

# Aeroterrestrial and Extremophilic Microalgae as Sources in Cosmetics

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Microscopic prokaryotic and eukaryotic algae (microalgae), which can be effectively grown in mass cultures, are gaining increasing interest in cosmetics. Up to now, the main attention was on aquatic algae, while species from aeroterrestrial and extreme environments remained underestimated. In these habitats, algae accumulate high amounts of some chemical substances or develop specific compounds, which cause them to thrive in inimical conditions. Among such biologically active molecules is a large family of lipids, which are significant constituents in living organisms and valuable ingredients in cosmetic formulations. Therefore, natural sources of lipids are increasingly in demand in the modern cosmetic industry and its innovative technologies. Among novelties in skin care products is the use of lipid nanoparticles as carriers of dermatologically active ingredients, which enhance their penetration and release in the skin strata.

carotenoids

Cyanoprokaryota

fatty acids

morphological type

PUFA

Ochrophyta

Rhodophyta

Chlorophyta

Streptophyta

sterols

## 1. Introduction

The increasing use of microalgae in the cosmetic industry as extraordinary rich source of novel high-value functional products, obtained in eco-friendly and cost-effective processes, is widely recognized <sup>[1][2]</sup>. To date, more than 15,000 novel compounds of algal origin have been identified <sup>[3]</sup>. Many bio-based microalgal products are often “multipurposed” and are applied in dermal cosmetics as sunscreens, skin sensitizers and colorants, as well as agents for moisturizing, water-binding, texturizing, thickening, tanning, whitening, etc. <sup>[2][4][5][6][7][8]</sup>. In such skin-related applications, the chemically and functionally diverse group of lipids and their derivatives comprise a significant gradient <sup>[9][10]</sup>. Apart from the fact that deficiencies in cutaneous lipids cause discomfort, which may lead to serious skin diseases (e.g., atopic dermatitis, psoriasis, acne, rosacea, hereditary ichthyoses, allergic and irritant contact dermatitis and hidradenitis suppurativa), the broad usage of lipids is based also on their ability to form a protective multifunction skin barrier and on their role as emollients or emulsifiers in the bulk of care and make-up products as well <sup>[9][11]</sup>. Today, with the flourishing development of nanotechnology, which leads to a fast product innovation <sup>[12][13]</sup>, the potential of lipid nanoparticles (LNP), which seem to be both effective and economic, has been recognized as promising <sup>[14]</sup>. For example, in dermal cosmetics, about a decade ago, it was already demonstrated that nano-sized sunscreen products have better performance than micron-sized materials <sup>[15]</sup>.

Therefore, currently, nano-sized systems are being increasingly studied and applied to encapsulate active ingredients in order to enhance the efficacy of their percutaneous delivery to targeted cells and are also used to improve the physiochemical stability of skin-based cosmetic products [16]. Such loaded LNP have the advantage of a cumulative effect achieved by a combination of their easier penetration with the enhanced and prolonged release of the carried ingredient to the targeted cellular and subcellular regions [17][18][19]. In this way, the overall functionality of the final product is improved, allowing LNP-based cosmetic formulations to be highly effective in skin protection, in treating dermatological disorders and in antiaging therapy [17][18][19]. In addition, many loaded LNP may provide glowing skin [19]. All these positive effects can be achieved not only by topical skin administrations but also by oral applications [19], and it is easily explainable that the modern dermal cosmetic industry is searching for new high-value functional lipid products of natural origins.

Moreover, in the recent conditions of our society, with growing consumer demands for vegetal oils, there is a rapidly increasing general interest in lipid-rich microalgae (>20% of lipids on a cell dry weight basis), named oleaginous [10][20]. Evidence has been accumulated that the average lipid content in microalgae varies between 1 and 70%, but in certain conditions, it can reach 90% of dry weight (for details, see Reference [21]). This commercial interest is strongly supported by the fact that many oleaginous microalgae can be cultivated at a production scale both autotrophically and heterotrophically, mostly with inexpensive nutrient regimes, and have faster growth rates with high biomass productivity as compared to terrestrial crops [2][22][23][24]. Further comparisons show that microalgae have even more advantages, since they can be grown all-year-round without the use of arable land, have low water consumption and have low environmental impact [25]. Another important fact that has to be taken into account is the great general biodiversity of microalgae, which is far away from being thoroughly studied and is gaining increasing attention due to recent surge in searching for indigenous commercially important strains or phycoprospecting [2][26][27].

Lipids produced by microalgae belong to two major groups of polar lipids and nonpolar, or neutral lipids [25][28][29]. Polar lipids have an important role in cell structure and cell signaling processes and are commonly known also as structural or membrane lipids [28][29]. They comprise a small part of the total lipid fraction in cells (ca. 20%) and usually have long chains of extractable fatty acids (FtAs) [25][28][29][30]. Nonpolar lipids have diverse biological functions, but most of them, triglycerides in particular, are often pointed out as responsible for energy storage [28]. Most oleaginous microalgae have the capacity to produce significant amounts of nonpolar lipids (up to 80% of the total cell lipid content), the accumulation of which can be influenced, especially in conditions of a lack of nutrients or in stress environments [25][28].

The capacity of microalgae to produce lipids in such appreciable amounts, combined with the advantages of their growing, has stimulated considerable interest in their screening for useful and unusual lipid compositions and their mass cultivation as a feedstock for various biotechnological products [29]. Until now, most research has been oriented towards freshwater, marine and hyperhaline aquatic species from the genera *Aphanizomenon*, *Arthrospira*, *Chlorella*, *Desmodesmus*, *Dunaliella*, *Haematococcus*, *Nannochloropsis*, *Scenedesmus* and *Spirulina* [2]. However, the commercial potential of microalgae inhabiting many other aeroterrestrial or extreme habitats remains untapped [2]. The species from these inimical environments had to develop ultrastructural, physiological

and biochemical adaptive features, which include a series of protective natural compounds of special interest for future applications in human life and cosmetics in particular [2]. Moreover, such microalgae can be successfully cultivated in outdoor conditions detrimental for standard crops and other algae [31].

## 2. Current Insights

The conducted analysis of publications on lipids from AEM issued in the last 56 years showed that most studies addressed PR and FA, specifically carotenoids and FtAs (mainly PUFA), but even these two lipid categories and their accumulation in AEM deserve more attention. In fact, from the eight major groups accepted in LIPID MAPS classification [32][33], only five (i.e., FA, GL, GP, ST, PR and PK) have been examined in different phyla of AEM, as follows: Cyanoprokaryota (FA, GL, ST and PR); Rhodophyta (FA, GL, ST, PR and PK); Ochrophyta (FA, GL and PR); Chlorophyta (FA, GL, GP, ST, PR and PK) and Streptophyta (PK)—**Table 1**. However, according to the data obtained, it is possible to state that stronger efforts are necessary to improve our knowledge regarding GL, GP and SL and their spread in AEM. Special attention has to be paid to SP, which, according to our best knowledge, remain unknown in AEM.

**Table 1.** Main lipid classes investigated in aeroterrestrial (AET) and extremophilic (EXT) microalgae of different taxonomic phyla and classes. Abbreviations: AA—arachidonic acid, ASX—astaxanthin, DGD—digalactosylglycerol, DGTA—diacylglyceryl-hydroxymethyl-*N,N,N*-trimethyl-β-Ala, DGTS—diacylglyceryl-*N,N,N*-trimethylhomo-Ser, EPA—eicosapentaenoic acid, FA—fatty acyls, FtAs—fatty acids, FAEs—fatty acid esters, GL—glycerolipids, GP—glycerophospholipids, MGD—monogalactosylglycerol, PC—phosphatidylcholine/lecithin, PE—phosphatidyletanolamine/cephalin, PG—phosphatidylglycerol, PI—phosphatidylinositol, PK—polyketides, PR—prenol lipids, PS—phosphatidylserine, PSD—phosphatidylglycerol, SQD—sulphoquinovosyl diacylglycerol, ST—sterol lipids, TGD—triagalactosylglycerol. In Bold are outlined AEM, noted in the cited literature as promising for commercial production and relevant lipids.

Taxonomic Group/Alga	Ecological Group	Investigated Lipid Classes with Examples of Detected Lipids	References
CYANOPROKARYOTA			
<i>Anabaena cylindrica</i>	AET	FA (PUFA—linoleic and linolenic acids, SAFA—palmitic acid and MUFA); GL; ST	[34]
<i>Anabaena cylindrica</i> 1403-2	AET	GL (MGD, DGD, SQD and PSD)	[35]
<i>Anabaena vaginicola</i>	AET	<b>PR</b> (lycopene, lutein, beta-carotene, zeaxanthin)	[36]
<i>Calothrix</i> sp.	AET	ST	[34][37][38][39] [40]

Taxonomic Group/Alga	Ecological Group	Investigated Lipid Classes with Examples of Detected Lipids	References
<i>Desmonostoc muscorum</i>	AET	FA (PUFA—hexadecadienoic and linoleic acids, SAFA—palmitic acid, MUFA—oleic and palmitoleic acids); GL; ST	[34][37][38][39] [40]
<i>Drouetiella lurida</i>	AET—soil, subaerial	ST (seven unsaturated ST)	[41]
<i>Microcoleus autumnalis</i>	AET—soil, subaerial	ST (cholesterol, $\beta$ -sitosterol and stigmasterol with squalene as a precursor; ergosterol)	[40]
<b><i>Nostoc calcarea</i></b>	AET—soil, subaerial	<b>PR</b> (lycopene, lutein, beta-carotene, zeaxanthin)	[36]
<i>Nostoc calcicola</i> B 1459-2	AET—soil, subaerial	FA (PUFA—linolenic acid, SAFA, MUFA), GL—MGD, DGD, SQD and PSD	[35]
<i>Nostoc carneum</i>	AET—soil, subaerial	ST	[34][37][38][39] [40]
“ <i>Nostoc canina</i> ”	AET (symbiont?)	FA (PUFA— linoleic acid, SAFA -palmitic acid, MUFA—palmitoleic and oleic acids); GL; ST (cholesterol and lanosterol)	[34]
<i>Nostoc commune</i>	AET	ST	[34][37][38][39] [40]
<i>Nostoc commune</i> var. <i>sphaeroides</i>	AET	ST (campesterol, sitosterol and clionasterol)	[42][39][43]
<i>Nostoc punctiforme</i> PCC73102	AET	FA (FAEs—oxylipins), PR (genes for ASX and canthaxanthin)	[44][45]
<i>Nostoc</i> sp. PCC7120	AET	FA (FAEs—oxylipins)	[46]
<i>Oscillatoria chalybea</i> B1459-2	AET	GL (MGD, DGD, TGD, SQD and PSD)	
<i>Oscillatoria</i> sp. PBGA3	AET—soil	FA (FtAs)	[47]
<i>Scytonema</i> sp.	AET	ST (cholest-5-en-3 $\beta$ -ol (18.9 %), 3 $\beta$ -methoxycholest-5-ene (16.2 %) and 3 $\beta$ -acetoxcholest-5-ene (11.2 %), ergosta-5,7,22,24(28)-tetraen-3 $\beta$ -ol)	[48]
<i>Tolypothrix tenuis</i> B1482-3	AET	GL (MGD, DGD, TGD, SQD and PSD)	[35]
<i>Tolypothrix</i> sp. PBGA1	AET	FA (FtAs)	[47]

Taxonomic Group/Alga	Ecological Group	Investigated Lipid Classes with Examples of Detected Lipids	References
<i>Tolypothrix</i> sp. PBGA2	AET	FA (FtAs)	[47]
RHODOPHYTA			
<i>Cyanidium caldarium</i>	EXT—thermal springs	GL; ST (ergosta-5,7,22,24(28)-tetraen-3 $\beta$ -ol)	[49]
<i>Cyanidioschyzon merolae</i>	EXT—thermal springs	PK	[50]
<i>Galdieria sulfuraria</i> (>47 strains)	EXT—thermal springs/AET—cryptoendolith	FA (PUFA—linoleic and linolenic acid, SAFA—palmitic acid, MUFA—oleic and palmitoleic acids); GL (MGD, DGD and SQD; PG, PC, PE, PI, PS and phosphatidate); GP; ST (ergosta-5,7,22,24(28)-tetraen-3 $\beta$ -ol and ergosterol); PR ( $\beta$ -carotene, lutein); PK	[51][52][53][49] [50]
<i>Galdieria sulfuraria</i> / <i>Galdieria</i> sp.	EXT—acidic but non-thermophilic	FA (PUFA—linoleic and linolenic acids, SAFA—palmitic, myristic and stearic acids, MUFA—oleic and palmitoleic acids)	[51][52]
<i>Galdieria</i> sp. USB-GBX-832	EXT—thermal springs	FA (PUFA—linoleic acid, AA and EPA; SAFA—palmitic and stearic acid, MUFA—oleic acid)	[54]
<b><i>Pophyridium purpureum</i></b>	AET-soil	FA (PUFA—AA and EPA); GL	[55]
OCHROPHYTA			
Eustigmatophyceae			
<i>Monodopsis subterraneus</i>	AET—soil	FA (PUFA—EPA), GL (DGD)	[56][57][58][59] [60][61]
<i>Monodus guttula</i>	AET	PR (tocopherols)	[2]
<i>Monodus</i> sp.	AET	PR (carotenoids—ASX, beta-carotene and lutein)	[62]
<b><i>Vischeria/Eustigmatos</i></b>	AET—soil, subaerial	PR (total carotenoids; ASX, beta-carotene, lutein and canthaxanthin)	[62]
Tribophyceae (=Xanthophyceae)			
<i>Botrydiopsis interdecens</i>	AET	PR (tocopherols)	[2]
<i>Heterococcus</i> sp.	AET	PR (tocopherols)	[2]

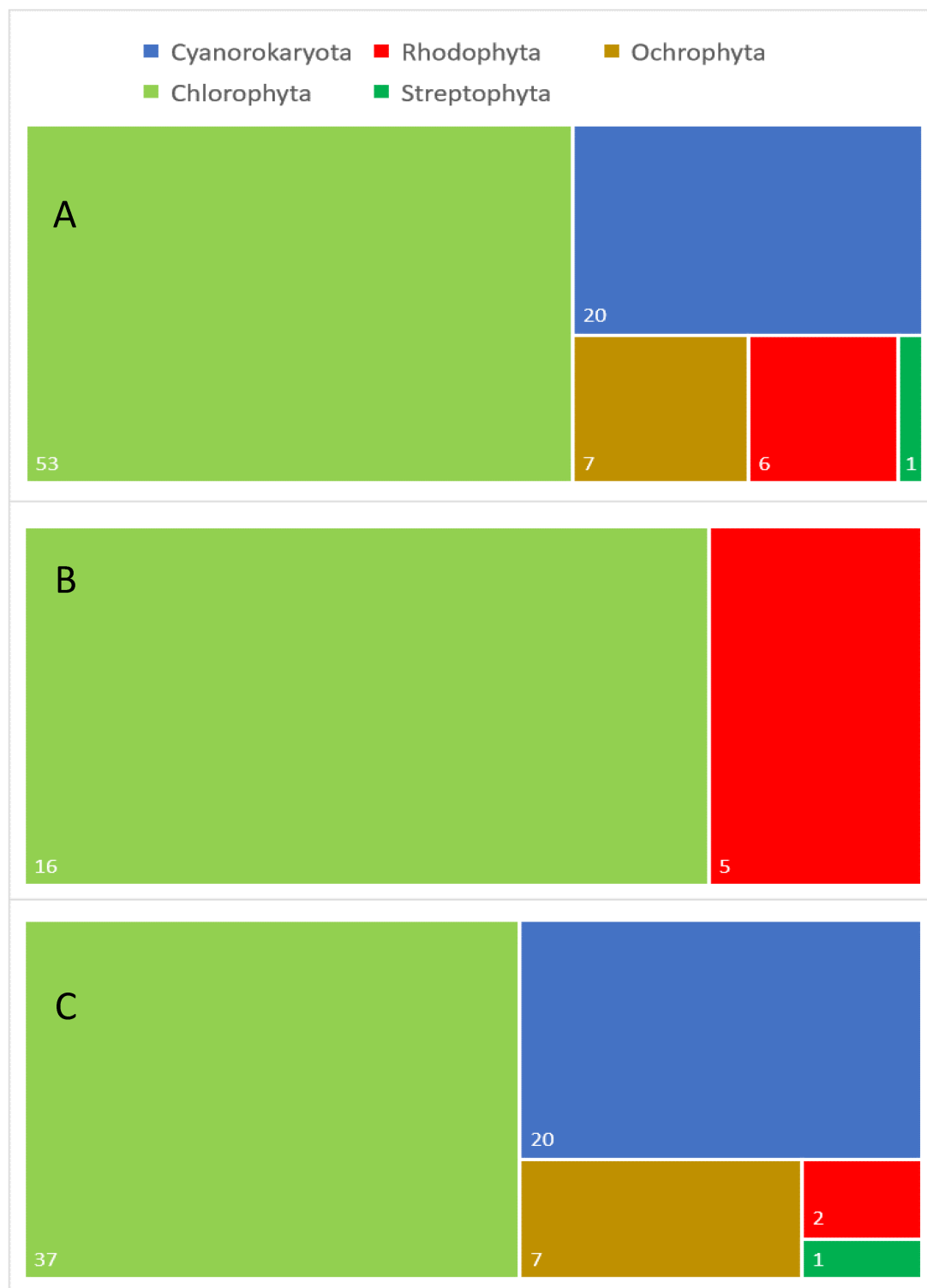
Taxonomic Group/Alga	Ecological Group	Investigated Lipid Classes with Examples of Detected Lipids	References
<i>Xanthonema</i> sp.	AET	PR (tocopherols)	[2]
CHLOROPHYTA			
<i>Acutodesmus dissociatus</i> TGA1	AET—soil	FA (SAFA—palmitic acid and MUFA—oleic acid)	[47]
<b><i>Auxenochlorella protothecoides</i></b>	AET/EXT—acidic	PR (carotenoids— <b>lutein</b> )	[63][64][65][66] [67][68][69]
<i>Auxenochlorella pyrenoidosa</i>	AET	PR (carotenoids—ASX, zeaxanthin, canthaxanthin, lutein)	[70][71][72][73]
<i>Bracteacoccus</i> sp.	AET	PR (tocopherols)	[2]
<i>Chlamydocapsa</i> sp.	EXT—snow	PR (canthaxanthin, tocopherols)	[2][74]
<i>Chlamydomonas nivalis</i>	EXT—snow	PR (ASX, canthaxanthin)	[74][75][76]
<i>Chlamydomonas reinhardtii</i>	AET	FA (hydrocarbons—C17 alkene n-heptadecene), GL (betaine lipids—DGTS); GP; ST (ergosterol); PK	[77][78][79][50] [80][81]
<i>Chlainomonas</i> sp.	EXT—snow	PR (ASX)	[82]
<i>Chlorella sorokiniana</i>	AET	ST (ergosterol)	[79]
<i>Chlorella variabilis</i>	AET	PK	[50][80][81]
<i>Chlorella variabilis</i> NC64A	AET (symbiotic)	ST (ergosterol)	[79]
<b><i>Chlorella vulgaris</i></b>	AET	FA (free FtAs, FAEs—lactones; hydrocarbons—NC64A eptadecane pentadecane, as well as 7- and 8-heptadecene); GL; ST (ergosterol, 7-dehydroporiferasterol, ergosterol peroxide, 7-dehydroporiferasterol per-oxide and 7-oxocholesterol); PR (carotenoids—ASX, zeaxanthin, canthaxanthin and <b>lutein</b> ), PK	[21][24][83][84] [77][85][70][71] [72][73]
<i>Chlorella</i> sp. PGA2	AET—soil	FA (SAFA, MUFA)	[47]
<i>Chlorella</i> sp. TGA2	AET—soil	FA (SAFA- palmitic acid, MUFA—oleic acid)	[47]
<i>Chlorella</i> sp. TGA4	AET—soil	FA (SAFA, MUFA)	[47]
<b><i>Chlorococcum</i> sp. (1)</b>	AET	PR (carotenoids—ASX (in a free form and as esters), adonixanthin (in a free form and as	[86][87][88][89] [90][91][92]

Taxonomic Group/Alga	Ecological Group	Investigated Lipid Classes with Examples of Detected Lipids	References
		esters), lutein, canthaxanthin and $\beta$ -carotene)	
<i>Chlorococcum</i> sp. MA-1	AET	PR (total carotenoids; ASX, lutein, canthaxanthin and $\beta$ -carotene)	[88]
<i>Chlorococcum</i> spp.	EXT—snow	PR ( $\beta$ -carotene, lutein and canthaxanthin)	[51][93][74][75] [76][94][95]
<i>Chloroidium ellipsoideum</i>	AET	PR (carotenoids— <b>zeaxanthin</b> )	[96]
<i>Chloromonas alpina</i>	EXT—snow	FA (PUFA, SAFA, MUFA), <b>PR</b> (ASX)	[51][93][97][98] [75][76][94][95]
<i>Chloromonas hindakii</i>	EXT—snow	FA (PUFA— $\alpha$ -linolenic, stereadonic and hexadecatetraenoic acids, SAFA—palmitic acid and MUFA—oleic acid); GP; <b>PR</b> (ASX)	[51][93][97][98] [75][76][94][95]
<i>Chloromonas nivalis</i>	EXT—snow	FA (PUFA—hexadecatetraenoic, SAFA and MUFA); <b>PR</b> (ASX, canthaxanthin)	[51][93][97][98] [74][75][76][94] [95]
<i>Chloromonas nivalis</i> subsp. <i>tatrae</i>	EXT—snow	FA (PUFA, SAFA and MUFA); PR (ASX)	[98]
<i>Chloromonas polyptera</i>	EXT—snow	FA (PUFA, SAFA and MUFA), <b>PR</b> (ASX)	[51][93][97][98] [75][76][94][95]
<i>Chloromonas remiasii</i> CCCryo 005–99	EXT—snow	FA (PUFA-hexadecatetraenoic acid, SAFA and MUFA), <b>PR</b>	[99][51][93][97] [98][75][76][94] [95]
<i>Chloromonas</i> spp.	EXT—snow	FA (PUFA, SAFA—palmitic acid and MUFA—oleic acid), <b>PR</b>	[93][97][98][75] [76][94][95]
<i>Chromochloris zofingiensis</i>	AET	PR (carotenoids—ASX, canthaxanthin, <b>zeaxanthin</b> , <b>lutein</b> and <b><math>\beta</math>-carotene</b> )	[70][86][87][100] [101][102][103] [104][105][106] [107][108][109]
<i>Coccomyxa acidophila</i>	EXT—acidic	PR (carotenoids— $\beta$ -carotene and <b>lutein</b> )	[110]
<i>Coccomyxa subellipsoidea</i>	AET	ST (phytosterols)	[79]
<i>Coccomyxa subellipsoidea</i> C-169	AET	PK	[50][80][81]
<i>Coccomyxa</i> sp.	AET	PR (tocopherols)	[2]

Taxonomic Group/Alga	Ecological Group	Investigated Lipid Classes with Examples of Detected Lipids	References
<i>Coelastrella oocystiformis</i>	AET	PR (carotenoids—ASX esters and canthaxanthin)	[101][109]
<b><i>Coelastrella striolata</i> var. <i>multistriolata</i></b>	AET—subaerial, soils	FA (PUFA—linoleic acid, SAFA—palmitic acid and MUFA—oleic acid); PR (carotenoids— <b>canthaxanthin</b> , <b>ASX</b> and <b>β-carotene</b> )	[111][112]
<i>Dunaliella acidophila</i>	EXT-acidic	FA (PUFA—linolenic, γ-linolenic and linoleic acids; SAFA; MUFA—oleic and elaidic acids; FAEs—lactones, methyl (12R)-hydroxyoctadeca-9Z,13E,15Z-trienoate, methyl (9S)-hydroxyoctadeca-10E, 12Z,15Z-trienoate and methyl ricinoleate; triacylglycerols—trilinolenin, triolein, trielaidin and tristearin); ST (β-sitosterol, isofucosterol, 24-methylenlophenol, (24S)-methyllophenol and two unidentified sterols, acylsterols and phytol); PR (lycopene, alpha-, beta and gamma-carotene)	[113][77]
<i>Edaphochlamys debaryana</i>	AET—soil	FA (FAEs—oxylipins)	[114]
<i>Hindakia tetrachotoma</i> PGA1	AET—soil	FA (SAFA—palmitic acid and MUFA—oleic acid)	[47]
<i>Monoraphidum</i> sp.	EXT—ice	FA (PUFA)	[31]
<i>Muriella terrestris</i>	AET	PR (tocopherols)	[2]
<b><i>Muriellopsis</i> sp.</b>	AET	PR (carotenoids— <b>lutein</b> )	[115][116][117] [118][119]
<i>Neochloris wimmeri</i>	AET	PR (carotenoids—ASX esters and canthaxanthin)	[101][109]
<i>Parietochloris alveolaris</i>	AET—oil, symbiont	FA (PUFA—EPA, AA and its precursor dihomo-γ-linolenic acid)	[120][121]
<i>Parietochloris alveolaris</i> K-1	AET	FA (PUFA—α-linolenic acid and EPA)	[122][123]
<i>Protosiphon botryoides</i>	AET—soil	PR (carotenoids—ASX esters and canthaxanthin)	[101][109]
<b><i>Pseudochoricystis ellipsoidea</i> MBIC11204</b>	EXT—thermal springs	FA (FtAs and <b>FAEs—hydrocarbons and triacylglycerols</b> )	[124]

Taxonomic Group/Alga	Ecological Group	Investigated Lipid Classes with Examples of Detected Lipids	References
<i>Raphidonema sempervirens</i>	EXT—snow	FA (PUFA, SAFA and MUFA); PR ( $\beta$ -carotene, ASX, lutein and tocopherols)	[2][93][97][98] [74]
<i>Sanguina aurantia</i>	EXT—snow	PR (ASX)	[125]
<i>Sanguina nivalis</i>	EXT—snow	PR (ASX)	[125]
<i>Scenedesmus vacuolatus</i>	AET	PR (carotenoids—ASX esters and canthaxanthin)	[101][109]
<i>Scenedesmus</i> spp.	AET	PR (total carotenoids, ASX and lutein)	[112][126][127]
<i>Stichococcus bacillaris</i>	AET	PR (tocopherols)	[2]
<i>Tetracystis</i> sp.	AET/EXT—cryotolerant	PR (canthaxanthin)	[128]
<b><i>Tetradesmus obliquus</i></b>	AET	FA (PUFA—linolenic, linoleic and linolelaidic acids and SAFA—oleic acid); PR (carotenoids—ASX and lutein)	[21][25][112] [129][130][131] [132][133][126] [127]
<i>Tetradesmus obliquus</i> (strain <i>Scenedesmus obliquus</i> SNW-N)	AET	PR (lutein)	[126]
<i>Tetradesmus obliquus</i> (strain <i>Scenedesmus obliquus</i> FSP-3)	AET	PR (lutein)	[134]
<i>Ulothrix zonata</i>	EXT—ice	FA (PUFA)	[111]
“Unidentified Chlamydomonadaceae”	EXT—snow	FA (PUFA, SAFA and MUFA); PR (ASX)	[47]
<b>Unidentified “Chlamydomonadales species” TGA3</b>	AET—soil, thermotolerant	FA (SAFA and MUFA)	[47]
Unidentified “Chlamydomonadales species” TGA5	AET—soil	FA (SAFA and MUFA)	[47]
STREPTOPHYTA			
<i>Klebsormidium flaccidum</i>	AET	PK	[50]

The taxonomic diversity of the examined AEM, expressed by the number of species, is as follows: Cyanoprokaryota—20, Rhodophyta—6, Ochrophyta—7, Chlorophyta—53 and Streptophyta—1 (**Figure 1A** and **Table 1**). Thus, AEM from green evolutionary lineages (Chlorophyta and Streptophyta) are the most investigated, but a strong discrepancy between the studies inside the green lineages is obvious, with only one species from Streptophyta (i.e., *Klebsormidium flaccidum*) investigated in comparison with 53 species of 34 genera from Chlorophyta. The next most-studied group is represented by prokaryotic blue–green algae, Cyanoprokaryota, from which 20 species of nine genera have been analyzed. The number of species investigated in Rhodophyta and Ochrophyta is significantly lower and almost similar (six and seven, respectively), but more genera have been covered by studies on Ochrophyta (seven) than from Rhodophyta (four). However, much more strains from Rhodophyta have been examined, with more than 47 strains investigated from a single species (i.e., the extremophilic *Galdieria sulfuraria*). Most of the studied AEM are unicellular (59), followed by filamentous (26) and coenobial algae (2). The highest morphological diversity has been found in the studied chlorophyte algae, while, from Cyanoprokaryota, only filamentous species and, from Rhodophyta, only unicellular species were examined for different lipids.



**Figure 1.** Taxonomic

diversity of aeroterrestrial and extremophilic microalgae analyzed for different lipids: **(A)** general taxonomic diversity of the analyzed algal species, **(B)** taxonomic diversity of the examined extremophilic species and **(C)** taxonomic diversity of the investigated aeroterrestrial species. Numbers in white indicate the exact number in each category.

Regarding the ecological affiliation of the examined microalgae (**Figure 1B,C**), it could be stated that the highest number (66) of studied species are aeroterrestrial, and they are the most taxonomically diverse, including representatives from all five major algal phyla (**Figure 1C**). By contrast, the number of examined extremophilic

species is lower (21), with only two phyla studied (i.e., Rhodophyta and Chlorophyta) (**Figure 1B**). Despite this generally low number, ten extremophilic algae (ca. 50%) have been considered as promising lipid sources (**Table 1**). However, it has to be boldly underlined that this analysis is based only on Latin species names provided in the available publications, since, for most of the strains, there are neither data from genetic studies nor detailed morphological and ecological descriptions. In the recent times of rapid taxonomical changes, providing such data in future publications is strongly recommended in order to obtain more precise information on the biochemical compositions of the studied microalgae.

The results obtained clearly showed that very few known AEM have been investigated for their lipid content, with most of the studies being quite scarce and oriented towards certain compounds. Less studies were comparative, but the differences in lipid contents were demonstrated with field materials and cultivated in different conditions algae, or ecologically different strains (e.g., thermophilic and non-thermophilic) were investigated. These results may stimulate further research for the best physiological and cultural conditions, which would lead to the optimal yield of algal biomass and certain lipids. As we have shown in the text above, data on all lipid classes in AEM are far away from being complete, and more investigations on certain compounds and in more AEM are needed in the future. Nevertheless, all collected evidence until now suggests the great potential of AEM as novel commercial lipid sources for versatile cosmetic substances and products for skin care. In this regard AEM are comparable with their aquatic (marine and freshwater) counterparts and land plants, which have been much more intensively studied [1][2][135]. Twenty-three AEM have been already pointed out as promising for obtaining certain compounds, most of them from Chlorophyta (**Table 1**). The potential of AEM as beneficial lipid sources can be recognized in two aspects, separately or in combination: (1) quantitative, since, in some AEM, the contents of valuable lipids are higher in comparison with other algae or plants (e.g., *Parietochloris alveolaris* is considered to be the richest natural source of the high value polyunsaturated  $\omega$ 6 AA, or *Chlorodinium ellipsoideum*, in which zeaxanthin exceeded more than nine times that of red pepper, a plant source of zeaxanthin) and (2) qualitative, since, in some AEM, rare and unusual lipids were discovered (e.g., the three hydroxy FtAs in *Dunaliella acidophila*, such as methyl (12R)-hydroxyoctadeca-9Z,13E,15Z-trienoate, methyl (9S)-hydroxyoctadeca-10E, 12Z,15Z-trienoate and methyl ricinoleate, or the unidentified ST of *Scytonema* sp. and *Dunaliella acidophila*). These compositional peculiarities in AEM, as it has been shown earlier, are due to their specific ecology and adaptations to survive inimically in other organism environments, and this potential is still untapped [2]. However, among the AEM examined for lipids occur species from genera that have already been recognized as potential toxin producers or allergic-causative agents [33][136]. On that account, in order to answer safety concerns, we strongly underline that all algae, chosen as lipid sources for direct use or for transformation to LNP, must be subjected to chemical analyses before introducing them into mass cultures and cosmetics formulations.

### 3. Conclusions

The cosmetics industry is increasingly exploring new compounds derived from natural products, preferably from plant origins, due to strong consumer demands [2][135]. In addition, nanotechnologies are delving deeper into people's lives, including the field of skin cosmetics [16]. It is well-known that skin lipid compositions and structures

are significant for proper skin functioning, and their deficit leads to skin diseases and disorders [9][10][11]. Therefore, in addition to traditional topical and oral lipid applications, there is a rising interest in enhancing the targeted lipid transport to different skin layers using nanosized systems, including LNP [12][13][14][15][16][17][18][19]. Currently, different methods for obtaining nanoparticles from lipids have been developed and standardized [14][19]. Since algae from different ecological and taxonomic groups are rich in biologically active compounds, including lipids, they are increasingly becoming the focus of biotechnology [1][2][3][4][5][6][7][8]. However, to date, mostly aquatic micro- and macroalgae have been investigated, whereas the algae from aeroterrestrial and versatile extremophilic habitats have been more neglected. At the same time, due to their peculiar ecology, AEM produce many specific compounds that are not available from other algae or accumulate higher amounts of other chemicals than other algae and plants [2]. To the best of our knowledge, there are no commercially produced skin care preparations, or LNP, yet based on lipids from AEM, despite some AEM being outlined as promising commercial lipid sources (Table 1). Therefore, we summarized the available, but quite scattered, data on the lipid contents of different species of AEM issued during the last 56 years.

According to the analysis of this knowledge, considering: (1) the successes in the clinical experiments for the treatment, alleviation or prevention of different skin disorders, as well as all other beneficial effects of versatile lipids, which occur in AEM; (2) the fact that both standard and unusual lipids have been detected, and most of them can be obtained in profitable amounts from AEM; (3) the possibilities to benefit from the direct application of lipids or from their enhanced penetration using LNP; (4) the developed methods for obtaining LNP [13]; (5) the advantages of the effective mass cultivation of AEM species even outdoor, unfavorable for algae from “standard” aquatic habitats, conditions, which can make more cost-effective and beneficial yields of both unusual and standard lipids; (6) the gradually increasing phycoprospection in the background of the enormous biodiversity of microalgae, which has been recognized but is far away from being utilized, we believe that all the provided data will serve as the groundwork to enhance and further encourage studies for broader applications of AEM-derived lipids in novel products of the future dermal cosmetics bioindustry.

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