive capacity, and weight gain (Remize et al., 2021). In addition, the use of microalgae is a solution to the problem of unbalanced diets of farm animal feeding (Navarro et al., 2016).

In the USA, farms are provided with algae ponds, where animal waste is utilized using algae (Makarova et al., 2009). In particular, microalgae represent an important factor in the biological indication of environmental conditions (O'Neill, Rowan, 2022, Cid et al., 2013).

Thus, the role of microalgae in the modern world is great. Based on the above, the key applications of microalgae can be summarized as follows (Fig. 1).

Considering the emerging progress in modern biotechnology, the main focus is on the development of microalgae for the production of cost-effective bio-renewable energy sources with high added value (Singh et al., 2022).

As noted earlier, microalgae have been extensively utilized in the production of biofuels. Note that algae are characterized by rapid growth, far outpacing the growth of plant food crops (Ivanova et al., 2020). This type of biomass is grown in areas unsuitable for crop production, being a waste-free, energy clean, energy- and resource-saving way of energy production. The yield of microalgae in terms of biomass and the amount of lipids exceeds the yield of land plants by dozens of times (Vlaskin et al., 2018). As a source of bioenergy, microalgae demonstrate high efficiency under minor environmental constraints (Zhang et al., 2022). It should be noted that microalgae cultivation does not require resources such as soil, fresh water, pesticides and fertilizers. Microalgae can be grown in both salt water and wastewater (Khan et al., 2018).

Lipids in microalgae can be utilized to produce gaseous fuels (hydrogen and biogas), liquid fuels (ethanol) and liquid hydrocarbon fuels (Sanghamitra et al., 2021).

Thus, microalgae have great potential as a low-cost and energy efficient source of biofuels. According to the modern classification of biofuels presented in the work (Chernova et al., 2010), the fuel produced using microalgae is called third generation biofuel. This type of fuel has an advantage because microalgae have a high growth rate, they do not require high quality land for their cultivation, and the lipids included in microalgae are highly productive.

The development of microalgae biomass energy at this stage includes the production of biodiesel from microalgae lipids by transesterification (Vignesh et al., 2021), the production of methane by anaerobic digestion (Qi et al., 2017), and the production of hydrocarbons or crude oil and similar substances by gasification and pyrolysis.

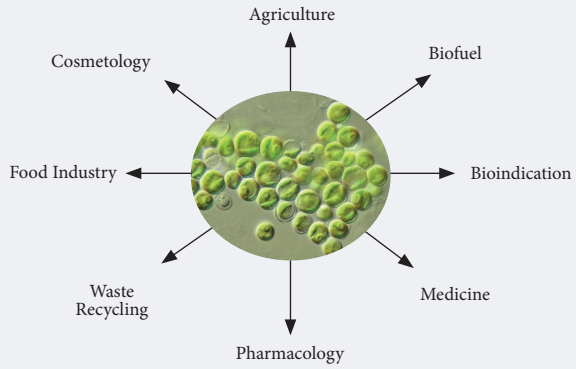
Despite all the above advantages, researchers have not been able to produce microalgae-based biofuels at a competitive cost at present. According to (Piligaev et al., 2014) there is a deterrent to large-scale production of third generation biofuels due to high costs compared to the production of fuel from conventional feedstocks. In addition, the reasons for low economic efficiency include such factor as lack of optimal cultivation technology (Strebkov et al., 2012).

However, the increasing interest in biofuel production during the last decade is directly related to several reasons. Firstly, the manufacture and use of biofuels is linked to the prospect of reducing carbon dioxide emissions. Secondly, there is a global increase in demand for hydrocarbon raw materials, while their reserves continue to be depleted. Specialists note that at current rates of consumption, oil reserves will be sufficient for no more than 40 years, and natural gas for 60 years. (Vorob'ev et al., 2015)

Thus, microalgae offer almost unlimited opportunities for the development of modern bioeconomy, given their metabolic flexibility and high rate of biomass yield, even when grown under harsh conditions, such as wastewater treatment or flue gas utilization. (Fernandez et al., 2021) Microalgae can play a crucial role in environmental protection due to their efficient CO2 capture and their potential as a solution for a carbon negative economy (Mendonça et al., 2024). In turn, circular bioeconomy directs the best optimal utilization of the resulting microalgae biomass to create a sustainable and environmentally friendly system (Ahmad et al., 2021).

Considering the wide range of applications of microalgae, market research on microalgae-based products has important scientific, economic and practical significance.

Figure 1. **Applications of microalgae products**



Source: authors.

Purpose of the study

The purpose of this study is to conduct a meticulous examination of the global microalgae market with the aim of providing comprehensive insights into the opportunities and prospects arising from scientific and technical advancements in microalgae-derived products. The research seeks to systematically evaluate the potential commercialization of these products across diverse regions worldwide by identifying the most promising microalgae strains, categorizing product types, and exploring their applications.

Key objectives include:

1. *Scientific and Technical Assessment:* To gauge the level of scientific and technical interest in microalgae, the study involves a detailed analysis of publication activity in Scopus-indexed journals. This assessment is conducted chronologically, categorically, and regionally to provide a thorough understanding of the evolving landscape of microalgae research.

2. *Commercialization Potential:* The research aims to assess the commercialization potential of microalgae-based products, focusing on key regions deemed most prospective for development: the Americas (USA), the Asia-Pacific region (China, Japan), and Europe (Germany). The evaluation is intricately linked to the current market dynamics of each region.

3. *Market Forecast:* A forward-looking market forecast is integral to the study, providing insights into the anticipated growth trajectory of the global microalgae market. This forecast considers factors such as historical trends, market dynamics, and the identified commercialization potential to project the market's future size and value.

Value

This article adds significant value to the existing body of knowledge on microalgae-based products and services. By conducting a thorough literature search and reviewing available materials, the study provides a comprehensive overview of the current state of research and industry trends related to microalgae.

The region-specific analysis of commercialization potential, focusing on key regions such as the Americas, Asia-Pacific, and Europe, adds practical relevance to the research. By linking these findings to current market dynamics, the article not only identifies promising opportunities but also provides actionable insights for stakeholders in the microalgae industry.

Thus, the study can be an essential resource for researchers, industry professionals, and policymakers seeking a comprehensive understanding of the field. The projected growth rates and market forecasts presented in the article contribute valuable foresight, making it a relevant and forward-looking resource in the domain of microalgae-based products and services.

Methodology

The research methodology employed in this study involved a literature search and a comprehensive review of available materials pertaining to microalgae-based products and services. The foundation of the study was laid through a meticulous examination of scientific papers, industry reports, and other relevant publications. This literature search aimed to capture the breadth and depth of existing knowledge and insights related to microalgae and their application and provide a contextual understanding of the evolution of interest in microalgae-derived products, offering insights into the trends and shifts that have shaped the field over time.

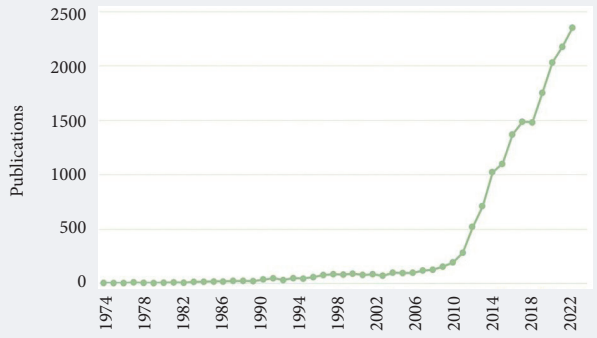
The systematic analysis of publication activity in Scopus-indexed journals, utilizing the main keyword "microalgae", formed a crucial part of gauging scientific and technical interest. This assessment was conducted chronologically, categorically, and regionally, providing a nuanced understanding of the dynamics influencing the research landscape.

The commercialization potential of microalgae-based products was evaluated through a region-specific approach, focusing on key regions identified as most promising for development—namely, the Americas (USA), Asia-Pacific (China, Japan), and Europe (Germany). This approach allowed for a detailed examination of the current market dynamics in each region and their implications for the commercialization prospects of microalgae products.

Market Analysis

For a deeper understanding of the trends in the development of the microalgae market, it is necessary to assess the scientific and technical interest in the subject under study. Thus, a systematic literature analysis of scientific research related to the study of microalgae, presented in the form of publications in journals indexed in the international scientific citation database Scopus, showed that from 1974 to 2022, 20 472 scien-

Figure 2. **Scientific papers related to microalgae research in Scopus journals by year**



Source: authors elaboration with data from Scopus Database.

tific documents with the word "microalgae" in the keywords were published worldwide.

The dynamics of scientific papers on microalgae research presented in Scopus-indexed journals is presented in Fig. 2:

At the same time, for 2000-2022, the majority of scientific research falls on such countries as China (6265), USA (4231), India (3120) (Fig. 3a, 3b). The number of studies affiliated with Russian organizations and scientists is 820 (17th place in the ranking by countries).

From 2000 to 2022, a significant number of scientific papers on microalgae (12,222) were published in environmental journals. A considerable number of scientific publications are presented in journals devoted to agricultural and biological sciences (11,741), chemical engineering (8,101), biochemistry, genetics and molecular biology (7,225), and energy (6,858).

It is worth noting, however, that while at the dawn of the current millennium (2000-2009), the bulk of research was in agricultural and biological sciences journals, between 2010 and 2019, more attention began to be paid to the role of microalgae in relation to environmental sciences. With the beginning of the current decade (2020-2022), the gap in favor of publications in environmental journals began to widen further (Figure 4).

Scopus Database

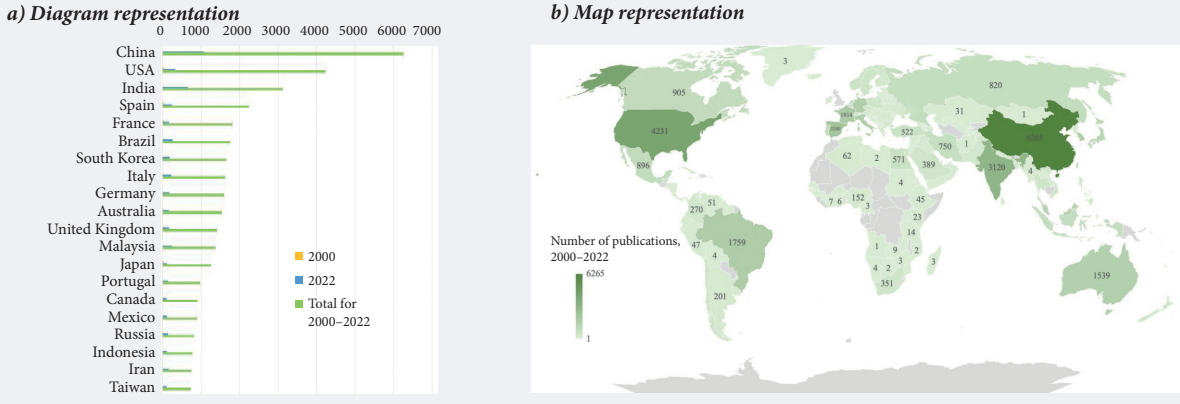
This trend is primarily due to the fact that the steady increase in general awareness and responsibility towards the environment plays a significant role in shaping the scientific agenda. In addition, environmental sciences are, for the most part, the connecting link between the rest of the branches of knowledge that are in one way or another related to microalgae.

The total number of publications related to microalgae in 2000 and 2022 by branch of knowledge is presented in Figure 5:

At the same time, the majority of articles in the above analysis results are devoted to the functions of microalgae in the environment (8,962 publications), their possible use for food and chemical production (4,275 and 4,271 publications, respectively). Delving deeper into the evaluation of research topics, it is found that articles are mainly focused on pigments (1861), proteins (1847), feeds (1818), drugs (1474), biofuels (1014) and biotechnology (892). In addition, articles on niche markets in biostimulants (13), bioplastics (14), vaccines (16), biofertilizers (22) and nanotechnology (59) have recently begun to appear.

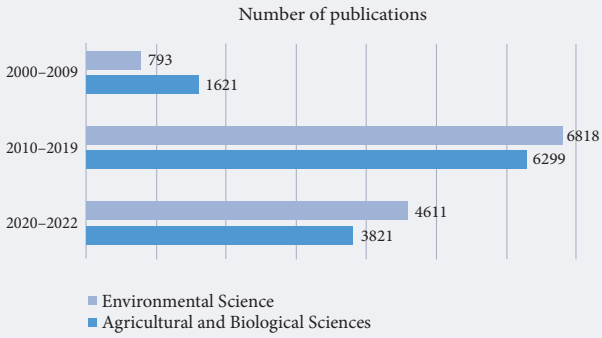
Figure 2 clearly shows a significant increase in the number of articles on this topic since 2010, which may be associated with the rapidly growing trend of microalgae application in the innovation sector of the economies of certain countries, including the use of microalgae as a raw material for biofuels.

Figure 3. **Scientific papers related to microalgae research in Scopus journals by country and territory**



Source: authors elaboration with data from Scopus Database.

Figure 4. **Dynamics of publication activity related to microalgae research in journals of agricultural and biological sciences and environmental sciences**



Source: authors elaboration with data from Scopus Database.

Table 1. **Main segments of the microalgae market**

Product type
• *Spirulina* • *Chlorella* • *Pufa* • *Lutein* • Other
Microalgae strain
• *Haematococcus Pluvialis* • *Phaeodactylum Tricornutum* • *Porphyridium Cruentum* • *Nannochloropsis* • Other
Application
• Food and drinks • Food additives • Pharmaceuticals • Cosmetics and personal care • Biofuels • Fertilizers • Feeds • Other
Region
• North America (USA, Canada, Mexico) • Europe (France, Germany, UK, Italy, Spain, Netherlands, Austria, Russia) • Asia-Pacific (Japan, China, India, Malaysia, Indonesia, South Korea) • Latin America (Brazil, Argentina) • Middle East and Africa (Saudi Arabia, UAE, Israel, South Africa)

Source: authors.

It is important to note that in the data presented above, a single publication may be affiliated with several countries and scientific sectors. Nevertheless, excluding duplication of publications could lead to incorrect interpretation of publication activity indicators.

When it comes to the global microalgae market, there is a similar dynamic for the academic community presented above.

Overall, the microalgae market is segmented on the basis of product type, microalgae strain, application, and region (PMR, 2023) (Table 1).

Market classification by region

Geographically, North America accounted for the largest share of the global microalgae market in 2022, followed by Europe and Asia Pacific[1]. The large market share held by North America is mainly attributed to the huge consumption of dietary supplements among the population, strict regulation on synthetic colorants, and increasing demand for natural cosmetics and biofertilizers. All this is supplemented by the presence of key microalgae biomass producers with huge production capacity in the region, especially in the U.S. (The Insight Partners, 2021).

The microalgae market by region (2018-2021, USD million) is depicted in Figure 6:

The U.S. microalgae market is estimated to be worth $285 million by the end of 2020. The country currently accounts for 29.14% of the global market. China, the second largest economy in the world, is projected to reach an estimated market size of USD 253.5 million in 2026. Other noteworthy geographic markets include Japan and Germany, each projected to grow at a CAGR of 4.2% and 4.7% respectively between 2020 and 2027[2].

USA

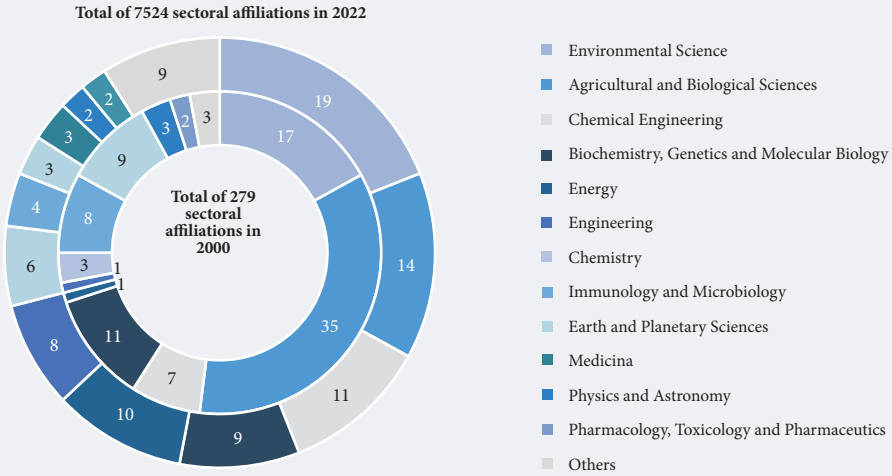
As mentioned above, the rapid pace of technological development and supportive government regulations have made North America the most promising market for the food and beverage, health and personal care sectors. Consumers in the U.S. and Canada are adopting healthy lifestyles and prefer products that offer health benefits. Thus, growing health concerns among consumers are driving the growth of the microalgae-based products market in the region. Owing to the increasing demand from customers for high quality products and services, companies are continuously focusing on innovation to serve their customers in the best possible manner. Moreover, high individual spending in North America has contributed to the growing demand for innovative food & beverages, personal care, and pharmaceutical products in the region. The growth of these industries directly influences the demand for microalgae-based products in the global market (The Insight Partners, 2021).

Favorable investment climate, elaborate investment attraction procedures, and advanced technologies have

[1] https://www.fao.org/in-action/sustainable-and-circular-bioeconomy/overview/en/, accessed 17.05.2024.

[2] https://www.researchandmarkets.com/reports/5790809/microalgae-global-market-report#rela1-5140359, accessed 11.09.2023.

Figure 5. **Scientific papers related to microalgae research in Scopus journals by industry (large circle - 2022, small circle - 2000)**



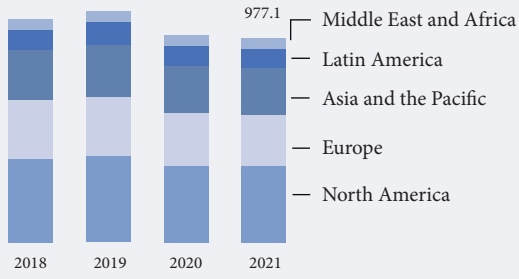
Source: authors elaboration with data from Scopus Database.

played a key role in the development of the microalgae market in the United States. Thus, the Emerging Markets Program[3], coordinated by the U.S. Department of Agriculture, provides support to U.S. agricultural producers to export their products (both traditional and innovative) to foreign markets, as well as the Borlaug Fellowship Program - aimed at supporting research and innovation, including biotechnology and GMOs[4].

In addition, government policies are expected to give even more momentum to natural ingredient producers in North America. For instance, the U.S. Food and Drug Administration (FDA) has approved the use of Lina Blue based on spirulina and beta-carotene derived from microalgae (Dunaliella salina) in candy as an alternative to synthetic colors (Chakraborty et al., 2019). Lina blue and beta-carotene extracted from Spirulina and Dunaliella salina microalgae impart blue, red, yellow or orange color to food products and are widely used in confectionery and dairy products, candy, chewing gum, ice cream and yogurt (Wang et al., 2022, Luzardo-Ocampo et al., 2021). In addition, Haematococcus pluvialis microalgae has been approved for use as a food additive ingredient in the U.S. and Canada[5].

As a result, by 2028, the market for microalgae-based products in North America is valued at USD 776.43 million (The Insight Partners, 2021) at a compound annual growth rate of 8.1% (2021-2028).

Figure 6. **Microalgae market by region (2018-2021, USD million)**



*Source: au*thorsbased on (The Insight Partners, 2021).

Asia-Pacific region (China, Japan)

Asia is estimated to witness the fastest CAGR in the market over a ten-year period due to the increasing use of microalgae-based products[6]. The application base of microalgae biomass is expanding and diversifying, which is encouraging manufacturers to explore opportunities to expand production capabilities (Sarwer et al., 2022). Moreover, increasing investments in the sustainability sector are expected to further boost the market growth (Khan et al., 2018).

The Chinese government is actively involved in implementing measures to promote the use of microalgae-based products, which is expected to boost the development (Chen et al., 2020). Overall, China is now one of the largest producers of microalgae biomass in the world (Chen et al., 2016).

The largest commercially produced microalgae by tonnage in China and in the world is spirulina (A. platensis and A. maxima). Spirulina was first cultivated in

[3] https://www.polarismarketresearch.com/industry-analysis/microalgae-market, accessed 11.09.2023.
[4] https://fas.usda.gov/programs/emerging-markets-program-emp, accessed 07.01.2024.

China in the 1970s, but technology limitations at the time did not lead to large-scale production. Since then, spirulina plants have been produced in almost every province and region, from southern Hainan to Inner Mongolia and from Yunnan to Zhejiang (Chen et al., 2016).

More than 60 spirulina plants with 750 ha of planting base produce 9,600 tons of dry weight of microalgae per year in China with an annual retail value of more than RMB 4 billion per year. Production costs are typically about one-tenth of the retail value, which increases when it reaches the consumer, taking into account operating profit, return on investment, marketing, formulation (e.g., tableting, etc.), packaging, delivery, distribution, advertising, retail sales, taxes, etc. (Chen et al., 2016).

Chlorella was first grown commercially in Japan as well as China in the 1960s, earlier than spirulina, but technology limitations at that time did not lead to large-scale production in China (Radmann et al., 2017, Chen et al., 2016). Over the past decade, China has also become one of the world's largest producers of chlorella, overtaking traditional production in Japan. Chlorella production is generally much smaller in volume than spirulina production, probably by a quarter, but the price per ton is much higher. Many spirulina facilities produce chlorella, usually as a smaller part of a larger spirulina production process. Chlorella production is technically more complex and expensive than spirulina because of the greater likelihood of contamination and the need for centrifuges to harvest these microscopic cells. This is in contrast to the easier collection of fibrous spirulina and fewer contamination problems due to the high bicarbonate environment. Chlorella is dried and sold similarly to spirulina as a dietary supplement, either in powder, tablet and capsule form (Chen et al., 2016).

Two other microalgae grown commercially in China are Dunaliella and Haematococcus, from whose biomass valuable carotenoids, beta-carotene and astaxanthin, respectively, are extracted. Dunaliella was first commercialized in Australia and Israel in the 1980s (Borowitzka, 2018).

The main existing market for astaxanthin is its sale as a feed additive for farmed salmon and trout to color fish meat (Stachowiak, Szulc, 2021). Meanwhile, the market price of synthetic astaxanthin is around 1000 USD/kg (Panis, Rosales Carreon, 2016).

Regarding the marketing of natural astaxanthin from microalgae, the only possible market for it is as a human food supplement, mainly because of its high selling price, almost 10 times the current price of synthetic astaxanthin (Panis, Rosales Carreon, 2016). The production of astaxanthin by Haematococcus pluvialis in China is developing rapidly, mainly in Yunnan and Hubei Province (Chen et al., 2016).

In Japan, the microalgae industry is not an industrial sector per se, as there is no direct business related to their collection, although it has potential for R&D applications such as absorbing CO2 emissions existing in the environment. Meanwhile, there are indirect sectors related to the production of microalgae biomass that can be processed into various products (Herrador, 2016).

Japan is one of the countries with the highest investments and expectations in the microalgae industry, focusing on the production of biomass-based products to address Japan's vulnerable energy supply situation as well as to open up new markets related to food, feed, and biochemicals (such as plastics). Major players such as DENSO Corporation, Euglena Corporation, ISUZU Motors Corporation, and All Nippon Airways are involved in the production of microalgae-based projects. The Japanese government is also involved in supporting these initiatives as well as universities such as the University of Tsukuba, which is a world leader in research and development that aims to develop microalgae technologies on various plants (Herrador, 2016).

In addition, Japanese scientists are investigating whether microalgae can remove radioactive cesium, iodine, and strontium from radioactively contaminated aquatic environments and reduce radioactive contamination in the Fukushima area. It has been determined that some species can absorb up to 89.2% of cesium; 41.3% of strontium and 65.9% of iodine (Fukuda et al., 2014).

Japan's New Energy and Industrial Technology Development Organization (NEDO) published a report in 2016 highlighting the importance of using microalgae for biofuel production, using sunlight energy to convert carbon dioxide into fuel as a renewable resource. The conversion efficiency is the highest among plant species. The report notes that "in the future, in order to reduce production costs, increase productivity per unit area, and reduce costs... a system for oil collection, recovery, and purification will be finalized," also indicating that "jet fuel" for airplanes will be produced (Herrador, 2016). There are even known cases of successful implementation of a project to replace traditional airplane fuel with environmentally friendly fuel produced from microalgae. Thus, in 2021, Japan's largest airlines performed domestic commercial flights using environmentally friendly aviation fuel derived from microalgae.[7]

[5] https://fas.usda.gov/programs/borlaug-fellowship-program, accessed 07.01.2024.

[6] https://www.meticulousresearch.com/product/europe-microalgae-market-5491, accessed 13.05.2023.

[7] https://www.transparencymarketresearch.com/microalgae-based-products-market.html, accessed 07.01.2024.

EU (Germany)

Europe held the second largest share of the global microalgae-based products market in 2020[8]. The demand for microalgae-based products in the region is growing due to factors such as significant growth in food & beverages, animal feed, pharmaceuticals & nutraceuticals, personal care products, and other end-use industries. The region has ample opportunities for market growth owing to rapid industrial development along with increasing R&D expenditure, which is expected to generally diversify the application base of microalgae-based products, which is also expected to drive market growth. Furthermore, rapid development of manufacturing base backed by improved economic activities and better investment opportunities will also fuel the growth of microalgae-based products in the regional market (Enzing et al., 2014).

Also noteworthy is the active development of environmental agenda in Europe, primarily related to the search for alternative energy sources to achieve the goals of the Paris Agreement[9].

The EU's current policy priorities promote the transition to a sustainable economy that balances the growth of economic activity, protecting natural resources and meeting the needs of a growing world population. The EU Bioeconomy Strategy (adopted in 2012 and updated in 2018) aims to implement a sustainable closed-loop bioeconomy across Europe and encourages the strengthening and development of EU biosectors and the pursuit of sustainable food and production systems (Vázquez-Romero et al., 2022). In parallel, the EU Blue Growth Strategy highlights blue biotechnology sectors among its priority objectives (European Commission, 2022).

In addition, the European Commission's Green Deal targets priority areas where the algae sector can make a relevant contribution. For example, to the EU's goal to become climate neutral by 2050, to the protection of biodiversity, to the development of a circular economy and to the farm-to-fork strategy for sustainable development in the food sector (European Commission, 2020).

Therefore, the European Union is actively involved in various projects to explore renewable resources, bioenergy and bioprocessing, including those related to microalgae (Enzing et al., 2014).

Germany accounted for the largest share of the microalgae market in Europe in 2021. Consumers in Germany are traditionally health-conscious, sensitive to environmental concerns, and willing to pay higher prices for more natural, environmentally friendly products with minimal processing. At the same time, this interest of German consumers in health and wellness products is fueled, among other things, by government education programs, media, and advertisements promoting healthy lifestyles[10].

As a result, the high increase in citizens' awareness makes food manufacturers think about producing and distributing healthy food and beverages.

However, there are a number of restrictions in the EU that result in only a small fraction of naturally occurring microalgae species being commercially exploited. It is argued that the rate of exploitation of new species is also hampered by administrative burdens, namely the need for any new products to go through the New Foods Regulation before they can be placed on the food market. In doing so, these procedures are costly and time-consuming. Yet, a number of companies are already cultivating microalgae on an industrial scale and have an established market (Araújo et al., 2021) (Table 2):

Food supplements and nutraceuticals (24%), cosmetics (24%) and feed (19%) are the main uses of microalgae biomass, accounting for 67% of the total utilization. Meanwhile, spirulina production is mainly directed towards food, food additives and nutraceuticals, accounting for 75% of the reported uses (Araújo et al., 2021).

Although commercial production of microalgae in the EU is well established, high production costs and technological limitations, as well as gaps in scientific understanding of large-scale algal cultivation, limit the commercialization of biomass as high-value products, except for large-scale low-cost applications such as fuels (Araújo et al., 2021).

The market value of microalgae biomass varies depending on several factors such as production system, production costs (energy and labor), geographical origin, certification schemes (e.g., organic production), and stage of the value chain (e.g., B2B or B2C sector) (Lucakova et al., 2022).

Meanwhile, the value of spirulina in the B2B sector (in terms of dry weight) and chlorella varies between 25-50 €/kg and 30-70 €/kg, respectively (Araújo et al., 2021; Verdelho Vieira et al., 2022). In contrast, the value in the B2C sector for both species varies between 150 and 280 Euro/kg (higher value for small packs, finished products) (Araújo et al., 2021).

For Nannochloropsis sp., the species most suitable as feed (Qiao et al., 2019; Premachandra et al., 2023), the B2B sector price values are in the range of 30-110 €/kg, while the market value in the B2C sector (as marine phytoplankton) can reach up to 1000 €/kg (Araújo et al., 2021).

The price of H. pluvialis in the B2C sector ranges from 150 to 300 €/kg, while the B2B price of pure astaxanthin oleoresin based on pure astaxanthin is in the

[8] https://www.greenairnews.com/?p=1239, accessed 13.05.2024.

[9] https://www.polarismarketresearch.com/industry-analysis/microalgae-market, accessed 11.09.2023.

[10] https://unfccc.int/sites/default/files/resource/The%20Long-term%20Strategy%20under%20the%20Paris%20Agreement.pdf, accessed 01.04.2022.

Table 2. **Companies cultivating microalgae on an industrial scale**

Microalgae types	Number of producing companies	Production volume (tonnes)
Spirulina	222	142
Chlorella sp.	30	82
Nannochloropsis sp.	25	21
Haematococcus pluvalis	17	66
Tysochrysis lutea	10	Less than 1
Dunaliella salina	8	2
Phaeodactylum tricornutum	8	4
Tetraselmis sp.	16	5
Scenedesmus sp.	9	n.a.
Porphyridium	7	Less than 1
Others*	37	n.a.

** Thalassiosira sp., Acutodesmus obliquus, Chaetoceros muelleri, Cyanidium caldarium, Euglena gracilis, Odontella aurita.*

Source: (Araújo et al., 2021).

range of 6,000-8,000 €/kg (Araújo et al., 2021). New applications of microalgae biomass are facing increasing market demand and still have room for significant increases in production (Barone et al., 2023).

Description of manufacturing companies

Currently, there are a significant number of companies producing microalgae-based products worldwide. At the same time, the main competitive advantages of the leading companies include:

- availability of their own innovative developments. For example, the Israeli company Algatech has developed a unique method of mass production of microalgae for the subsequent production of astaxanthin in the desert zones of Israel[11].
- high share of leading companies in the market of the most attractive segments.

For instance, some of the key players in the algal pigments market are: Earthrise Nutritionals, LLC (U.S.), Cyanotech Corporation (U.S.), Zhejiang Binmei Biotechnology Co., Ltd. (China), Bluetec Naturals Co., Ltd. (China), BlueBioTech Int. GmbH (Germany), Algatechologies Ltd. (Israel), EID Parry (India) Limited (India), DIC Corporation (Japan), Tianjin Norland Biotech Co., Ltd (China), AlgaeCan Biotech Ltd. (Canada), AstaReal AB (Sweden), Algae Health Sciences (USA), Sochim International SpA (Italy), DD Williamson & Co., Inc. (USA), Chlostanin Nikken Nature Co. Ltd. (China) and BASF Corporation (Germany) among others.

Along with large companies - leaders of the microalgae industry, new start-ups are also being actively created. Information about them is presented in Tables 3 and 4.

Prospects for market development

According to the United Nations, the world's population is expected to grow by more than 50% from 2000 (6.14 billion people)[12] to 9.7 billion in 2050 (United Nations, 2022), and thus the amount of food produced must double to meet the needs of this population (Henchion et al., 2017). Meanwhile, meeting the protein needs of the huge population is the key aspect and growth driver of the microalgae market (Fatima et al., 2023).

Moreover, there is currently an explosive growth of interest in microalgae biotechnology globally, with start-ups and commercial enterprises successfully operating abroad to produce microalgae biomass and bioproducts from it (Garrido-Cardenas, 2018). Examples of successful realization of such projects are AlgaePARC (Amsterdam, Holland), Cyanotech (Hawaii, USA), Roquette Klötze GmbH&Co. KG (Klötze, Germany), AstaREAL AB (Gustavsberg, Sweden), Algatech (Keturah, Israel).

Scientists have also largely succeeded in unlocking the potential of microalgae for the production of a wide range of substances and materials, from cosmetics and food products to various types of plastics and biofuels (Kandasamy et al., 2022). An undeniable advantage of microalgae is the environmental friendliness of their application and production (Parveen et al., 2023).

Microalgae are increasingly being tested as nutraceuticals in the feed industry, especially in aquaculture, as a means to improve the immune response of marine animals (Khan et al., 2018; Camacho et al., 2019; Das et al., 2021). Unfortunately, commercial utilization has encountered difficulties due to high production costs associated with storage. In addition, the commercial use of microalgae as prebiotics in feed formulations has faced several challenges related to microalgae processing methods that have yet to be resolved to reduce production costs (Camacho et al., 2019).

Scaling up production is also still a major challenge. Currently, full-scale commercial microalgae-based production is only established for β-carotene and astaxanthin (Camacho et al., 2019). In spite of this, according to the bibliometric analysis carried out in the framework of this work, it is revealed that scientists are constantly conducting research to intensify the growth of microalgae and, consequently, increase their biomass.

According to a recent study by Persistence Market Research, the market for microalgae-based products is expected to grow at an average annual rate of 5.4%

[11] https://www.meticulousresearch.com/product/europe-microalgae-market-5491, accessed 13.05.2023.

[12] https://data.worldbank.org/indicator/SP.POP.TOTL?end=2000&start=2000, accessed on 08.01.2024.

Table 3. **List of international startups developing microalgae solutions**

Company name (Country)	Year of foundation	Description of activities
Brevel (Israel)	2022 (project establishment) 2017 (company establishment)	Produces plant protein adapted to the needs of the food industry.
Brilliant Planet (UK)	2022 (project establishment) 2017 (company establishment)	Develops a unique solution to reduce the world's carbon footprint: the company creates tanks of seawater, providing ideal breeding conditions for algae. The algae, in turn, can absorb carbon emissions in large quantities.
NewFish (New Zealand)	2020	Creation of food products using microalgae fermentation technology
Quazy Foods (Germany)	2021	Development of competitive, healthy, and sustainable microalgae-based functional ingredients while protecting aquatic ecosystems. Also sensory and nutritional optimization of microalgae strains for wide application in food products
PhycoWorks Ltd (UK)	2021	Creating valuable products from waste, accelerating the transition to a circular bioeconomy
Minus Materials (USA)	2021	Minus Materials is industrializing limestone formation. Utilizes microalgae, sunlight and seawater to capture and store carbon dioxide in the form of biogenic limestone. They reduce the formation of limestone quarries while isolating and storing carbon dioxide in the process
Algiecel ApS (Denmark)	2021	ALGIECEL utilizes natural microalgae organisms, a very compact and high-performance photobioreactor technology that fits into standard shipping containers, and a new revenue sharing business model offering carbon capture as a service
GC Lipid Tech (Canada)	2021	The company develops clean technology solutions using microalgae. GC Lipid Tech is committed to developing clean technology solutions using microalgae and providing the world with a variety of sustainable, efficient and safe biotechnologies
Ittinsect (Italy)	2020	Ittinsect specializes in the biotechnological processing of insects, microalgae and agricultural by-products to create highly effective and sustainable aquaculture feeds. The company's mission is to make aquaculture independent of marine resources by offering a product that provides fast and consistent fish growth, a robust immune system and less risk of digestive inflammation than traditional feeds. Ittinsect products produce 10% less CO2-eq emissions per kilogram than comparable conventional feeds, contributing to a lower environmental impact and helping to reduce stress on small pelagic fish
Sophie's Bionutrients (Singapore)	2017	The company grows microalgae inside bioreactors. This process can be controlled to produce protein in a matter of days. The company uses limited water and local food waste to produce protein from microalgae in metropolitan areas in many parts of the globe. Sophie's Bionutrients can also produce whole algae ingredients for a variety of food applications in the form of plant-based meats and functional foods
Realm (Germany)	2022	REALM is developing a new cost-effective approach to growing microalgae while treating wastewater and reducing freshwater demand
Algaenergy (Spain)	2009	AlgaEnergy started with the development of microalgae-based agricultural biostimulants in 2009, a world first. AlgaEnergy sells microalgae-based agricultural biostimulants worldwide. Each biostimulant consists of an optimized combination of different microalgae species in optimized proportions depending on their composition, which individually provide the necessary elements for the physiological development of the plants. The enormous biodiversity offered by microalgae, AlgaEnergy's knowledge, and the five cultivation technologies the company utilizes allow AlgaEnergy to select the ideal microalgae species depending on the desired product. But now AlgaEnergy's product line goes beyond their patented microalgae. The company offers a unique new class of crops that combine microalgae with plant nutrients and biologicals
SeaH4 (South Africa)	2021	A groundbreaking zero CO2 alternative to fossil fuels, ready for consumer use and requiring no investment in transportation infrastructure. SeaH4 fuel requires no changes to engines or distribution network
Algaementum (Portugal)	2023	Algaementum aims to create specialized cultivation sites in central-eastern Portugal in 2024. Where an abundance of sunlight, clean water and skilled human capital combine to provide unique opportunities for algae cultivation. Free from plastic, toxins and heavy metal pollution, Algaementum is committed to producing the most nutritious food (and feed) ingredients in accordance with the EU's high ethical and organic standards
Carbon Kapture (UK)	2020	Carbon Kapture is a startup focused on carbon capture and sequestration through a global network of seaweed farms

Source: authors.

and exceed a valuation of USD 5 billion by 2033 (PMR, 2023). However, according to the authors of this article, the value may be more conservative (US$2 billion by 2030), taking into account the compound annual growth rate (averaged by analysts' data at 6.8%) and the 2021 base effect of US$977.1 million.

The South Asia and East Asia market will expand at a CAGR of 7.8% and 6.8%, respectively, during the forecast period 2021-2031 (PMR, 2023). North America and Europe will continue to dominate the market with market shares of 28.8% and 27.9%, respectively (PMR, 2023).

The European market will grow significantly over the forecast period due to increasing opportunities for the use of microalgae, especially spirulina and chlorella, in the production of health and nutritional products,

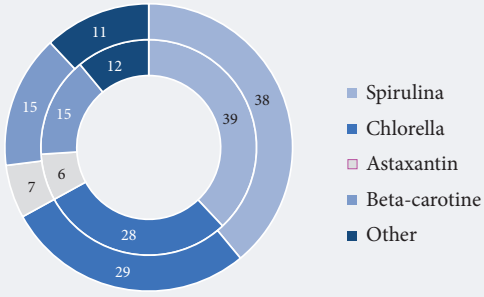
Table 4. **List of Russian startups developing microalgae solutions**

Company name (Year of establishment)	Revenue (2022, thousand rubles)	Company description
Biotrek (2022)	-	Development of solutions for improving microalgae cultivation conditions using artificial intelligence
Algafood (2021)	2 233	Production of microalgae for food industry with full composition of amino acids and vitamins
Lya Vodoroslya (2023)	-	Development of technology for growing matrix and industrial cultures of different strains of marine microalgae
Ei-dzhi-ti (2020)	92	Algoremediation of water bodies to prevent their degradation due to significant anthropogenic impact and active saturation of water bodies with toxic biogenic elements (eutrophication), the unbalanced content of which contributes to the rapid development of algae and the appearance of cyanobacteria. Chlorella not only actively purifies water from organic compounds, but also from inorganic ones, for example, reduces the content of phosphorus, ammonium, formaldehyde, ammonia and others.
AA Plus Tech (2020)	-	Conversion of greenhouse gases into "healthy products" using photosynthesis of microorganisms. We are an international team with cross-industry expertise, representing a unique blend of managerial and specialized competencies in biophysics, biology, digital technologies, CO2 transformation into healthy products - dietary supplements, nutraceuticals, ingredients (algal proteins, antioxidants, food colors, PUFAs, etc.).The project is based on a cloud-based management system using AI and continuous remote non-invasive diagnostics functions, as well as continuous end-to-end accounting of CO2 equivalent in the final product.
TSVT (2021)	375	Design and manufacture of bioreactors and, on their basis, multiplatform reactor biostations. The key technology is the formation of a controlled gas vortex, which results in gentle, non-contact mixing of the culture medium and the useful substance
Algavitapro (2018)	32 724	Genetic sequencing services. Creation and market launch of an agricultural feed additive combining the properties of a prebiotic (green microalgae chlorella) and orexigen (functional peptide rubiskolin-6), which is able to increase average daily feed intake and conversion, weight gain and final weight of livestock, thus improving the economic efficiency of agricultural enterprises and farms.
Yar Lain (2015)	111 460	Development of production of organo-mineral fertilizer Chudorost based on microalgae biomass
Novye Pishchevye Biotekhnologii (2020)	-	Development of bioavailable nutraceuticals and methods of their targeted delivery for use in functional nutrition based on carotenoid extracts of Chlorella microalgae (core), biodegradable material (shell), and technologies of food products for functional nutrition with their use
Nikafresh (2020)	-	Development of innovative technology of nano-encapsulated carotenoids with high bioavailability and resistant to temperature and UV influences

Source: authors.

the shift away from synthetic dyes, growing demand for natural blue dyes, and increasing investments in the phycocyanin industry[13]. In addition, the European Union is investing in the microalgae market to achieve its goal of creating renewable energy and reducing carbon dioxide emissions. The European Commission is collaborating with several projects to improve the biofuel production system. Increased EU funding for microalgae research and development and implementation of standardization methods for the production and use of microscopic algae based products and ingredients in various industries would help the EU market to flourish (Kuech et al., 2023).

Figure 7. **Microalgae market (2020 small circle fact and 2028 large circle forecast)**



*Source: au*thors based on (The Insight Partners, 2021).

As mentioned above, the dietary supplements and pharmaceuticals segment will account for the largest market share, however, the animal feed and aquaculture segment is expected to have a significant compound annual growth rate due to the shift in consumer focus towards more nutritious feed products (PMR, 2023).

Also, production of lutein used as a food and feed additive could be another promising area of growth for the microalgae market (Lin et al., 2015). Among others, lutein has antioxidant properties, anti-cancer effects, promotes the development of infants' nervous system (Hu et al., 2018), and plays an important role in preventing cataracts (Manayi et al., 2016).

Sales of microalgae lutein-based products are expected to reach USD 450 million by 2027 (Saha et al., 2020) at a compound annual growth rate of around 6.10% (Saha et al., 2020; Fu et al., 2023).

[13] https://www.cbi.eu/market-information/natural-ingredients-health-products/chlorella-and-spirulina/market-potential, accessed on 08.01.2024.

The market for microalgae-based products by microalgae species in 2020 (small circle) and 2028 (large circle) can be reflected as follows (The Insight Partners, 2021) (Figure 7).

Conclusion

Microalgae are a promising "agricultural crop" that plays the most important role in the functioning of the entire biosphere. Recently, their industrial production has attracted more and more attention, as they find their application in different spheres of national economy. These include the production of food, fodder, fertilizers, as well as a new promising direction - biofuel production.

Market trends and the growing interest of consumers to natural and healthy products forced scientists and business representatives to develop new products with functional ingredients. Microalgae have been recognized as a source of functional ingredients with beneficial health effects as these microorganisms produce polyunsaturated fatty acids, polysaccharides, natural pigments, essential minerals, vitamins, enzymes, and bioactive peptides.

The microalgae market size in 2021 was valued at USD 977 million, with an average annual market growth rate of 6,8% projected. Thus, in the authors' view, by the end of 2030, microalgae related companies are projected to generate over USD 2 billion in revenue.

The market for microalgae-based products in South Asia and East Asia is expected to expand at a CAGR of 7.8% and 6.8%, respectively, during the forecast period 2021-2031. However, North America and Europe will remain dominant in the market with market shares of 28.8% and 27.9%, respectively.

Therefore, the production of microalgae-based products is a dynamic, multi-sectoral market with huge potential in many sectors of the economy.

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