Journal of Applied Phycology
https://doi.org/10.1007/s10811-024-03345-4

REVIEW

Green beauty unveiled: Exploring the potential of microalgae for skin whitening, photoprotection and anti-aging applications in cosmetics

Hazel Jing-Yi Leong[1] · Ming-Li Teoh[1,2] · John Beardall[3] · Peter Convey[4,5]

Received: 21 June 2024 / Revised: 30 July 2024 / Accepted: 22 August 2024

Abstract
Microalgae are gaining considerable attention in the field of cosmeceuticals due to their unique profile. In particular, the diverse range of valuable bioactive compounds isolated from microalgae are known to exhibit multiple properties, including anti-aging, antioxidant, whitening, moisturising, and photoprotection, which have contributed to their distinctive profile. In recent years, there has been an increasing effort around exploration of novel natural biologically active substances from microalgae. This trend is in part driven by the global progression towards a 'greener' lifestyle. Since compounds derived from microalgae can offer skin benefits without inducing any adverse effects on human health, they are recognised as promising ingredients for innovative cosmetics and cosmeceutical applications. This review paper provides an overview of the changing balance of reliance on traditional topical agents and the prominent role of microalgae as an alternative source for whitening, photo-protection and anti-aging cosmetic applications.

Keywords Microalgae · Cosmetics · Bioactive compounds · Applications · Sustainability

Introduction

Cosmetics are products applied to the human body for the purpose of alteration or enhancement of appearance. Cosmeceuticals contain active nutrients or ingredients such as vitamins, minerals, essential amino acids, fatty acids and antioxidants that are designed to cleanse, beautify, and promote attractiveness. The active ingredient can be incorporated in products in the form of creams, ointments, powders, gels, or lotions (Hatziantoniou et al. 2024). The value of the global cosmeceutical industry was estimated at nearly US$50 billion in the year 2021 and is likely to increase to ~ US$114 billion by 2030. The Asia Pacific region currently dominates this with ~ 40% of the market (Cosmeceuticals Market Size, Share & Growth Analysis [2030] 2023). The increasing recognition of the cosmetic industry's value has been accompanied by a reliance on synthetic chemicals. This has also led to a growing interest in natural product alternatives that offer a wealth of benefits for skin care. The global surge in environmental awareness and improving health trends through the adoption of 'green' consumption patterns are leading to increased demand for, and use of, environmentally friendly products, such as cosmetics with natural ingredients that avoid the use of chemical additives. The development of allergic reactions and skin damage issues arising from the use of synthetic beauty products inevitably draw the attention of consumers to the environmental impacts of cosmetic items (Pudaruth et al. 2015). This trending desire in healthy, safe, and clean cosmetics is promoting the active transition towards natural products as a safer alternative due to the potential adverse effects that traditional products may have (Suphasomboon and Vassanadumrongdee 2022).

Marine resources represent a plentiful and prospective source of distinctive as well as active compounds with the potential to produce green and eco-friendly products (Ariede et al. 2017; Guillerme et al. 2017). Among these

✉ Ming-Li Teoh
MingLi.Teoh@taylors.edu.my

1 School of Biosciences, Faculty of Health and Medical Sciences, Taylor's University, Subang Jaya 47500, Selangor, Malaysia

2 Clean Technology Impact Lab, Taylor's University, Subang Jaya 47500, Selangor, Malaysia

3 School of Biological Sciences, Monash University, Clayton, VIC 3800, Australia

4 British Antarctic Survey, NERC, High Cross, Madingley Road, Cambridge CB3 0ET, UK

5 Department of Zoology, University of Johannesburg, PO Box 524, Auckland Park 2006, South Africa

Published online: 11 September 2024

resources, seaweeds have successfully gained attention as sources of cosmeceuticals recently due to their effectiveness in skincare, as demonstrated in numerous scientific studies (López-Hortas et al. 2021; Noviendri et al. 2022). For instance, brown algae are a well-known source for fucoxanthin, a xanthophyll that has demonstrated bioactivities such as photoprotection (Matsui et al. 2016; Tavares et al. 2020) and anti-aging (Cao et al. 2020). In the current literature landscape, there has been increased focus on the exploration of microalgae due to their fast growth rate, high biomass, and minimal need for cultivation space. These advantages promote their potential as valuable bioactive sources (Yap et al. 2021).

Microalgae are photoautotrophic microorganisms that produce distinct functional secondary metabolites in response to stress (Zhuang et al. 2022; Kolackova et al. 2023). Some of these compounds have diverse biochemical properties relevant to human nutrition and health. These compounds derived from microalgae, such as pigments, lipids, phenolics, and polysaccharides, have gained traction in the cosmeceutical industry due to their valuable functions such as whitening, photoprotective, anti-aging, antioxidant, and anti-inflammatory activities (Thiyagarasaiyar et al. 2020; Yarkent et al. 2020; Saide et al. 2021; Martínez-Ruiz et al. 2022). Hence, exploration of microalgal products opens possibilities for the development of novel cosmetics and cosmeceutical formulations.

Microalgae have the potential to provide alternative sustainable resources of high value bioproducts due to their natural availability, diversity, and versatility (Nethravathy et al. 2019). The sustainable and unique characteristics of microalgae underpin their potential for use in the development and manufacture of cosmetic products. Studies have demonstrated this through the incorporation of extracted microalgal compounds as a primary active ingredient in diverse products such as sunscreens, face lotions, creams, shampoos, body soaps, and colorants for cosmetic formulations (Yarkent et al. 2020). Aside from these products, microalgae also have potential benefits in wellness treatments such as thalassotherapy due to their abundance of bioactive compounds. Therefore, it is of interest to spa and thalassotherapy centres to incorporate microalgal products in their treatments for the improvements in skin moisture, elasticity, and fatigue (Mourelle et al. 2017).

Growing environmental awareness globally and resulting increases in green consumption patterns are highlighting the crucial need for consumer research in this burgeoning sector. Hence, this review provides an overview of the changing balance in the use of long-established topical agents used in whitening cosmetics and other products obtained from microalgae as a favourable alternative for the future beauty industry.

Existing whitening cosmetics and their drawbacks

Various traditional agents such as hydroquinone, kojic acid, and azelaic acid, are commonly used in the cosmetic industry with a wide range of functions. These synthetic ingredients are known to be incorporated in formulations of many cosmetic products. They are often used to treat skin pigmentary disorders and acne-related skin issues. These agents also provide anti-aging, anti-bacterial, and anti-inflammatory activities (Owolabi et al. 2020; Liu 2022; King et al. 2023). While it is clear that marketed products incorporate these agents in their formulation, accurate and up-to-date information regarding their efficacy and safety remains inadequate. These widely used topical agents have proven effectiveness in treating aesthetic-related skin disorders in past studies; however, potentially adverse effects have received insufficient attention in clinical trials and safety profile studies (Table 1) (Sinha et al. 2016; Meena et al. 2017; Shakeel et al. 2021).

Hyperpigmentation disorders, acne and aging skin are amongst the common aesthetic conditions affecting all skin types. A range of topical medications, chemical peels, injectable products, and energy-based devices are among the current therapeutic options commercially available for these disorders. Topical treatments, including creams, gels, lotion, foams, solutions, and ointments, are generally the first line of treatment, and they are widely and easily available 'over the counter' (OTC) and are affordable (Alghamdi et al. 2021; Moolla and Miller-Monthrope 2022). This ease of availability also underlies cases of misuse increasing in prevalence in recent years, with the highest rates of such abuse being recorded in Africa, Asia, the Caribbean and the Middle East, as well as in immigrant populations in North American and Europe regions (Ah et al. 2019; Khamanarong et al. 2021). Most individuals using these products do so due to reasons related to social preference (peer group pressure) and of the perceived importance of better skin appearance (Ah et al. 2019; Alghamdi et al. 2021).

As an example, the use of topical hydroquinone for depigmenting purposes has become widespread in recent decades and its use is common in managing various pigmentation-related conditions such as melasma, age spots, freckles, and post-inflammatory hyperpigmentation (PIH) resulting from acne or trauma (Juliano 2022). Although hydroquinone is often regarded as the dermatological gold standard among traditional topical treatments for the treatment of such conditions, many reports have associated its use with various adverse side effects, particularly when used long-term, including skin irritation and contact dermatitis, while ochronosis, nail discolouration, corneal degeneration, and conjunctival melanosis have also been discovered when

Table 1 Uses of topical agents and their reported adverse effects

Compound	Uses	Reported side effects	Reference
Hydroquinone	Hyperpigmentation, melasma, pitted scars, actinic lentigines	Cutaneous irritation (erythema, stinging)	Bandyopadhyay 2009; Nordlund et al. 2006
		Nail discolouration	Glazer et al. 2016; Mann and Harman 1983; Ozluer and Muir 2000; Parlak et al. 2003
		Ochronosis	Bhattar et al. 2015; Gandhi et al. 2012; Nordlund et al. 2006
		Conjunctival melanosis	Nordlund et al. 2006
		Corneal degeneration	Nordlund et al. 2006
		Impaired wound healing	Ladizinski et al. 2011
		Peripheral neuropathy	Ladizinski et al. 2011
		Trimethylamine/Fish odour syndrome	Ladizinski et al. 2011
Tretinoin	Treatment of acne, photodamaged skin	Cutaneous irritation (erythema, peeling, dryness, itching, burning/stinging)	Sitohang et al. 2022
		Respiratory events (sinusitis and bronchitis)	Shapiro et al. 2011
		Intracranial hypertension	Gasparian et al. 2021
		Neurological and/or chiatric events (headache, dizziness, change in mood)	Shapiro et al. 2011
		Otocerebral anomalies	Selcen et al. 2000
Kojic acid	Melasma, hyperpigmentation, lentigines, anti-aging, acne treatment, yeast and candidiasis infection treatment	Cutaneous irritation (rashes, itchiness, redness)	Burnett et al. 2010; Liu 2022; Phasha et al. 2022; Saeedi et al. 2019
Azelaic acid	Comedonal and inflammatory (papulopustular, nodular, nodulocystic) acne treatment, melasma, lentigo maligna	Cutaneous irritation (erythema, burning/stinging)	Baliña and Graupe 1991; Fitton and Goa 1991; Liu et al. 2006
		Hypopigmentation	Grobel and Murphy 2018

hydroquinone is used persistently (Bandyopadhyay 2009; Gandhi et al. 2012; Glazer et al. 2016). Trimethylaminuria, commonly known as "fish odour syndrome", is a rare consequence of prolonged hydroquinone use and results from trimethylamine excretion in urine, vaginal secretions, sweat and saliva (Ladizinski et al. 2011).

Other established topical agents, including tretinoin, kojic acid, and azelaic acid, have been considered as alternatives to hydroquinone. Known adverse effects of some of these agents, such as kojic acid and azelaic acid are mild and transient when applied at the recommended concentration (Liu et al. 2006; Liu 2022). Common side effects include local cutaneous irritation symptoms (Fitton and Goa 1991; Liu et al. 2006; Grobel and Murphy 2018; Liu 2022). Aside from the clinical consequences noted on the skin, non-cutaneous adverse effects involving respiratory and neurological events have been reported in past studies of topical tretinoin usage (Shapiro et al. 2011). Selcen et al. (2000) revealed the association of otocerebral anomalies associated with topical tretinoin use. During the early development of the structures during embryogenesis, severe malformations of auricles were evident from tretinoin toxicity.

While various local adverse effects caused by topical agents have been documented, information relating to systemic impacts is scarce. In order to improve the efficacy and reduce the occurrence of side effects, the combination of other agents such as hydroquinone and tretinoin has been used to develop combinations of topical cream product (Ah et al. 2019). However, contact dermatitis characterised by acute onset redness, itching, burning, and cauterised appearance of facial skin, was still prominent in patients after usage (Nordlund et al. 2006; Mathe et al. 2021). Such outcomes have led to increasing concerns about the long-term effects caused using these established topical agents.

Role of microalgae in skin whitening, photoprotection and anti-aging products

Increasing awareness of the negative effects that synthetic materials can have on both health and the environment have fuelled a notable alteration in customer preferences towards natural skin care products. As a result, research interest in cosmeceuticals is shifting towards natural bioactive compounds generated from a variety of natural resources (Amberg and Fogarassy 2019).

Microalgae are known renewable and sustainable sources due to their economical cultivation and versatile capabilities in producing a broad spectrum of metabolites (Mourelle et al. 2017; Puchkova et al. 2020). They are an eco-friendly choice for cosmetics, aligning with the growing demand for 'green' cosmeceuticals. Microalgae are now a popular choice in cosmeceutical research on account of the high diversity of bioactive compounds that impart a plethora of remarkable skin benefits (Puchkova et al. 2021; Martínez-Ruiz et al. 2022).

Various microalgal-derived compounds including pigments, proteins, peptides, polyunsaturated fatty acids (PUFAs), phytosterols, polyphenols, amino acids, carbohydrates, and vitamins have been revealed to exhibit biological activities such as protection from stress (antioxidant, anti-aging and anti-inflammatory properties) and promotion of skin quality (skin brightening, moisturising activity and collagen synthesis) (Choo et al. 2020; Martínez-Ruiz et al. 2022). This diverse range of beneficial compounds combined with their strong safety profiles has led to enthusiasm for research exploring their application in the cosmetic industry (Aslam et al. 2021; Udayan et al. 2023).

Skin whitening and pigmentation control

Light skin tones have long been associated in Asian cultures with youth and beauty. Considerable growth in investment in the manufacture of skin-whitening products and their use has been evident in Asian markets, largely in China, Korea, Japan, and India (Pillaiyar et al. 2017; Masum et al. 2019; Khamanarong et al. 2021). The pigmentation of human skin, hair, and eyes is determined by the amount of melanin produced through melanogenesis. The functional role of this pigmentation is to act as a protective barrier against damaging UV injury to the skin. However, an uncontrolled generation or accumulation of melanin also gives rise to potentially significant aesthetic problems, such as melasma, post-inflammatory hyperpigmentation, lentigo, and even cancer (Pillaiyar et al. 2017; Favas et al. 2021). To overcome such conditions, research effort has focused on the key regulatory enzyme in melanogenesis, tyrosinase.

Tyrosinase is a crucial determinant in melanin synthesis, and tyrosinase inhibitors have therefore been the centre of attention in research studies into reducing or inhibiting skin pigmentation (Pillaiyar et al. 2017). Commercially available topical agents for hyperpigmentation treatment, including hydroquinone, kojic acid, azelaic acid, and arbutin, are well-known tyrosinase inhibitors. However, despite their widespread use in the market as whitening agents in the market, these compounds have disadvantages (Pillaiyar et al. 2017; Favas et al. 2021). In additions to reported adverse effects such as contact dermatitis, irritation, high toxicity, and skin sensitivity, many of these compounds also showed poor skin penetration and low formulation stability (Masum et al. 2019). As a result, there is a crucial need to discover and develop novel tyrosinase inhibitors from various sources that are effective with minimal side effects and microalgae can be a promising alternative.

Initial studies have reported a range of microalgal extracts demonstrating tyrosinase inhibition similar to traditional whitening agents. Some carotenoids and phenolic compounds derived from microalgae exhibit effective anti-melanogenic effects accompanied by other biological functions, including antioxidant, anti-cancer, and anti-aging activities. These have been demonstrated in compounds derived from microalgal species including *Arthrospira platensis* (Sahin 2018), *Nostoc verrucosum* (Sato et al. 2023), *Schizochytrium limacinum* (Kose 2023), *Dunaliella tertiolecta* (Ji et al. 2021), *Haematococcus pluvalis* (Rao et al. 2013), *Oscillatoria agardhii* (Sano and Kaya 1996), *Nannochloropsis* sp. (Kim et al. 2021), and *Chlamydomonas reinhardtii* (Sedjati et al. 2020) (Table 2).

UV protection

High doses of ultraviolet (UV) radiation cause cell damage and produce reactive oxygen species (ROS). Photoaging is the superposition of the addition of solar radiation damage to the intrinsic aging process of the skin. Underlying mechanisms include reduction of skin collagen content due to upregulation of matrix metalloproteinases (MMPs), hyperpigmentation, and solar elastosis (Araújo et al. 2022). These consequences can be associated with increased inflammation as well as oxidative stress (Campiche et al. 2018). The UV part of the electromagnetic spectrum is primarily responsible for the detrimental effects of solar radiation. UV radiation is classified into three categories, namely UV-A (320–400 nm), UV-B (290–320 nm), and UV-C (200–290 nm).

Generally, UV-A and UV-B exposure are of concern related to UV radiation as they comprise a high proportion of the solar radiation energy that reaches the Earth's surface (Santiesteban-Romero et al. 2022). UVC is of higher energy but is completely absorbed by oxygen and ozone in the atmosphere (Araújo et al. 2022). Chronic exposure to UV without protection induces alterations related to skin aging and greater risk of skin cancers (Santiesteban-Romero et al. 2022). Growing concerns regarding the ecologically and dermatologically negative impacts of most currently available sun protectants have, again, accelerated the need for development of safer alternatives.

Microalgae are a polyphyletic and biochemically varied assemblage of chlorophyll *a*-containing microorganisms

Table 2 Microalgae species, extracted compounds, extraction methods and their potential use in cosmetics

Microalgae species	Biocompound/Extract	Extraction method	Uses in cosmetics	References
Arthrospira platensis	Ferulic acid, caffeic acid	Ethanol	Anti-melanogenesis	Sahin 2018
Nostoc verrucosum	N/A	Hexane	Anti-melanogenesis	Sato et al. 2023
Schizochytrium limacinum	Fatty acids	N/A	Anti-melanogenesis	Kose 2023
Dunaliella tertiolecta	N/A	Ethyl acetate	Anti-melanogenesis, anti-oxidant	Ji et al. 2021
Haematococcus pluvalis	Astaxanthin and astaxanthin esters	Acetone/hexane	Anti-melanogenesis, antioxidant, anticancer	Rao et al. 2013
	Astaxanthin	-	Photoprotection, anti-aging	Li et al. 2020
Oscillatoria agardhii	Oscillapeptin G	Chloroform–methanol-water	Anti-melanogenesis	Sano and Kaya 1996
Pleurochrysis carterae	N/A	Hot water extract	Anti-melanogenesis	Sato et al. 2019
Nannochloropsis sp.	PUFAs (EPA), carotenoids (astaxanthin, canthaxanthin, B-carotene, zeaxanthin, violaxanthin), and phenolic compounds	Ethanol	Anti-melanogenic, antioxidant, anti-aging/wrinkling	Kim et al. 2021
	N/A	Maceration with propylene glycol	Antioxidant, anti-aging	Letsiou et al. 2017
	Pigment (violaxanthin)	Ethanol by ultrasonication	Photoprotection	Kim et al. 2019
	Phenols (Caffeic acid, p-coumaric acid, naringenin, hesperitin)	Methanol	Antioxidant	Zainoddin et al. 2020
Scenedesmus rubescens	Amino acids (alanine and glycine), vitamin b3	Water	Photoprotection, anti-melanogenesis, anti-aging	Campiche et al. 2018
Tetraselmis suecica	N/A	Water by ultrasonication	Photoprotection, anti-aging, antioxidant	Jo et al. 2012
	Pigments (chlorophylls and carotenoids)	Acetone	Antioxidant	Sedjati et al. 2020
Chlorella vulgaris	N/A	Hexane	Photoprotection	Lee et al. 2016
	Zeaxanthin	N/A	Photoprotection	Girolomoni et al. 2020
	Chlorophyll	Water by maceration	Antioxidant	Agustina et al. 2020
Pediastrum sp.	Pigments, polyphenols	N/A	Photoprotection, antioxidant	Cecil et al. 2022
Coelastrella rubescens	Carotenoids and MAAs	N/A	Photoprotection	Zaytseva et al. 2021
Chlamydomonas reinhardtii	Carotenoids (neoxanthin, violaxanthin, lutein, B-carotene)	Ethanol by ultrasonication	Anti-melanogenesis	Sedjati et al. 2020
	Sulfated polysaccharides	Hot water	Anti-aging	Falcao et al. 2020
Dunaliella salina	Carotenoids (phytoene, phytofluene)	Supercritical carbon dioxide (CO_2)	Anti-aging, photoprotection	Havas et al. 2022
Aphanothece halophytica	Mycosporine-like amino acids (mycosporine-2-glycine (M2G))	Methanol by sonication	Anti-aging	Tarasuntisuk et al. 2018
Trachydiscus minutus	N/A	Water	Anti-aging	Georgakis et al. 2023
Nostochopsis lobatus	Polysaccharide	Hot water extract	Anti-aging	Yamaguchi and Koketsu 2016
Chlorella pyrenoidosa	Pigment-protein complex (PPC)	Water and spirituous soaking extraction	Anti-aging, anti-inflammation	Zhang et al. 2019
	Peptide	Hot water extraction	Photoprotection	Shih and Cherng 2012
Pophyridium cruentum	phycoerythrin	Water by maceration	Antioxidant	Agustina et al. 2020
Spirulina sp.	Phycocyanin, beta carotene, chlorophyll	Water by ultrasonication	Antioxidant	Hadi and Dianursanti 2021
Nannochloropsis oculata	Carotenoids, pigments	Ethanol	Antioxidant	Gkioni et al. 2022

capable of oxygenic photosynthesis that are primarily found in aquatic environments, often experiencing high UV radiation levels (Dionisio-Sese 2010; Araújo et al. 2022). To protect themselves from UV radiation damage while allowing exposure to visible radiation, needed to drive photosynthesis, some microalgae synthesise organic metabolites that can be incorporated into cosmetics to combat the harmful effects of UV radiation (Núñez-Pons et al. 2018; Saide et al. 2021). The presence and role of UV-absorbing compounds such as mycosporine-like amino acids (MAAs), sporopollenin, and scytonemin to mention a few, have been extensively studied and have shown promising results in effectively absorbing and filtering UV radiation (Núñez-Pons et al. 2018; Santiesteban-Romero et al. 2022; Ručová et al 2023). Such compounds function in UV protection by absorbing and scattering UV radiation, effectively preventing it from penetrating the skin and causing damage. Examples of other defence and/or tolerance mechanisms functioning within microalgae include DNA repair, synthesis of antioxidants, suppression of MMPs production, and promotion of fibroblast proliferation (Araújo et al. 2022; Rincón-Valencia et al. 2022).

The susceptibility of different microalgal species to UV radiation varies greatly though research has shown that Antarctic microalgal species are strong photoprotectors due to their evolutionary adaptations to the extremely harsh environment of polar regions (Teoh et al. 2004, 2020; Santiesteban-Romero et al. 2022; Montuori et al. 2023). They are characterised by high xanthophyll to chlorophyll ratios, implying a high content of UV-absorbing compounds (Santiesteban-Romero et al. 2022). Comparably, tropical microalgae have also exhibited a high potential to contain natural antioxidants such as carotenoids and phenols due to constant exposure to their surroundings that are characterised by high temperature, light, and UV radiation (Wong et al. 2011; Rahman et al. 2020; Wang et al. 2023). The harsh habitat that they exist in requires photoprotective compounds and defence mechanisms to shield themselves from potential damage triggered by excessive exposure to solar radiation and subsequently oxidative stress (Rahman et al. 2020; Sheibani Madrahi & Naeimpoor 2023).

Research on microalgae and their UV-protective properties has shed light on the potential of these organisms as sources of sustainable and effective alternative sources of compounds for UV protection (Dianursanti et al. 2020). For instance, most of commercial cosmetics used to date invoke a large range of *Spirulina* (*Arthrospira*) properties. Ragusa and colleagues (2021) reviewed the current emergence of *Spirulina* in effective and safe cosmetics applications including as a sunscreen (Ragusa et al. 2021). Moreover, a study by Ariede et al. (2020) that investigated the potential of *Botryococcus braunii* dry biomass in enhancing UV-B protection in topical formulations revealed an improved sun protection factor (SPF) when the biomass was combined with a self-emulsifying base. This study presents the on-going safety and efficacy improvements incorporating microalgae in cosmetics applications.

This opens new opportunities for the development of eco-friendly sun protectants. Through leveraging the inherent UV-protective attributes of microalgae and advancing understanding of underlying molecular mechanisms, innovative opportunities are likely to emerge to enable development of sun-care products that are both environmentally responsible and beneficial for human health.

Anti-Aging/Anti-wrinkle

Aging is a physiological process of atrophy that occurs over time. Intrinsic (genetic) and extrinsic (external) factors trigger and accelerate skin aging through the gradual structural disorganisation in the skin, causing wrinkles, blemishes, flaccidity, fragility, and dryness. Intrinsic elements include hormone responses, metabolic processes, stress, and lifestyle choices, while UV radiation, pollution, and toxicity reactions are examples of extrinsic influences (Falcao et al. 2020). Collagenase, elastase, and hyaluronidase are enzymes pivotal in the aging process, affecting the skin's filling, elasticity, and moisture, respectively. Activity of these enzymes has been reported to be elevated in the presence of high levels of ROS (Hadi and Dianursanti 2021).

Microalgae extracts have shown to be effective inhibitors of these enzymes. Metabolites including carotenoids, PUFAs, peptides, phenols and phytosterols are known to be strong antioxidants, free radical scavengers and photoprotectors contributing inhibitory effects on such enzymes (Choo et al. 2020). As a result, induced cellular damage, ROS production, extracellular matrix (ECM) degradation and cellular senescence are suppressed. For instance, amino acids and carotenoids isolated from *Aphanothece halophytica* (Tarasuntisuk et al. 2018) and *Dunaliella salina* (Havas et al. 2022), respectively displayed protection from glycation-induced aging.

The explant model conducted by Havas et al. (2022) confirmed that compounds extracted from *D. salina* exhibited anti-glycation along with anti-inflammatory activity through reductions in key interleukins. Zhang et al. (2019) showed similar indications of anti-inflammatory and anti-aging properties expressed by a pigment-protein complex (PPC) derived from *Chlorella pyrenoidosa*. Further studies have confirmed that *Nannochlorpsis* sp. (Letsiou et al. 2017; Zainoddin et al. 2020; Kim et al. 2021), *Chlamydomonas reinhardtii* (Falcao et al. 2020), *Trachydiscus minutus* (Georgakis et al. 2023), *Nostochopsis lobatus* (Yamaguchi and Koketsu 2016), *Pophyridium cruentum* (Agustina et al. 2020), and *Spirulina* sp. (Hadi and Dianursanti 2021) all exhibit commercial potentiality in cosmetics due to their potent anti-aging and antioxidant effects (Table 2).

Patents are important indicators of the potential applications of research outputs and can be granted for any device, substance, process, or method that is novel, inventive and functional. The aptitude mention of microalgal in patents for cosmetic products and formulations is notable (Pazik and Gagala 2023). For instance, an invention that incorporated *Nannochloropsis gaditana* extract in cosmetic formulations indicated protection against oxidative stress and provided enhancement of skin elasticity. The protective role was achieved through stimulating increased expression of transcripts of fibrillin in skin cells, strengthening skin elasticity since this protein provides the scaffold for the proper conformation of elastin (Koutsianas et al. 2017).

Microalgae are increasingly accepted to be a sustainable choice for skin care products due to their capacity for self-renewal, basic nutritional requirements, minimal cultivation space, and low environmental impact characteristics. They can provide a wide range of applications capable of inhibiting skin aging features such as wrinkles development, pigmentation, collagen degradation and loss of elasticity (Favas et al. 2021).

Clinical efficacy of microalgae in cosmetic formulations and products

To realise the potential for microalgae-based cosmetic products in the industry, clinical trials, and tests of the efficacy of cosmetic formulations using microalgae are vital (Bagatin and Miot 2013). While there is ample research demonstrating the benefits of microalgae in skincare, there is a need for more comprehensive clinical trials to validate these claims and establish the effectiveness of microalgae-based cosmetic products (Puchkova et al. 2020; Martínez-Ruiz et al. 2022; Santiesteban-Romero et al. 2022). In addition to the existing research on microalgae, further in-depth studies are required to understand the specific mechanisms of action of different microalgal species and their bioactive compounds on the skin. This deeper understanding can provide insights into how these compounds interact with skin cells and the potential long-term effects of using microalgae-based skincare products (Thiyagarasaiyar et al. 2020).

Table 3 presents a list of clinical effects recognised from testing of cosmetic products formulated with different microalgal species such as *Arthrospira* (*Spirulina*) *platensis* (Delsin et al. 2015; Silva et al. 2019; Jungclaus et al. 2023), and *Neochloris oleoabundans* (Morocho-Jácome et al. 2022). These studies displayed effective outcomes with no side effects reported. However, the studies had small sample sizes and were of short duration. Thus, there is an urgent need for increased and larger sample sizes to authenticate the safety and effectiveness of microalgae use in cosmetics. On the other hand, in vitro skin models have been progressively advanced and employed. The availability of the models introduced that can reproduce the key components of healthy and sick human skin will significantly aid in the design of novel cosmetic products (Cruz et al. 2023). Such models provide advantages of being affordable, accurate, fast, and simple to assess a product's efficacy, making a strong case for further research in developing this technology.

Exploring the synergistic effects of combining microalgae with other natural skincare ingredients can open new possibilities for formulating innovative and effective cosmetic products. By delving into the interactions between microalgae and other natural compounds, cosmetic researchers can create tailored formulations that address a wide range of skin concerns while minimising the use of synthetic chemicals. As the cosmetic industry continues to pivot towards sustainability and natural alternatives, investing in extensive clinical trials and research on microalgae holds the key to unlocking their full potential. Collaborations between cosmetic companies, research institutions, and regulatory bodies can shape the future of microalgae in cosmetics, paving the way for safe, efficacious, and sustainable skincare solutions.

Unlocking the potential: recent development of microalgal production and the market demand

Owing to their rapid growth, efficient space utilisation, low costs and wide range of possible applications, microalgae are consistently gaining traction in contemporary research agendas (Zhuang et al. 2022). Extraction of products from microalgal biomass is under constant development. As with all biotechnological processes, the optimisation of multiple parameters across solvent type, extraction period, solvent-to-biomass ratio and cell disruption method is carried out in order to maximize yield with minimized costs.

Solvent extraction, ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE) are some common examples of extraction methods currently available (Salinas-Salazar et al. 2019). The recent use of compressed fluids-based extraction techniques such as supercritical fluid extraction (SFE), pressurised liquid extraction (PLE), and gas-expanded liquids (GXL) have also been proposed to have exceptional potential in the recovery of natural bioactive compounds (Herrero 2023). By bridging the gap between the research laboratories and the market, such approaches can be used to generate accessible compounds based on natural bioactive substances that may be employed in cosmetic applications (Ariede et al. 2017; Guillerme et al. 2017; Amador-Luna et al. 2023).

Table 3 Past clinical efficacy studies on cosmetic products with microalgae formulation

Microalgae Species	Product (containing extract)	Cosmetic Purpose	Population Information	Tests Conducted	Test Duration	Findings	Reference
Spirulina platensis[1]	Gel-cream	Skin care and improvement	40 healthy females aged 18–39 (young group) and 40–65 (mature group)	- Skin hydration - Transepidermal water loss - Skin microrelief - Sebum content - Morphological and structure epidermal features	28 days	Improved epidermis structure and maintained skin hydrolipidic film balance	Delsin et al. 2015
	Cream	Molluscum Contagiosum (MC) treatment	31 Portuguese children aged below 16 years old with active MC lesions	- MC infection status (lesions) - Antibacterial effects	1–9 months (mean treatment is 3.9 months)	Demonstrated clearance of MC lesions	Jungclaus et al. 2023
Spirulina platensis[1] and *Ascophyllum nodosum*	Conditioner	Hair care	26 participants aged 18–35 years old with oily hair	- Tensile strength - Hair gloss analysis - Hair combing analysis	28 days	Improved hair mechanical properties and fibers surface	Silva et al. 2019
Neochloris oleoabundans	Gel	Skin care	14 health participants (5 males, 9 females) aged 31.5 ± 12.6 years with phototype II-IV skin	- Stratum corneum (SC) hydration - Transepidermal water loss (TEWL) - Anti-inflammatory activity	2 h	Demonstrated delayed erythema onset	Morocho-Jácome et al. 2022

[1]The current name for *Spirulina platensis* is *Arthrospira platensis*

Central to ongoing research is the refinement of cosmetic formulations with effective active ingredients. Familiar microalgal taxa including *Spirulina, Tetraselmis* sp.*, Dunaliella* sp.*,* and *Chlorella vulgaris*, are known to be excellent potential sources of anti-aging cosmetic substances with high levels of antioxidant activity. The stabilities and sensory characteristics of creams supplemented with the aforementioned microalgae were recently investigated (Dammak et al. 2022). To date, marketed aesthetic and personal care products with the incorporation of microalgae are largely focussed on haircare (shampoo and conditioner) and skin care (sunscreen, anti-aging creams, and emollients) sectors (Joshi et al. 2018; Silva et al. 2019; Gupta et al. 2023). Such extraction and utilisation of microalgae-derived compounds reflect a paradigm shift in the cosmetic industry toward embracing sustainable and eco-friendly ingredients.

Driven by growing demand, many companies directly manufacture and advertise cosmetic products with 'green' claims. However, a lack of regulation and false marketing information are barriers that could undermine consumer confidence in this developing industry. Consumers are known to be confused by the diverse standards and exaggerated marketing of green cosmetics (Lin et al. 2018). Media reports suggest that some cosmetic brands make only the claim of green credentials in the absence of adopting them in practice. A robust perception of green cosmetics depends on clear confirmation of key factors including the incorporated ingredients and the manufacturing process as well as packaging utilisation (Lin et al. 2018; Ma et al. 2018; Suphasomboon and Vassanadumrongdee 2022).

According to market research, brand trust is a highly significant element influencing buying (Suphasomboon and Vassanadumrongdee 2022). Thus, a product must be authenticated with established research competence and aligned sustainability (Pitaloka and Widiatami 2022). The commercialisation of microalgae for cosmetic use entails a complex process, from harvesting and biological identification to meeting regulatory standards, while the latter may also need creation and documentation. It is essential to adhere to strict guidelines to secure the safety and value of algal products for cosmetic implementations (Segal and Yang 2015; Vieira et al. 2020). As the industry continues to explore the potential of microalgae, the development of mild extraction procedures and the enhancement of market application processes are critical for harnessing the full potential of these valuable bioresources.

To make microalgae industrial utilisation economically sustainable various approaches have been made to overcome challenges associated with cost, operation, maintenance, and social barriers. Recent efforts have introduced the utilisation of continuous cultures, phycoprospecting, genetic modifications, and increased automation and computer control of cultures (Novoveská et al. 2023). Photobioreactors (PBR) are commonly used in cultivation, but recent review studies have proposed cultivation through high rate microalgal ponds (HRAPs), also known as open raceway ponds (ORPs) (Rafa et al. 2021; De Morais et al. 2023). Such cultivation systems were reviewed in the context of microalgal-based biodiesel production and wastewater treatment and have been shown to be cost-effective and require low energy to enhance biomass production (Show et al. 2017). Nevertheless, both cultivation methods have their limitations in different aspects (Novoveská et al. 2023).

To counter the limitations faced by both PBRs and ORPs, hybrid systems integrating both cultivation methods can maximize both algal biomass and lipid productivity (Rafa et al. 2021). Microalgae species including *H. pluvialis* (Huntley and Redalje 2007), *A. platensis* (Chernova and Kiseleva 2017), and *Tetraselmis* sp. (Narala et al. 2016) have been subjected to hybrid cultivation and displayed enhanced biomass production, high lipid productivity and lower risk of contamination. Alternatively, a techno-economic evaluation by Vázquez-Romero et al. (2022) has revealed that the production of biomass in a vertically stacked tubular PBR, combined with ultrafiltration (UF) and spray drying, was the most promising strategy to increase photosynthetic efficiency and reduce the production cost.

Incorporating microalgae in cosmetics formulations can be cost-effective in the long run, despite initial challenges in harvest, extraction, and production. While the initial cost of extracting bioactive compounds from microalgae may be higher than synthetic alternatives, the long-term sustainability and environmental benefits make it a compelling choice. Microalgae are highly renewable and can be cultivated in controlled environments, reducing the reliance on finite synthetic chemical feedstock. Additionally, the diverse range of bioactive compounds found in microalgae can offer multiple functionalities within the same raw material, potentially replacing the need for multiple synthetic ingredients. These multifaceted benefits of microalgae can contribute to streamlining the formulation process and reducing overall production costs.

It is important to note that the cost-effectiveness of incorporating microalgae in cosmetics formulations depends on various factors such as the scale of production, technological advancements in extraction methods, and market demand. As research and development in microalgae cultivation and extraction technologies continue to progress, the cost-effectiveness of utilising microalgae in cosmetics formulations is likely to improve, making it a more viable and sustainable option compared to synthetic products.

Figure 1 depicts the current challenges facing the industrial application of microalgae and their potential solutions. Solving these challenges requires a collaborative effort from researchers, industry stakeholders and policymakers. Ongoing research, technological innovation, and a commitment

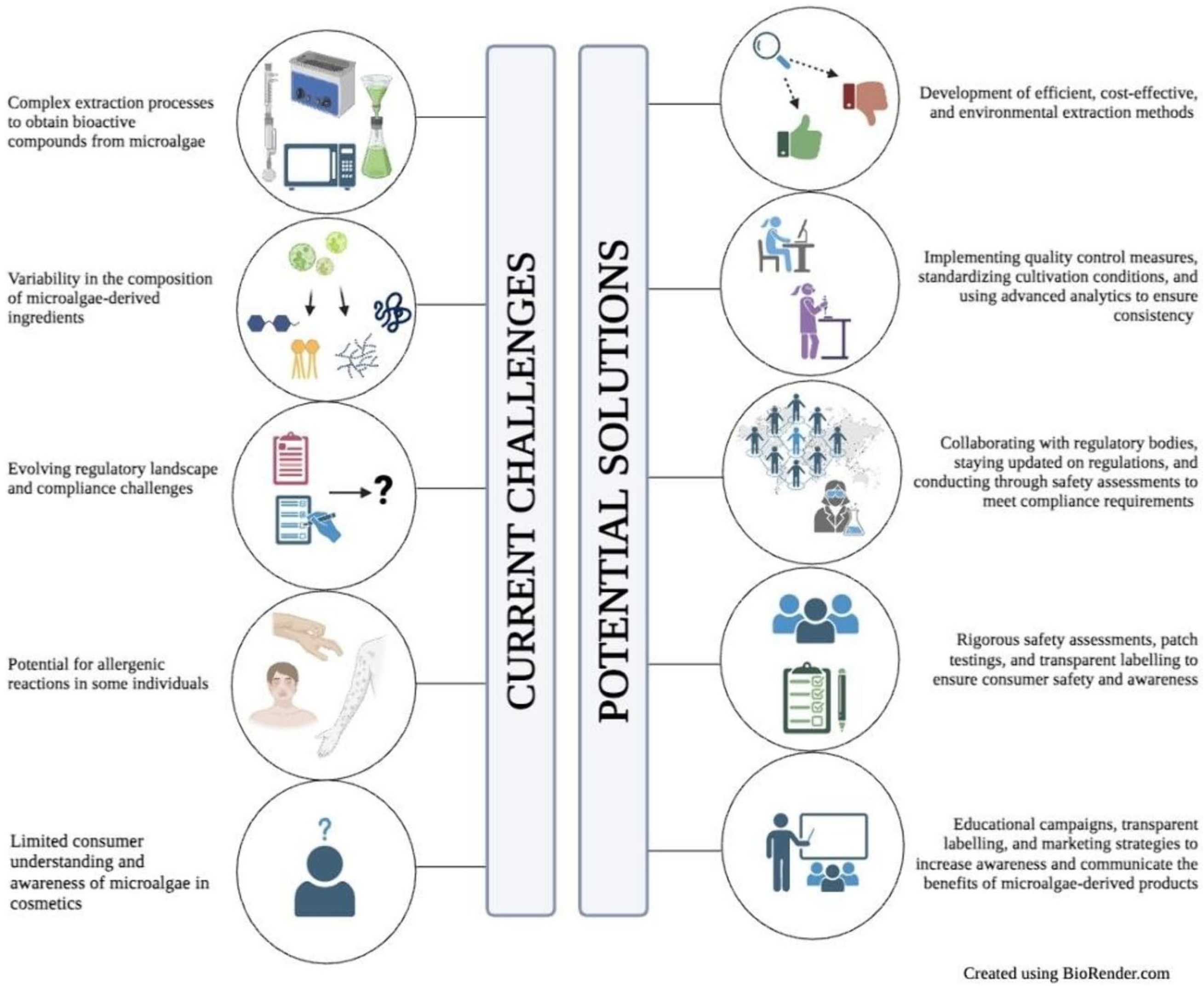

Fig. 1 Current challenges of microalgae in cosmeceuticals and the potential solutions

to sustainable practices are essential for unlocking the full potential of microalgae in cosmetics. As the industry continues to develop, overcoming these challenges will contribute to the widespread adoption of microalgae-derived ingredients, offering sustainable and effective solutions in the beauty and skincare market.

Conclusion and future direction

The use of microalgae in sustainable beauty and cosmetics products represents a promising and evolving field. As the industry, as well as wider society, embraces a more sustainable and eco-conscious approach, microalgae offer a renewable resource with diverse applications in skincare. The unique properties of microalgae products, including their antioxidant, moisturizing, and anti-aging benefits, align well with the growing demand for natural and effective cosmetic products. However, despite their great potential, at present the development and use of extensive clinical trials, efficacy validation, and effective extraction techniques are inadequate. Compounding this, the availability of robust reports on the safety and efficacy of currently widely used traditional topical drugs are generally limited and out of date. Therefore, future studies should address such aspects concerning the continuous pavement for integrating microalgae into cosmetic formulations.

The contemporary emphasis on the use of microalgal products in the cosmetic industry embodies a progressive shift towards natural and sustainable solutions. This creates exciting opportunities for developing eco-friendly products that prioritise environmental conservation and human well-being. As research continues to unravel the largely untapped potential of microalgae, the cosmetic industry is poised for revealing new opportunities towards embracing these bioresources.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1007/s10811-024-03345-4.

Acknowledgements This work was supported by Taylor's University through its TAYLOR'S RESEARCH SCHOLARSHIP Programme.

Author Contribution H.J.Y.L. and M.L.T. designed the outline of the review paper. H.J.Y.L. conducted the literature review and compiled the initial draft. M.L.T., J.B. and P.C. critically revised the manuscript for important intellectual content. All authors read and approved the final manuscript.

Funding This research was supported by the Ministry of Higher Education (MOHE) Malaysia through the Fundamental Research Grant Scheme (FRGS/1/2023/STG01/TAYLOR/02/1).

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

References

Agustina S, Aidha NN, Oktarina E, Setiawati I (2020) Antioxidant activity of *Porphyridium cruentum* water extracts for cosmetic cream. IOP Conf Ser: J Mat Sci Eng 980:012042

Ah Y, Hwang S, Jun K, Choi SA, Yu YM, Kim E, Kim DY, Shin WG, Lee J (2019) Real-world safety evaluation of topical corticosteroid use: A community pharmacy-based, prospective, observational study. Bas Clin Pharmacol Toxicol 125:405–413

Alghamdi WA, Khalifah NA, Alshammari H, Althamin FA, Althamin BA, Alsultan HH (2021) The misuse of topical creams among females in Saudi Arabia 2020. Discov Sci Soc 25:2203–2212

Amador-Luna VM, Montero L, Herrero M (2023) Compressed fluids for the extraction of bioactive compounds from plants, food by-products, seaweeds and microalgae – an update from 2019 to 2023. Trends Anl Chem 169

Amberg N, Fogarassy C (2019) Green consumer behavior in the cosmetics market. Resour 8:137

Araújo RG, Alcantar-Rivera B, Meléndez-Sánchez ER, Martínez-Prad MA, Sosa-Hernández JE, Iqbal HMN, Parra-Saldivar R, Martínez-Ruiz M (2022) Effects of UV and UV-vis irradiation on the production of microalgae and macroalgae: New alternatives to produce photobioprotectors and biomedical compounds. J Mol 27:5334

Ariede MB, Candido TM, Jacome ALM, Velasco MVR, De Carvalho JCM, Baby AR (2017) Cosmetic attributes of algae – A review. Algal Res 25:483–487

Ariede MB, Morocho-Jácome AL, Candido TM, Lourenço FR, Kato ETM, Lima FV, Rosado C, Velasco MVR, Carvalho JCM, Baby AR (2020) Is the *Botrycoccus braunii* dry biomass an adjuvant for anti-UVB topical formulations? Sci Pharm 88:22

Aslam A, Bahadar A, Liaquat R, Saleem M, Waqas A, Zwawi M (2021) Algae as an attractive source for cosmetics to counter environmental stress. Sci Total Environ 772:144905

Bagatin E, Miot HA (2013) How to design and write a clinical research protocol in cosmetic dermatology. Ann Bras Dermatol 88:69–75

Baliña LM, Graupe K (1991) The treatment of melasma 20% azelaic acid versus 4% hydroquinone cream. Int J Dermatol 30:893–895

Bandyopadhyay D (2009) Topical treatment of melasma. Indian J Paediatr Dermatol 54:303

Bhattar P, Zawar V, Godse K.gPatil, S, Nadkarni N and Gautam M, (2015) Exogenous ochronosis. Indian J Paediatr Dermatol 60:537

Burnett CL, Bergfeld WF, Belsito DV, Hill RA, Klaassen CD, Liebler DC, Marks JG, Shank RC, Slaga TJ, Snyder PW, Andersen FA (2010) Final report of the safety assessment of kojic acid as used in cosmetics. Int J Toxicol 29:244S-273S

Campiche R, Sandau P, Kurth E, Massironi M, Imfeld D, Schuetz R (2018) Protective effects of an extract of the freshwater microalga *Scenedesmus rubescens* on UV-irradiated skin cells. Int J Cosmet Sci 40:187–192

Cao L, Lee SG, Lim KT, Kim HR (2020) Potential anti-aging substances derived from seaweeds. Mar Drugs 18:564

Cecil T, Jorman AHR, Leenin FR, Anthony RS, Jessie V (2022) Effects of ultraviolet radiation on production of photoprotective compounds in microalgae of the genus *Pediastrum* from high Andean areas of Peru. J Appl Pharm Sci 12:3

Chernova NI, Kiseleva SV (2017) Microalgae biofuels: Induction of lipid synthesis for biodiesel production and biomass residues into hydrogen conversion. Int J Hydrogen Energy 42:2861–2867

Choo WT, Teoh ML, Phang SM, Convey P, Yap WH, Goh BH, Beardall J (2020) Microalgae as potential anti-inflammatory natural product against human inflammatory skin diseases. Front Pharmacol 11:1086

Cosmeceuticals Market Size, Share & Growth Analysis [2030] (2023) Market Research Report FBI102521; p. 132. https://www.fortunebusinessinsights.com/cosmeceuticals-market-102521. Accessed 30 May 2024

Cruz AM, Gonçalves MC, Marques MS, Veiga F, Paiva-Santos AC, Pires PC (2023) *In vitro* models for anti-aging efficacy assessment: A critical update in dermocosmetic research. J Cosmet Sci 10:66

Dammak M, Ben Hlima H, Smaoui S, Fendri I, Michaud P, Ayadi MA, Abdelkafi S (2022) Conception of an environmental friendly O/W cosmetic emulsion from microalgae. Environ Sci Pollut Res 29:73896–73909

De Morais EG, Sampaio ICF, Gonzalez-Flo E, Ferrer I, Uggetti E, García J (2023) Microalgae harvesting for wastewater treatment and resources recovery: A review. New Biotechnol 78:84–94

Delsin SD, Mercurio DG, Fossa Mm, Maia C (2015) Clinical efficacy of dermocosmetic formulations containing *Spirulina* extract on young and mature skin: effects on the skin hydrolipidic barrier and structural properties. J Clin Pharmacol Biopharm 4:144

Dianursanti, Prakasa MB, Nugroho P (2020) The effect of adding microalgae extract *Spirulina platensis* containing flavonoid in the formation of sunscreen towards cream stability and SPF values. AIP Conf Proc 2255:040022

Dionisio-Sese ML (2010) Aquatic microalgae as potential source of UV-screening compounds. Philipp J Sci 139:5–16

Falcao B, Vishwakarma J, Jadav H, Vavilala S (2020) In vitro evaluation of the antioxidant and anti-skin aging properties of green algal sulfated polysaccharides. Arch Microbiol Immunol 4:75–90

Favas R, Morone J, Martins R, Vasconcelos V, Lopes G (2021) Cyanobacteria and microalgae bioactive compounds in skin-ageing: Potential to restore extracellular matrix filling and overcome hyperpigmentation. J Enzyme Inhib Med Chem 36:1829–1838

Fitton A, Goa KL (1991) Azelaic acid: A review of its pharmacological properties and therapeutic efficacy in acne and hyperpigmentary skin disorders. Drugs 41:780–798

Gandhi V, Verma P, Naik G (2012) Exogenous ochronosis after prolonged use of topical hydroquinone (2%) in a 50-year-old Indian female. Indian J Dermatol 57:394

Gasparian S, Geng X, Hawy E (2021) Intracranial hypertension associated with topical tretinoin use. Am J Ophthalmol Case Rep 23:101130

Georgakis ND, Ioannou E, Chatzikonstantinou M, Merino M, Chronopoulou EG, Mullor JL, Madesis P, Labrou NE (2023) The cosmeceutical potential of the yellow-green alga *Trachydiscus minutus* aqueous extract: Preparation of a natural-based dermal formula as a proof of concept. J Cosmet Sci 10:75

Girolomoni L, Bellamoli F, Valbuena GC, Perozeni F, D'Andrea C, Cerullo G, Cazzaniga S, Ballottari M (2020) Evolutionary divergence of photoprotection in the green algal lineage: A plant-like violaxanthin de-epoxidase enzyme activates the xanthophyll cycle in the green alga *Chlorella vulgaris* modulating photoprotection. New Phytol 228:136–150

Gkioni MD, Andriopoulos V, Koutra E, Hatziantoniou S, Kornaros M, Lamari FN (2022) Ultrasound-Assisted extraction of *Nannochloropsis oculata* with ethanol and betaine: 1,2-Propanediol eutectic solvent for antioxidant pigment-rich extracts retaining nutritious the residual biomass. Antioxidants 11:1103

Glazer A, Sofen BD, Gallo ES (2016) Nail discoloration after use of hydroquinone. JAAD Case Reports 2:57–58

Grobel H, Murphy SA (2018) Acne vulgaris and acne rosacea. In: Rakel D (ed) Integrative Medicine, 4th edn. Elsevier, Amstedam, pp 759–770

Guillerme JB, Couteau C, Coiffard L (2017) Applications of marine resources in cosmetics. J Cosmet Sci 4:35

Gupta A, Singh AP, Singh VK, Singh PR, Jaiswal J, Kumari N, Upadhye V, Singh SC, Sinha RP (2023) Natural sun-screening compounds and DNA-repair enzymes: Photoprotection and photoaging. J Catal 13:745

Hadi AM, Dianursanti (2021) Essence formulation using extract from microalgae *Spirulina* sp. as anti-aging and anti-inflammatory using variance of solvent and sonication time. AIP Conf Proc 2344:020017.

Hatziantoniou S, Kapetanstratakis IS, Drakoulis N (2024) Cosmetics and personal care products. In: Wexler P (ed) Encyclopedia of Toxicology, vol 3, 4th edn. Elsevier, Amsterdam, pp 259–270

Havas F, Krispin S, Cohen M, Loing E, Farge M, Suere T, Attia-Vigneau J (2022) A *Dunaliella salina* extract counteracts skin aging under intense solar irradiation thanks to its antiglycation and anti-inflammatory properties. Mar Drugs 20:104

Herrero M (2024) Towards green extraction of bioactive natural compounds. Anal Bioanal Chem 416:2039–2047

Huntley ME, Redalje DG (2007) CO_2 Mitigation and renewable oil from photosynthetic microbes: A new appraisal. Mitig Adapt Strateg Glob Chang 12:573–608

Ji K, Kim Y, Kim YT (2021) A study on the tyrosinase inhibitory and antioxidant effect of microalgae extracts. Microbiol Biotechnol Lett 49:167–173

Jo WS, Yang KM, Park HS, Kim GY, Nam BH, Jeong MH, Choi YJ (2012) Effect of microalgal extracts of *Tetraselmis suecica* against UVB-induced photoaging in human skin fibroblasts. Toxicol Res 28:241–248

Joshi S, Kumari R, Upasani VN (2018) Application of algae in cosmetics: An overview. Int J Innov Res Sci Eng Technol 7:1269–1278

Juliano CCA (2022) Spreading of dangerous skin-lightening products as a result of colourism: A review. Appl Sci 12:3177

Jungclaus K, Mascarenhas R, Tellechea O, Reich JLK, Reich K (2023) Open-label observational study of a topical formulation of calcium spirulan contained in a defined extract of the microalga *Spirulina platensis* in the treatment of children with molluscum contagiosum. J Dermatol Res Pract 2023:8871299

Khamanarong Y, Laohasiriwong W, Sakphisutthikul C (2021) Misuse of topical creams aimed at preventing melasma and freckles among working women. J Southwest Jiaotong Univ 56:126–136

Kim H, Jung JH, Kim JY, Heo J, Cho D, Kim H, An S, An I, Bae S (2019) The protective effect of violaxanthin from *Nannochloropsis oceanica* against ultraviolet B-induced damage in normal human dermal fibroblasts. J Photochem Photobiol 95:595–604

Kim SY, Kwon YM, Kim KW, Kim JYH (2021) Exploring the potential of *Nannochloropsis* sp. extract for cosmeceutical applications. Mar Drugs 19:690

King S, Campbell J, Rowe R, Daly M, Moncrieff G, Maybury C (2023) A systematic review to evaluate the efficacy of azelaic acid in the management of acne, rosacea, melasma and skin aging. J Cosmet Dermatol 22:2650–2662

Kolackova M, Janova A, Dobesova M, Zvalova M, Chaloupsky P, Krystofova O, Adam V, Huska D (2023) Role of secondary metabolites in distressed microalgae. Environ Res 224:115392

Kose A (2023) Chemical composition and tyrosinase inhibitory activities of fatty acids obtained from heterotrophic microalgae, *S. limacinum* and *C. cohnii*. Appl Biochem Biotechnol 195:369–385

Koutsianas N, Letsiou S, Gardikis K, Dragani P (2017) A combination of a *Nannochloropsis gaditana* extract and a propolis extract as active component in cosmetic formulations for dermal use. International Patent Application WO2017216588A1

Ladizinski B, Mistry N, Kundu RV (2011) Widespread use of toxic skin lightening compounds: Medical and psychosocial aspects. Dermatol Clin 29:111–123

Lee JJ, An S, Kim KB, Heo J, Cho DH, Oh HM, Kim HS, Bae S (2016) Extract of *Ettlia* sp. YC001 exerts photoprotective effects against UVB irradiation in normal human dermal fibroblasts. J Microbiol Biotechnol 26:775–783

Letsiou S, Kalliampakou K, Gardikis K, Mantecon L, Infante C, Chatzikonstantinou M, Labrou NE, Flemetakis E (2017) Skin protective effects of *Nannochloropsis gaditana* extract on H_2O_2-stressed human dermal fibroblasts. Front Mar Sci 4:221

Li X, Matsumoto T, Takuwa M, Saeed ESAM, Hirabashi T, Kondo H, Fujino H (2020) Protective effects of astaxanthin supplementation against ultraviolet-induced photoaging in hairless mice. J Biomed 8:18

Lin Y, Yang S, Hanifah H, Iqbal Q (2018) An exploratory study of consumer attitudes toward green cosmetics in the UK market. Admin Sci 8:71

Liu JK (2022) Natural products in cosmetics. Nat Prod Bioprospect 12:40

Liu RH, Smith MK, Basta SA, Farmer ER (2006) Azelaic acid in the treatment of papulopusutular rosacea. Arch Dermatol 142:1052

López-Hortas L, Flórez-Fernández N, Torres MD, Ferreira-Anta T, Casas MP, Balboa EM, Falqué E, Domínguez H (2021) Applying seaweed compounds in cosmetics, cosmeceuticals and nutricosmetics. Mar Drugs 19:552

Ma G, Rau PLP, Guo Z (2018) The effects of environmental awareness and consumption value on green makeup product purchase intentions. J Psychol 09:1898–1916

Mann RJ, Harman RRM (1983) Nail staining due to hydroquinone skin-lightening creams. Brit J Dermatol 108:363–365

Martínez-Ruiz M, Martínez-González CA, Kim DH, Santiesteban-Romero B, Reyes-Pardo H, Villaseñor-Zepeda KR, Meléndez-Sánchez ER, Ramírez-Gamboa D, Díaz-Zamorano AL, Sosa-Hernández JE, Coronado-Apodaca KG, Gámez-Méndez AM, Iqbal HMN, Parra-Saldivar R (2022) Microalgae bioactive compounds to topical applications products—A review. J Mol 27:3512

Masum NM, Yamauchi K, Mitsunaga T (2019) Tyrosinase inhibitors from natural and synthetic sources as skin-lightening agents. Rev Agric Sci 7:41–58

Mathe N, Balogun M, Yoo J (2021) A case report on the use of topical cysteamine 5% cream in the management of refractory post inflammatory hyperpigmentation (PIH) resistant to triple combination cream (hydroquinone, topical corticosteroids, and retinoids). J Cosmet Dermatol 20:204–206

Matsui M, Tanaka K, Higashiguchi N, Okawa H, Yamada Y, Tanaka K, Taira S, Aoyama T, Takanishi M, Natsume C, Takakura Y, Fujita N, Hashimoto T, Fujita T (2016) Protective and therapeutic effects of fucoxanthin against sunburn caused by UV irradiation. J Pharmacol Sci 132:55–64

Meena S, Gupta L, Khare A, Balai M, Mittal A, Mehta S, Bhatri G (2017) Topical corticosteroids abuse: A clinical study of cutaneous adverse effects. Indian J Dermatol 62:567

Montuori E, Saggiomo M, Lauritano C (2023) Microalgae from cold environments and their possible biotechnological applications. Mar Drugs 21:292

Moolla S, Miller-Monthrope Y (2022) Dermatology: How to manage facial hyperpigmentation in skin of colour. J Drugs Context 11:2021-11-2

Morocho-Jácome AL, Santos BBD, Carvalho JCMD, Almeida TSD, Rijo P, Velasco MVR, Rosado C, Baby AR (2022) Microalgae as a sustainable, natural-oriented and vegan dermocosmetic bioactive ingredient: The case of *Neochloris oleoabundans*. Cosmetics 9:9

Mourelle M, Gómez C, Legido J (2017) The potential use of marine microalgae and cyanobacteria in cosmetics and thalassotherapy. Cosmetics 4:46

Narala RR, Garg S, Sharma KK, Thomas-Hall SR, Deme M, Li Y, Schenk PM (2016) Comparison of microalgae cultivation in photobioreactor, open raceway pond, and a two-stage hybrid system. Front Energy Res 4:00029

Nethravathy MU, Mehar JG, Mudliar SN, Shekh AY (2019) Recent advances in microalgal bioactives for food, feed, and healthcare products: Commercial potential, market space, and sustainability. Compr Rev Food Sci Saf 18:1882–1897

Nordlund J, Grimes P, Ortonne J (2006) The safety of hydroquinone. J Eur Acad Dermatol Venereol 20:781–787

Noviendri D, Hasrini RF, Subaryono ME (2022) Biopigments (phycoerythrin, fucoxanthin and siphonaxanthin) from seaweeds and their potential applications as ingredients in cosmeceutical industries: A review. IOP Conf Ser: Environ Earth Sci 1118:012028

Novoveská L, Nielsen SL, Eroldoğan OT, Haznedaroglu BZ, Rinkevich B, Fazi S, Robbens J, Vasquez M, Einarsson H (2023) Overview and challenges of large-scale cultivation of photosynthetic microalgae and cyanobacteria. Mar Drugs 21:445

Núñez-Pons L, Avila C, Romano G, Verde C, Giordano D (2018) UV-protective compounds in marine organisms from the Southern Ocean. Mar Drugs 16:336

Segal M, Yang JC (2015) Issues in the risk assessment of the use of microalgae for production purposes. Biosafety and the Environmental Uses of Micro-Organisms. Conference Proceedings. OECD Publishing, Paris, pp 93–99

Owolabi JO, Fabiyi OS, Adelakin LA, Ekwerike MC (2020) Effects of skin lightening cream agents – Hydroquinone and kojic acid, on the skin of adult female experimental rats. Clin Cosmet Investig Dermatol 13:283–289

Ozluer SM, Muir J (2000) Nail staining from hydroquinone cream. Aust J Dermatol 41:255–256

Parlak AH, Aydoğan İ, Kavak A (2003) Discolouration of the fingernails from using hydroquinone skin-lightening cream. J Cosmet Dermatol 2:199–201

Pazik A, Gagala U (2023) Patent trends in cosmetics industry for 2024. JWP Group. https://www.jwp-poland.com/patent-trends-in-cosmetics-industry-for-2024/

Phasha V, Senabe J, Ndzotoyi P, Okole B, Fouche G, Chuturgoo A (2022) Review on the use of kojic acid—A skin-lightening ingredient. J Cosmet Sci 9:64

Pillaiyar T, Manickam M, Namasivayam V (2017) Skin whitening agents: Medicinal chemistry perspective of tyrosinase inhibitors. J Enzyme Inhib Med Chem 32:403–425

Pitaloka LK, Widiatami AK (2022) Climate change issue and consumer behavior in purchasing beauty product. IOP Conf Ser: Environ Earth Sci 1098:012030

Puchkova T, Khapchaeva S, Zotov V, Lukyanov A, Solovchenko A (2021) Marine and freswater microalgae as a sustainable source of cosmeceuticals. Mar Biol J 6:67–81

Pudaruth S, Juwaheer TD, Seewoo YD (2015) Gender-based differences in understanding the purchasing patterns of eco-friendly cosmetics and beauty care products in Mauritius: A study of female customers. J Soc Responsib 11:179–198

Rafa N, Ahmed SF, Badruddin IA, Mofijur M, Kamangar S (2021) Strategies to produce cost-effective third-generation biofuel from microalgae. Front Energy Res 9:749968

Ragusa I, Nardone GN, Zanatta S, Bertin W, Amadio E (2021) *Spirulina* for skin care: A bright blue future. J Cosmet Sci 8:7

Rahman NA, Katayama T, Wahid MEA, Kasan NA, Khatoon H, Yamada Y, Takahashi K (2020) Taxon- and growth phase-specific antioxidant production by chlorophyte, bacillariophyte, and haptophyte strains isolated from tropical waters. Front Bioeng Biotechnol 8:581628

Rao AR, Sindhuja HN, Dharmesh SM, Sankar KU, Sarada R, Ravishankar GA (2013) Effective inhibition of skin cancer, tyrosinase, and antioxidative properties by astaxanthin and astaxanthin esters from the green alga *Haematococcus pluvialis*. J Agric Food Chem 61:3842–3851

Rincón-Valencia S, Mejía-Giraldo JC, Puertas-Mejía MÁ (2022) Algae metabolites as an alternative in prevention and treatment of skin problems associated with solar radiation and conventional photoprotection. Braz J Pharm Sci 58:201046

Ručová D, Vilková M, Sovová S, Vargová Z, Kostecká Z, Frenák R, Routray D, Bačkor M (2023) Photoprotective and antioxidant properties of scytonemin isolated from Antarctic cyanobacterium *Nostoc commune* Vaucher ex Bornet & Flahault and its potential as sunscreen ingredient. J Appl Phycol 35:2839–2850

Saeedi M, Eslamifar M, Khezri K (2019) Kojic acid applications in cosmetic and pharmaceutical preparations. Biomed Pharmacother 110:582–593

Sahin SC (2018) The potential of *Arthrospira platensis* extract as a tyrosinase inhibitor for pharmaceutical or cosmetic applications. S Afr J Bot 119:236–243

Saide A, Martínez KA, Ianora A, Lauritano C (2021) Unlocking the health potential of microalgae as sustainable sources of bioactive compounds. Int J Mol Sci 22:4383

Salinas-Salazar C, Saul Garcia-Perez J, Chandra R, Castillo-Zacarias C, Iqbal HMN, Parra-Saldívar R (2019) Methods for extraction of valuable products from microalgae biomass. In: Alam MA, Wang Z (eds) Microalgae biotechnology for development of biofuel and wastewater treatment. Springer, Singapore, pp 245–263

Sano T, Kaya K (1996) Oscillapeptin G, a Tyrosinase inhibitor from toxic *Oscillatoria agardhii*. J Nat Prod 59:90–92

Santiesteban-Romero B, Martínez-Ruiz M, Sosa-Hernández JE, Parra-Saldívar R, Iqbal HMN (2022) Microalgae photo-protectants and related bio-carriers loaded with bioactive entities for skin applications—An insight of microalgae biotechnology. Mar Drugs 20:487

Sato K, Hiraga Y, Yamaguchi Y, Sakaki S, Takenaka H (2023) Anti-melanogenic and anti-oxidative effects of *Nostoc verrucosum* (ashitsuki) extracts. J Cosmet Sci 10:30

Sato K, Yamaguchi Y, Sakaki S, Takenaka H (2019) *Pleurochrysis carterae* hot-water extract inhibits melanogenesis in murine melanoma cells. J Cosmet Sci 6:60

Sedjati S, Pringgenies D, Fajri M (2020) Determination of the pigment content and antioxidant activity of the marine microalga *Tetraselmis suecica*. Jordan J Biol 13:55–58

Selcen D, Seidman S, Nigro MA (2000) Otocerebral anomalies associated with topical tretinoin use. Brain Develop 22:218–220

Shakeel S, Nesar S, Iffat W, Rehman H, Aziz S, Mumtaz T, Hadi H, Jamshed S (2021) Pharmacists' insights and behaviors in preventing the misuse of topical corticosteroids in Pakistan: A mixed-method study. J Cosmet Sci 8:72

Shapiro S, Heremans A, Mays DA, Martin AL, Hernandez-Medina M, Lanes S (2011) Use of topical tretinoin and the development of noncutaneous adverse events: Evidence from a systematic review of the literature. J Am Acad Dermatol 65:1194–1201

Sheibani Madrahi G, Naeimpoor F (2023) Effect of synchronized abiotic stressors and UV on scytonemin synthesis by marine cyanobacterium *Leptolynbya mycodia* in sequential two-stage cultivation. J Appl Phycol 35:43–56

Shih MF, Cherng JY (2012) Protective effects of *Chlorella*-Derived Peptide Against UVC-Induced cytotoxicity through inhibition of caspase-3 activity and reduction of the expression of phosphorylated FADD and cleaved PARP-1 in skin fibroblasts. J Mol 17:9116–9128

Show P, Tang M, Nagarajan D, Ling T, Ooi CW, Chang JS (2017) A holistic approach to managing microalgae for biofuel applications. Int J Mol Sci 18:215

Silva LN, Leite MGA, Maia Campos PMBG (2019) Development of hair care formulations containing *Spirulina platensis* and *Ascophyllum nodosum* extracts. Int J Phytocos Nat Ingred 6:13

Sinha A, Kar S, Yadav N, Madke B (2016) Prevalence of topical steroid misuse among rural masses. Indian J Dermatol 61:119

Sitohang IBS, Makes WI, Sandora N, Suryanegara J (2022) Topical tretinoin for treating photoaging: A systematic review of randomized controlled trials. Int J Women's Dermatol 8:003

Suphasomboon T, Vassanadumrongdee S (2022) Toward sustainable consumption of green cosmetics and personal care products: The role of perceived value and ethical concern. Sustain Prod Consum 33:230–243

Tarasuntisuk S, Patipong T, Hibino T, Waditee-Sirisattha R, Kageyama H (2018) Inhibitory effects of mycosporine-2-glycine isolated from a halotolerant cyanobacterium on protein glycation and collagenase activity. Lett Appl Microbiol 67:314–320

Tavares RSN, Kawakami CM, Pereira KDC, Do Amaral GT, Benevenuto CG, Maria-Engler SS, Colepicolo P, Debonsi HM, Gaspar LR (2020) Fucoxanthin for topical administration, a phototoxic vs. photoprotective potential in a tiered strategy assessed by in vitro methods. Antioxidants 9:328

Teoh ML, Chu WL, Marchant H, Phang SM (2004) Influence of culture temperature on the growth, biochemical composition and fatty acid profiles of six Antarctic microalgae. J Appl Phycol 16:421–430

Teoh ML, Sanusi NS, Wong CY, Beardall J (2020) Effects of the sunscreen ultraviolet filter, oxybenzone, on green microalgae. Adv Polar Sci 31:112–123

Thiyagarasaiyar K, Goh BH, Jeon YJ, Yow YY (2020) Algae metabolites in cosmeceutical: An overview of current applications and challenges. Mar Drugs 18:323

Udayan A, Pandey AK, Sirohi R, Sreekumar N, Sang BI, Sim SJ, Kim SH, Pandey A (2023) Production of microalgae with high lipid content and their potential as sources of nutraceuticals. Phytochem Rev 22:833–860

Vázquez-Romero B, Perales JA, Pereira H, Barbosa M, Ruiz J (2022) Techno-economic assessment of microalgae production, harvesting and drying for food, feed, cosmetics, and agriculture. Sci Total Environ 837:155742

Vieira MV, Pastrana LM, Fuciños P (2020) Microalgae encapsulation systems for food, pharmaceutical and cosmetics applications. Mar Drugs 18:644

Wang N, Pei H, Xiang W, Li T, Lin S, Wu J, Chen Z, Wu H, Li C, Wu H (2023) Rapid screening of microalgae as potential sources of natural antioxidants. Foods 12:2652

Wong CY, Teoh ML, Phang SM, Chu WL (2011) Effect of ultraviolet radiation (UVR) on the tropical microalga *Chlorella vulgaris*. Malaysian J Sci 30:3–15

Yamaguchi Y, Koketsu M (2016) Isolation and analysis of polysaccharide showing high hyaluronidase inhibitory activity in *Nostochopsis lobatus* MAC0804NAN. J Biosci Bioeng 121:345–348

Yap JK, Sankaran R, Chew KW, Halimatul Munawaroh HS, Ho SH, Rajesh Banu J, Show PL (2021) Advancement of green technologies: A comprehensive review on the potential application of microalgae biomass. Chemosphere 281:130886

Yarkent Ç, Gürlek C, Oncel SS (2020) Potential of microalgal compounds in trending natural cosmetics: A review. Sustain Chem Pharm 17:100304

Zainoddin HAH, Omar EA, Kamal NNSNM, Omar WAW (2020) The role of *Nannochloropsis sp.* methanolic extract in reducing hydrogen peroxide-induced DNA damage in L929 cell line. Pertanika J Trop Agric Sci 43:81–90

Zaytseva A, Chekanov K, Zaytsev P, Bakhareva D, Gorelova O, Kochkin D, Lobakova E (2021) Sunscreen effect exerted by secondary carotenoids and mycosporine-like amino acids in the aeroterrestrial chlorophyte *Coelastrella rubescens* under high light and UV-A irradiation. Plants 10:2601

Zhang R, Chen J, Mao X, Qi P, Zhang X (2019) Anti-inflammatory and anti-aging evaluation of pigment–protein complex extracted from *Chlorella pyrenoidosa*. Mar Drugs 17:586

Zhuang D, He N, Khoo KS, Ng EP, Chew KW, Ling TC (2022) Application progress of bioactive compounds in microalgae on pharmaceutical and cosmetics. Chemosphere 291:132932