Algae as an alternative to the methods of production and use of conventional biomass(review article)

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Abstract: Algae have been present in the water treatments technologies, food for animals makingprocesses or even for diet supplements production for many years now. Recent years, however, have brought a number of ideas and discoveries for a wider use of these autotrophs. Their use is related to the broadly understood environmental protection and many threads of combating climate change. Currently, one of the most common ways of using algae is the production of liquid biofuels of the 3rd and 4th generation and unconventional biomass generation. Biofuels obtained from algae, in addition to lower amounts of harmful substances contained in them, are often characterized by a negative emission balance. It is related to the fact that those organisms, being in an exponential growth phase, assimilate the carbon dioxideneeded for photosynthesis. The production of energy substances from algae and microalgae in the teeth of draining fossil fuel deposits and their destructive impact on the environment. That sooth combined with the ease and low cost of culture, condition they become a real alternative to existing energy sources. Unique properties of algae linked with the fact that they are among the best, known biological energy converters opens the way to a number of opportunities to use them in other economic sectors. Certainly, the technological revolution in the energy market in addition to the requirement to create the most efficient reactors, in-depth research on the properties of fuels and the producers themselves still needs to be regulated by law. Algae can be grown in polluted waters, and the energy raw materials produced from them are able to reach (without emission logistic costs) a negative balance of CO_2 emissions. This phenomenon and the fact that apart from fuels and biogas, they can be used for purposes such as carbon sequestration, creating energy biomass, medicines and dietary supplements, as well as food for animals, for example, the most reasonable choice would be to create advanced regulations regarding the closed- circuit policy in the energy sector, based precisely on biologically active organisms. This work focuses on gathering and presenting basic information regarding current technologies related to algae, their potential uses in the energy sector, and the long-term prospects for their development. It also takes into account the issues associated with the holistic nature of energy harvesting methods such as the one discussed.

Key words: algae, bioeconomy, biofuels, biorefinery

Introduction

Already in 2007, the IPCC published a report in which scientists estimated that with 90% probability global warming has no temporary nature and that climate crisis is largely caused by human activities (IPCC, 2007). These activities cover many issues, however the extraction of fossil fuels and the generation of energy from them is one of the main drivers of greenhouse gas emissions. And as we know, it is they that cause the increase in the average global temperature.

In order to better understand the problem of amount of carbon dioxide emitted, it is worth looking at couple of figures and putting them together (Dubiński et al., 2010: 3):

– The burning of fossil fuels emits about 10 billion metric tons of carbon dioxide each year.

– Oceans absorb 1.6 billion tons more CO_2 than they produce themselves

– Soils and all vegetation absorb 3 billion tons od CO_2 more than they produce.

It can be noted that every year about 5.4 billion tons of carbon dioxide remains in the atmosphere, coming only from the combustion of traditional fuels. What compounds the magnitude of the surplus of carbon dioxide in the atmosphere is that the burning of fossil fuels is responsible for less than 30% of all human-related CO_2 emissions (2008 data) (Dubiński et al., 2010).

The whole problem and its origins are very complicated and the issue of changing and improving the global situation is very complex. Nevertheless, improving the processes of extracting energy from fossil fuels such as oil or coal or patenting new ways of producing energy seem to be steps that will significantly slow the warming process and halt some of the adverse environmental changes. Recent estimates show that global energy demand will increase by about 30% over the next 18 years. (United Nations Data) Because of predictions, close to certainty, that electricity will be the dominant energy carrier, modern solutions are already being implemented to improve the efficiency, cleanliness and integrity of the entire energy system. In the face of projected global energy demand in the coming years, one of the most economically important technological issues is to provide citizens and industry chains such energy with simultaneous as little harmful impact on the environment and climat as possible.

The hope here is renewable energy sources, which are capable of providing us with much cleaner energy than fossil fuels (Kozłowski, 2019: 2-3).

Renewable energy sources (RES) are an alternative to traditional, primary, non-renewable energy carriers (fossil fuels). Their resources are replenished by natural processes, which practically allows to treat them as inexhaustible. In addition, obtaining energy from these sources is, compared to traditional (fossil) sources, more environmentally friendly. The use of RES significantly reduces the harmful impact of energy on the environment, mainly by reducing emissions of harmful substances, especially greenhouse gases (IEA and United Nations).

In the widely held for years debate on climate change and the possibility of combating global warming the role of biomass is extensively discussed. Many scientists pin their hopes on it asa source of clean and fully renewable energy. Its high calorific value combined with ease of production and low cost is making energy derived from biological resources andenvironmental waste increasingly popular. Of course, the production of biomass material mustnot compete with food crops, and the use of agricultural fields for energy crop production is just such a competition. Scientists, over the years, have been able to study and modify some plants in such a way that their production can take place on poor quality soils (Jęczmionek, 2010: 7).

Biomass material gaining in popularity are algae and microalgae. This is due to their ease of breeding, their exceptionally good biomass performance as a direct combustion product, and by their wide range of uses to create or refine other energy feedstocks.

Characteristics of algae

Algae are microscopic, often single-celled organisms that inhabit the aquatic environment. They constitute a highly diverse group of eukaryotes and procaryotes (Kumar et al., 2010: 2-4) (Khani, 2018: 1), inhabiting widely differing aquatic territories (Skjånes, 2012: 2-3) (Khani, 2018: 1-2),. So far, about 300,000 species of these organisms have been recognized, but their number is estimated to be at least hundreds of thousands (Alam, 2015: 2-3). Individual species of algae differ from each other, often even significantly. However, they are united by a number of features, which make them unique and may in the future constitute one of the basic rungs of the energy revolution. They contain sizable amounts of proteins, nucleic acids, carbohydrates, mineral salts and fats (up to 77% of dry weight) (Shroeader et al., 2013: 3). They are able to thrive in both saline and fresh surface waters. These microorganisms are autophototrophs, using solar energy and carbon dioxide and mineral salts for their own development and growth (Chisti, 2020: 3). What distinguishes algae from other biomass sources is their very rapid mass gain and the fact that they are among the best natural converters of solar energy on earth (Subhadra, 2011: 1-4).

As photosynthesizers, these organisms living in huge amounts in the oceans, together with photosynthetic bacteria and photoplancton are responsible for 50% of the oxygen that is found in our lungs with every single breath (National Ocean Service data). It is thanks to them that we say the oceans produce such huge amounts of respiratory gas. Despite their huge contribution to the entire biosystem of planet Earth, they have no organs or qualified internal structures. Nor do they form specialized cellular formations such as leaves or roots. Their phenomenon focuses on chlorophyll and mechanisms for converting sunlight into energy, food and building compounds. These organisms, despite their small size and marginal cultivation requirements, are characterized by a huge ratio of biomass to volume and an extremely rapid process of photosynthesis, which makes them one of the best converters of solar energy on Earth.

Algae have been known to man for hundreds of years. Today, these organisms are grown on alarge scale mainly for the pharmaceutical and cosmetic industries. However, the fact of high content of proteins, amino acids or various elements makes the possibilities of using algae much greater. For several years, the energy sector has been looking to algae - as a source of biomass and substrates for the production of energy raw materials - as a solution to the problems generated by traditional, fossil energy sources.

A breakthrough in this field turned out to be the discovery of biofuels and their potential. These are alternatives to petroleum-based energy sources for, among other things, widespread transportation. The development of this field of technology has caused scientists to come across algae as a substrate for the production of just such chemical compounds. Theseorganisms are characterized by higher photosynthetic potential than plants (Maojidek, 2021: 1,23) (Alam, 2015: 2) and, in addition, are rich in various types of lipids. Fats constitute, under certain conditions and for a certain species, up to 77% of the dry weight of a microalgae cell (Shroeader et al., 2013: 3). It is likely that this characteristic, combined with cost-effectiveness and simplicity of production, proved to be a significant factor in assessing the suitability of algae for the energy sector, with transportation fuels emphasized.

Algae have become the subject of much research over time, both in terms of technology and processes for growing them. They are a common laboratory material even in technical universities. This whole cognitive branch of science and technology has solved some of the problems that were posed by energy crops bred for the production of first and second generation biofuels. Plants that are their primary source, namely oilseed crops, often withquite high soil requirements, were considerable competition for food grown around the world.This aroused a conflict of interest for large companies that competed for farmland with fertile soil (Tudge, 2021: 13-15) (Mahmood, 2023: 14,15). What is more important, that issue started the discussion on the ethical aspectsof such an phenomenon. The seizure of land for food production, whether for animals or humans, at a time of hunger crisis in some parts of the world, was definitely not a positive sign.

Thus, the potential of algae has been recognized at the right time, and the development of research and technology makes it possible to look at them optimistically as a solution to many existing problems. First of all, algae are a great competitor for energy crops (Mata 2010). Some estimates suggest that it is possible to obtain 7-31 times more biodiesel from algae oil than from rapeseed oil (palm oil, in this case) (Demirbas, 2010:1). Others, also show that from one acre of land occupied by algae, it ispossible to obtain 30 times more energy than from soybean crops (Datta, 2019: 6).

An additional advantage of algae is the amount of space used to produce them. Cultivated fields occupy huge areas, requiring nurturing, tending or watering, and the harvesting process itself also takes a lot of time in accordance with the area. Algae and microalgae are grown in photobioreactors with huge capacities, but multi-layered - in suspension. The only prerequisite is to provide them with access to light and to properly design the culture system. In this way, from the same usable area we are able to obtain higher yields of algae. This phenomenon is further compounded by the fact of their very rapid growth, the lack of seasonality of breeding and their relatively easy processing.

Algae are organisms that can tolerate very high levels of carbon dioxide, which opens up a range of applications for them. They can not only be a substrate for biomass production but also be CO2 sequesters themselves (Singh, 2011: 5). In the era of emissions trading, this could be a worthwhile solution. Algae cultivation near large industrial plants, in closed loop systems, canbring many environmental and financial benefits (Dismukes et al., 2008).

Those organisms additionally do not require crystal clear water (Rahman, 2020). Post-process liquids, after removing any azatoates, phosphorus or ammonium nitrogen, can be used to fill photobioreactors. This is undoubtedly a huge advantage for plants wishing to introduce closed-loop circuits in their production processes. Algae, as a source for the production of oils competitive to those obtained, for example, from rapeseed, have another extremelyimportant advantage. It is their emission balance. When a kilogram of algae-derived biomassis produced, 1.83 kg of carbon dioxide is absorbed from the air (Dragone et al., 2010: 4).

III and IV generation of biofuels

Undoubtedly, the energy revolution has been part of the Industry 4.0 revolution for years. In addition, with The Paris Agreement signed by 194 countries (Paris Agreement, 2015), huge challenges have been posed to the entire sector, both socially and technologically. Today, highly developed countries are already entering the stage of introducing Industry 5.0.

The assumptions of this revolution are primarily - further networking of machines, transferring their synergies to the Internet but also, or primarily - further economic growth, but in balance with the environment. This prerequisite, not directly, but nevertheless, puts emphasis on technologies for energy extraction, processing and distribution.

Knowing that electrification of all transportation is not feasible without excessive exploitationof the environment (Pitron, 2018), due to small deposits of rare earth elements relative to demand, it becomes the responsibility of companies in the energy sector to develop other options. One of these is the development of biofuel technologies. Their current market is mostly associated with bioethanol and biodiesel. These are first- or second-generation fuels, depending on the material from which they are produced. The criterion that divides biofuels into first-generation or second-generation is whether they were produced from food crops or oil crops, but not in any way a source of food - whether for animals or human.

The proliferation and presently prevalent adoption of these biofuels has been an undeniable success. Names such as biodiesel have even become widely understood terms. However, there are many more types of first- and second-generation biofuels. Beginning with bioethanol in various forms, PVO vegetable oils, before FAME methyl esters and FAEE ethyl estersdescribed as biodiesel, and ending with products of secondary processing of biofuels - bio- ETBE formed from bioethanol refined (Biernat, 2012: 1-3). The most important aspect, however, in the whole socio-economic transformation seems to be educating people with the simultaneous introduction of technologically and ideologically improved processes. Such technologies can be characterized by processes for the production of third- and fourth-generation biofuels.

In the general terms, these biofuels are fuels produced from algal biomass, the cultivation of which takes much less space than is needed to obtain the same amount from lignocellulosic plants (Brennan et al., 2010). The main biofuels derived from algae are bio-ethanol and biodiesel, but biohydrogen production technologies are becoming more common.

Undoubtedly, a positive phenomenon is the growing interest in their topic in recent years. Biofuels created from algae seem to be a solution to some of the problems that today's economy is facing. First of all, there is the problem of cultivating energy crops.

The biofuel market is constantly growing, and the use of alternative fuels to petroleum is becoming more widespread. Until now, the only source of oils used as substrates for biofuel production has been plants - often food crops. This gave rise to first-generation biofuels. However, when it was realized that using plants intended for food purposes to produce fuels raised moral conflicts, energy plants were patented. They are not used for producing food for animals or humans, but this does not change the fact that farmers compete for fertile land to obtain the highest possible yields. Competition between the food production sector and theone responsible for the creation of fuels also raises many controversies.

Of course, there are energy plants that do not require highly fertile soils and are even able to grow on marshy or clayey terrain - an example is Camelina Sativa, whose oil in many countries (mainly Germany and US) (Jęczmionek, 2010: 2-3) is an alternative to rapeseed oil for biodiesel production. However, comparing the possibilities of utilization, the surface area used for production, or the carbon footprint, the competition between higher plants and algae leaves nodoubt. Algae growth takes much less time and cultures are not dependent on the seasons. Withthe use of algae for biomass production, fields of crops remain available to those in the food sector. In a situation where people in various corners of the world, often where energy crops are grown, are suffering from hunger, this is a much-needed solution (Lam, 2012).

Both third- and fourth-generation biofuels are classified as advanced fuels, i.e. those whose development is currently expected to bring tangible results only in the future. This is due to the fact that biofuels extracted from algae are able to absorb carbon dioxide from the atmosphere (Park et al., 2012: 2) (Dragone et al., 2010: 4). This is a process that is invisible to the bare eye in real time, but we can expect environmental improvements on a global scale, assuming full-scale deployment ofsuch fuels.

Their cultivation and processing is generally technologically difficult (Alam, 2015: 3). Due to temperatures oscillating between 20-30 degrees which are required for their growth, these organisms cannot be grown anywhere on earth. However, providing them with the optimum development conditions, this technology is becoming very promising for the development of the fuel sector. All this is due to their tremendously rapid growth. Deserts are a place strongly considered in the context of growing algae there. This is due to the huge amount of light available in these areas for a large part of the day (Singh et al., 2021). In fresh culture, which is in an exponential growth stage, algae can double its population in 24 hours. Thus, algae are cultured in huge open tanks resembling reservoirs. Such a photobioreactor operates on the principles of semi-continuous breeding from which fresh biomass is collected on an ongoing basis (Amini, 2020: 5).

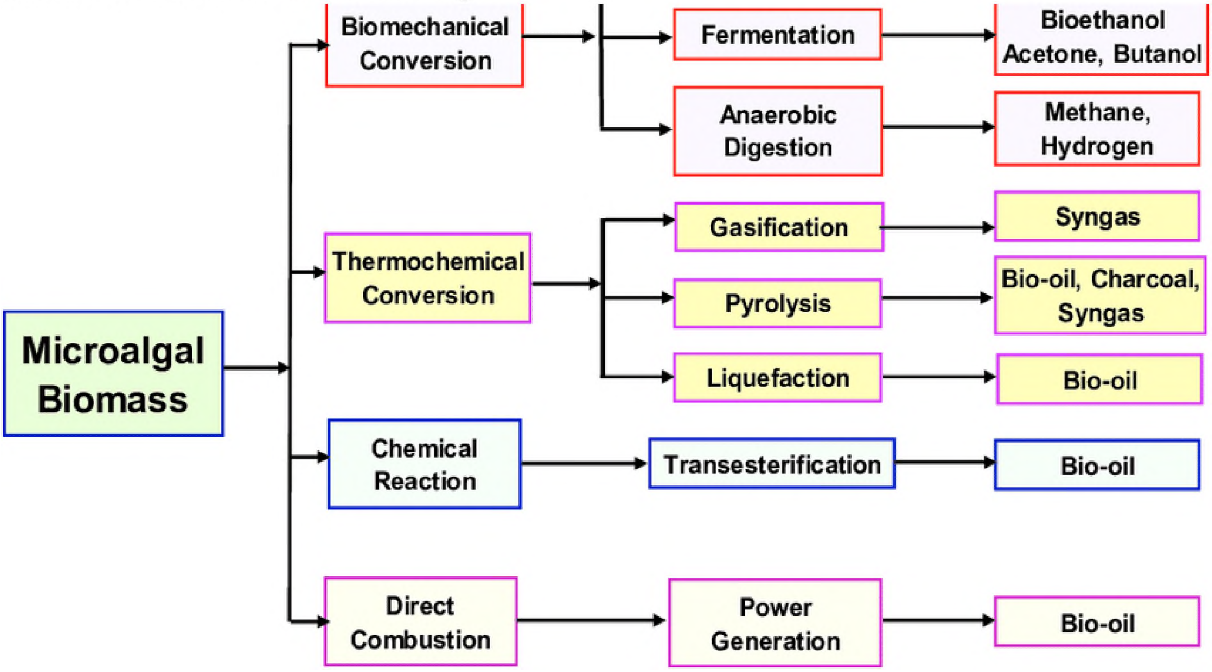
In addition to open cultivation tanks, closed-loop systems are also used to protect algae cultures from contamination. These are generally large cultivation ponds that are separated from the atmosphere. However, this method is less cost-effective due to the need for additional equipment to supply carbon dioxide. The material used must also be a barrier against pollution while allowing light to pass through as efficiently as possible.

The most advanced method of cultivating these organisms is through specially designed photobioreactors. These technologically advanced systems are the most expensive option for cultivation and are not the best solution for economic production facilities, but rather for research and experimental purposes. These reactors mainly serve to understand mass transfer mechanisms, which are fundamental in obtaining biomass from algae (Datta, 2019: 6).

An additional issue is the technology of harvesting and concentrating algae from cultivation tanks, which involves drying, sieving on special screens, and various types of extractions. An additional promising technology for collecting and thickening algal biomass is a special foam column that uses a special surfactant, CTAB, which acts as both a collector and foamingagent (Al-Hemeri et al., 2022: 1-2).

Algae culture sites use both those that are autotrophs and chemotrophs, whose metabolic mechanisms differ. To further increase the already high lipid content of algal dry matter, nitrogen starvation technologies are used (Singh, 2011). The bio-oil obtained in such a scheme is thus a better material for biofuel production. This is due to the presence of more triacylglycerols (TAGs) which are the most important of the substrates for biodiesel production (Meng J. et al., 2009: 1,3).

Scheme 1. Use of biomass from algae



Source: Mobin, 2012: 8.

Currently, advanced biotechnology and genetic engineering methods allow for the improvement of algae. As a relatively well-known genetically and simple group of living organisms, they can be subjected to various modifications. This has led to the development of the fourth group of biofuels, which are obtained from biomass derived from algae that have undergone genetic modifications (Lu et al., 2011: 4-8). Their production is supposed to be based on CCS - carbon capture and storage principles. This applies not only to the algae themselves, but alsoto the technologies used in the entire logistics cycle related to this generation of biofuels. The ultimate goal is to create a range of solutions that will incorporate carbon sequestration in many areas of the economy.

Such a procedure aims to address the emissions that the world is currently facing. This means that in the case of fourth-generation biofuels, engineers want to achieve a completely closed cycle that serves not only the production of biofuels and other cycle products but also the absorption of excess carbon dioxide from the air and its conversion into biomass.

Fourth-generation biofuel technologies include, among others, the following technologies (Lin et al., 2021: 2-4):

– SOLAZYME, which involves non-solar production of JET fuels from algae oils obtained from organisms grown on sewage or agricultural sludge.

– SOLENA, which is based on the production of diesel and advanced JET fuels rough theplasma gasification of waste biomass.

An additional element being developed in the area of third and (primarily) fourth-generationbiofuel production is biorefineries.

Biorefineries in closed loop economy

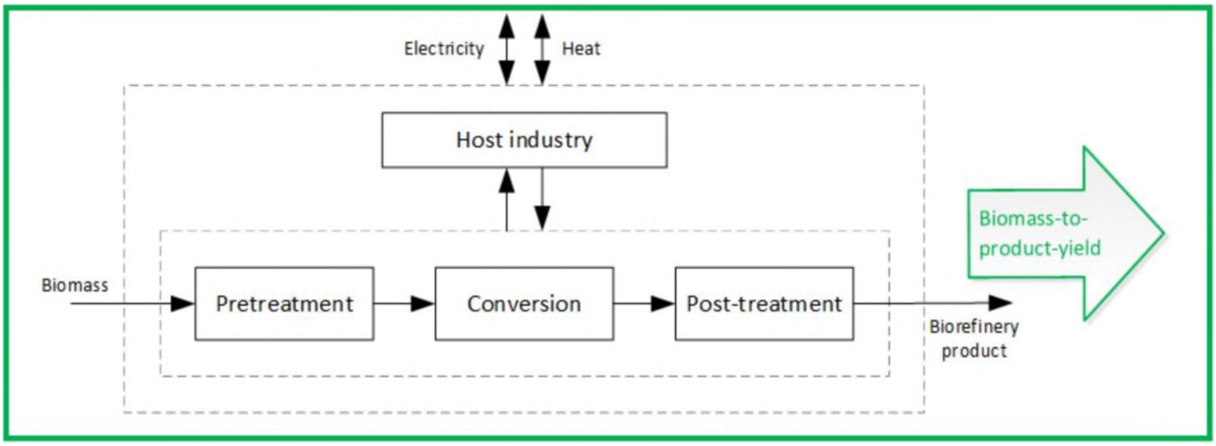
Biofuels, as products obtained from algae cultivation, are considered as a long-term goal. However, currently, the greatest emphasis is placed on the development of other methods utilizing algae to address issues related to low emissions and the fight against the climate crisis.

In recent years, bioeconomy has definitely marked its presence among traditional economic and technological models. Its foundation lies in the utilization of green, low-emission energy sources, which are intended to be used to produce products with the lowest possible impact on the natural environment (Maciejczak et al., 2013: 2-4). The idea behind bioeconomy-based systems is to ensure energy stability and security, to move away from traditional fuels and to significantly improve the climate situation affecting the whole world. The guiding idea behind the technological advancement and implementation of bioeconomy is cooperation and the exploitation of nature and techniques such as biotechnology for its careful use and responsible processing for one's own purposes (Rathore, 2016: 3).

When talking about algae, it is impossible to overlook two important issues. The first is the blue bioeconomy, which is a model based on the production of energy and fuels from living marine resources such as algae, sponges, etc (Wijffels, 2008: 2,6). The second issue is how the goals of the blue bioeconomy are to be achieved. This method involves the introduction and popularization of closed-loop systems (Schoenmakere et al., 2018: 17,33). These systems, based on the utilization andprocessing of their own waste, as well as the use of other renewable energy sources for production, are intended to have a positive impact on the overall operation of the national economy and, in the longer term, the global economy. Job creation, technological development, urban integration, and collaboration among local communities are just some of the benefits brought by this energy model (Geng et al., 2019). The use of closed-loop systems is one of the most common paths to achieving sustainability for farms and manufacturing plants (Horvath et al., 2019: 1-2).

An integral part of closed-loop farms and businesses are biorefineries – the utilization of certain marine organisms, mainly algae, to collaborate with specific production stages. Biorefineries, by definition, are "systems that combine biomass conversion processes and devices for its processing into a single facility producing chemicals, fuels, and energy" (Harasym, 2011: 1) (IEA Bioenergy Task 42). It is also important to note that biorefineries involve a shift from the traditional linear economic model of extraction and disposal, to a modern bioeconomic system that emphasizes remanufacturing, reuse, and processing to achieve climate goals while ensuring continuous economic growth (Carus et al., 2018) (Jørgensen et al., 2018: 37,39).

Scheme 2. A simplified scheme of operation of a biorefinery



Source: Zetterholm et al., 2020: 8.

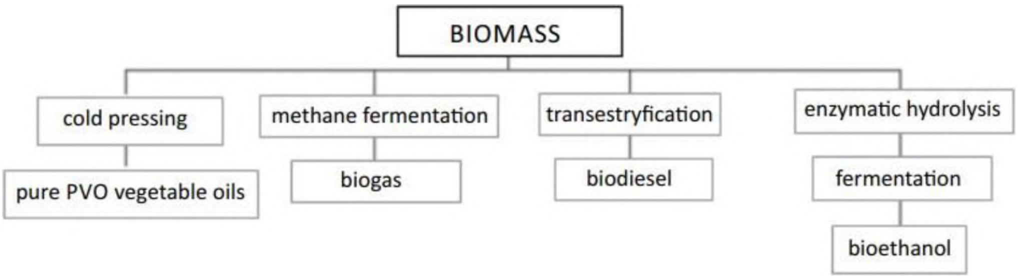
This model ensures better disposal of waste by converting it into usable energy or returning it to the power grid. However, cost reduction is not only associated with self-energy production. The processing of waste results in a significant utilization of a large part of it, and the by-products of these transformations, which are not needed for energy production, often serve as excellent nutritional components for animal feed, making them a marketable product.

The utilization of microorganisms for wastewater treatment is one of the earliest applications that have been developed and implemented on a technological scale. One of the first installations of this kind was built in California, based on the assumptions and analyses of Professor William Oswald's team (Fernandez et al., 2017: 5).

These processes generate enormous amounts of algal biomass, which can be further processedin subsequent stages (Olguin et al., 2003) (Flesch et al., 2013: 2) (Jebali et al., 2018: 1). In addition to using living microorganisms as a source of biomass for further processes, biorefineries can utilize lignocellulosic materials (Kajaste et al., 2014: 1,7) such as agricultural residues, municipal waste (Horvath et al., 2019: 6), and by-products from sugar processing.

Processes like hydrothermal carbonization (HTC) allow to produce heat, biochar, and even drop-in biofuels from biomass obtained from biorefineries (Heilmann, 2010: 1-3). HTC is one of the most efficient and technologically advanced method for converting biomass of various origins into energy products or bioenergy directly (Maniscalco, 2020: 16). Other processes applicable in biorefineries includepyrolysis, fermentation, gasification, enzymatic hydrolysis, and more (Zabed et al., 2017: 11).

Scheme 3. Possibilities of using biomass



Source:own elaboration.

Depending on the goal of a biorefinery, several operational models can be distinguished (IEA Bioenergy Task 42, 2022):

– Energy-driven (or biofuel-driven) biorefineries: These systems aim to produce energy, cogenerate, or recover energy from waste materials. However, this is the least economically viable pathway for biorefinery utilization. It requires significant financial investments and the adaptation of the energy market to accommodate the reception, settlement, and distribution of energy produced by prosumers (Leong et al. 2021: 7,11).

–.Product-driven biorefineries: These biorefineries focus on processing biomass to obtain smaller quantities of high-value-added products that can be used in various sectors of the economy to produce different types of energy. Common products derived from such installations include chemicals like drop-in biofuels and biochar. The utilization in this case is much broader. Besides heat/electricity generation, these substances can be used for carbon capture in the transportation sector (HanPark et al., 2012: 4-5) or carbon sequestration in soil (Bhuiya et al., 2016).

Additionally, biorefineries can be distinguished based on the feedstock used, which correlates with the category of biofuels produced from such installations. As in the case of biofuels, biorefineries are built for:

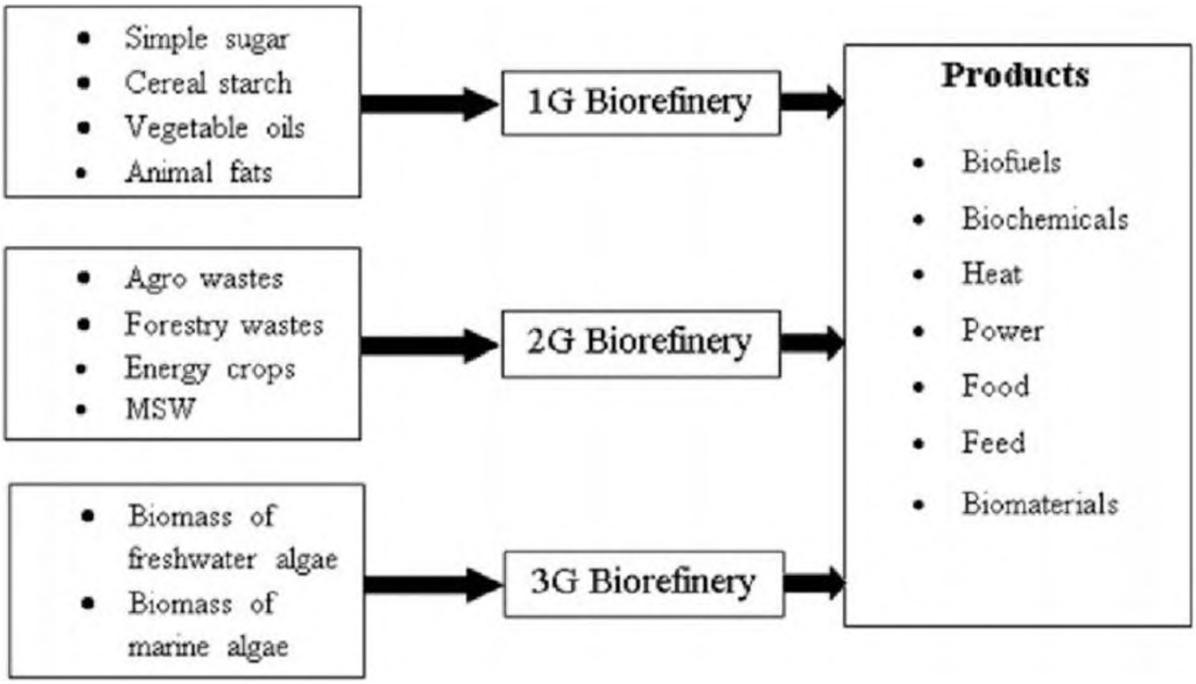
– First generation: Utilizing biomass from energy crops, primarily for the production of various oils, which are further processed and adapted for use.

– Second generation: Using non-food plant species, forest waste, and broadlyunderstood lignocellulosic biomass, often generated as by-products from previousproduction stages.

– Third generation: These are the most advanced biorefineries, utilizing biomass from living aquatic organisms such as algae. They represent the most advanced types of biorefineries among the aforementioned categories. The processing of biomass material yields not only energy products, but also valuable substrates for further use insectors such as pharmaceuticals, food production, or supplementation (Rathore 2016: 4).

It is the third generation biorefineries that address most of the challenges faced by engineers and chemical technicians, in terms of ensuring efficiency in sustainable energy production. These challenges included competition between biomass plants and food crops, high water consumption, the need for extensive cultivation areas, and the efficiency of bioconversion processes, which is highest with algae.

Scheme 4. Characteristics of each generation of biorefinery



Source: Chowdhury et al. 2018: 5.

It is obvious that small-scale production facilities or small farms are not able to obtain the financial resources needed to build a biorefinery and upgrade their entire energy system. However, a closed-loop economy can be a significant factor in the development of a network of cooperation between facilities with different characteristics and needs. In this way, the cooperation of local farms combined with a circular economy allows to meet the regulations on short supply chains.

Speaking of the entire bioeconomy, which includes technological, social, economic and ecological aspects (Kamble et al., 2020), it is essential not to forget one of the most important aspects, which are supply chains. On the one hand, they must be reliable and ensure continuity, and on the other hand, they must be fair and distributed in a way that benefits all entities involved in this model of cooperation. Modeling the profitability of installations such as biorefineries requires a wide range of information. Starting from biomass sourcing (Geographic Information Systems or computer modeling of cultivation) through logistics of the transport chain, to the creation of evolutionary algorithms that can integrate all the data and present the mostefficient solutions through analysis (Schröder et al., 2019: 7-9). In the current times of rapid implementation of Industry 4.0, the possibilities of modeling, instrumental analysis, and economic analysis canbe supported by systems and programs based on artificial intelligence. Ranging from the modeling of irrigation systems and the analysis of weather forecasting to the assessment of profitability for various methods, solutions, or technological modifications. The cognitive nature of the entire bioeconomy is unquestionable. It combines factors from the fields of economics, social sciences, energy, biotechnology, chemistry, and genetic engineering, necessitating a holistic approach to the planning and implementation of such systems. In orderto streamline the entire process and provide it with the greatest chances of success, eliminating the risk of design errors, society and authorities face the complex task of combining the knowledge of specialists from different, often distant fields, supporting investors and using the latest technologies such as machine learning and the Internet ofThings. This is a particularly important aspect, the intermediate goal of which is to facilitate the integration and cooperation of various economic centres.

Currently, most closed-loop biorefineries are built on a pilot scale. Due to the financial outlays required to build such installations and integrate the entire supply network, the time needed to construct and launch such projects is considerable. However, there are already several full-scale biorefineries operating around the world. A perfect example example is the BioRen facility, funded by EU funds, which is a project led by the company RenaSci (Plata et al., 2023: 10).

Anyhow, accelerating the process of implementing biorefinery technologies is a key factor in fulfilling climate objectives and achieving a rapid and smooth transition to a new model of theglobal economy. The processes occurring in biorefineries are already supported by technologies such as neural networks, machine learning, and artificial intelligence, primarily for:

– Analyzing the characteristics of the biomass used to determine the best process conditions (Nag et al., 2021: 3,5).

– Predicting the performance of specific technological processes, especially enzymatic treatments or hydrolytic pre-treatments (Vani et al., 2015: 2).

– Modeling the kinetics of processes occurring in bioreactors and determining theinfluence of physicochemical factors (Gama et al., 2017).

– Predicting the energy efficiency of products obtained in processes (Meena et al., 2021: 1-4).

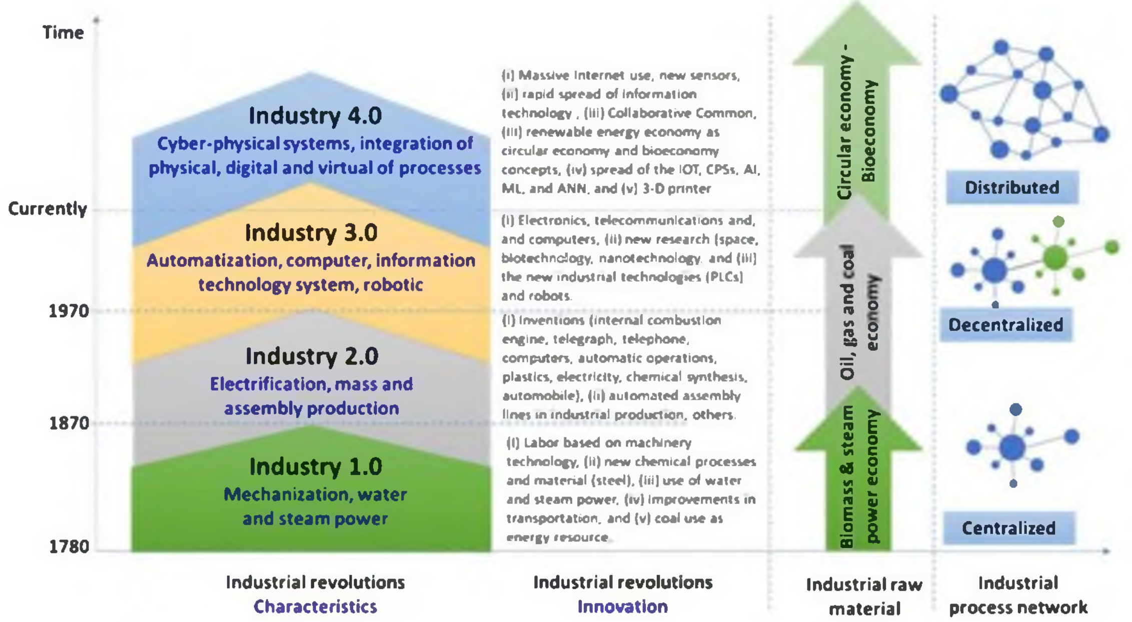
– Designing and analyzing online wastewater treatment and valuable biomass recovery (Kamali et al., 2021: 2,6,8).

– Assisting in climate, geographical, and weather analysis to determine the optimallocation for biorefinery construction (Sahoo et al., 2016).

– Designing and optimizing supply chains for biomass materials, waste collection, and process logistics (Liao et al., 2021: 5,7-8).

– Analyzing economic factors such as NPV, ROI, PBP, and LCA, as well as conducting more comprehensive and extensive analyses such as MCDA or SLCA (Ubando et al., 2020: 2) (Rakotovao et al., 2018: 2,5).

Scheme 5. Characteristics of technological revolutions



Source: Clauser et al., 2022: 2.

The development of biorefineries is an inevitable action for global economies, especially atthe local level. Energy, medicine, agriculture, and many other industries can collaborate in overlapping models. Modernization and transition to an economy entirely based on new economic trends is certainly a costly and long-term effort. It requires the development of logistics, transport, and simultaneous energy transformation. Social issues should not be forgotten either, including education of societies and training personnel who will play a significant role in modern technologies (Priefer, 2017: 6,10,15).

Conlusions

Energy has become one of the most important social topics worldwide in recent years. The path that the entire world has taken towards zero emissions is a long-term goal that requires the development of new ideas and technologies. Undoubtedly, the usage of algae in modern energy technologies is a developmental issue, and this trend should be closely monitored. However, society still has a long way to go. New economic pathways, based on the broad concept of bioeconomy, circular economy, or blue economy, will undoubtedly be partly basedon renewable biomass such as algae. However, apart from the advantages that come with the use of new technologies for development, there are significant challenges ahead. The global implementation of these economic models poses a range of social and technological challenges. There is a need for coordination among various sectors, including local communities, the public sector, and the private sector. As always, the entire process of transformation should be based on educating society, training new professionals, and establishing a position in the international market. Investment in research and development is also necessary to improve biorefinery technologies, logistical systems, and supply chain management models. Additionally, it is important to optimize work processes and analyses, which can largely be delegated to new technologies like AI or machine learning algorithms. The implementation of AI technology into bioeconomy and the broader industry of Industry 4.0 creates prospects for development and innovation. However, there are also challenges, such as the need to ensure adequate cybersecurity measures, data protection, and ethical useof artificial intelligence.

Society is only at the beginning of the journey towards complete 4.0 transformation. However, current scientific and technological advancements allow for an optimistic outlookon the future utilization of algorithms in economics and the circular economy. The path to fullimplementation may not be easy and will be filled with obstacles. Nevertheless, a well- thought-out bioeconomic model will lead to continuous economic growth while respecting theenvironment and addressing climate responsibility.

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