sustainability

MDPI

Review

Bio-Based Circular Economy and Polygeneration in Microalgal Production from Food Wastes: A Concise Review

Adewale Giwa [1,2,*], Farah Abuhantash [1,2], Bushra Chalermthai [1,2] and Hanifa Taher [1,2,*]

1 Department of Chemical Engineering, Khalifa University of Science and Technology, Abu Dhabi P.O. Box 127788, United Arab Emirates
2 Research and Innovation Center on CO_2 and H_2 (RICH), Khalifa University of Science and Technology, Abu Dhabi P.O. Box 127788, United Arab Emirates
* Correspondence: adewale.giwa@ku.ac.ae (A.G.); hanifa.alblooshi@ku.ac.ae (H.T.)

Abstract: The production of biofuels from microalgae has gained considerable attention due to the rapid diminution of fossil fuels. Despite major advantages, microalgal biofuels deployment still faces obstacles associated with the cost of biomass production and waste disposal. The production could become more cost-effective and feasible if the wastes in the production processes are recycled/reused and the biofuels produced are co-produced with high-value co-products. The aim of this review is to discuss and analyze the importance of recycling/reusing wastes and co-producing high-value products to be implemented with biofuels from microalgal-based processes. Recent advances in circular economy/integration and polygeneration, as proper strategies, are discussed. Circular economy and integration entail the reuse of food wastes, waste biomass, and wastewater in microalgal conversion processes for producing biofuels. The main focus of the section of this review on circular economy is food waste reuse for microalgal production. Polygeneration is the production of multiple products, including a biofuel as the main product and multiple co-products to ensure process cost reduction. The results reported in relevant studies have shown that microalgal growth and metabolite accumulation could be favored by mixotrophic cultivation using wastes from the conversion processes or reused food wastes. The co-production of high-value products, including pharmaceuticals, proteins, carbohydrates, pigments, bioplastics, pellets, and biofertilizers may also favor the sustainability of biofuel production from microalgae.

Keywords: microalgae; food wastes; circular economy; circular integration; polygeneration; sustainability

Citation: Giwa, A.; Abuhantash, F.; Chalermthai, B.; Taher, H. Bio-Based Circular Economy and Polygeneration in Microalgal Production from Food Wastes: A Concise Review. *Sustainability* **2022**, *14*, 10759. https://doi.org/10.3390/su141710759

Academic Editor: Barry D. Solomon

Received: 28 June 2022
Accepted: 19 August 2022
Published: 29 August 2022

1. Introduction

The current global energy crisis that is associated with an overuse of fossil fuels has increased attention toward finding alternative clean energy sources. Among the replacements, which have attracted extensive research attention, is the production of biofuels, such as biodiesel, bioethanol, biohydrogen, and biogas, as non-toxic and renewable fuels. Several feedstocks are being explored, and biofuels are classified into three different categories, which are first-, second-, and third-generation biofuels. The first-generation biofuels are those produced from food crops such as biodiesel from sunflower and bioethanol from starch. In the second categories, biofuels are produced from non-food crops such as bioethanol from lignocellulose biomass and biodiesel from waste oils. Due to such feedstocks' conflict with food and water security, interest toward the use of third-generation biofuels has increased, as it is mainly produced from microalgae and microbes. Biofuel production from algae has successfully positioned itself as one of the most promising alternatives due to its favorable features. Microalgae possess a higher carbon dioxide (CO_2) fixation rate and areal productivity, faster growth rate, and are more easily adjustable to environmental changes than plants, in addition to their adaptability to grow in seawater and wastewater. Biofuels derived from microalgae are among the third-generation biofuels that totally open up a new dimension in the renewable energy industry, as their utilization provides benefits toward solving the food crisis. However, the production of biofuel from microalgae is still not economically feasible. It involves different routes that produce a significant amount of residual wastes that are disposed and burned, leading to the release of significant amounts of CO_2 that cause climate change and global warming, in addition to the high cost associated with the proper management of wastes.

There are two important approaches to increasing the profitability and reducing waste accumulation from microalgae-based processes. These ways are circular economy/integration and polygeneration. Circular economy (CE) involves the recycling of wastes back to the same process, whereas circular integration involves the reuse of wastes through their integration with another process. The global interest toward CE, with an aim of reducing the risks associated with waste accumulation and material inadequacy for sustainability, is increasing. An example of circular integration is the use of food wastes from another process as media for microalgae cultivation. Wastes from the microalgae cultivation process can be recycled back to the process itself, as an example of CE. For example, the wastewater obtained after harvesting algal biomass can be recycled back to the cultivation pond or photobioreactor. Moreover, left-over waste obtained after the extraction of metabolites from microalgae biomass can be reused in another process. Based on the Food and Agriculture Organization of the United Nations, it was estimated that, yearly, a third of the food produced worldwide goes into waste, accounting for 1.3 billion tonnes [1]. The term food waste (FW) refers to commercial, industrial, and domestic mixed-food residues such as fruits, bakery, vegetables, grains, and meat meant for human consumption (not fruit peels, or seeds, which would be referred to as 'organic waste') [2]. The proportions of global FW are estimated to be 40–50% fruits and vegetables, 30% grain crops, 20% meat, seed oils and dairy products, and 35% fish, where the cost is almost USD 1 trillion annually [3]. Food wasted by consumers in North America and Europe are 95–115 kg/year per capita, while this number in South/Southeast Asia and sub-Saharan Africa is 6–11 kg/year [4]. In 2014, in China, approximately 245,000 tons of FW was generated per day [5]. In the United Arab Emirates, food waste was estimated to be 197 kg/year per person, costing AED 13 billion (USD 3.54 billion) annually [6].

The treatment of FWs is currently of great interest to researchers since these wastes can be utilized as a valuable resource media with high nutrient content or can be converted to feed for animals [7]. This is usually carried out by processes such as composting, anaerobic digestion, or incineration and, over the years, the use of FWs for fermentative and cultivation processes has increased. A fermentative process is used to produce short-chain organic acids such as succinic and lactic acids and polyhydroxybutyrate, while cultivation converts FW into food and feed for microalgae cultivation [8]. Polyhydroxybutyrate is a polymer used in several applications including agriculture and in the textile and packing industries. In addition to these, other organic acids can be also derived from such processes by using FW such as acetic propionic and butyric acids, depending on FW composition and microbial communities. The use of FW as microalgae cultivation media saves a cost that would have otherwise been expended on purchasing synthetic or commercial media for microalgae cultivation. Therefore, a valid and valuable cost-saving approach for growing some kinds of microalgae is the use of FW as a media source, as an alternative to traditional culture media such as F/2 medium, Johnson's medium, BG11 medium, and others. Because FW has a complex structure, and, therefore, nutrients recovery requires some pretreatments, i.e., reduction in particle size, delignification, and degradation (since most of FW contain polysaccharides), they need to be hydrolyzed first. In anaerobic digestion, food waste can be used as a co-culture with microalgae for methanogenesis or biogas production.

Polygeneration is another technique for improving the cost effectiveness and sustainability of microalgae-based processes for production of biofuels and biochemicals. Polygeneration is the production of two or more products from the same process to increase productivity and reduce the overall cost of production. Unlike co-generation that produces electricity and heat from a process, polygeneration is a thermochemical approach where one of the products is a chemical. Within a biorefinery concept, polygeneration involves the conversion of biomass into many value-added products. In microalgae-based processes, polygeneration is mainly in the area of co-production or concurrent production of biochemicals from the bioenergy production process. In many microalgal processes, the main product is a biofuel, and the co-products could be pharmaceuticals, proteins, carbohydrates, pigments, bioplastics, pellets, or biofertilizers. Some of the products that could be co-produced from the same microalgal biomass are summarized in Figure 1.

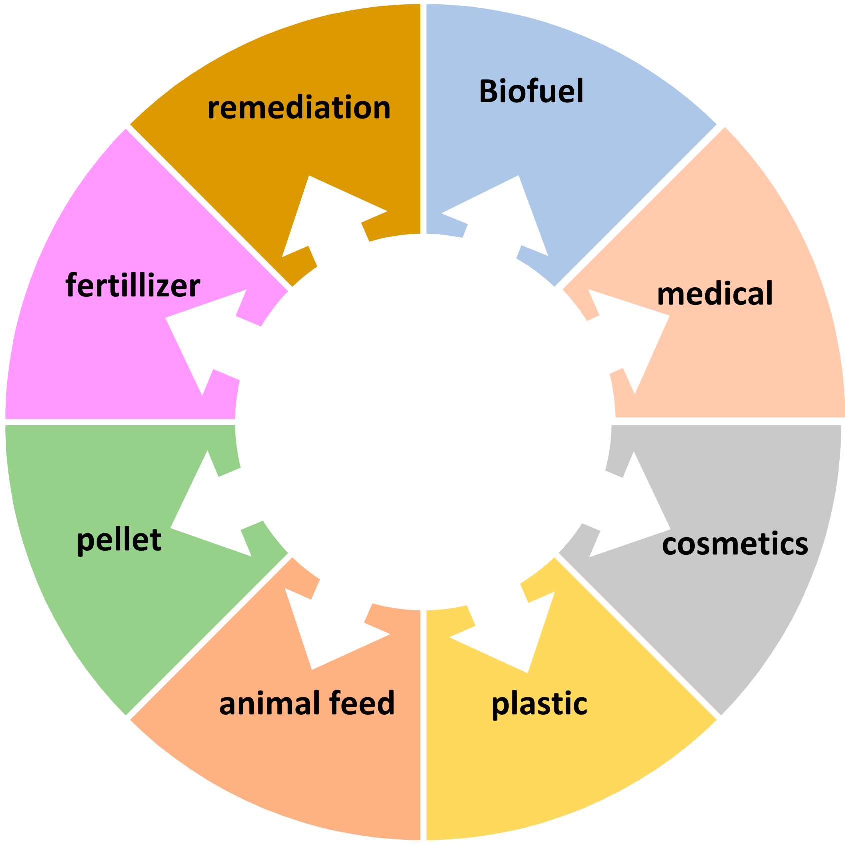

Figure 1. Polygeneration of products from microalgae.

In this paper, an overview of circular bioeconomy and polygeneration approaches in microalgal conversion to biofuels and biochemicals are presented. The findings reported in recent publications on these two areas are discussed and analyzed. The review focuses on the typical use of FW in microalgal processes and discusses the implications of these findings for in the context of improving the economic viability of microalgal biofuel production.

2. Circular Bioeconomy

As the current fossil fuels economies are linear and open cycle models that follow a resource take–product make–waste dispose approach, rational use of resources is not implemented. These models work to produce more products from cheap resources, which is not advantageous from both an environmental and economic prospective. In this model, the collection of raw materials leads to high energy and water consumption, emissions of toxic substances, and disruptions of natural resources. In addition, when wastes are discarded, space is taken up from natural areas, and toxic substances are emitted. On the other hand, circular economy model reduces the need of raw material, reuses product as a resource, and recycles process waste to maintain the added value while eliminating waste, well known as the 3R principle. Thus, economic benefits from the circular approach implementation are obvious and clear.

Circular bioeconomy, as the name indicates, is the effective management of bio-based resources and wastes via the integration of circular economy principles into the bioeconomy where the production of high value products, such as the production of food and biochemical, pharmaceutical, and bioenergy is aimed in a closed looped system. By realizing circular economy, carbon utilization is maximized, while its footprint is minimized. In addition, the discharge of nutrients (nitrogen and phosphorus) to water is diminished [9]. The tool, therefore, improves the use of resources, minimizes wastes accumulation, and ensure sustainability, as it focuses on circulating process of raw material and products in the market for a longer time before they are disposed. Despite the abundant amount of FW produced worldwide, few studies have been performed to use them for the cultivation of microalgae to produce high-value products. Such wastes contain large amounts of nutrients, where as much as 30–60% of starch, 5–10% of proteins, and 10–40% of lipids can be recovered [10–12]. Since most of the food residues are rich in nutrients, they could be a source of media for the cultivation of microalgae. Food residues can be converted into high-quality protein for use as animal feed, high-value products such as carotenoids, biofuels, and greywater purification, among other applications, via microalgae cultivation. In other cases, microalgae digestion can also be used to produce energy such as methane, and, by co-digesting it with FW, the production of methane could be greatly enhanced [13].

Food waste anaerobic digestate or effluent, simply referred to as food waste effluent, offers the same benefits as industrial wastewater for microalgae cultivation. However, industrial wastewater may contain toxins, which can inhibit the growth of different microalgal strains [14]. Unlike conventional media, effluent requires some adjustments before being used for algal cultivation. Generally, "strength", i.e., toxic concentrations of nutrients and high turbidity are the main disadvantages. High ammonium content would inhibit algal growth [15], mainly because the high quantities of ammonium result in producing the free ammonia that diffuse and accumulate in a microalgae cell, ending up with a toxic affect. Dilution with freshwater and nitrification are two common solutions used to solve the issue [16]. Because algal cells growth also requires some essential elements which may not be available in the FW effluents, additives are used. Park et al. [17] reported significant enhancement in *C. vulgaris* biomass yield through the addition of Mg^{2+} to anaerobic digestion piggery effluent. Grown microalgal cells also help to treat FW by removing the nitrogen and phosphate, as they utilize these nutrients for growth [18]. The results also showed that microalgae cultivation can reduce the COD of waste effluents and digestates up to 90%, as reported by Chuka-Ogwude et al. [19,20].

The diversity of the organisms in food waste effluents can make the dynamics of the relationship between microalgae and bacteria in FW effluent complicated. The organic matter can be oxidized by bacteria (by consuming the oxygen) to inorganic compounds. Meanwhile, the microalgae can use light to uptake the inorganic nutrients where the biomass is produced during this step, thereby releasing the oxygen required by the bacteria for the oxidizing step. Some factors involved in the algal cultivation system (such as variable pH, high light, high-dissolved oxygen, and shear produced by mixing) have been found to limit the survival of up to 99% of many pathogenic bacteria such as coliforms and Salmonella [21]. According to this scheme, these operating conditions are too stringent for bacteria to thrive, and most bacteria are eliminated under mixotrophic conditions. A "natural" equilibrium between microalgae in bacteria establishes whatever the conditions are in the reactor. The main biological phenomena, in general, are shown in Figure 2. Therefore, the consensus is that, for most species, biomass growth and the productivity of microalgae is improved under mixotrophic conditions [19].

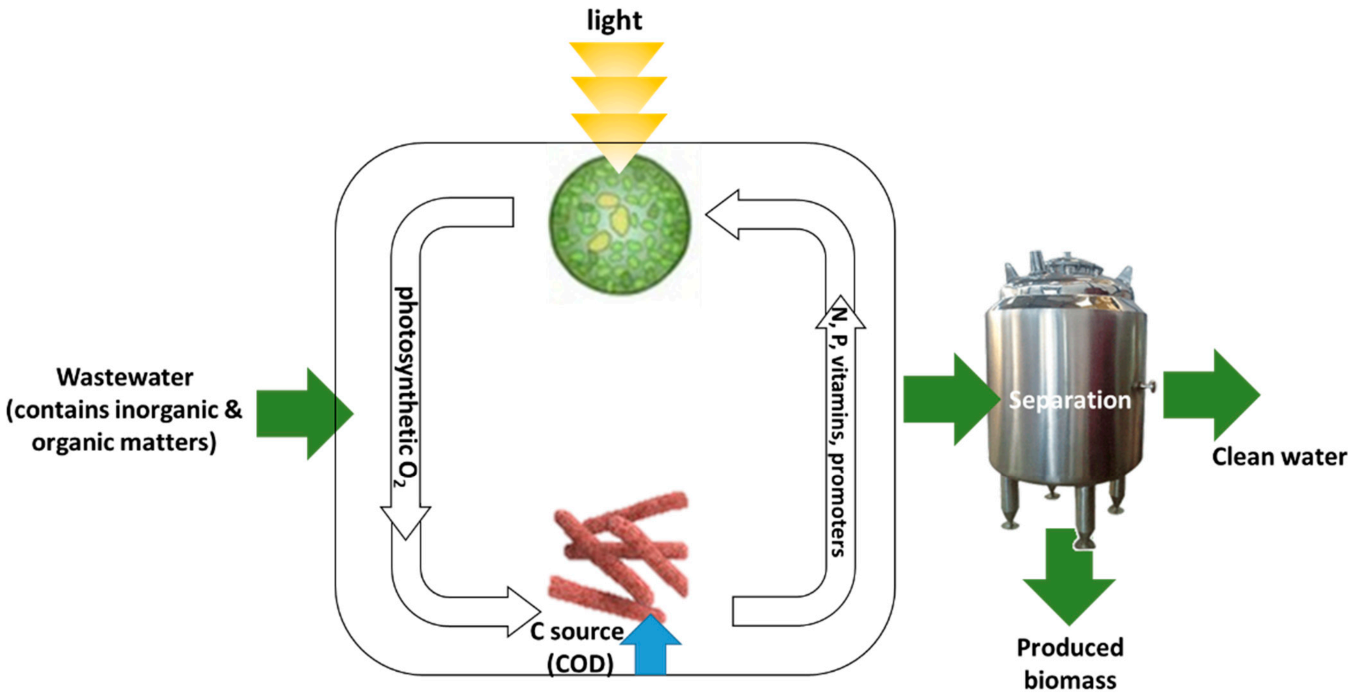

Figure 2. Main biological phenomena taking place when using microalgae/bacteria consortia for nutrients' recovery from wastewater effluents (redrawn from [22]).

The optimization of the productivity of microalgae is of the utmost importance while cultivating microalgae with FW effluent [18]. The simplified pathways of utilizing microalgae cultivated from effluents are shown in Figure 3. Such microalgae can be used for many applications, such as dried pellets, human and animal feed, among others. Chi et al. [23] focused on growing *Cryptococcus cruvatus* and *Rhodotorula glutinis* in a mixed media containing hydrolyzed FW and municipal wastewater. These strains could accumulate considerable amounts of lipids within their cells, reaching 18.7–28.6%. Similarly, Abreu et al. [24] investigated the cultivation of *Chlorella vulgaris* in dairy industry waste, namely in hydrolyzed cheese whey powder solution, and aerated with 2% *v/v* CO_2-enriched air (CO_2). The strain was found to grow better than if grown in a mixture of glucose and galactose, which is mainly due to the presence of other macronutrients (i.e., phosphorous and calcium) in the hydrolyzed wastes. Such macronutrients play an important role in forming the structural component of microalgae cells and their growth. This was also found when non-hydrolyzed wastes were also examined; however, pigment production was more dominant compared to lipid production.

Mixotrophic cultivation is considered as a promising strategy for achieving a cost reduction in microalgal biomass production. In addition, cultivation with hydrolyzed cheese whey increased the lipid content by six times of the content obtained when it was cultivated in photoautotrophic culture, which yielded 42 mg/L/d. However, the protein content was highest in the photoautotrophic conditions, rather than in the cheese whey media. Chew et al. [25] observed that, by cultivating *C. vulgaris* in a mixed media containing 25–35% organic cafeteria FW compost and the rest as inorganic compost, an increase in the content of lipids, proteins, and carbohydrates was observed, compared to cultivation using the inorganic medium only. This may be due to the presence of organic carbon in the compost. The lipids and carbohydrates were extracted by solvent extraction using a mixture of chloroform/methanol/water and sulfuric acid, respectively. The proteins were extracted by disrupting the microalgal cells using ultrasonication for 20 min. The study concluded that the highest contents of lipids and proteins were accumulated (219.7 mg/g and 126.4 mg/g, respectively) at a cultivation mixture ratio of 25:75 and 35:65 organic to inorganic compost, respectively. However, the highest carbohydrate concentration of

346.5 mg/g was accumulated at a culture media of 100%, and was organic, with 75:25 compost solution to water dilution. It was concluded that using organic medium can reduce cultivation cost, while increasing biomass production of microalgae. Meanwhile, the presence of excess nutrients in food wastes may be a limitation to microalgal growth. Therefore, it is recommended that the nutrients in food waste should be in an appropriate quantity by adjusting their concentrations using the water dilution method. Lau et al. [26] studied the cultivation of *C. vulgaris* in an FW media made up of cakes, noodles, pastry, rice, meat, and vegetables from Starbucks and a fast-food restaurant. With the FW providing excess nutrients for cultivation, the lipid and protein content in the microalgae decreased from 300 to 200 mg/g. However, at day 7 of cultivation, the lipid content increased back to 300 mg/g. The carbohydrate content, on the other hand, increased from 200 mg/g to 400 mg/g at day 4 of cultivation due to the conversion of the carbon in the food waste to carbohydrates, instead of its conversion to biomass. Stagnation of the growth of the microalgae was observed. Such changes in the contents of carbohydrates, lipids, and proteins are mostly correlated to the depletion of nitrogen and phosphorous. It was concluded that *C. vulgaris* can be cultivated in hydrolyzed FW; however, growth inhibition due to excess nutrients and a corresponding increase in the concentration of carbohydrates may be observed. The findings discussed in relevant works on the use of wastes for microalgal cultivation are summarized in Table 1.

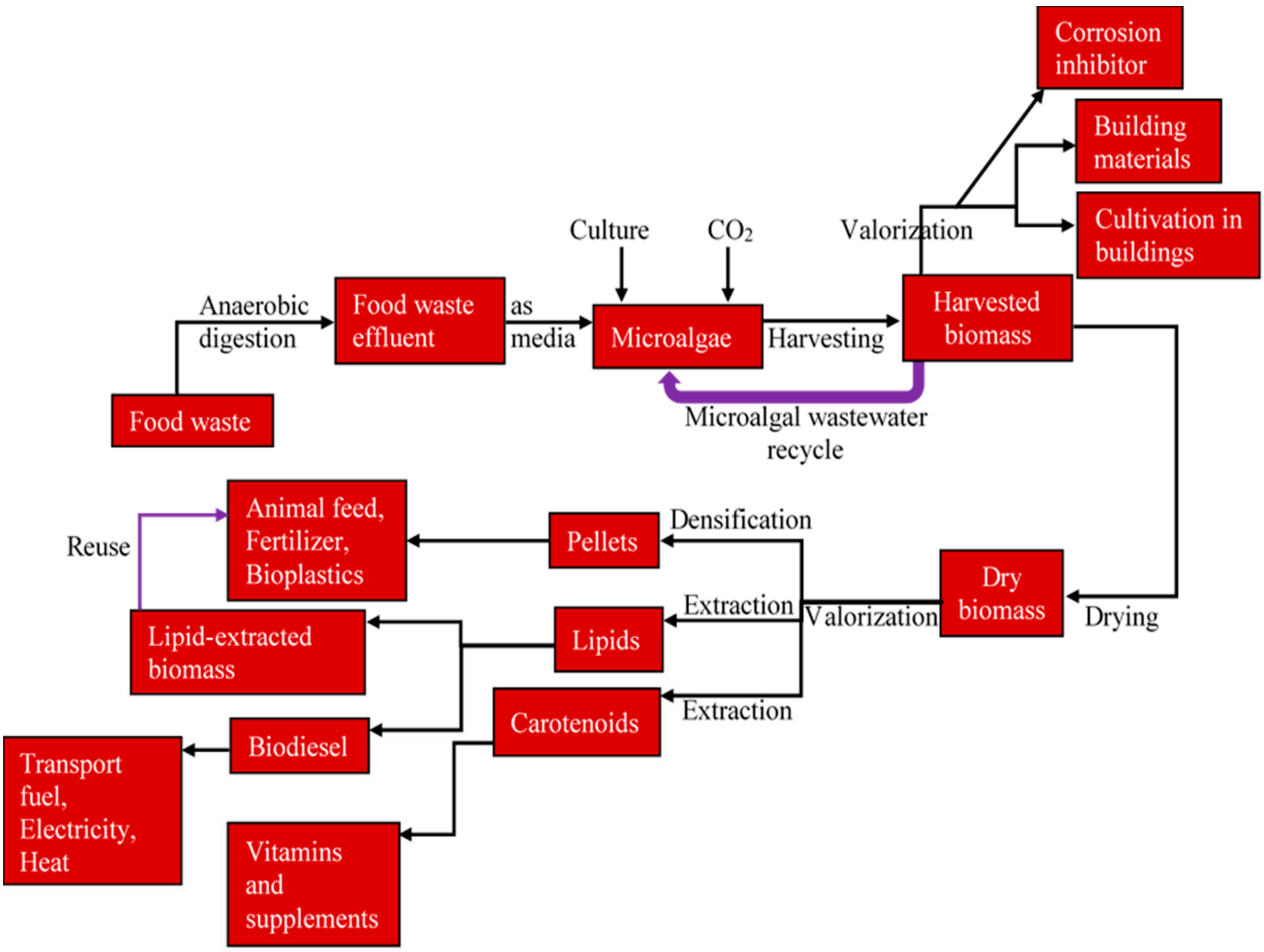

Figure 3. Simplified pathways of utilizing microalgae cultivated from food waste effluents.

Table 1. A summary of findings reported in literature on microalgae cultivation using waste medium and yield of produced products.

	Species	Growth Media	Extraction (Conditions)	Yield (*wt*/*wt*)	Comments	Ref.
Lipids						
	C.curvatus	Cafeteria food waste	N/A	28.6%	Low lipid productivity due to C/N ratio. Lipid accumulates using food waste	[23]
	R.glutinis	Cafeteria food waste	N/A	19.6%	Low lipid productivity due to C/N ratio. Lipid accumulates using food waste	[23]
	C. vulgaris	Cheese whey powder	SLE	42% [a]	Higher lipid content by using hydrolyzed cheesy whey powder	[24]
	S. mangrovei	Rice, noodles, meat, and vegetables	SLE	30%	Accumulated fatty acids are suitable for biodiesel production	[12]
	C. pyrenoidosa	Synthetic wastewater	NA	65.2%	Highest lipid productivity was achieved at salinity of 1.0%	[27]
	C. vulgaris	Cake, pastry, noodles, rice, meat, and vegetable waste	SLE (60 °C)	22.2%	Lipid content decreased from 300 to 200 mg/g between days 4 and 6 in cultivation while increased to 300 mg/g at day 7	[26]
	C. vulgaris	Milk processing wastewater	dichloromethane and methanol (2:1 *v*/*v*)	421.56 [e]	Biomass productivity reaching 20 $mgL^{-1}d^{-1}$	[28]
	C. sorokiniana	Sewage Wastewater	MAE (100 °C)	19.8%	Increased biomass production resulted in an increase in lipid yield	[29]
	S. obliquus	Sewage Wastewater	MAE (100 °C)	16%	Increased biomass production resulted in an increase in lipid yield	[29]
	S. obliquus	Municipal Wastewater	Freeze drying-MAE (100 °C)	25.39%	Use of freeze drying as pre-treatment increased lipid yield	[30]
	Micractinium sp.	Municipal Wastewater	SLE (25 °C)	36.29%	The metabolic profiles have significant differences in the exponential and stationary phases of growth	[31]
	C. pyrenoidosa	Canteen food waste	NA	12–15%		[32]
Proteins						
	C. vulgaris	25% cafeteria organic food waste and 75% inorganic food waste	SLE (80 °C)	10.1%	At a ratio of 25–35:75–65 organic to inorganic food waste, a higher amount of lipids was accumulated	[25]
	C. vulgaris	Cheese whey powder	SLE	26% [a]	Higher protein content by using hydrolyzed sample	[24]
	S. mangrovei	Rice, noodles, meat, and vegetables	SLE	10%	The protein content makes the microalgae of interest as a food and feed source	[12]
	C. pyrenoidosa	Rice, noodles, meat, and vegetables	SLE	10%	The protein content makes the microalgae of interest as a food and feed source	[12]
	C. vulgaris	Cake, pastry, noodles, rice, meat, and vegetable waste	SLE	22.2%	Protein content was reduced from 33.3% to 22.2% *w*/*w* after day 4 of cultivation	[26]
	C. sorokiniana	Wastewater	SLE (8080 °C)	25.5%	Increased in the growth pattern could decrease protein content	[29]
	S. obliquus	Wastewater	SLE (8080 °C)	28.5%	Increased in the growth pattern could decrease protein content	[29]
	S. obliquus	Wastewater	Freeze drying-MAE (100 °C)	31.26%	Sun-drying resulted in lower protein yields than other drying processes	[30]

Table 1. *Cont.*

	Species	Growth Media	Extraction (Conditions)	Yield (*wt*/*wt*)	Comments	Ref.
	A. protothecoides	Shrimp boiling water residues	NA	NA	High growth rates, up to 2.4 d^{-1} Protein rich biomass	[33]
	C. vulgaris	35% cafeteria organic food waste and 65% inorganic food waste	Ultrasonication and SLE	2.0%	At a ratio 25–35:75–65 organic to inorganic food waste, a higher amount of lipids was accumulated	[25]
Carbohydrates						
	S. mangrovei	Rice, noodles, meat, and vegetables	SLE	30–40%	Carbohydrates were the most effective accumulation product when compared to lipids and proteins	[12]
	C. pyrenoidosa	Rice, noodles, meat, and vegetables	SLE	30–40%	Carbohydrates were the most accumulation product when compared to lipids and proteins	[12]
	C. vulgaris	Cake, pastry, noodles, rice, meat, and vegetable waste	SLE (121 °C)	44.4%	For 7 days cultivation, increasing the duration increased carbohydrate accumulation	[26]
	C. sorokiniana	Wastewater	SLE (121 °C)	20%	Increasing biomass concentrations (inoculum) increased carbohydrate yield	[29]
	S. obliquus	Wastewater	SLE (121 °C)	20.4%	Increasing biomass concentrations (inoculum) increased carbohydrate yield	[29]
	C. vulgaris	75% organic food waste and 25% inorganic food waste	SLE(121 °C)	N/A	Use of compost medium combination decreased carbohydrate content by 7%	[25]
	S. obliquus	Wastewater	Freeze drying-MAE (100 °C)	19.8%	No significant difference in carbohydrate yield between sun-dried and oven-dried samples	[30]
Pigments (Carotenoids)						
	Desmodesmus sp.	Industrial wastewater	SLE (25 °C)	6.70 [b]	Light intensity significantly affects carotenoid content	[34]
	Nannochloropsis sp.	Industrial wastewater	SLE (25 °C)	2.56 [ab]	Light intensity significantly affects carotenoid content	[34]
	C. sorokiniana	BG-11	SLE (40 °C)	5.78 [c]	Pretreatment using high pressure cell supported lutein recovery	[35]
	H. pulvialis	N/A	SC-CO_2 + ethanol (25 °C, 550 bar)	18.5 [d]	Highest product yield purity was at 80 °C and 400 bar	[36]
	H. pulvialis	N/A	SC-CO_2 + ethanol (25 °C, 550 bar)	7.15 [c]	Highest product purity was found at 80 °C and 550 bar	[36]
	H. pluvialis	Palm oil mill effluent	NA	22.43	Cells grow better in continuous illumination at 6000 lux Highest cellular content was obtained in in 7.5% effluent	[33]
	Scenedesmus sp.	Brewery wastewater	SLE	7.54 [e]	Carotenoids concentration in the hybrid process increased from 5.97 mg L^{-1} to 7.54 mg L^{-1}.	[37]
Pigments (Chlorophyll)						
	N. gaditana	N/A	SC-CO_2 (60 °C, 400 bar)	2.24 [f]	Chlorophyll got extracted at 200 bar. Use of CO_2 provided selective of chlorophyll	[38]
	S. quadricauda	Dairy wastewater	SLE (60 °C)	9.45 [e]	Use of dairy wastewater reduces pigments production	[39]
	T. suecica	Dairy wastewater	SLE (60 °C)	11.7 [e]	Use of dairy wastewater reduces pigments production	[39]

Table 1. *Cont.*

Species	Growth Media	Extraction (Conditions)	Yield (*wt*/*wt*)	Comments	Ref.
Scenedesmus sp.	Brewery wastewater	SLE	20.40 [e]	Chlorophyll concentration in the hybrid process increased from 9.32 mg L^{-1} to 20.40 mg L^{-1}	[37]
Pigments (Phycobiliproteins)					
S. platensis	Zarrouk medium/GIMAP	N/A	92%	Extraction of phycobiliproteins was possibly achieved by adjusting pH of the buffer without cell rupture	[40]
A. platensis	Zarrouk medium	N/A	10%	White light promoted highest biomass production with an insignificant effect on protein and phycobiliprotein contents	[41]

[a] *wt*/*v*; [b] mg total carotenoids/g; [c] mg lutein/L/d; [d] mg astaxanthin/g dw.; [e] mg/L; [f] µg/mg dw.; SLE: supported liquid extraction; MAE: microwave-assisted extraction.

The main achievement is that lipids, carbohydrates, proteins, carotenoids, chlorophylls, and phycobiliproteins have been accumulated in several microalgae species using food wastes from cafeteria food, cheese whey powder, rice, noodles, meat, vegetables, cake, and pastry and wastewater sources, including industrial wastewater (milk processing wastewater, shrimp boiling water, palm oil mill effluent), municipal wastewater/sewage, and synthetic wastewater as growth media.

3. Polygeneration Products from Microalgae

3.1. Biofuels Production

Biofuels are considered to be a renewable alternative energy source that can replace fossil fuels. This includes production of biodiesel, bioalcohol, biogas, and biohydrogen. As the third generation, biofuels derived from microalgae biomass have several advantages. However, production cost is still challenging. Recent research on microalgal biofuel production is still primarily focusing on the sole production of biodiesel, bio-oil, and syngas production. The major aspects of novelty in biodiesel production studies are enhanced lipid accumulation using nanomaterials and simultaneous extraction and the transesterification of lipids. Lipids are accumulated in large amounts in microalgae and can reach 30–50% of the microalgae weight, depending on the cultivation media. A high carbon to nitrogen ratio was found to increase the lipid content [42] and therefore lipid availability. Stress conditions such as pH shift, high temperature, and high salinity are sometime needed [43,44] to accumulate more lipids within cells. Enhanced lipid accumulation has also been achieved by nanoparticles, which provides nutritional supplements for an increased microalgal lipid content. From this prospective, Zero-valent iron nanoparticles (nZVI) was found to improve lipid accumulation for more than 30% in *Trachydiscus minutus* % [45], 41.9% in *Tetraselmis suecica* [46], and 46.3% in *Pavlova lutheri*. The lipid content of *Chlorella fusca* LEB 111, cultivated in a modified BG11 medium by replacing sodium carbonate with 15% *v/v* CO_2 gas, with the support of nanofiber containing 4 *wt*/*v* of iron oxide nanoparticles, was investigated by Silva Vaz et al. [47]. Used nanofibers were polyacrylonitrile dissolved in dimethylformamide-containing nanoparticles. Nanoparticles were used as physical adsorbents of CO_2 in the cultivation, and results showed that cells grown with nanofibers ended up with an increase in CO_2 fixation from 245.4 to 310.9 mg/L/d and a lipid content from 31.0 to 41.9%, compared to that without the nanofiber. Because the mass production of microalgal biodiesel is also slowed down by the cost associated with biomass harvesting, exceeding 20% of the production cost, Yin et al. [48] investigated the use of *Daphine* for the harvesting via ingesting.

Lipids, which are enzymatically transesterified to biodiesel, have been extracted using different extraction techniques, such as solvent extraction, including using Soxhlet [49], microwave-assisted extraction, ultrasonic extraction [50], the osmotic pressure method [51], enzyme extraction [52,53], super-critical extraction [53–55], and electroporation [56,57]. Research on simultaneous extraction and reaction (SER), i.e., concurrent lipid extraction and transesterification for biodiesel production, has also surged recently [54,55,58,59]. The use of supercritical CO_2 (scCO_2) and ionic liquids for SER is the main novel aspect in this area. The employment of scCO_2 is beneficial because it is considered to be non-toxic and prevents the contamination of biomass when lipids are extracted from it, unlike conventional chemical solvents. Moreover, scCO_2 ensures the uniformity of the content of the transesterification reactor due to its pressure, and it ensures that the enzymes that are used to speed up reaction are not inhibited due to the hydrophilic nature of alcohol and that is present in the reaction system during transesterification [59].

Although scCO_2 can extract more lipids in the SER system, up to 20% of the lipids are found to be unused during transesterification and are left over as residue in the transesterification reactor [59]. Consequently, more excess methanol would leave the transesterification reactor, because the excess methanol requirement would depend on the overall lipids in the reactor, both the useful ones and the residual. This also leads to a higher energy consumption because heat and pressure are required. Future research should focus on improving the efficiency of such SER systems.

On the other hand, the complete recovery of scCO_2 from methanol for reuse purpose may not be possible, and an electrochemical reduction in CO_2 may also occur if CO_2 comes into contact with water, thereby limiting the recycle potential of CO_2. Meanwhile, in spite of these challenges, which are expected to be addressed in future research, there has been an increase in SER studies in recent years. Up to 80% of lipids can be removed by scCO_2, and a constant extraction rate may be achieved [55]. Moreover, up to 80% of extracted lipids in SC-CO_2 may be converted into biodiesel [54,55]. Microalgae species, including *Nannochloropsis gaditana* [59], *Scenedesmus* sp. [58], *Nannochloropsis* sp. [60,61], and *Chlorella* sp. [62], have been recently studied in SER with the use of scCO_2.

To reduce the costs, the use of FWs for biodiesel production is also considered. As mentioned earlier, FWs are hydrolyzed as the culture medium and nutrient source for microalgal biomass production, resulting in the accumulation of considerable amounts of transesterifable lipids within cells. Hydrolysis is typically carried in the presence of *Aspergillus awamori* and *Aspergillus oryzae*. Pleissner et al. [32] investigated the use of FWs collected from canteens, and the hydrolysate was used to grow *Schizochytrium mangrovei* and *Chlorella pyrenoidosa* species that accumulate lipids suitable for biodiesel production. Papanikolau et al. [63] investigated the possibility of using waste cooking olive oil to produce the lipid-rich biomass of *Aspergillus* sp. and *Penicillium expansum* in a carbon-limited culture, and considerable amounts of lipids were accumulated, reaching a biomass productivity of 0.74 g/g. As with scCO_2, ionic liquids (ILs) were also considered as a more environmentally friendly alternative to conventional chemical solvents for lipids extraction and biodiesel production from microalgal-produced biomass. Ionic liquids are known as non-volatile solvents that exhibit high thermal stability. Imidazolium-based ILs have been mainly used for lipid extraction from microalgae, wherein 19% of lipids were extracted from *C. vulgaris* by a mixture of [Bmim][CF_3SO_3]-IL and methanol [64]. Kim et al. [65] combined the use of [Bmim][$MeSO_4$] with ultrasonication and could extract up to 47 mg/g of the dry cell weight of lipids from *C. vulgaris*.

Concurrent extraction and reaction using wet microalgae is also an emerging area of interest. By evaluating switchable solvents, whose hydrophobicities can be switched reversibly, lipids were extracted from wet algal biomass. Lipids have been extracted from *Chlorella* sp., using switchable solvents such as N,N-dimethylcyclohexylamine (DMCHA), N-ethylbutylamine (EBA), and dipropylamine [62]. These solvents were used independently, and their performances were compared. Up to 13.6% of the lipid extraction yield was obtained. The lipids were converted to biodiesel in simultaneous extraction-transesterification systems, and biodiesel yield was enhanced by 33%. Advances in the production of biochar, syngas, and bio-oil from microalgae have been recently achieved, mainly through anaerobic digestion/co-digestion, gasification, and hydrothermal liquefaction, respectively [66–69]. In addition, some strains have been reported to produce biohydrogen [70]. Although the commercial viability or cost-competitiveness of these initiatives is not impressive at the moment, they offer good prospects for improvements in the future through polygeneration [69,71]. Pharmaceuticals, proteins, carbohydrates, pigments, bioplastics, pellets, and biofertilizers are some co-products that can be polygenerated with biofuels from microalgae.

3.2. Co-Products Production

3.2.1. Pharmaceuticals and Cosmetics

Microalgae can be used to produce a wide variety of pharmaceutical products, such as those with antimicrobial, antifungal, and antiviral properties. *Chlorella* and *Spirulina* are used for the production of a wide variety of vitamins and antioxidants in the form of tablets, capsules, and liquid. These can also be used to produce beverages such as microalgal health drinks, microalgal sour milk, and microalgal green tea [72]. Some skin disorders such as aging, tanning, and problems related with pigmentation can also be treated by microalgae [72,73]. *Chlorella* and *Spirulina* are used for producing cosmetic products such as cream, lotion, shampoo and sunscreen [74]. The degradation of skin collagen can be inhibited by the phenolic compounds obtained from marine microalgae by forming matrix metalloproteinase, thereby preventing skin aging [75]. Some other useful products include hair conditioners, suspending agents, and wound-healing agents, which can be obtained from fucoidans (from brown algae), carrageenans (from red algae), and ulvans (from green algae) [76].

Other microalgae species also provide several health benefits. Dunaliella has been known to contain metabolites, which are sources of pro-vitamin A, anti-inflammatory, and anticancer agents [77,78]. However, few data are available regarding the risks and safety of its consumption. Meanwhile, Scenedesmus has been shown to exhibit no negative effects and is safe for human consumption; its consumption, to a certain extent (20 g/d), has no adverse effects [72]. *D. salina* can accumulate up to 14 wt.% β-carotene when the optimum conditions for carotenogenesis are provided. Moreover, 1–8% astaxanthin dry weight can be obtained from *H. pluvialis*. Astaxanthin has the ability to undergo esterification, exceptional antioxidant activity, and a greater degree of polarity. The astaxanthin in encysted *H. pluvialis* cells consists of approximately 70% monoesters, 25% diesters, and 5% free form [66,79].

Table 2 provides a more detailed analysis of the composition of nutrients in some selected microalgal strains of significant importance for food and feed development.

Table 2. Common microalgae and their applications for production of pharmaceutical HVPs.

Species	HVP	Application Area	Application	Form	Production Companies	Ref.
D. Salina	β-carotene	Pharmaceutical, food supplements and cosmetics	Food colorant, Provitamin A, anti-inflammatory, antioxidant and chemo preventative	Powder	BlueBioTech GmbH.—Dunaliella salina	[80]
H. pluvialis	Astaxanthin	Nutrition and pharmaceuticals	Antioxidant, cardiovascular health, and skin health	Powder, Capsules and soft gels	Cyanotech Co.—BioAstin, BlueBioTech GmbH. –Astaxanthin AstaReal Co.	[80–82]
Schizochytrium spp.	Fatty acids (Omega 3)	Nutrition, pharmaceuticals	Anti-inflammatory, brain health	Powder, capsules, tablets, oils	GoerlichPhamra. GmbH—Omega 3	[83]
Spirulina spp.	Carotenoids, phycocyanin	Nutrition, pharmaceuticals	Antioxidant, cardiovascular health, and immune support, colorant	Cold press tablet, powder	Earthrise LLC.—Spirulina Cyanotech Co.—Hawaiian Spirulina BlueBioTech GmbH.—*Spirulina platensis*, Binmei Biotechnology Co.—Blue Spirulina and Spirulina powder	[80,81,84,85]
C. pyrenoidosa	Protein, vitamins and minerals	Nutrition	Body health, antioxidant, anti-inflammatory	Powder	BlueBioTech GmbH.—*Chlorella pyrenoidosa*	[80]
Nannochloropsis spp.	Whole cell	Aquaculture feed	Poultry, fish, shrimps and swine feed, green water Rotifer enrichment	Biomass—liquid	BlueBioTech—Aquaculture	[80]

3.2.2. Proteins and Carbohydrates

Proteins and amino acids make up 6–70 weight % of microalgae depending on the microalgal class and species and growth environmental factors. Protein is the main constituent of some microalgae [86]. Some microalgal species have higher protein content (510–710 g kg^{-1} dry powder) than egg and soybean (132 and 370 g kg^{-1}) [87]. Meanwhile, only a few microalgae species (including *Athrospira* and *Chlorella*) are being used for commercial-scale protein extraction, as they accumulate high amounts of protein [88]. Extracted proteins can be used for human or animal nutrition or as nutraceuticals and, by 2054, it is estimated that around 50% of the protein in the market could be extracted from algae or insects [89]. Microalgal proteins have already started appearing in the market as cosmetic products due to their attractive biological activities such as collagen stimulation and their ability to increase skin elasticity and slow down skin aging [90,91].

Microalgae contains about 10–25% of carbohydrates and can be found in the form of starch, cellulose, sugars, and other polysaccharides [92]. Carbohydrates in microalgae are accumulated in a non-equivalent manner; however, some microalgae such as *Porphyrodium cruentum* can also accumulate by up to 50% of the weight of microalgae. *Porphyrodium cruentum* accumulates carbohydrates by up to 57% of its weight carbohydrates, while *Chlamydomonas* species accumulate to a maximum of 17% of its weight as carbohydrates [93,94]. The most common microalgae species used for polysaccharide extraction are the *Chlorella*, *Tetraselmis*, *Isochrysis* species, as well as *Rhodella reticulata* [95]. Extracted carbohydrates are used in several industrial applications such as in the production of agar, carrageenan, alginate, and fucoidan [89]. Agar is a mixture of polysaccharides extracted from marine algae such as the *Gracilara* and *Gelidium* species. It has an expected market growth of about 3% per year [96]. On the other hand, carrageenan is used by the food and pharmaceutical industries as a thickening and gelling agent. Alginate is commonly used in the dairy food industry, as it aids in the fine appearance of products, and fucoidan is very attractive in the pharmaceutical industry due to its anticoagulant, antitumor, antioxidant, and antivirus bioactivities [97,98]. The market share of all hydrocolloid carbohydrates such as agar, carrageenan, and others will experience an annual growth rate of 5.3% from 2018 to 2023, with a value of USD 11.4 billion in 2023 [99].

3.2.3. Pigments

Pigments are also found in the composition of microalgae, which are classified into three groups based on pigmentation: phycobiliproteins, chlorophylls, and carotenoids. Pigments are well known for their health benefits as antioxidants, anti-inflammatory, antimutagenic, as well as their anticancer activity and ability to increase the production of red blood cells and prevent cardiovascular disease [97,100,101]. They are used in the pharmaceutical, food, and cosmetic industries as dietary supplements due to their high-value and high-health bioproducts.

Generally, there are more than 600 lipid-soluble carotenoids found in plants, algae, and bacteria, which are characterized by a distinct red-yellow pigment. Carotenoids mainly exist in two structural forms of hydrocarbons: oxygenated (commonly known as xanthophylls) and unoxygenated (commonly known as carotenes). They are further branched into pro-vitamin A and non-provitamin A carotenoids, which can and cannot be converted into retinol, respectively [102]. The main commercial types of carotenoids are β-carotene, lutein, astaxanthin, zeaxanthin, and lycopene. Due to their health-promoting properties, such as antioxidants, anticancer, and anti-inflammatory properties, they are of a great interest to the pharmaceutical, food, and cosmetic industries [103]. The market of carotenoids has a compound annual growth rate of 5.7% and has been predicted to reach USD 2 billion by 2022 [104].

On the other hand, chlorophylls are characterized by the green pigment and play a role in photosynthesis [105]. Chlorophylls are divided into different types, most commonly chlorophyll a and chlorophyll b [106]. Chlorella microalga is famous for accumulating chlorophyll with a weight percentage of about 7% [89]. Due to its green color, which is derived from a natural source, the demand for it by different industries such as food, pharmaceutical, and cosmetics industries is increasing [107]. The extraction of chlorophylls from microalgae is considered to have an economic potential; however, to reach a high accumulation level of chlorophyll in the algae, several studies have been carried out to relate the accumulation of stress conditions to the main condition of light intensity. After the extraction of chlorophylls, the residual biomass can go through the process of biofuel extraction [108,109].

Conversely, phycobiliproteins are hydrophilic and can be found only in cyanobacteria and some microalgal species such as *Rhodophyta phylum*, *Glaucophytes*, and *Cryptophytes*. They are divided into four groups (phycoerythrin, phycoerythrocyanin, phycocyanin, and allophycocyanin) based on their adsorption spectra. Their variation in adsorption and composition is due to the applied growth stress conditions and media. Several studies have been performed on different species of microalgae to maximize the phycobiliprotein accumulation in their cells. It was observed that, for *spirulina platensis*, the application of White LED and recycled medium led to the highest concentration of phycocyanin [110,111]. They are of interest in the pharmaceutical and medical market due to their fluorescent properties; hence, they are used in immunological methods as well as in microscopy and DNA tests [107,112].

3.2.4. Bioplastics

Bioplastic production is an area that has been minimally investigated to date; however, it is gaining increased interest due to increased demand. A bioplastic is a plastic which comes wholly or in part from bio-based sources [113]. The global production of plastics in 2014 was more than 300 million metric tons per year and is expected to double by 2034. This increase in production will require a use of 20% of the oil's consumption worldwide [114]. In order to maintain the less than 2 °C increase in global warming by 2050, most plastics should be replaced by bioplastics.

Materials used to produce biodegradable plastics include Polyhydroxyalkanoates (PHA), polysaccharides, polylactides, aliphatic polyesters, and co-polymers, and they are currently being studied and developed [115,116].

Methods to produce bioplastics from algal biomass include: (1) extraction of cellulosic and starch that is accumulate as granules compounds, (2) production of PHA by modified microalgal cells, (3) blending bioplastics with synthetic polymers, and (4) indirect production from thermoplastic polyester such as polylactic acid (PLA). Because starch is naturally hydrophilic and cannot be used directly in bioplastic production, it is mixed with other substances and a plasticizer to enhance material properties, i.e., stretchability and thermoplasticity, which is not the case if PHA is used. Typically, lactic acid is produced from microalgae via the fermentation of bacteria and polymerized to PLA, which can decompose completely into water and CO_2.

Several studies have been made on the different applications of biopolymers, and bioplastics from microalgal species [117,118]. Thermoplastic, biodegradable, and engineered bioplastics can be produced from microalgae. Out of the many possible algal biomass, *Chlamydomonas*, *Spirulina*, *Botryococcus*, and *Chlorella* are the most promising strains [119–121]. A study tried to modify amidoxime extracted from *Spirulina* by using it with polyethyleneimine to purify solutions from uranium ion contamination [122]. Other studies have shown the suitability of some microalgal species to produce D&L–lactic acid, which is used in greenhouse gas CO_2 fixation [123,124].

3.2.5. Animal Feed

Animal feed can be produced from about 30% of the algal biomass worldwide [125]. Animal feed can be produced from microalgae such as *Dunaliella*, *Chlorella*, and *Nannochloropsis*, among others. *Chlorella* spp. has a high protein content, is cost-efficient, and can be easily grown; hence, it can be used as a protein source [126]. In addition, *Scenedesmus* spp. provides a useful source of fatty acids in animal feed. [127].

Spirulina spp. can be used as livestock feed, as they contain useful nutrients such as carbohydrates, proteins, and vitamins [128]. It was found in a study that, when 16% of dried algae was added to a broiler diet, the chicks' body weight and feed conversion ratio increased [129,130]. The color of the egg yolk also improved when about 2–2.5% of the algae was added to the poultry feed [131]. However, one problem that has been faced in the use of dry microalgae as animal feed is the high content of cellulose cell wall material present in the feed (except *Spirulina* spp.), making it difficult to digest. This makes it commercially unfavorable, even to cattle that have the ability to digest cellulosic material. A low amount of 5–10% algae can be used to feed poultry, which can be beneficial to them in terms of their better development of color within the skin and egg yolk due to the carotenoid; however, algae concentrations higher than that can lead to adverse effects [132].

Microalgae-based feeds are used in aquaculture independently or in combination with regular feeds [92,133,134]. It is an economically feasible alternative for feed or feed supplement in fishmeal-based aquaculture. It provides nutrition, color to the fishes, and enhances other biological activities. Microalgae-based feed is a successful alternative to fishmeal due to its high content of proteins, carbohydrates, vitamins, carotenoids. Some of the common strains used as feed in aquaculture are *Pavlova*, *Nannochloropsis*, *Arthrospira*, and Haematococcus [135].

3.2.6. Pellets

Microalgae can be dried and grinded to form pellets with a density as high as 600 kg/m^3 [136]. Because of a pellet's high density, the costs of handling, storage, and transportation of the microalgal biomass can be reduced. Pellets can be used as fuels for industrial and residential applications, as well as for animal feed, thereby providing useful applications as co-products [137–139]. Thapa et al.'s research [140] used dried fine powder *Rhizodonium* spp., which was a waste product obtained from a wastewater treatment system, as a natural binding agent for the densification of Miscanthus (silvergrass). The result showed that the compressed discs containing over 20% algae had better strength than pure miscanthus discs. To make energy production from microalgae feasible, the co-pelletization of microalgae with a woody biomass has also been proposed [140]. Hosseinizand [136] investigated the densification mechanism of pure and mixed *Chlorella* algae with pine sawdust. The results showed that the energy for densifying pine sawdust was reduced, and that the properties of the pellets were improved, that is, the less the porosity, the higher moisture adsorption and better durability and density were observed [136].

3.2.7. Biofertilizers

Crop production requires sufficient amounts of main nutrients such as nitrogen, which are typically provided by chemical fertilizers. The intensive use of such chemicals causes the deterioration of soil and underground water pollution. As a replacement, some microalgal residues can be used as a biofertilizer. The use of biofertilizers produced from microalgae could, however, provide a cost-effective alternative. They can change soil structure and support the solubilization of nutrients in soil, thereby improving soil fertility and stimulating plant growth by improving nutrient availability. This has become noticeable.

Study by Faheed et al. [141] revealed that the germination of the seeds of *Lactuca sativa* in a culture medium containing the dry powder of *C. vulgaris* (3 g dry algae per kg soil) inside a greenhouse was significantly enhanced. The strain was isolated from River Nile Sohage, enriched with specific medium for chlorophyte, and grown at 25 °C with 2500 Lux illumination for 2 weeks. The total amount of pigments was determined using the Metzner et al. [142] method, which showed that the lettuce seedlings significantly increased while soluble carbohydrate content decreased from 28 to 18 mg/g. The same effect of *C. vulgaris* was also reported by Bumandalai and Tserennadmid [143], who investigated the germination of tomato and cucumber seeds. Seeds were germinated in a culture medium containing algal suspension (0.17 and 0.25 g/L) and were found to increase shoot and root lengths.

Important nutrients for plant growth such as nitrogen, phosphorus, and potassium can also be increased with the use of filamentous microalgae [144]. The growth of plants such as maize also improved by 51.1% when *Spirulina platensis* and *Chlorella vulgaris* were used with cow dung manure for 2 months of planting under greenhouse conditions [145].

4. Conclusions

From this review, it can be concluded that the use of food waste as a medium in microalgae cultivation and the polygeneration of microalgal-based products are two methods of achieving the sustainability of biofuel production from microalgae. It can also be concluded that microalgae have found their use in a wider variety of applications, not just in their well-established and commercialized production of biofuels, but also in their co-production of high-value products such as pharmaceuticals, biofuels, bioplastics, and others. Ongoing research on circular economy/integration and polygeneration in microalgae biorefineries is critical to improving the costs of producing biofuels from microalgae and utilizing wastes in the microalgal value chain. This research is necessary in order to ensure transition from lab to market, thereby providing the best benefits from the microalgae. The commercialization of the processes for producing some of the co-products is expected to be well-developed in the near future.

Author Contributions: Conceptualization, A.G. and F.A.; resources, B.C.; data curation, A.G., B.C.; writing—original draft preparation, A.G., F.A. and B.C.; writing—review and editing, A.G. and H.T.; supervision, H.T.; project administration, A.G. and B.C.; funding acquisition, H.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Khalifa University of Science and Technology, grant number 8474000190.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. FAO Technical Platform on the Measurement and Reduction of Food Loss and Waste | Food and Agriculture Organization of the United Nations. Available online: https://www.fao.org/platform-food-loss-waste/en/ (accessed on 5 March 2022).
2. Pleissner, D.; Lin, C.S.K. Valorisation of Food Waste in Biotechnological Processes. *Sustain. Chem. Processes* **2013**, *1*, 21. [CrossRef]
3. Dubai Municipality The UAE Food Bank. Available online: https://www.dm.gov.ae/foodbank/ (accessed on 23 May 2022).
4. Gustavsson, J.; Cederberg, C.; Sonesson, U.; Van Otterdijk, R.; Mayberk, A. Global Food Losses and Food Waste: Extent, Causes and Prevention, Food and Agricultural Organisation of the United Nations 2011. Available online: https://www.fao.org/3/i2697e/i2697e.pdf (accessed on 27 June 2022).
5. Gao, A.; Tian, Z.; Wang, Z.; Wennersten, R.; Sun, Q. Comparison between the Technologies for Food Waste Treatment. *Energy Procedia* **2017**, *105*, 3915–3921. [CrossRef]
6. Rizvi, A. UAE Working to Cut Food Waste by Half by 2030, Says Minister–The National 2020. Available online: https://www.thenationalnews.com/uae/government/uae-working-to-cut-food-waste-by-half-by-2030-says-minister-1.980752#:~:text=UAE%20working%20to%20cut%20food%20waste%20by%20half,Almheiri%2C%20the%20Minister%20of%20State%20for%20Food%20Security (accessed on 13 January 2021).
7. Schanes, K.; Dobernig, K.; Gözet, B. Food Waste Matters–A Systematic Review of Household Food Waste Practices and Their Policy Implications. *J. Clean. Prod.* **2018**, *182*, 978–991. [CrossRef]
8. Pleissner, D.; Smetana, S. Estimation of the Economy of Heterotrophic Microalgae- and Insect-Based Food Waste Utilization Processes. *Waste Manag.* **2020**, *102*, 198–203. [CrossRef] [PubMed]
9. Calicioglu, O.; Demirer, G.N. Role of Microalgae in Circular Economy. In *Integrated Wastewater Management and Valorization Using Algal Cultures*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 1–12.
10. Sayeki, M.; Kitagawa, T.; Matsumoto, M.; Nishiyama, A.; Miyoshi, K.; Mochizuki, M.; Takasu, A.; Abe, A. Chemical Composition and Energy Value of Dried Meal from Food Waste as Feedstuff in Swine and Cattle. *Nihon Chikusan Gakkaiho* **2001**, *72*, 34–40. [CrossRef]
11. Zhang, A.Y.Z.; Sun, Z.; Leung, C.C.J.; Han, W.; Lau, K.Y.; Li, M.; Lin, C.S.K. Valorisation of Bakery Waste for Succinic Acid Production. *Green Chem.* **2013**, *15*, 690–695. [CrossRef]

12. Pleissner, D.; Lam, W.C.; Sun, Z.; Lin, C.S.K. Food Waste as Nutrient Source in Heterotrophic Microalgae Cultivation. *Bioresour. Technol.* **2013**, *137*, 139–146. [CrossRef]
13. Zhen, G.; Lu, X.; Kobayashi, T.; Kumar, G.; Xu, K. Anaerobic Co-Digestion on Improving Methane Production from Mixed Microalgae (*Scenedesmus* sp., *Chlorella* sp.) and Food Waste: Kinetic Modeling and Synergistic Impact Evaluation. *Chem. Eng. J.* **2016**, *299*, 332–341. [CrossRef]
14. Mondal, S.; Bera, S.; Mishra, R.; Roy, S. Redefining the Role of Microalgae in Industrial Wastewater Remediation. *Energy Nexus* **2022**, *6*, 100088. [CrossRef]
15. Qian, J.; Zhang, J.; Jin, Z.; Cheng, J.; Li, J.; Song, H.; Lu, Q.; Li, H.; Wan, T.; Fu, S.; et al. Enhancing Algal Yield and Nutrient Removal from Anaerobic Digestion Piggery Effluent by an Integrated Process-Optimization Strategy of Fungal Decolorization and Microalgae Cultivation. *Appl. Sci.* **2022**, *12*, 4741. [CrossRef]
16. Svehla, P.; Radechovska, H.; Pacek, L.; Michal, P.; Hanc, A.; Tlustos, P. Nitrification in a Completely Stirred Tank Reactor Treating the Liquid Phase of Digestate: The Way towards Rational Use of Nitrogen. *Waste Manag.* **2017**, *64*, 96–106. [CrossRef] [PubMed]
17. Park, J.; Jin, H.-F.; Lim, B.-R.; Park, K.-Y.; Lee, K. Ammonia Removal from Anaerobic Digestion Effluent of Livestock Waste Using Green Alga *Scenedesmus* sp. *Bioresour. Technol.* **2010**, *101*, 8649–8657. [CrossRef] [PubMed]
18. Giwa, A.; Chalermthai, B.; Moheimani, N.; Taher, H. Effective Nutrient Removal and Metabolite Accumulation by *C. vulgaris* Cultivated Using Digested Food Waste and Brine. *Environ. Technol. Innov.* **2021**, *24*, 101935. [CrossRef]
19. Chuka-ogwude, D.; Ogbonna, J.; Moheimani, N.R. A Review on Microalgal Culture to Treat Anaerobic Digestate Food Waste Effluent. *Algal Res.* **2020**, *47*, 101841. [CrossRef]
20. Chuka-ogwude, D.; Ogbonna, J.; Borowitzka, M.A.; Moheimani, N.R. Screening, Acclimation and Ammonia Tolerance of Microalgae Grown in Food Waste Digestate. *J. Appl. Phycol.* **2020**, *32*, 3775–3785. [CrossRef]
21. Moheimani, N.R.; Vadiveloo, A.; Ayre, J.M.; Pluske, J.R. Nutritional Profile and in Vitro Digestibility of Microalgae Grown in Anaerobically Digested Piggery Effluent. *Algal Res.* **2018**, *35*, 362–369. [CrossRef]
22. Acién Fernández, F.G.; Gómez-Serrano, C.; Fernández-Sevilla, J.M. Recovery of Nutrients From Wastewaters Using Microalgae. *Front. Sustain. Food Syst.* **2018**, *2*, 59. [CrossRef]
23. Chi, Z.; Zheng, Y.; Jiang, A.; Chen, S. Lipid Production by Culturing Oleaginous Yeast and Algae with Food Waste and Municipal Wastewater in an Integrated Process. *Appl. Biochem. Biotechnol.* **2011**, *165*, 442–453. [CrossRef]
24. Abreu, A.P.; Fernandes, B.; Vicente, A.A.; Teixeira, J.; Dragone, G. Mixotrophic Cultivation of *Chlorella vulgaris* Using Industrial Dairy Waste as Organic Carbon Source. *Bioresour. Technol.* **2012**, *118*, 61–66. [CrossRef]
25. Chew, K.W.; Chia, S.R.; Show, P.L.; Ling, T.C.; Arya, S.S.; Chang, J.S. Food Waste Compost as an Organic Nutrient Source for the Cultivation of *Chlorella vulgaris*. *Bioresour. Technol.* **2018**, *267*, 356–362. [CrossRef]
26. Lau, K.Y.; Pleissner, D.; Lin, C.S.K. Recycling of Food Waste as Nutrients in *Chlorella vulgaris* Cultivation. *Bioresour. Technol.* **2014**, *170*, 144–151. [CrossRef] [PubMed]
27. Yang, Z.-Y.; Gao, F.; Liu, J.-Z.; Yang, J.-S.; Liu, M.; Ge, Y.-M.; Chen, D.-Z.; Chen, J.-M. Improving Sedimentation and Lipid Production of Microalgae in the Photobioreactor Using Saline Wastewater. *Bioresour. Technol.* **2022**, *347*, 126392. [CrossRef] [PubMed]
28. Verma, R.; Suthar, S.; Chand, N.; Mutiyar, P.K. Phycoremediation of Milk Processing Wastewater and Lipid-Rich Biomass Production Using *Chlorella vulgaris* under Continuous Batch System. *Sci. Total Environ.* **2022**, *833*, 155110. [CrossRef]
29. Gupta, S.K.; Ansari, F.A.; Nasr, M.; Rawat, I.; Nayunigari, M.K.; Bux, F. Cultivation of *Chlorella sorokiniana* and *Scenedesmus obliquus* in Wastewater: Fuzzy Intelligence for Evaluation of Growth Parameters and Metabolites Extraction. *J. Clean. Prod.* **2017**, *147*, 419–430. [CrossRef]
30. Ansari, F.A.; Gupta, S.K.; Nasr, M.; Rawat, I.; Bux, F. Evaluation of Various Cell Drying and Disruption Techniques for Sustainable Metabolite Extractions from Microalgae Grown in Wastewater: A Multivariate Approach. *J. Clean. Prod.* **2018**, *182*, 634–643. [CrossRef]
31. Piligaev, A.V.; Sorokina, K.N.; Shashkov, M.V.; Parmon, V.N. Screening and Comparative Metabolic Profiling of High Lipid Content Microalgae Strains for Application in Wastewater Treatment. *Bioresour. Technol.* **2018**, *250*, 538–547. [CrossRef] [PubMed]
32. Pleissner, D.; Lau, K.Y.; Ki Lin, C.S. Utilization of Food Waste in Continuous Flow Cultures of the Heterotrophic Microalga *Chlorella pyrenoidosa* for Saturated and Unsaturated Fatty Acids Production. *J. Clean. Prod.* **2017**, *142*, 1417–1424. [CrossRef]
33. Fernando, J.S.R.; Premaratne, M.; Dinalankara, D.M.S.D.; Perera, G.L.N.J.; Ariyadasa, T.U. Cultivation of Microalgae in Palm Oil Mill Effluent (POME) for Astaxanthin Production and Simultaneous Phycoremediation. *J. Environ. Chem. Eng.* **2021**, *9*, 105375. [CrossRef]
34. Safafar, H.; Van Wagenen, J.; Møller, P.; Jacobsen, C. Carotenoids, Phenolic Compounds and Tocopherols Contribute to the Antioxidative Properties of Some Microalgae Species Grown on Industrial Wastewater. *Mar. Drugs* **2015**, *13*, 7339–7356. [CrossRef]
35. Chen, C.Y.; Jesisca; Hsieh, C.; Lee, D.J.; Chang, C.H.; Chang, J.S. Production, Extraction and Stabilization of Lutein from Microalga *Chlorella sorokiniana* MB-1. *Bioresour. Technol.* **2016**, *200*, 500–505. [CrossRef]
36. Molino, A.; Mehariya, S.; Iovine, A.; Larocca, V.; Di Sanzo, G.; Martino, M.; Casella, P.; Chianese, S.; Musmarra, D. Extraction of Astaxanthin and Lutein from Microalga *Haematococcus pluvialis* in the Red Phase Using CO_2 Supercritical Fluid Extraction Technology with Ethanol as Co-Solvent. *Mar. Drugs* **2018**, *16*, 432. [CrossRef] [PubMed]
37. Song, C.; Hu, X.; Liu, Z.; Li, S.; Kitamura, Y. Combination of Brewery Wastewater Purification and CO_2 Fixation with Potential Value-Added Ingredients Production via Different Microalgae Strains Cultivation. *J. Clean. Prod.* **2020**, *268*, 122332. [CrossRef]

38. Macías-Sánchez, M.D.; Mantell, C.; Rodríguez, M.; Martínez De La Ossa, E.; Lubián, L.M.; Montero, O. Supercritical Fluid Extraction of Carotenoids and Chlorophyll a from *Nannochloropsis gaditana*. *J. Food Eng.* **2005**, *66*, 245–251. [CrossRef]
39. Daneshvar, E.; Zarrinmehr, M.J.; Koutra, E.; Kornaros, M.; Farhadian, O.; Bhatnagar, A. Sequential Cultivation of Microalgae in Raw and Recycled Dairy Wastewater: Microalgal Growth, Wastewater Treatment and Biochemical Composition. *Bioresour. Technol.* **2019**, *273*, 556–564. [CrossRef] [PubMed]
40. Kshirsagar, H.H.; Revankar, M.S.; Kamat, M.Y.; Lele, S.S. Cultivation of Spirulina in Gas Induced Photobioreactor and Isolation of Phycobiliproteins. *Indian J. Biotechnol.* **2002**, *1*, 255–262.
41. Rizzo, R.F.; dos Santos, B.N.C.; de Castro, G.F.P.d.S.; Passos, T.S.; Nascimento, M.d.A.; Guerra, H.D.; da Silva, C.G.; Dias, D.d.S.; Domingues, J.R.; de Lima-Araújo, K.G. Production of Phycobiliproteins by *Arthrospira platensis* under Different Lightconditions for Application in Food Products. *Food Sci. Technol.* **2015**, *35*, 247–252. [CrossRef]
42. Panahi, Y.; Khosroshahi, A.Y.; Sahebkar, A.; Heidari, H.R. Impact of Cultivation Condition and Media Content on *Chlorella vulgaris* Composition. *Adv. Pharm. Bull.* **2019**, *9*, 182–194. [CrossRef]
43. Chu, W.L. Strategies to Enhance Production of Microalgal Biomass and Lipids for Biofuel Feedstock. *Eur. J. Phycol.* **2017**, *52*, 419–437. [CrossRef]
44. Kwak, H.S.; Kim, J.Y.H.; Woo, H.M.; Jin, E.S.; Min, B.K.; Sim, S.J. Synergistic Effect of Multiple Stress Conditions for Improving Microalgal Lipid Production. *Algal Res.* **2016**, *19*, 215–224. [CrossRef]
45. Pádrová, K.; Lukavský, J.; Nedbalová, L.; Čejková, A.; Cajthaml, T.; Sigler, K.; Vítová, M.; Řezanka, T. Trace Concentrations of Iron Nanoparticles Cause Overproduction of Biomass and Lipids during Cultivation of Cyanobacteria and Microalgae. *J. Appl. Phycol.* **2015**, *27*, 1443–1451. [CrossRef]
46. Kadar, E.; Rooks, P.; Lakey, C.; White, D.A. The Effect of Engineered Iron Nanoparticles on Growth and Metabolic Status of Marine Microalgae Cultures. *Sci. Total Environ.* **2012**, *439*, 8–17. [CrossRef] [PubMed]
47. Da Silva Vaz, B.; Alberto Vieira Costa, J.; Greque de Morais, M. Physical and Biological Fixation of CO_2 with Polymeric Nanofibers in Outdoor Cultivations of *Chlorella fusca* LEB 111. *Int. J. Biol. Macromol.* **2020**, *151*, 1332–1339. [CrossRef] [PubMed]
48. Yin, S.; Jin, W.; Zhou, X.; Han, W.; Gao, S.; Chen, C.; Ding, W.; He, Z.; Chen, Y.; Jiang, G. Enhancing Harvest of Biodiesel-Promising Microalgae Using Daphnia Domesticated by Amino Acids. *Environ. Res.* **2022**, *212*, 113465. [CrossRef]
49. Shet, A.R. Parametric Optimization of Oil Extraction and Lipase Catalyzed Biodiesel Production from Rice Bran. *Biosci. Biotechnol. Res. Commun.* **2021**, *14*, 340–345. [CrossRef]
50. Zhang, X.; Yan, S.; Tyagi, R.D.; Drogui, P.; Surampalli, R.Y. Ultrasonication Assisted Lipid Extraction from Oleaginous Microorganisms. *Bioresour. Technol.* **2014**, *158*, 253–261. [CrossRef] [PubMed]
51. Yoo, G.; Park, W.-K.; Kim, C.W.; Choi, Y.-E.; Yang, J.-W. Direct Lipid Extraction from Wet Chlamydomonas Reinhardtii Biomass Using Osmotic Shock. *Bioresour. Technol.* **2012**, *123*, 717–722. [CrossRef]
52. Chen, Q.; Liu, D.; Wu, C.; Xu, A.; Xia, W.; Wang, Z.; Wen, F.; Yu, D. Influence of a Facile Pretreatment Process on Lipid Extraction from *Nannochloropsis* sp. through an Enzymatic Hydrolysis Reaction. *RSC Adv.* **2017**, *7*, 53270–53277. [CrossRef]
53. Taher, H.; Al-Zuhair, S.; Al-Marzouqi, A.H.; Haik, Y.; Farid, M. Effective Extraction of Microalgae Lipids from Wet Biomass for Biodiesel Production. *Biomass Bioenergy* **2014**, *66*, 159–167. [CrossRef]
54. Taher, H.; Al-Zuhair, S.; Al-Marzouqi, A.H.; Haik, Y.; Farid, M.; Tariq, S. Supercritical Carbon Dioxide Extraction of Microalgae Lipid: Process Optimization and Laboratory Scale-Up. *J. Supercrit. Fluids* **2014**, *86*, 57–66. [CrossRef]
55. Taher, H.; Al-Zuhair, S.; Al-Marzouqi, A.H.; Haik, Y.; Farid, M. Enzymatic Biodiesel Production of Microalgae Lipids under Supercritical Carbon Dioxide: Process Optimization and Integration. *Biochem. Eng. J.* **2014**, *90*, 103–113. [CrossRef]
56. Garoma, T.; Janda, D. Investigation of the Effects of Microalgal Cell Concentration and Electroporation, Microwave and Ultrasonication on Lipid Extraction Efficiency. *Renew. Energy* **2016**, *86*, 117–123. [CrossRef]
57. Mubarak, M.; Shaija, A.; Suchithra, T.V. A Review on the Extraction of Lipid from Microalgae for Biodiesel Production. *Algal Res.* **2015**, *7*, 117–123. [CrossRef]
58. Shomal, R.; Hisham, H.; Mlhem, A.; Hassan, R.; Al-Zuhair, S. Simultaneous Extraction–Reaction Process for Biodiesel Production from Microalgae. *Energy Rep.* **2019**, *5*, 37–40. [CrossRef]
59. Taher, H.; Giwa, A.; Abusabiekeh, H.; Al-Zuhair, S. Biodiesel Production from *Nannochloropsis gaditana* Using Supercritical CO_2 for Lipid Extraction and Immobilized Lipase Transesterification: Economic and Environmental Impact Assessments. *Fuel Processing Technol.* **2020**, *198*, 106249. [CrossRef]
60. Reddy, H.K.; Muppaneni, T.; Patil, P.D.; Ponnusamy, S.; Cooke, P.; Schaub, T.; Deng, S. Direct Conversion of Wet Algae to Crude Biodiesel under Supercritical Ethanol Conditions. *Fuel* **2014**, *115*, 720–726. [CrossRef]
61. Patil, P.D.; Gude, V.G.; Mannarswamy, A.; Deng, S.; Cooke, P.; Munson-McGee, S.; Rhodes, I.; Lammers, P.; Nirmalakhandan, N. Optimization of Direct Conversion of Wet Algae to Biodiesel under Supercritical Methanol Conditions. *Bioresour. Technol.* **2011**, *102*, 118–122. [CrossRef]
62. Al-Ameri, M.; Al-Zuhair, S. Using Switchable Solvents for Enhanced, Simultaneous Microalgae Oil Extraction-Reaction for Biodiesel Production. *Biochem. Eng. J.* **2019**, *141*, 217–224. [CrossRef]
63. Papanikolaou, S.; Dimou, A.; Fakas, S.; Diamantopoulou, P.; Philippoussis, A.; Galiotou-Panayotou, M.; Aggelis, G. Biotechnological Conversion of Waste Cooking Olive Oil into Lipid-Rich Biomass Using *Aspergillus* and *Penicillium* Strains. *J. Appl. Microbiol.* **2011**, *110*, 1138–1150. [CrossRef]

64. Kim, Y.-H.; Choi, Y.-K.; Park, J.; Lee, S.; Yang, Y.-H.; Kim, H.J.; Park, T.-J.; Hwan Kim, Y.; Lee, S.H. Ionic Liquid-Mediated Extraction of Lipids from Algal Biomass. *Bioresour. Technol.* **2012**, *109*, 312–315. [CrossRef]
65. Kim, Y.-H.; Park, S.; Kim, M.H.; Choi, Y.-K.; Yang, Y.-H.; Kim, H.J.; Kim, H.; Kim, H.-S.; Song, K.-G.; Lee, S.H. Ultrasound-Assisted Extraction of Lipids from *Chlorella vulgaris* Using [Bmim][MeSO4]. *Biomass Bioenergy* **2013**, *56*, 99–103. [CrossRef]
66. Giwa, A.; Adeyemi, I.; Dindi, A.; Lopez, C.G.B.; Lopresto, C.G.; Curcio, S.; Chakraborty, S. Techno-Economic Assessment of the Sustainability of an Integrated Biorefinery from Microalgae and Jatropha: A Review and Case Study. *Renew. Sustain. Energy Rev.* **2018**, *88*, 239–257. [CrossRef]
67. Miao, C.; Chakraborty, M.; Chen, S. Impact of Reaction Conditions on the Simultaneous Production of Polysaccharides and Bio-Oil from Heterotrophically Grown *Chlorella sorokiniana* by a Unique Sequential Hydrothermal Liquefaction Process. *Bioresour. Technol.* **2012**, *110*, 617–627. [CrossRef] [PubMed]
68. Plude, S.; Demirer, G.N. Valorization of Harmful Algal Blooms and Food Waste as Bio-methane. *Environ. Prog. Sustain. Energy* **2020**, *40*, e13561. [CrossRef]
69. Azadi, P.; Brownbridge, G.P.E.; Mosbach, S.; Inderwildi, O.R.; Kraft, M. Production of Biorenewable Hydrogen and Syngas via Algae Gasification: A Sensitivity Analysis. *Energy Procedia* **2014**, *61*, 2767–2770. [CrossRef]
70. Nunes, N.S.P.; Ansilago, M.; Oliveira, N.N.; Leite, R.S.R.; da Paz, M.F.; Fonseca, G.G. Biofuel Production. In *Microalgae Cultivation, Recovery of Compounds and Applications*; Academic Press: Cambridge, MA, USA, 2021; Chapter 6; pp. 145–171.
71. Taylor, R.P.; Jones, C.L.; Laubscher, R.K. Recovery of Methane and Adding Value to the Digestate of Biomass Produced by High Rate Algal Ponds or Waste Activated Sludge, Used to Treat Brewery Effluent. *J. Water Process Eng.* **2020**, *40*, 101797. [CrossRef]
72. Bhalamurugan, G.L.; Valerie, O.; Mark, L. Valuable Bioproducts Obtained from Microalgal Biomass and Their Commercial Applications: A Review. *Environ. Eng. Res.* **2018**, *23*, 229–241. [CrossRef]
73. Wang, H.M.D.; Chen, C.C.; Huynh, P.; Chang, J.S. Exploring the Potential of Using Algae in Cosmetics. *Bioresour. Technol.* **2015**, *184*, 355–362. [CrossRef]
74. Ariede, M.B.; Candido, T.M.; Jacome, A.L.M.; Velasco, M.V.R.; de Carvalho, J.C.M.; Baby, A.R. Cosmetic Attributes of Algae–A Review. *Algal Res.* **2017**, *25*, 483–487. [CrossRef]
75. Thomas, N.V.; Kim, S.K. Beneficial Effects of Marine Algal Compounds in Cosmeceuticals. *Mar. Drugs* **2013**, *11*, 46–64. [CrossRef]
76. Aditya, T.; Bitu, G.; Mercy, E.G. The Role of Algae in Pharmaceutical Development. *J. Pharm. Nanotechnol.* **2016**, *4*, 82–89.
77. Sui, Y.; Vlaeminck, S.E. Dunaliella Microalgae for Nutritional Protein: An Undervalued Asset. *Trends Biotechnol.* **2020**, *38*, 10–12. [CrossRef] [PubMed]
78. Molino, A.; Iovine, A.; Casella, P.; Mehariya, S.; Chianese, S.; Cerbone, A.; Rimauro, J.; Musmarra, D. Microalgae Characterization for Consolidated and New Application in Human Food, Animal Feed and Nutraceuticals. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2436. [CrossRef]
79. Khanum, F.; Giwa, A.; Nour, M.; Al-Zuhair, S.; Taher, H. Improving the Economic Feasibility of Biodiesel Production from Microalgal Biomass via High-value Products Coproduction. *Int. J. Energy Res.* **2020**, *44*, 11453–11472. [CrossRef]
80. Bluebiotech BlueBioTech. Available online: https://bluebiotech.com.au/ (accessed on 27 June 2022).
81. Cyanotech Cyanotech BioAstin®Hawaiian Astaxanthin®. Available online: https://www.cyanotech.com/astaxanthin/ (accessed on 27 June 2022).
82. Astareal Astareal Natural Astaxanthin. Available online: https://astareal.com/en/ (accessed on 27 June 2022).
83. Georlich From Idea to Success–Your "One-Stop" Supplier for Food Supplements. Available online: https://goerlich-pharma.com/en/ (accessed on 27 June 2022).
84. Earthrise Earthrise Californian Spirulina. Available online: https://www.earthrise.com/ (accessed on 27 June 2022).
85. Binmei Wholesale Spirulina & Blue Spirulina Protein Powder | Binmei. Available online: https://www.binmei-global.com/product/ (accessed on 27 June 2022).
86. Wells, M.L.; Potin, P.; Craigie, J.S.; Raven, J.A.; Merchant, S.S.; Helliwell, K.E.; Smith, A.G.; Camire, M.E.; Brawley, S.H. Algae as Nutritional and Functional Food Sources: Revisiting Our Understanding. *J. Appl. Phycol.* **2017**, *29*, 949–982. [CrossRef] [PubMed]
87. Buono, S.; Langellotti, A.L.; Martello, A.; Rinna, F.; Fogliano, V. Functional Ingredients from Microalgae. *Food Funct.* **2014**, *5*, 1669–1685. [CrossRef]
88. Barkia, I.; Saari, N.; Manning, S.R. Microalgae for High-Value Products towards Human Health and Nutrition. *Mar. Drugs* **2019**, *17*, 304. [CrossRef]
89. Khanra, A.; Srivastava, M.; Rai, M.P.; Prakash, R. Application of Unsaturated Fatty Acid Molecules Derived from Microalgae toward Mild Steel Corrosion Inhibition in HCl Solution: A Novel Approach for Metal–Inhibitor Association. *ACS Omega* **2018**, *3*, 12369–12382. [CrossRef]
90. Apone, F.; Barbulova, A.; Colucci, M.G. Plant and Microalgae Derived Peptides Are Advantageously Employed as Bioactive Compounds in Cosmetics. *Front. Plant Sci.* **2019**, *10*, 756. [CrossRef]
91. Martins, A.; Vieira, H.; Gaspar, H.; Santos, S. Marketed Marine Natural Products in the Pharmaceutical and Cosmeceutical Industries: Tips for Success. *Mar. Drugs* **2014**, *12*, 1066–1101. [CrossRef]
92. Dineshbabu, G.; Goswami, G.; Kumar, R.; Sinha, A.; Das, D. Microalgae–Nutritious, Sustainable Aqua- and Animal Feed Source. *J. Funct. Foods* **2019**, *62*, 103545. [CrossRef]
93. González-Fernández, C.; Ballesteros, M. Linking Microalgae and Cyanobacteria Culture Conditions and Key-Enzymes for Carbohydrate Accumulation. *Biotechnol. Adv.* **2012**, *30*, 1655–1661. [CrossRef] [PubMed]

94. Markou, G.; Angelidaki, I.; Georgakakis, D. Microalgal Carbohydrates: An Overview of the Factors Influencing Carbohydrates Production, and of Main Bioconversion Technologies for Production of Biofuels. *Appl. Microbiol. Biotechnol.* **2012**, *96*, 631–645. [CrossRef]
95. Mourelle, M.L.; Gómez, C.P.; Legido, J.L. The Potential Use of Marine Microalgae and Cyanobacteria in Cosmetics and Thalassotherapy. *Cosmetics* **2017**, *4*, 46. [CrossRef]
96. Bixler, H.J.; Porse, H. A Decade of Change in the Seaweed Hydrocolloids Industry. *J. Appl. Phycol.* **2011**, *23*, 321–335. [CrossRef]
97. Cotas, J.; Leandro, A.; Pacheco, D.; Gonçalves, A.M.M.; Pereira, L. A Comprehensive Review of the Nutraceutical and Therapeutic Applications of Red Seaweeds (*Rhodophyta*). *Life* **2020**, *10*, 19. [CrossRef] [PubMed]
98. Parreidt, T.S.; Müller, K.; Schmid, M. Alginate-Based Edible Films and Coatings for Food Packaging Applications. *Foods* **2018**, *7*, 170. [CrossRef]
99. Singh, S. Hydrocolloids Market Worth $11.4 Billion by 2023–Exclusive Report by MarketsandMarketsTM. 2020. Available online: https://www.prnewswire.com/news-releases/hydrocolloids-market-worth-11-4-billion-by-2023--exclusive-report-by-marketsandmarkets-300788865.html (accessed on 27 June 2022).
100. Galasso, C.; Gentile, A.; Orefice, I.; Ianora, A.; Bruno, A.; Noonan, D.M.; Sansone, C.; Albini, A.; Brunet, C. Microalgal Derivatives as Potential Nutraceutical and Food Supplements for Human Health: A Focus on Cancer Prevention and Interception. *Nutrients* **2019**, *11*, 1226. [CrossRef]
101. Kulczyński, B.; Gramza-Michałowska, A.; Kobus-Cisowska, J.; Kmiecik, D. The Role of Carotenoids in the Prevention and Treatment of Cardiovascular Disease–Current State of Knowledge. *J. Funct. Foods* **2017**, *38*, 45–65. [CrossRef]
102. Cardoso, L.A.; Karp, S.G.; Vendruscolo, F.; Kanno, K.Y.; Zoz, L.I.; Carvalho, J.C. Biotechnological Production of Carotenoids and Their Applications in Food and Pharmaceutical Products. In *Carotenoids*; InTech Open: London, UK, 2017; p. 125. Available online: https://www.intechopen.com/chapters/54486 (accessed on 27 June 2022).
103. Rammuni, M.N.; Ariyadasa, T.U.; Nimarshana, P.H.V.; Attalage, R.A. Comparative Assessment on the Extraction of Carotenoids from Microalgal Sources: Astaxanthin from H. Pluvialis and β-Carotene from D. Salina. *Food Chem.* **2019**, *277*, 128–134. [CrossRef]
104. McWilliams, A. FOD025F The Global Market for Carotenoids BCC Research Report Overview The Global Market for Carotenoids. 2018. Available online: https://www.bccresearch.com/market-research/food-and-beverage/the-global-market-for-carotenoids.html (accessed on 27 June 2022).
105. Odjadjare, E.C.; Mutanda, T.; Olaniran, A.O. Potential Biotechnological Application of Microalgae: A Critical Review. *Crit. Rev. Biotechnol.* **2017**, *37*, 37–52. [CrossRef]
106. Crampon, C.; Nikitine, C.; Zaier, M.; Lépine, O.; Tanzi, C.D.; Vian, M.A.; Chemat, F.; Badens, E. Oil Extraction from Enriched *Spirulina platensis* Microalgae Using Supercritical Carbon Dioxide. *J. Supercrit. Fluids* **2017**, *119*, 289–296. [CrossRef]
107. Hamed, I. The Evolution and Versatility of Microalgal Biotechnology: A Review. *Compr. Rev. Food Sci. Food Saf.* **2016**, *15*, 1104–1123. [CrossRef]
108. Gonçalves, V.D.; Fagundes-Klen, M.R.; Goes Trigueros, D.E.; Kroumov, A.D.; Módenes, A.N. Statistical and Optimization Strategies to Carotenoids Production by *Tetradesmus acuminatus* (LC192133.1) Cultivated in Photobioreactors. *Biochem. Eng. J.* **2019**, *152*, 107351. [CrossRef]
109. He, Q.; Yang, H.; Wu, L.; Hu, C. Effect of Light Intensity on Physiological Changes, Carbon Allocation and Neutral Lipid Accumulation in Oleaginous Microalgae. *Bioresour. Technol.* **2015**, *191*, 219–228. [CrossRef] [PubMed]
110. Gargouch, N.; Karkouch, I.; Elleuch, J.; Elkahoui, S.; Michaud, P.; Abdelkafi, S.; Laroche, C.; Fendri, I. Enhanced B-Phycoerythrin Production by the Red Microalga *Porphyridium marinum*: A Powerful Agent in Industrial Applications. *Int. J. Biol. Macromol.* **2018**, *120*, 2106–2114. [CrossRef] [PubMed]
111. Ho, S.H.; Liao, J.F.; Chen, C.Y.; Chang, J.S. Combining Light Strategies with Recycled Medium to Enhance the Economic Feasibility of Phycocyanin Production with *Spirulina platensis*. *Bioresour. Technol.* **2018**, *247*, 669–675. [CrossRef]
112. Yaakob, Z.; Ali, E.; Zainal, A.; Mohamad, M.; Takriff, M. An Overview: Biomolecules from Microalgae for Animal Feed and Aquaculture. *J. Biol. Res.-Thessalon.* **2014**, *21*, 6. [CrossRef]
113. Beckstrom, B.D.; Wilson, M.H.; Crocker, M.; Quinn, J.C. Bioplastic Feedstock Production from Microalgae with Fuel Co-Products: A Techno-Economic and Life Cycle Impact Assessment. *Algal Res.* **2020**, *46*, 101769. [CrossRef]
114. Ellen MacArthur Foundation. The New Plastics Economy: Rethinking the Future of Plastics. 2016. Available online: https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics (accessed on 27 June 2022).
115. Anushri, S.; Archana, T. Polyhydroxyalkonates: Green Plastics of the Future. *Int. J. Biomed. Adv. Res.* **2012**, *3*, 770–774.
116. Vroman, I.; Tighzert, L. Biodegradable Polymers. *Materials* **2009**, *2*, 307–344. [CrossRef]
117. Costa, S.S.; Miranda, A.L.; de Morais, M.G.; Costa, J.A.V.; Druzian, J.I. Microalgae as Source of Polyhydroxyalkanoates (PHAs)–A Review. *Int. J. Biol. Macromol.* **2019**, *131*, 536–547. [CrossRef] [PubMed]
118. Etman, S.M.; Elnaggar, Y.S.R.; Abdallah, O.Y. Fucoidan, a Natural Biopolymer in Cancer Combating: From Edible Algae to Nanocarrier Tailoring. *Int. J. Biol. Macromol.* **2020**, *147*, 799–808. [CrossRef] [PubMed]
119. Cabanelas, I.T.D.; Marques, S.S.I.; de Souza, C.O.; Druzian, J.I.; Nascimento, I.A. Botryococcus, What to Do with It? Effect of Nutrient Concentration on Biorefinery Potential. *Algal Res.* **2015**, *11*, 43–49. [CrossRef]
120. Shuba, E.S.; Kifle, D. Microalgae to Biofuels: 'Promising' Alternative and Renewable Energy, Review. *Renew. Sustain. Energy Rev.* **2018**, *81*, 743–755. [CrossRef]

121. Safi, C.; Zebib, B.; Merah, O.; Pontalier, P.-Y.; Vaca-Garcia, C. Morphology, Composition, Production, Processing and Applications of *Chlorella vulgaris*: A Review. *Renew. Sustain. Energy Rev.* **2014**, *35*, 265–278. [CrossRef]
122. Bayramoglu, G.; Akbulut, A.; Arica, M.Y. Study of Polyethyleneimine- and Amidoxime-Functionalized Hybrid Biomass of *Spirulina (Arthrospira) platensis* for Adsorption of Uranium (VI) Ion. *Environ. Sci. Pollut. Res.* **2015**, *22*, 17998–18010. [CrossRef]
123. Hirayama, S.; Ueda, R. Production of Optically Pure D-Lactic Acid by *Nannochlorum* sp. 26A4. *Appl. Biochem. Biotechnol. Part A Enzym. Eng. Biotechnol.* **2004**, *119*, 71–77. [CrossRef]
124. Nguyen, C.M.; Kim, J.S.; Hwang, H.J.; Park, M.S.; Choi, G.J.; Choi, Y.H.; Jang, K.S.; Kim, J.C. Production of L-Lactic Acid from a Green Microalga, Hydrodictyon Reticulum, by *Lactobacillus Paracasei* LA104 Isolated from the Traditional Korean Food, Makgeolli. *Bioresour. Technol.* **2012**, *110*, 552–559. [CrossRef]
125. Becker, W. Microalgae in Human and Animal Nutrition. In *Handbook of Microalgal Culture*; Wiley-Blackwell: Hoboken, NJ, USA, 2007; Available online: https://onlinelibrary.wiley.com/doi/10.1002/9781118567166.ch25 (accessed on 27 June 2022).
126. Lum, K.K.; Kim, J.; Lei, X. Dual Potential of Microalgae as a Sustainable Biofuel Feedstock and Animal Feed. *J. Anim. Sci. Biotechnol.* **2013**, *4*, 53. [CrossRef]
127. Ishaq, A.G.; Matias-Peralta, H.M.; Basri, H. Bioactive Compounds from Green Microalga Scenedesmus and Its Potential Applications: A Brief Review. *Pertanika J. Trop. Agric. Sci.* **2016**, *39*, 1–16.
128. Holman, B.W.B.; Malau-Aduli, A.E.O. Spirulina as a Livestock Supplement and Animal Feed. *J. Anim. Physiol. Anim. Nutr.* **2013**, *97*, 615–623. [CrossRef] [PubMed]
129. Evans, A.M.; Smith, D.L.; Moritz, J.S. Effects of Algae Incorporation into Broiler Starter Diet Formulations on Nutrient Digestibility and 3 to 21 d Bird Performance. *J. Appl. Poult. Res.* **2015**, *24*, 206–214. [CrossRef]
130. Shanmugapriya, B.; Babu, S.S.; Hariharan, T.; Sivaneswaran, S.; Anusha, M.B. Dietary Administration of *Spirulina platensis* as Probiotics on Growth Performance and Histopathology in Broiler Chicks. *Int. J. Rec. Sci. Res.* **2015**, *6*, 2650–2653.
131. Zahroojian, N.; Moravej, H.; Shivazad, M. Effects of Dietary Marine Algae (*Spirulina platensis*) on Egg Quality and Production Performance of Laying Hens. *J. Agric. Sci. Technol.* **2013**, *15*, 1353–1360.
132. Milledge, J.J. Commercial Application of Microalgae Other than as Biofuels: A Brief Review. *Rev. Environ. Sci. Bio/Technol.* **2011**, *10*, 31–41. [CrossRef]
133. D'Este, M.; Alvarado-Morales, M.; Angelidaki, I. *Laminaria digitata* as Potential Carbon Source in Heterotrophic Microalgae Cultivation for the Production of Fish Feed Supplement. *Algal Res.* **2017**, *26*, 1–7. [CrossRef]
134. Yadav, G.; Meena, D.K.; Sahoo, A.K.; Das, B.K.; Sen, R. Effective Valorization of Microalgal Biomass for the Production of Nutritional Fish-Feed Supplements. *J. Clean. Prod.* **2020**, *243*, 118697. [CrossRef]
135. Madeira, M.S.; Cardoso, C.; Lopes, P.A.; Coelho, D.; Afonso, C.; Bandarra, N.M.; Prates, J.A.M. Microalgae as Feed Ingredients for Livestock Production and Meat Quality: A Review. *Livest. Sci.* **2017**, *205*, 111–121. [CrossRef]
136. Hosseinizand, H. Drying and Co-Pelletization of Microalgae with Sawdust. 2018. Available online: https://open.library.ubc.ca/soa/cIRcle/collections/ubctheses/24/items/1.0371249 (accessed on 27 June 2022).
137. Huang, Z.L.; Li, H.; Yuan, X.Z.; Lin, L.; Cao, L.; Xiao, Z.H.; Jiang, L.B.; Li, C.Z. The Energy Consumption and Pellets' Characteristics in the Co-Pelletization of Oil Cake and Sawdust. *RSC Adv.* **2016**, *6*, 19199–19207. [CrossRef]
138. Li, H.; Jiang, L.-B.; Li, C.-Z.; Liang, J.; Yuan, X.-Z.; Xiao, Z.-H.; Xiao, Z.-H.; Wang, H. Co-Pelletization of Sewage Sludge and Biomass: The Energy Input and Properties of Pellets. *Fuel Process. Technol.* **2015**, *132*, 55–61. [CrossRef]
139. Tibbetts, S.M. The Potential for 'Next-Generation', Microalgae-Based Feed Ingredients for Salmonid Aquaculture in Context of the Blue Revolution. In *Microalgal Biotechnology*; Intechopen: London, UK, 2018; Available online: https://www.intechopen.com/chapters/59033 (accessed on 27 June 2022).
140. Thapa, S.; Johnson, D.B.; Liu, P.P.; Canam, T. Algal Biomass as a Binding Agent for the Densification of Miscanthus. *Waste Biomass Valorization* **2015**, *6*, 91–95. [CrossRef]
141. Faheed, F.; Abd-El Fattah, Z. Effect of *Chlorella vulgaris* as Bio-Fertilizer on Growth Parameters and Metabolic Aspects of Lettuce Plant. *J. Agric. Soc. Sci.* **2008**, *4*, 165–169.
142. Metzner, H.; Rau, H.; Senger, H. Untersuchungen Zur Synchronisierbarkeit Einzelner Pigmentmangel-Mutanten von Chlorella. *Planta* **1965**, *65*, 186–194. [CrossRef]
143. Bumandalai, O.; Tserennadmid, R. Effect of *Chlorella vulgaris* as a Biofertilizer on Germination of Tomato and Cucumber Seeds. *Int. J. Aquat. Biol.* **2019**, *7*, 95–99.
144. Renuka, N.; Prasanna, R.; Sood, A.; Ahluwalia, A.S.; Bansal, R.; Babu, S.; Singh, R.; Shivay, Y.S.; Nain, L. Exploring the Efficacy of Wastewater-Grown Microalgal Biomass as a Biofertilizer for Wheat. *Environ. Sci. Pollut. Res.* **2016**, *23*, 6608–6620. [CrossRef] [PubMed]
145. Dineshkumar, R.; Subramanian, J.; Gopalsamy, J.; Jayasingam, P.; Arumugam, A.; Kannadasan, S.; Sampathkumar, P. The Impact of Using Microalgae as Biofertilizer in Maize (*Zea mays* L.). *Waste Biomass Valorization* **2019**, *10*, 1101–1110. [CrossRef]