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Microalgae-based green products in the circular economy

Karolina Dziosa[1], Danuta Ciechańska[2,3,*] and Marta Kutyna-Bakalarska[4]

[1] Bioeconomy and Ecoinnovation Centre, Łukasiewicz Research Network–Institute for Sustainable Technologies, Radom, Poland
[2] Association Bioeconomy Cluster, Lodz, Poland
[3] International Centre for Research on Innovative Bio-based Materials (ICRI-BioM), Lodz University of Technology, Lodz, Poland
[4] Grupa MASPEX, Wadowice, Poland

* Correspondence author; E-mail: klasterbiogospodarki@gmail.com.

Abstract: The paper presents the nature, properties, conversion methods and trends in the use of microalgae biomass in various branches of the economy, in particular in the food sector. Possibilities of practical use of microalgae culture as one of the stages of the post-production water purification process in the dairy industry were presented. The implementation of circular economy principles in this sector has been focused on creating closed water cycles through the use of membrane installations combined with a system for the management of activated sludge in the microalgae biomass cultivation process. Sludge from dairy production is rich in nutrients that are used for the growth of microalgae cells. Microalgae biomass can be used as a renewable raw material, e.g. for the production of bio-chars, sorption biomaterials, as a substitute for lubricants and many others. The article focuses on microalgae used as sorption biomaterials and their importance in closing production water cycles in the food industry. Post-production sewage from the dairy industry contains a sufficiently large amount of biogenic substances that can be used to cultivate microalgae with properties dedicated to processing into biochars with a structure and functional features suitable for processing into sorption biomaterials.

Keywords: microalgae biomass; microalgae-based biochar; cultivation of microalgae *Chlorella sp*. on activated sludge; microalgae in circular economy

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1. Introduction

Some of the biggest problems of the modern world are the degradation of the natural environment, climate change and the limited availability of natural resources. This problem is visible on various planes (water, air and soil) [1]. Currently, it is also a very big problem to find an appropriate space where an increasing amount of waste and sewage could be stored and then (if possible) processed. This is primarily due to economic development and the growing consumerism of modern society [1]. This issue is becoming not only a local but also a global phenomenon [1,2]. EU waste policy aims to protect the environment and human health and help the EU's transition to a circular economy. It sets objectives and targets to improve waste management, stimulate innovation in recycling and limit landfilling. 5 tonnes of waste is produced by the average European each year. Only 38% of waste in the EU is recycled and over 60% of household waste still goes to landfill in some EU countries [3].

In recent years, numerous actions have been taken to counteract these undesirable phenomena. An important role in this process is played by the development of circular bioeconomy, which uses renewable biological resources (plant and animal raw materials as well as microorganisms) in a sustainable way for the purposes of creating goods and services [1,2].

Circular bioeconomy shapes a completely new market for production and services, which requires both innovative and advanced knowledge and qualified staff [1–3] and as a result will stimulate and maintain economic growth. It also allows reducing the level of dependence on fossil fuels, and also contributes to improving the economic and environmental balance of primary and secondary production [2,3]. The development of the circular bioeconomy is largely based on the industrial use of waste biomass management processes from production and consumption processes.

A special role in the development of bioeconomy is played by the development of innovative methods for the management of various types of biomass raw materials from primary production, especially agriculture, forestry, fisheries, and recently also from aquaculture. In the latter area, attention should be paid to microalgae, which in the near future may become a very valuable source of biomass, constituting a raw material for the production of high-quality new food, feed and health products, while contributing to progress in the field of sustainable production of new biomaterials based on them [4–7].

2. Background on microalgae

Algae belong to the kingdom Prostita, where life forms distinguished by the lack of morphological specialization are grouped [8,9]. Thanks to the ability to photosynthesise, they are similar to plants and produce the same reserve substances as plants. Algae cells contain pigments that absorb light for photosynthesis [10,11]. The amount of light that the algae receive determines their characteristic color. The dominant color of algae cells influences their nomenclature within clusters.

Therefore, algae can be divided into:

● green algae—containing the following pigments: green (chlorophyll), yellow (xentophyll) and orange (carotene), ● red algae—containing dyes: green (chlorophyll), red

(phycoerythrin) and blue (phycocyanin), ● brown algae—containing dyes: green (chlorophyll), yellow (xentophyll) and brown (fucoxanthin) [10,11]

Due to the high ability to adapt to changing environmental conditions and cultivation conditions, the most common algae are freshwater microalgae of the genus *Chlorella sp*. green microalgae can be used as new biomaterials [12].

2.1. Importance of microalgae in nature microalgae composition and their effect on natural environment

Microalgae contain many valuable nutrients such as vitamins, amino acids, carbohydrates, proteins, lipids and microelements [13]. Carbohydrates constitute the majority of the dry mass of algae, as much as 60%. This group includes the following chemical compounds: mucopolysaccharides (hyaluronic acid, chondroitin sulfate), alginic acid and its salts, fucans (laminarin, fucoidin), mannitol and sorbitol, carrageenans. Microalgae have been shown to produce protein (13.3%–58% dry weight, including all essential amino acids) and lipid fractions (2.04%–80% dry weight, including commonly deficient long-chain omega-3 fatty acids and other essential fatty acids) at levels much higher than oilseeds [9]. These are primarily glycoproteins and metalloproteins. The group of amino acids includes: alanine, aspargine, glycine, lysine, serine, isoleucine, leucine, methionine, phenylalanine, threonine, tryptophan, valine. Among the lipids there are unsaturated fatty acids: arachidonic, eicosapentaenoic and sometimes γ-linolenic acid (GLA). The vitamins contained in algae include group B (B1, B2, B5, B6, B12), as well as vitamins: E, C, D and carotenoids. In addition to the chemical compounds listed above, algae contain microelements such as: zinc, copper, bromine, iodine, iron and organometallic or complex compounds: magnesium and manganese [14].

Another advantage of microalgae as part of the natural environment is their usefulness in nature conservation. In the processes of biosorption and bioaccumulation, they are used for wastewater treatment [15]. Their ability to concentrate toxic metal ions, such as [15,16]: cadmium, lead, copper, zinc, chromium, is used. In addition to the proven advantages they bring to the natural environment, they can also pose a threat to the entire ecosystem [16,17]. The phenomenon of water blooms caused by the growth of algae continues to grow in size. The massive development of these organisms causes the emergence of further ecological threats. First of all, water quality deteriorates. In addition, there are material losses due to the weakening of fishing and tourism [16,17]. One of the solutions to problems with excessive algae bloom in the aquatic environment is their catching and utilization of the obtained algae biomass, e.g. for energy purposes.

2.2. Microalgae conditions for the effective growth

Microalgae are considered the most resilient organisms on Earth, able to grow in a variety of conditions. They occur in all geographic zones, in fresh and salty, cold and warm waters [10,18]. They also inhabit terrestrial environments, although to a lesser extent, where they live on the surface of soils. They also live in extreme environments where water is scarce, even in highly

saline lands, in snows, glaciers, in hot desert areas and in geothermal geysers. They are abundant on rocks and tree bark, as well as in degraded nature, which is constantly in contact with abundant pollution due to the presence of heavy metals [19,20]. The pace of this process and the quality of their growth, regardless of the place of their occurrence or breeding, are determined by ecological factors: biotic and abiotic.

Biotic factors—Environmental conditions (all living organisms) that directly or indirectly affect the development of microalgae populations. There are mutual interactions between them, thanks to which they can support or inhibit each other in development through food competition, including predation and parasitism. Moreover, there is cooperation with other organisms and competition between algae for space [10].

Algae take food from the environment evenly over their entire surface [21]. They assimilate nitrogen in the form of nitrates and ammonium salts. On the other hand, nitrites are beneficial for the growth of microalgae if taken in low concentrations. At higher concentrations, they cause toxic effects. Phosphorus is assimilated by microalgae cells in the form of orthophosphates. The process of uptake of phosphorus compounds by microalgae depends on the reaction of the environment. The pH in the range of 6–7 was found to be the most favorable [22]. In turn, sulfur is taken up in the form of sulfates. It has no nutritional value, but sulphides play an auxiliary role in the absorption of silicon by diatoms and promote the growth of some planktonic algae [10].

Pathogens such as bacteria, fungi and viruses have many structures and physiological and biochemical properties that favor their colonization [10,23]. They infect microalgae in cell interactions, secreting toxic substances, which slow down the metabolism of microalgae and lead to discoloration and cell death. The development of the infection depends on the attachment of the pathogen to the surface of the organ, the germination of spores and the formation of infectious structures, as well as the penetration into the interior of the microalga and the phenomenon of colonization itself. The occurrence of each stage results from numerous determinants, but mainly from the secretion of enzymes and toxic compounds [24].

Fungi live only in an acidic environment, below the pH value of 6 [23]. They parasitize on microalgae through direct contact of the mycelium with the algae cells. They damage the cell structure and cytoplasmic membranes, affecting their permeability [23]. Viral infections cause a lot of changes in algae cells. They weaken their motor activity and the ability to bind carbon dioxide, and even the functions of absorbing food. They affect the disruption of the chloroplast structure, including the transport of assimilants. Virus infection damages the structure and permeability of biological membranes in cells. At the site of virus infection, vesicles usually appear on the membrane, which additionally affects the metabolism of metabolites contained in microalgae cells. Changes in the form of organelles are noticeable in the cytoplasm of virus-infected cells, and often their disintegration is visible [24].

Interactions between the algae and the rest of the phytoplankton result in the secretion of secondary metabolites and play an important role in the environment. The content, and mainly the phytoplankton biomass, plays an important role in the functioning of the food web of aquatic ecosystems. Therefore, the key adaptation is the production of active organic compounds. It is conducive to the achievement of a competitive advantage by microalgae

over other forms of life [10,20]. In addition, changes in the composition and structure of microorganisms depend on the content of harmful compounds affecting specific individuals by their complete elimination, inhibition or stimulation [20].

Abiotic factors—Among the physical and chemical characteristics that affect the growth of microalgae are primarily: light, temperature, salinity, concentration of nutrients, pH and atmospheric pressure [19,20,25]. The basic factor determining the growth of microalgae is access to light, more precisely its color and the ratio of the length of light and dark periods, the so-called photoperiod in the circadian cycle [10,20,25]. Under natural conditions, the amount of light reaching the surface layers of water depends on the position of the sun, the transparency of the water, and its depth. A smaller angle of incidence ensures less loss of light rays due to reflection. Biologically active radiation in waters usually reaches the depth of 10 m–50 m, creating the photic zone. The growth of microalgae in the aquatic environment is not uniform. Their greatest development occurs at a depth of 0.5 m–2 m. [20]

Most of them skillfully change and adjust their color to the conditions at a specific depth, and thus adapt to different types of radiation [10,20,25,26]. Algae cultures carried out in photobioreactors require artificial exposure, with periods of light and darkness (so-called photoperiod). In the case of too intense light, the phenomenon of photoinhibition occurs, which leads to the inhibition of the growth of microalgae in the culture, while too low light intensity slows down the growth of their cells. For microalgae cells, the most favorable photoperiod is 16 h light/8 h dark [6,20,25].

The amount of supplied thermal energy varies throughout the day and year, as a result of the position of the sun in relation to the water table. It naturally depends on the latitude where the microalgae live. Flowing waters, e.g. rivers, show the most uniform temperature throughout their mass, because they are constantly mixed due to flow movements. In turn, stagnant waters, such as lakes with little or no water current are characterized by temperature fluctuations in the annual cross-section. Due to the division of layers of deep stagnant waters, the water near the surface is warmer and less dense than the lower, darkened parts [20,25,26]. For the proper growth of microalgae in open water reservoirs and photobioreactors, the optimum temperature is between 20 ℃ and 30 ℃ [27]. The temperature lower than 16 ℃ slows down the growth, and the temperature exceeding 35 ℃ is a lethal temperature for many varieties, causing cell death [10,20,25].

In addition, the growth of microalgae is conditioned by the salinity of the environment in which they live. Stress caused by the presence of salt contributes to numerous biochemical and bioenergetic changes in microalgae. It causes an increase in the catabolic processes of polymers and fats. It causes changes in energy transfer and changes in membrane permeability. It multiplies the amount of energy needed to maintain ionic homeostasis and electrochemical gradients towards the biosynthesis of organic compounds, which significantly participate in osmoregulation and help in the renewal of cellular structures [10,26,27].

The pH value limits the availability of dissolved forms of inorganic carbon used in photosynthesis. The basic substrate here is carbon dioxide, which is absorbed in the dark phase. A lower pH results in a lower solubility of carbon dioxide and a reduction in nitrogen uptake many times over. However, at elevated pH, carbon dioxide is converted into

bicarbonate ions, available only for a small number of algae species. Increasing pH changes bicarbonate ions into carbonate ions—completely unabsorbable. Oxygen and carbon dioxide should, however, be subject to constant control, because too high concentration of oxygen leads to the inhibition of photosynthesis, and the surplus of carbon dioxide results in changes in pH and stopping the growth of algae [10,19,26]. As the density of the microalgae culture increases, the pH increases. Introducing an additional stream of carbon dioxide to the culture along with the air makes it possible to reduce alkalinity and control this undesirable phenomenon in relation to biomass production.

Microalgae have the same basic nutritional needs as aquatic plants. They can only absorb nutrients dissolved in water. Algae cells need minerals rich in: − biogenic elements (O, C, N, P, S), − macroelements (Na, K, Mg, Cl, Ca), − microelements (Fe, Zn, Cu, Mn, B, Mo, Co). Chemical factors affecting the growth of algae come down to the isolation of strategic toxic compounds [6,7,10,25], such as: sulfur dioxide and derivatives, polycyclic aromatic hydrocarbons (PAHs) [10]. It is also nitrogen oxides, fluorine, lead, cadmium and compounds of these elements.

A very important factor for the growth of microalgae is also their mixing, which prevents sedimentation and maintains uniform conditions throughout the breeding tank. Mixing is a process that provides all cells with comparable access to light and medium during the culture and improves gas exchange between the air and the culture liquid [27].

2.3. Algae cultivation systems

Creating optimal conditions for the growth of algae is a key issue during their cultivation aimed at obtaining biomass. Due to the fact that these organisms are metabolically plastic, it is worth providing them with favorable breeding conditions. Appropriate suspension temperature, irradiation intensity, pH, salinity, methods of mixing and cultivation affect the production effect and the amount of costs incurred in the biomass conversion process. Breeding operations can be carried out in open systems and in controlled closed systems [28].

Open cultures can be located in places with appropriate climatic conditions, *i.e.* temperature and a long period of intense solar radiation [28,29]. However, convenient terrain and developed infrastructure are required, ensuring easy access to water with the desired parameters and CO_2.

Open breeding systems are most often found in the vicinity of plants emitting exhaust gases or fermentation plants [29,30]. Unfortunately, in our climatic conditions, the nature of daily and annual changes in temperature and sunlight means that the cultivation of microalgae in open water systems does not bring the expected results [29,30].

The disadvantage of culture in an open system is the contact of algae with other organisms in the ecosystem. Zooplankton feed on algae, and viruses, bacteria and fungi compete with algae cells for nutrients. There is a significant risk of infection from microorganisms [30,31]. In view of the above, maintaining optimal culture conditions in open tanks causes many difficulties. In addition, it raises another problem, which is the separation

of biomass from a liquid stream with a low concentration of cells, which increases the cost of biomass production [30,31].

Controlled closed systems for the cultivation of microalgae are called photobioreactors (PBR-PhotoBioReactor). The process in these devices consists in the use of transparent materials for the construction of culture vessels, facilitating the access of light. Systems can operate inside or outside buildings. They are illuminated with sunlight, which, if necessary, can be replaced with artificial light sources [31], or a combination of both options simultaneously. Tungsten and fluorescent solutions are used as a source of artificial lighting. The use of LED technology is also gaining recognition due to its energy efficiency and the ability to emit light waves similar to photosynthetically active radiation. As studies [32] show, the wavelength of light gains particular importance in relation to biomass production, but also in relation to their internal composition (production of metabolites). There is also a need to take care of the proper temperature of the culture in closed systems. In cultures focused on biomass production, the most optimal temperature is in the range of 16 ℃–30 ℃ [22,31,33].

Closed algae breeding systems give the opportunity to obtain a biomass harvest even several times greater than it is possible with the use of open systems. High productivity is all the more appreciated because it shows significant values per unit per occupied breeding area. Thanks to this, the construction of a production plant does not require a particularly large area [34–36]. Undoubtedly, the advantages of photobioreactors include their resistance to contamination and the possibility of convenient control of breeding parameters, which contributes to ensuring rational water management and saving the use of chemicals [32,37]. One of the biggest problems during the whole process of microalgae culture is the separation of cells from the culture medium and is considered to be expensive in terms of energy and economy [7].

In an effort to reduce the costs of obtaining biomass from microalgae, research is constantly being conducted aimed at finding economically advantageous separation methods. Techniques that have proven effective in purifying water from organic pollutants are currently gaining recognition such as: filtration; flotation; sedimentation; flocculation; centrifugation and membrane techniques [38–45]. In the case of *Chlorella sp*. microalgae, it is beneficial to use a combination of several separation methods, e.g. sedimentation and centrifugation, in order to obtain the best possible separation of biomass from the substrate. It is important that after separating the biomass from the substrate, processes are quickly applied that will allow for its long storage, parametric stability and preserve all chemical, physical and biological properties of the biomass. One such process may be freeze-drying, a process consisting of three stages: freezing, sublimation and desorption [46].

The quantity and quality of microalgae biomass, obtained with the use of possible separation methods and technologically processed, affects the manner of its further use. Properly selected, optimally selected conditions for the cultivation of microalgae and the efficiency of dehydration of the obtained biomass are the basis for the development of more and more effective methods of its processing and constantly open up new possibilities in its further processing and management, e.g. in the energy, food, cosmetics, pharmaceutical and agricultural industries [47].

2.4. Trends on industrial for microalgae biomass application

Due to the prospective application potential, biomass and substances obtained from microalgae are of interest to many research centers around the world. Successive development of knowledge and conducted experiments allowed the use of biomass from microalgae as new bioproducts in many industries. Among the most promising directions for the use of microalgae biomass, the following can be distinguished: industrial wastewater treatment, production of bioactive substances and production of bioenergy (thermal conversion) [48].

Energy industry—biomass obtained from the cultivation of freshwater microalgae can be a substitute for substrates from which alternative fuels and biogas are obtained. Microalgae are of great interest worldwide due to their wide potential for use as a renewable, sustainable and economical source of biofuels. As biofuels, they are an excellent substitute for liquid fossil fuels in terms of cost, sustainability and environmental protection. Microalgae can be considered as a sustainable energy source of next generation biofuels [24,48].

Organic farming—in recent years, there has been an intensive development of organic farming, the aim of which is to eliminate artificial fertilizers and synthetic plant protection products. Biomass obtained from microalgae is rich in micro- and macroelements, fatty acids, amino acids and protein and can be a high-value feed additive, which will be more assimilable by animal organisms. Both the biomass obtained from algae and its extracts are used as an additive to fertilizers, physioactivators, plant growth stimulants and root system as plant protection agents. The advantage of this type of biostimulants is biodegradability and non-toxicity to humans and animals. Algae biomass is also used in soil fertilization. Compost with the addition of algae improves its fertility and allows it to maintain an appropriate degree of humidity [49,50].

Environmental protection—biomass from microalgae, formed as a result of eutrophication processes in large water reservoirs, from which it is regularly removed, can be used e.g. in the processes of biosorption and bioaccumulation, in the concentration of toxic metal ions, and in the treatment of wastewater from biogenic compounds. Microalgae are also of great interest because they have the valuable property of absorbing nitrogen and carbon oxides with the release of pure oxygen and nitrogen and useful by-products. There is a huge interest in the use of microalgae in the world to reduce pollutant emissions, e.g. from coal-fired boiler houses or factories [49]. In the sequestration process, biomass energy can be used to produce biofuels and produce energy carriers such as methane and hydrogen [49,51].

Food industry—both micro- and macro-algae are used for nutritional purposes, on the basis of which dietary supplements and food additives (stabilizers, emulsifiers, thickeners, water-binding agents, gelling agents) are produced. As food, algae are valued for their high content of vitamins (A, B1, B2, B6, C), minerals (iodine, potassium, iron, magnesium, calcium) and polysaturated fatty acids (omega-3 and omega-6) [49,52].

Cosmetic industry—in cosmetics, sea algae are widely used, which contain alginic acid, which acts as an emulsifier (additive to shower gels, shampoos and toothpastes) and has a moisturizing and protective effect. Valuable ingredients contained in algae cells include:

polysaccharides, D-mannitol and sorbitol, which nourish and moisturize the skin, as well as unsaturated fatty acids, which stimulate the reconstruction and protection of the epidermis, soothe irritations, and have anti-allergic and anti-inflammatory properties [49,53].

Pharmaceutical industry—many preparations are obtained from algae, which are used in pharmaceuticals, e.g. eliminate swelling and inflammation, strengthen capillaries and regulate skin pH. Extracts from some algae contain chemical components with anti-allergic, anti-inflammatory, anti-stress, antibiotic, detoxifying and anti-thrombotic properties. Algae extracts contain biologically active substances that affect the physiological and metabolic processes of the entire body. Some species of algae contain glycoproteins with anti-inflammatory and antibiotic properties, activating immune processes, lowering blood pressure and cholesterol levels, and alleviating the negative effects of excessive ultraviolet radiation [49,54].

Chemical industry—biomass obtained from microalgae culture is a potential raw material for the production of e.g. dyes, antioxidants, enzymes, proteins and other chemicals [54]. Microalgae biomass can be used e.g. sorption biomaterials for removing pollutants from industrial wastewater, heavy metals from water and soil [49,55] as well as for the production of bioplastics for packaging [56]. The sustainable development of algae as bioplastics for packaging contributes to minimizing resource consumption, waste generation and regulating greenhouse gas emissions [56].

2.5. Microalgae biomass conversion to green products

Out of concern for the protection of the natural environment and the resulting reduction of greenhouse gas emissions [57], the European Green Deal Policy was developed to create a modern, resource-efficient economy, enabling counteracting the loss of biodiversity and reducing the level of pollution, as well as more efficient use of resources thanks to the transition to clean circular economy (CE) [49,57]. In order to increase the effectiveness of actions aimed at replacing non-renewable energy sources with renewable sources [49], e.g. biomass processing technologies through thermochemical and biochemical processes [49,58], e.g. for new ecological biomaterials, bio-based plastics, bio-char (Figure 1).

The possibility of replacing conventional energy sources is seen in the use of clean renewable energy, including biofuels of the second and third generation, which are obtained from materials that do not compete with food [59]. Second-generation biofuels are used to lignocellulosic biomass, sludge from municipal sewage and agricultural residues. Third-generation fuels, referred to as fuels of the future, are obtained from oil produced from algae biomass, capable of accumulating large amounts of lipids (e.g. *Chlorella sp*.) [60–63].

The very rapid development of industry in the world is associated with an increasing demand for energy, and at the same time creates many threats, especially related to pollution and degradation of the natural environment. The world's energy demand is met by hard coal, crude oil and natural gas, the resources of which are limited and will be exhausted in the next few decades. Therefore, the possibility of replacing conventional energy sources is seen in the use of clean, renewable energy. Some of the currently used ecological lubricants are based

on unmodified vegetable oils. Chemically, these are triacylglycerols (TAG), *i.e.* esters of glycerin and fatty acids. As a result of their transesterification with methanol, fatty acid methyl esters (FAME) are obtained, which are used as biofuels and biocomponents of diesel fuels. In Europe, so far mainly rapeseed and sunflower oil have been used for these purposes, which necessitated the search for oil plants that are outside the scope of interest of the food industry. Natural triglycerides are very easily biodegradable and are extremely effective lubricants (characterized by high viscosity indexes). However, their thermal, oxidative and hydrolytic stability is limited. Therefore, pure vegetable oils are usually used in conditions of low thermal forces. Algae oil could be a potential replacement or component of ecological lubricants, especially those based on food oils, especially since appropriate control of their cultivation processes allows for increasing the production of desired metabolites.

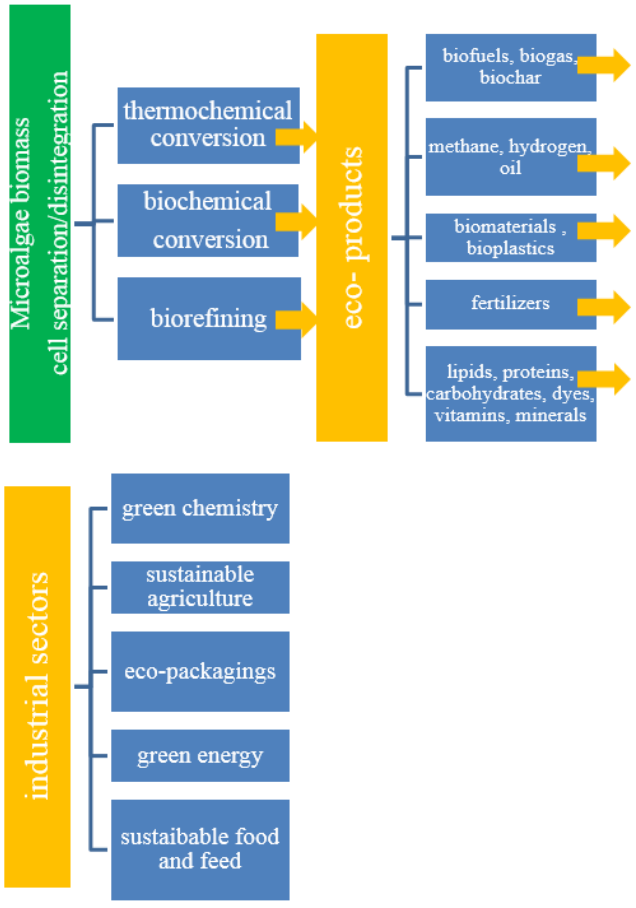


Figure 1. Refining and conversion of microalgae biomass (author's concept).

The demand for ecological consumables while maintaining the principles of environmental protection causes interest in materials obtained from renewable sources. This applies to the use of biofuels and biodegradable lubricants derived from biomass. So far, edible plants have been used for their use, e.g. rapeseed or sunflower with a clean, unmodified composition. An example of a new solution is the use of microalgae biomass rich in metabolites, which in their composition are similar to vegetable oils and do not compete with them in the context of cultivation and use in the food industry, and additionally it is possible

to control the microalgae cultivation process in order to obtain the largest possible amount of metabolites contained in them e.g. fatty acids.

Research on the possibility of using microalgae oil as a substitute for vegetable oils intended for the lubrication of steel elements and elements covered with WC/C coatings, carried out at Łukasiewicz — Institute for Sustainable Technology in Radom. Lubricating properties of algae oil in the steel-steel tribological combination are only slightly inferior to those of oil rapeseed, and in the coating-coating combination (WC/C type)—significantly exceed them, both in terms of anti-wear and anti-seize [64,65].

Chlorella sp. microalgae freeze-dried oil was obtained with a chemical composition similar to that of vegetable oils [66]. Physical and chemical properties (kinematic viscosity, density, viscosity index, water content, sulfur content and oxidation induction time) and lubricating properties assessed on the basis of G_{oz} anti-wear and P_t anti-seize properties of steel elements (bearing steel balls) in accordance with the guidelines of the PN-76/C-04147 standard using the T0-2 four-ball apparatus are comparable to the lubricating properties of vegetable oil. The differences in the anti-wear and anti-seize properties of microalgae oils obtained in the studies can be corrected by using an antioxidant additive that will improve both the thermo-oxidative stability of the microalgae oil (the largest differences compared to vegetable oil) and additionally improve the lubricating properties [65].

The study of the lubricating properties of microalgae oils of elements made of bearing steel covered with a 2 μ-thick low-friction coating type WC/C, which consisted of three layers: Cr, tungsten carbide (WC) and hydrogenated amorphous carbon (C) supersaturated with tungsten, shows that microalgae oil is characterized by better anti-wear and anti-seize properties than vegetable oil. The wear load limit G_{oz} of microalgae oil is 18% higher than that of vegetable oil and twice as high as that of a steel friction pair. Pt seizing load is 1.5 times higher than rapeseed oil and 2.5 times higher than microalgae oil in steel system [64].

3. Microalgae biomass in circular economy

The Circular Economy (Circular Economy) is a business model that minimizes the consumption of raw materials and the generation of waste. It assumes the creation of closed process loops in which waste generated is treated as raw materials in subsequent production phases. Such action helps create a sustainable, low-emission and competitive economy. The essence of the presented process solutions was to demonstrate the possibility of using post-production wastewater from the food industry as a valuable medium containing biogenic substances necessary for the growth of microalgae. Effective processing of microalgae biomass is aimed at effective conversion into biochar, which is proposed as a raw material for the production of sorption biomaterials, among others. used to purify post-production water and obtain biogenic substances for microalgae cultivation. This process is consistent with the assumptions of the circular economy regarding rational water and sewage management.

The concept of closing water circuits in production processes with the use of modular membrane installations using biotechnological methods to remove biogenic components from industrial wastewater (dairy industry, agri-food industry, paper, textile, chemical

industry) and municipal wastewater (urban sewage treatment plants) is of great importance interest of research centers and production companies. Significant importance on design of production processes based on closing loop has rational water and sewage as well as raw material and product management created by usage of eco-design of innovative bio-products manufacture and building of integrated value chains (Figure 2).

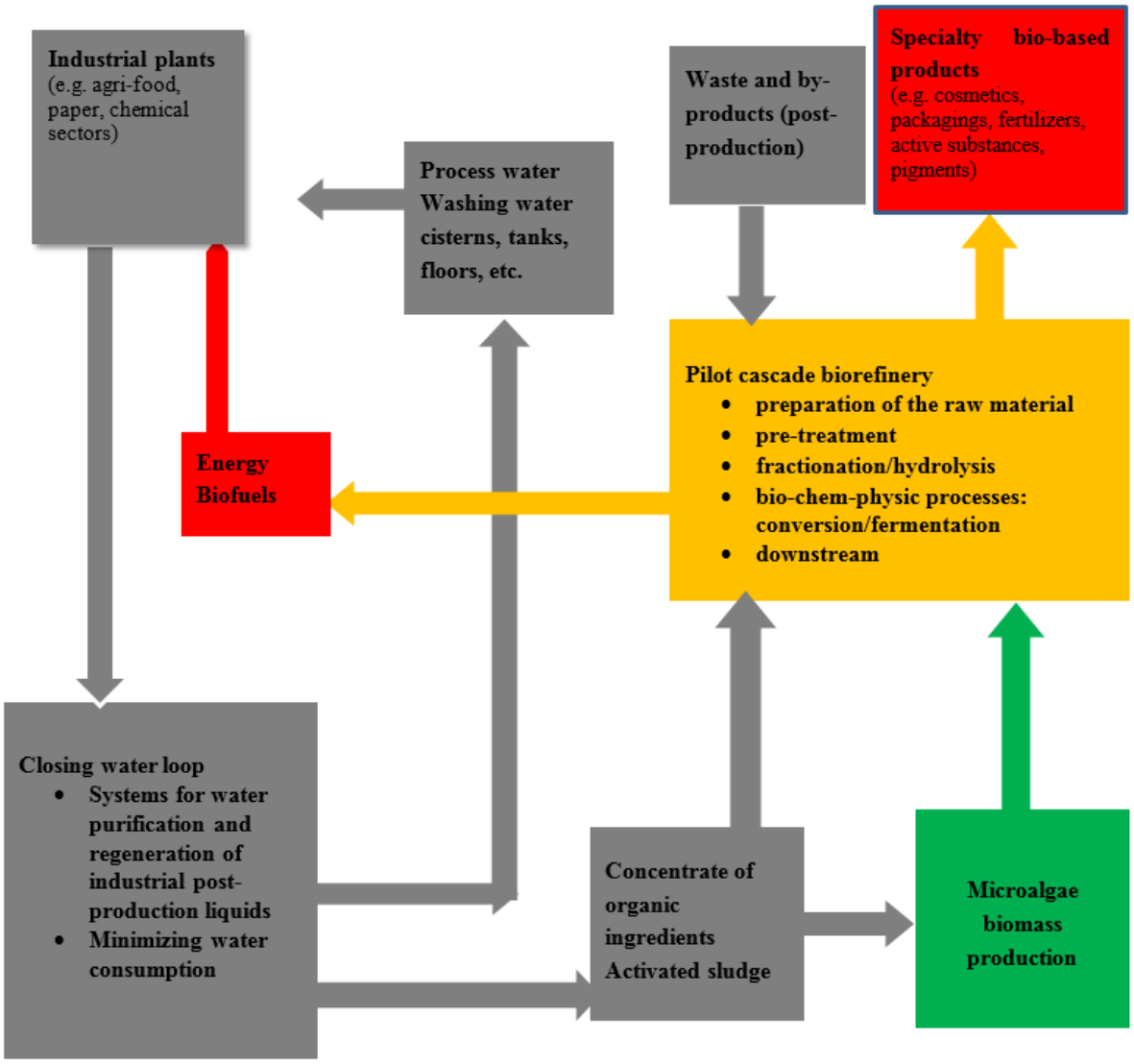


Figure 2. The concept of closing water loop in production processes based on the use of water treatment systems with the practical use of waste and post-production sewage. (author's concept).

Installations for closing water loops in production processes integrated with a system for biotechnological processing of residues after purification of process waters for microalgae cultivation, are a real alternative to traditional water and sewage management solutions for industrial companies, especially in the food industry. The obtained biomass of microalgae can be used as an ingredient for the production of bioproducts such as biochars, ingredients of agro products or in biorefining processes to obtain, among others, bioactive substances, mono and oligomeric fractions for polymeric materials, biofuels and others.

One of the fastest-growing sectors of the economy in Poland, which generates large amounts of waste and sewage, possible for circular management, e.g. for the cultivation of microalgae and processing into useful bio-based products is the agri-food sector.

The leader on the market of juices, nectars and drinks in Poland, Tymbark—MWS Co. a company belonging to the MASPEX capital group, one of the largest companies in the food products segment in Central and Eastern Europe which has in its portfolio products that do not contain artificial colors and preservatives. Tymbark's juices and drinks owe their unique taste because of carefully selected, ripe fruit and vegetables, delivered by the best and proven suppliers who meet high quality requirements. One of the areas in which the company is active is sustainable development and implementation of circular economy assumptions. The plant had attempted to analyze the use of sewage sludge in the development of an integrated system for the production of algae biomass for energy purposes, *i.e.* for the production of biogas [67].

Industrial design has assumed the development of an installation that allows for a very intensive biomass growth process in a closed system, making the process independent of the impact of the environment, while guaranteeing the maintenance of constant process parameters. Previous biomass production technologies used the natural light or light generated by sodium lamps. In these solutions, high-pressure sodium or fluorescent lamps were most often used, emitting light that partly covers the photosynthetic needs of plants. Part of the energy of these lamps emitted is in a spectral range unrecognizable by chlorophyll antennas. The solution might be LED sources that allow the selection of appropriate wavelengths effectible in the process of photosynthesis, with simultaneous lower energy consumption, which determines the economic, performance and ecological advantages (reduced energy demand).

LEDs emit relatively little heat energy (high efficiency). Thanks to this, it was possible to place LED panels at a short distance above the crops without fear of excessive drying or burning of the plants. Plants have received more light. The small amount of heat emitted by lighting alone facilitates the process of air-conditioning the breeding room, which was important for the rate of plant development, due to the known interaction of light and temperature in the processes of photomorphogenesis. LED panels have had a negligible effect on the ambient temperature in bioreactors, which is why their use allows for precise temperature control. The purpose of investigations on this innovation was to obtain a solution that would allow for the intensification of biomass production and making it independent of external conditions. Laboratory scale investigations indicated that mentioned experiment, due to the nature of the technology, should be conducted on a minimum semi-technical scale, allowing for the appropriate assessment of economic effects.

It was assumed to study the influence of the length of the radiation beam through LED sources on biomass increments depending on the type of culture forming the biomass. The above experiments were carried out on a laboratory scale. Results from laboratory scale indicated that innovative experiment should be explored on a minimum semi-technical scale, which allows possibilities to assess the economic effects.

The branch of the food industry in which the production and maintenance of infrastructure requires the supply of large amounts of water used for energy, technological, economic and hygienic purposes is the dairy industry. Two types of waste are generated in dairy plants: production (milk residues and milk products, characterized by alkaline reaction and containing large amounts of biogenic compounds of nitrogen and phosphorus) and non-production (used washing baths, characterized by acid reaction and containing organic compounds and washing substances, *i.e.* acids, bases, detergents). For the natural environment, dairy wastewater is a serious problem that requires an urgent solution, especially in the context of the need to recover water for reuse.

The presence of biogenic compounds in the wastewater, in particular nitrogen and phosphorus, which cannot be effectively removed using traditional methods (anaerobic and aerobic) used in the treatment of dairy wastewater, can be used for the cultivation of microalgae because the above-mentioned biogenic compounds are necessary for their life. Controlled stimulation of microalgae cultures with technological processes makes it possible to obtain final products with assumed properties and a specific composition of metabolites, required for further practical use (Figure 3).

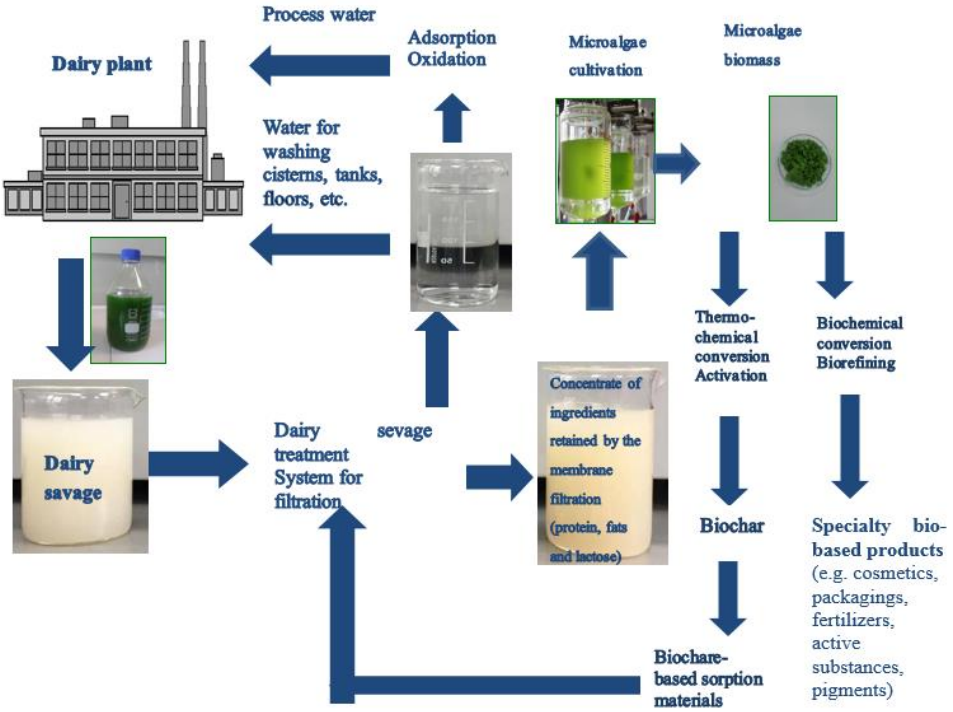


Figure 3. Closing loop in dairy plant by wastewater treatment and practical use of activated sludge for microalgae biomass production (based on [68]).

The use of an appropriate set of membrane techniques gives the possibility of fractionation of wastewater mixtures into fractions of different compositions. This process involves the formation of retentate, which is difficult to treat. For this purpose, biological methods based on bioaugmentation and microalgae culture can be used. Combination of mentioned biological processes the efficiency of the removal of nitrogen and phosphorus compounds from the retentate after ultrafiltration of dairy wastewater has considerably

increased [69]. After separation of algal biomass, the purified water met the environmental requirements for the discharge of wastewater into waters or soil within the content of these substances. Biomass, after dehydration and essential technological processing, can be a valuable raw material with high energy potential [70].

In Łukasiewicz—Institute of Technology for Exploitation in Radom, research was carried out using dairy production wastewater as a medium for the cultivation of *Chlorella sp*. microalgae. total nitrogen and total phosphorus. The bioavailability of ammonium nitrogen as a biogenic component is related to the development processes of microalgae. The greater the number of algae cells in the culture, the greater the demand for nutrients. During the experimental work, the following reduction was achieved: ammonium nitrogen by 92% from the initial level of 3.8 mg/L to 0.309 mg/ L, total nitrogen by 70% from 105 mg/ L to 31.0 mg/ L total phosphorus by 55% from 20.2 to 8.89 mg/ L. The obtained results confirm that it is possible to effectively cultivate *Chlorella* microalgae using raw dairy wastewater as a culture medium [71].

Utilitarian studies of microalgae biomass conducted at the above mentioned Institute were focused on the use of biomass obtained in culture with the use of industrial wastewater for the production of bio-chars with parameters that predispose them to be used as sorption materials. After separation from the culture medium, the microalgae biomass was subjected to low-temperature pyrolysis. DSC thermal analysis of the product obtained in the pyrolysis process showed that the biocarbon samples obtained were characterized by: temperature T_p-169.5 ℃, T_{max}-353 ℃, T_k-520.3 ℃; heat-704.89 μVs/mg. On the basis of the TG curve, the weight loss in the range of the greatest energy changes was assessed, which was 0.208 mg [72]. Microtopography of the surface of the microalgae biomass and the product obtained in the pyrolysis process, made using scanning electron microscopy, showed significant differences in the morphology of both examined objects. The obtained biochars are characterized by a much more developed specific surface area and pores of various sizes and shapes (in particular, macro and meso pores). Biochars with a well-developed surface area were used to produce sorption materials. Verification tests confirmed the possibility of cultivating *Chlorella sp*. microalgae on a substrate that was real dairy wastewater and converting the post-culture biomass in the pyrolysis process at 600 ℃. The use of a sorbent in the form of biocarbon for cleaning used washing baths from a dairy plant made it possible to reduce pollutants, *i.e.* turbidity, suspended solids, total organic carbon, sulphates and chlorides in the case of using biocarbon obtained from microalgae biomass grown on dairy wastewater [73].

4. Conclusion

Biomass comes in particular from agriculture, but also from forestry and related industries, such as fishing and aquaculture. Attention should be paid to algae, which can also be used as biomass. Algae may become a very valuable source of biomass in the near future. Since work and research on algae-based biomaterials is still under development and there are still many research areas that need to be explored. The work presents a new solution involving the use of biomass obtained from algae as a new biochar-based biomaterial that can be used as a

sorbent in the treatment of industrial food wastewater. The use of these wastewaters (depending on their composition) as a substrate for microalgae cultivation was investigated. One of the undoubted benefits of using this type of materials will be the reduction of the amount of waste that is generated during their life cycle and in the food industry, and even if it is created, it can be reprocessed.

The presence of biogenic compounds in sewage, in particular nitrogen and phosphorus, which cannot be effectively removed by traditional methods (anaerobic and aerobic) used in dairy wastewater treatment, can be used for the cultivation of microalgae, because the above-mentioned relationships are essential to their lives. Controlled stimulation of microalgae cultures with technological processes allows to obtain end products with the assumed properties and specific composition of metabolites required for further practical use. Two types of waste are generated in dairy plants: production (milk residues and milk products, characterized by an alkaline reaction and containing large amounts of biogenic nitrogen and phosphorus compounds) and non-production (used rinsing baths, characterized by an acidic reaction and containing organic substances). cleaning compounds and substances (e.g. acids, alkalis, detergents). For the natural environment, dairy wastewater is a serious problem that requires an urgent solution, especially in the context of the need to recover water for reuse. These issues became an inspiration for research related to the practical use of microalgae to produce biochars with the properties and structure required for the production of sorption materials. In terms of implementing rational water and wastewater management in industrial practice by closing water cycles, research work on improving the cultivation of microalgae on post-production wastewater from the food industry in correlation with designing the properties of sorption biochars is of particular practical importance.

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Conflicts of interests

The authors declare no conflict of interest.

Authors' contribution

Conceptualization: Karolina Dziosa and Danuta Ciechańska; methodology: Karolina Dziosa and Danuta Ciechańska; validation: Karolina Dziosa, Danuta Ciechańska. and Marta Kutyna-Bakalarska; investigation: Karolina Dziosa and Marta Kutyna-Bakalarska; resources: Karolina Dziosa, Danuta Ciechańska and Marta Kutyna-Bakalarska; data curation: Karolina Dziosa, Marta Kutyna-Bakalarska and Danuta Ciechańska; writing—original draft preparation: Danuta Ciechańska and Karolina Dziosa; writing—review and editing: Danuta Ciechańska and Karolina Dziosa; visualization: Danuta Ciechańska and Karolina Dziosa;

supervision: Danuta Ciechańska. All authors have read and agreed to the published version of the manuscript.

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