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OBM Geriatrics

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Review

Rejuvenating the Skin: The Role of Macro and Microalgae in Preventing Aging

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Academic Editor: Taihao Quan

Special Issue: Aging of the Human Skin and Its Prevention

OBM Geriatrics
2025, volume 9, issue 2
doi:10.21926/obm.geriatr.2502308

Received: January 26, 2025
Accepted: April 13, 2025
Published: April 17, 2025

Abstract

The increasing consumer demand for cosmetic products has led to the widespread use of synthetic substances, which are inexpensive and readily available but can sometimes harm the skin and body. Examples include hydroxybenzoic acid esters (parabens) and phthalates, which are considered endocrine disruptors, and synthetic fragrances that may cause irritation or allergies. Consequently, there has been a shift in consumer preferences towards natural cosmetic products. In response to this demand and the expanding market for skincare products, the search for natural ingredients as alternatives to synthetic ones has intensified. Algae-derived compounds have emerged as promising candidates due to their photoprotective properties and diverse biological activities, including UV absorption, antioxidant effects, matrix metalloproteinase inhibition, anti-aging, and immunomodulatory properties. These substances, which include phenolic compounds ranging from simple molecules to highly polymerized forms, offer significant skin benefits. Marine algal products, with their antioxidants, sunscreen, thickening, and moisturizing properties, can effectively enhance skin protection against various forms of damage. The main groups of macro and microalgae, such as Chlorophyta (green algae), Heterokontophyta (brown algae), Rhodophyta (red algae), Cyanobacteria (blue-green algae), Bacillariophyceae (diatoms), and Haptista (coccolithophores), all possess beneficial properties for use in cosmetics.

Keywords

Algae; cosmetics; anti-aging; anti-wrinkling; skin whitening; moisturizing agent; antioxidants

1. Introduction

The high consumer demand for cosmetic products has led to the incorporation of numerous synthetic substances, which are easy and cheap to obtain but sometimes cause harm to the skin and the body. Some examples are hydroxybenzoic acid esters (parabens) or phthalates, which are questioned for being considered endocrine disruptors, or synthetic fragrances, which can cause irritation or allergies [1]. As a result, people have changed their preferences and opted for natural cosmetic products. In this context, and with a constantly expanding market for skin care products, the ongoing search for natural ingredients as alternatives to synthetic ones is necessary. This has led to the development of natural cosmetic formulas that meet this demand, and algae-derived compounds can play a significant role.

Algae-derived photoprotective substances offer a safer alternative, exhibiting a wide range of biological activities such as UV absorption, antioxidant effects, matrix metalloproteinase (MMPs) inhibition, anti-aging, and immunomodulatory properties. Structurally, these substances include phenolic compounds, which range from simple phenolic molecules to highly polymerized forms known for their skin benefits [2]. Due to their antioxidant, sunscreen, thickening, and moisturizing properties, marine algal products can be effective alternatives in cosmetics, enhancing skin protection against abrasions, tanning, and other forms of damage [3]. Macro and microalgae include the following main groups, all of which possess beneficial properties for use in cosmetics: Chlorophyta (green algae), Ochrophyta (including Phaeophyceae, i.e., brown algae), Rhodophyta (red algae), Cyanophyta (blue-green algae), Bacillariophyta (diatoms), Haptista (e.g., coccolithophores) [4].

2. Mechanisms of Skin Aging

Over the last two decades, concern about population aging has given rise to numerous plans, mainly sponsored by the World Health Organization (WHO), which promotes the decade of healthy aging "to improve the lives of older people, their families, and the communities in which they live" (UN Decade of Healthy Aging, https://www.who.int/initiatives/decade-of-healthy-ageing). This has led to a number of investigations, both to investigate the mechanisms of aging and to propose measures to prevent some of the associated diseases, such as cancer.

Skin aging is a multisystem degenerative process involving the skin and the skin support system. The changes occur gradually and can be observed on the skin's surface (duller microrelief, thinner epidermis, certain skin dryness, more visible pores, small actinic keratoses, vascularization alterations, and uneven pigmentation). This results in the presence of wrinkles, fine lines, dark spots, tissue ptosis, loss of elasticity, and, in certain areas, unwanted hair growth [5].

2.1 Theories and Causes of Aging

López-Otín et al. [6, 7] identified and categorized the cellular and molecular hallmarks of aging. The following twelve hallmarks of aging were identified: genomic instability, telomere attrition, epigenetic alterations, loss of proteostasis, disabled macroautophagy, deregulated nutrient-sensing, mitochondrial dysfunction, cellular senescence, stem cell exhaustion, altered intercellular communication, chronic inflammation, and dysbiosis. From them, the causes of aging can be summarized, and the various theories developed in recent years are also explained.

Currently, aging is considered a complex phenomenon in which different cascading processes intervene, which can be summarized as follows [6-11]:

- Primary processes that generate damage:
  - Genomic instability: DNA damage alters vital processes such as replication, transcription, and translation, leading to cell death.
  - Telomere shortening: each cell cycles until the DNA cannot be copied and the cell cannot replicate.
  - Epigenetic alterations: which affect all cellular processes, including transcription and gene silencing, DNA replication and repair, and cell cycle progression.
  - Loss of proteostasis: due to the inability to eliminate defective proteins.
  - Disabled macro-autophagy, which reduces organelle turnover.
- Antagonistic processes that respond to damage:
  - Deregulation in nutrient detection: in which hormones (growth hormone and its second messenger IGF-1) and other mechanisms such as mTOR (mammalian target of rapamycin), AMPK (AMP-activated protein kinase), and sirtuins intervene.
  - Mitochondrial dysfunction: when cells age, the efficiency of the respiratory chain tends to decrease, and less ATP is produced.
  - Cellular senescence: with a deficient cell replacement system.
- Integrated processes responsible for the phenotype.
  - Stem cell exhaustion: since tissue regeneration decreases.
  - Alteration of intercellular communication: whether endocrine, neuroendocrine, or neuronal, associated with inflammatory processes (chronic inflammation or "inflammaging") and age-associated dysbiosis.

2.2 Intrinsic and Extrinsic Aging

In 2008, Farage et al. defined aging as a process in which intrinsic and extrinsic determinants progressively lead to deterioration of physiological function and a loss of structural integrity. Inherent aging of the skin, also known as chronological aging, occurs inevitably as a natural consequence of physiological changes over time with a significant genetic component that conditions its progression; genetic, hormonal, and metabolism factors are involved. Extrinsic factors include a wide range of external exposure and factors related to lifestyle and general health [12]. Several studies focused on photoaging, highlighting the influence of sunlight, and specifically ultraviolet radiation (UV), establishing the differences between physiological aging and photoaging [13]. Thus, multiple pieces of evidence refer to the crucial role of extrinsic factors involved in aging, which can be summarized as lifestyle (nutrition, sleep deprivation, tobacco smoking, etc.), environment pollution, and the above-mentioned sunlight exposure, in addition to ionizing radiation, chemical substances and toxins in general [14, 15].

The intrinsic and extrinsic factors involved in aging are summarized in Figure 1.

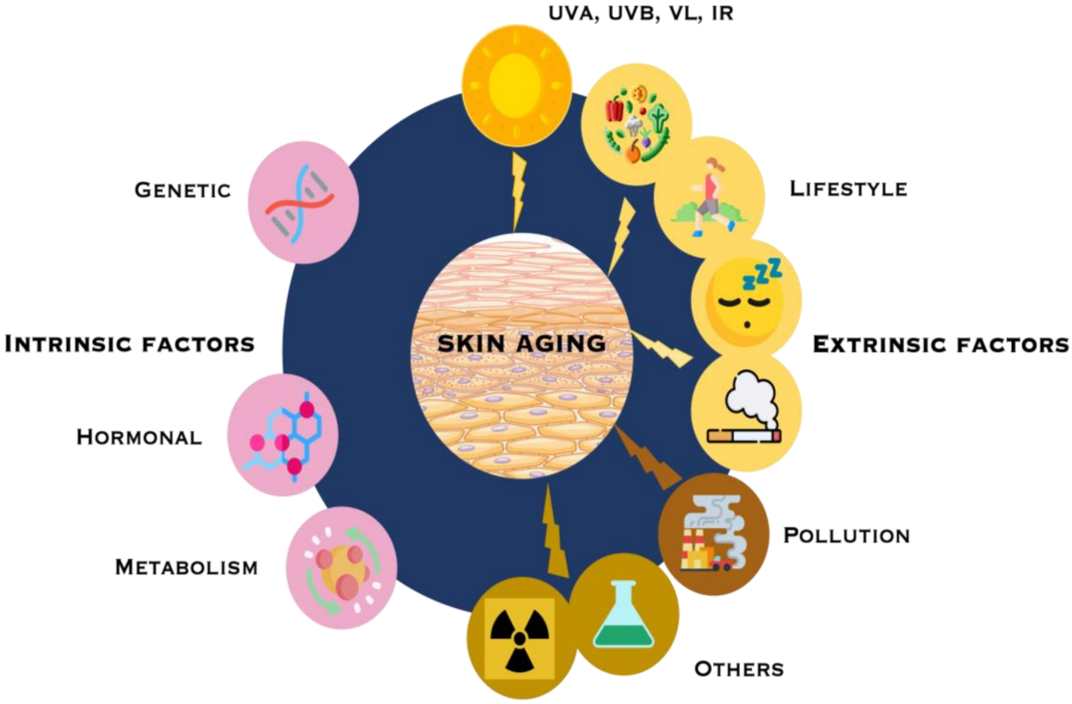

Figure 1 Intrinsic and extrinsic factors that are involved in skin aging.

Intrinsic aging is currently explained as a process of accumulation of cellular damage; in the skin, there is a decrease in cell renewal and a deterioration of the components of the extracellular matrix of the dermis, such as glycosaminoglycans and collagen and elastin fibers [16]. Likewise, oxidative stress also contributes to intrinsic skin aging due to an increase in the generation of reactive oxygen species (ROS) (by mitochondrial leak, inflammation, or others), which the skin's antioxidant systems are unable to combat, but also by age-related decreases in cellular repair capacity [17].

This process of cellular senescence, characterized by a stable form of cell cycle arrest, is primarily activated to protect the skin from insults. Still, senescent skin cells tend to accumulate with aging and, despite ceasing to proliferate, remain metabolically active, secreting factors known as the senescence-associated secretory phenotype (SASPs), promoting tissue dysfunction, which induces senescence in neighboring cells through a process called paracrine senescence, that contributes to chronic inflammation, and to the development of an aging phenotype [18]. Moreover, the secretome of intrinsically aged dermal fibroblasts was found to display a unique protein pattern termed “skin aging-associated secreted proteins” or SAASP, which differ from classical SASPs, in which an increase in MMPs and proinflammatory mediators are found [19, 20]. Furthermore, age-related cellular degeneration involves the accumulation of advanced glycation end products (AGEs) that damage collagen and the extracellular matrix of the dermis. AGEs also bind to specific receptors on immune cells, triggering the release of inflammatory mediators and the generation of ROS, leading to increased production of AGE damage [21].

Inflammaging is defined as a sterile, slow-progressing, low-grade inflammation that is a normal aging process and cannot be separated from the aging of the immune system, which is called "immunosenescence." But inflammation is not only due to intrinsic processes that can cause signs such as telomere shortening, genomic instability mitochondrial dysfunction, or stem cell exhaustion. Still, it is also combined with some external environmental factors [22].

Factors linked to extrinsic aging have been widely studied. Ultraviolet radiation (UVR) is the most common environmental factor in skin aging, with around 80% of exogenous skin aging being related to UVR, which produces alterations in DNA that, in turn, can lead to a mutation in the tumor suppressor gene p53, which has been recognized as an indicator of UV exposure. The production and release of ROS is also another consequence of UV exposure; ROS can induce the synthesis of MMPs by stimulating the mitogen-activated protein kinase (MAPK) signaling pathway. It is well known that MMPs play a key role in skin aging by their ability to degrade collagen and elastin in the extracellular matrix (ECM). In conclusion, long-term exposure to UV radiation will produce oxidative stress and excess ROS, leading to an inflammatory response that further accelerates skin aging [15]. In addition, recent studies have shown that visible light (wavelength 400-770 nm) and infrared light (770 nm-1 mm) are implicated in causing photoaging. Infrared light decreases collagen type 1 production by reducing the production of procollagen-1-stimulating transforming growth factors TGF-β in human skin [23].

Air pollution is another factor that has been shown to induce senescence in human skin cells, especially in keratinocytes, through the production of ROS [24], and tobacco use is another accelerating factor that acts by increasing oxidative stress, which can also trigger the secretion of proinflammatory cytokines and MMPs. Changes in skin microbiomes are also linked to environmental factors, including cumulative UV exposure, smoking, and pollution, leading to subsequent immune senescence [25]. Furthermore, recent studies have shown that aging is associated with reducing the variety of microorganisms in the skin microbiome, leading to increased susceptibility to skin diseases [26]. As local inflammation and secretion of SASPs from the skin microenvironment (consisting of keratinocytes, melanocytes, and fibroblasts) increases, a shift toward cellular senescence triggers inflammation and the subsequent expressions of clinical skin aging phenotypes, such as wrinkles [25].

In an attempt to reverse aging, "The information theory of aging (ITOA)" has been launched. ITOA asserts that the aging process is driven by the progressive loss of youthful epigenetic information, such that epigenetic reprogramming could improve the function of damaged and aged tissues by catalyzing the reversal of aging [27]. In addition, research into reliable biomarkers of aging is another objective, especially those related to aging-related diseases, such as diabetes, osteoarthritis, Alzheimer's disease, cancer, and cardiovascular diseases [28-30].

2.3 The Role of UV Exposure in Skin Pigmentation and Melanin Regulation

One of the main signs of photoaging is the presence of pigmentation changes, mainly linked to excessive exposure to ultraviolet light. When the skin is directly exposed to UV rays, it darkens. Tyrosinase, the key enzyme in melanin production, regulates mammalian skin color. Melanin serves a protective role by shielding the skin from the harmful effects of UV radiation and reactive oxygen species (ROS). However, excessive UV exposure can disrupt normal pigmentation, leading to uneven skin tone, including bright white spots, dark brown patches, and other irregularities [31].

3. The Skin Benefits of Various Algae Types

Algae, often overlooked as mere aquatic plants, have garnered significant attention in recent years for their myriad benefits to the skin. These versatile organisms, ranging from microscopic microalgae to large seaweeds, are packed with numerous nutrients and bioactive compounds that offer numerous advantages for skin health and appearance [32].

The most widely used algae in cosmetic applications, brown algae (Phaeophyceae), are rich in antioxidants, making them ideal for supporting skin hydration and elasticity. Known for its high carotenoid content, the red algae (Rhodophyta) helps smooth fine lines and wrinkles. They're also considered some of the best UV protectants, helping to shield the skin from harmful sun exposure. Though less commonly found in cosmetics, antioxidant-rich green algae (Chlorophyta) help to firm and smooth the skin and serve as a natural thickening agent in skincare products. Often referred to as Spirulina, blue-green algae (Cyanobacteria) are packed with antioxidants, effectively protecting skin while supporting overall health (Table 1). They're frequently used in smoothies and nutritional supplements [33].

Table 1 Some algae and their skin benefits.

Species	Taxonomic group	Assay type	Compounds	Activities	References
Cyanobacteria and Microalgae					
Chaetoceros calcitrans	Bacillariophyceae	TPC DPPH Griess	Fucoxanthin, astaxanthin, violaxanthin, zeaxanthin, canthaxanthin and lutein	Anti-inflammatory, antioxidant, scavenging, and anti-aging activity	[34]
Limnospira (formerly *Spirulina)*	Cyanobacteria	Clinical efficacy of dermo-cosmetic formulations	Phycocyanin, peptides, vanillic acid, caffeic acid and ferulic acid	Benefits on hydration, skin barrier function and oil control. Anti-aging effects.	[35]
Chlorella vulgaris	Chlorophyta	*In vivo*	Triacylglycerols, PUFAs ω-6 family, including linoleic acid (LA), γ-linolenic acid (GLA), and arachidonic acid (ARA), α-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA)	Hydrating, skin brightening, thickening, and anti-aging agents	[36, 37]
Macroalgae					
Alaria esculenta	Phaeophyceae	ELISA	Alga extract from Biotech Marine (Pontrieux, France)	Decrease in progerin production, anti-elastase, and anti-collagenase	[38]
Champia novae-zelandiae	Rhodophyta	Chromatographic methods	Shinorine, Palythine, Asterina-330, Porphyra-334 and Mycosporine-Glycine	UV-protective effect, antioxidant	[39]
Chondrus crispus	Rhodophyta	-	Carrageenan, Phycobiliproteins, and Mycosporine-like amino acids.	Skin hydration	[34]
Codium fragile	Chlorophyta	-	Polysaccharides	Skin hydration	[32]
Costaria costata	Phaeophyceae	*In vivo*	Triolein	Skin anti-aging	[38]
Ecklonia cava	Phaeophyceae	*In vivo*	Dieckol	Inhibition of tyrosinase and melanin synthesis	[40]

Ecklonia cava subsp. *kurome* (formerly *Ecklonia kurome*) *Eisenia bicyclis*	Phaeophyceae	*In vitro*	Crude phlorotannins (phloroglucinol, eckol, phlorofucofuroeckol A, dieckol, and 8,8′-bieckol)	Anti-wrinkling (inhibition of hyaluronidase)	[41]
Ecklonia cava *Ecklonia cava* subsp. *stolonifera* (formerly *Ecklonia stolonifera*) *Eisenia bicyclis*	Phaeophyceae	*In vivo* *In vitro*	Eckol and Dieckol	Anti-photoaging	[42]
Ericaria amentacea	Phaeophyceae	*In vitro* *In vivo*	Cystoketal chromane, Cystoketal quinone, Demethyl cystoketal chromane, Demethoxy cystoketal chromane and Dehydrated cystoketal	Antioxidant, anti-collagenase, anti-hyaluronidase, anti-tyrosinase	[43]
Ericaria selaginoides (formerly *Cystoseira tamariscifolia*)	Phaeophyceae	HAase Inhibition	Bifuhalol and diphloroethol	Anti-aging, antioxidant, anti-wrinkling (inhibition of hyaluronidase), anti-inflammation	[44]
Gracilaria chilensis	Rhodophyta	Chromate-graphic methods	Shinorine, Palythine, Asterina-330, Porphyra-334, Aplysiapalythine A, Mycosporine-Glycine, Mycosporine-Alanine-Glycine and Palythene	UV-protective effect, antioxidant	[45]
Phorphyra umbilicalis	Rhodophyta	*In vitro* *In vivo*	Porphyra-334	Anti-aging	[34]
Phorphyra umbilicalis	Rhodophyta	*In vitro* *In vivo*	Fat-soluble derivatives of vitamins A, C and E	Hydration, skin protective, anti-wrinkle, anti-roughness	[46]
Pyropia plicata	Rhodophyta	Chromate-graphic methods	Shinorine, Palythine, Asterina-330, Porphyra-334, Aplysiapalythine A, Mycosporine-Glycine, Mycosporine-Alanine-Glycine and Palythene	UV-protective effect, antioxidant	[45]

Rhizoclonium hieroglyphicum	Chlorophyta	*In vivo*	Polysaccharides and amino acids	Skin moisturizing effect	[47]
Saccharina latissima	Phaeophyceae	TEAC assay	Phloroglucinol	Biocosmetics	[48]
Ulva australis (formerly *Ulva pertusa*)	Chlorophyta	*In vitro* *In vivo*	Ulvan	Anti-aging, antiherpetic	[49]

Limnospira (formerly *Spirulina*), a blue-green microalga (Cyanobacteria), is rich in proteins, vitamins, minerals, and antioxidants. It contains high levels of vitamins A, B, C, D, and E, which help to nourish and revitalize the skin. *Limnospira*'s antioxidants, such as phycocyanin, protect the skin from oxidative damage caused by free radicals, slowing the aging process and reducing the appearance of fine lines and wrinkles. Additionally, its anti-inflammatory properties can help soothe irritated skin and reduce redness, making it ideal for sensitive skin types [35].

Chlorella, another nutrient-dense green microalga, is known for its detoxifying abilities. It is rich in chlorophyll, which helps to cleanse the skin by removing toxins and impurities. *Chlorella*'s high content of vitamins and minerals, including vitamins A, B, and C, promotes skin regeneration and repair, enhancing skin elasticity and firmness. Its anti-inflammatory properties help to calm irritated skin and reduce the appearance of acne and other blemishes [50].

Red algae, a common ingredient in skincare products, are known for their hydrating and anti-aging benefits. They are rich in polysaccharides, such as carrageenan and agar, which form a protective barrier on the skin, locking in moisture and keeping the skin hydrated. Red algae also contain antioxidants, such as beta-carotene and zeaxanthin, that help protect the skin from environmental damage and reduce the signs of aging. Their high mineral content, including calcium and magnesium, strengthens the skin's natural barrier and improves overall skin health [51].

Brown algae, including species like *Saccharina latissima* (kelp) and *Fucus vesiculosus* (bladderwrack), are renowned for their anti-aging and skin-firming properties. These algae are rich in fucoidan, a polysaccharide with potent anti-inflammatory and antioxidant properties that help protect the skin from UV damage and reduce the appearance of fine lines and wrinkles. Brown algae also contain alginic acid, which helps to detoxify the skin by removing heavy metals and other impurities. The high iodine content in brown algae supports healthy skin metabolism and promotes radiant complexion [32, 52].

Green algae, such as *Ulva* (formerly *Enteromorpha*), contain vitamins, minerals, and amino acids that nourish and rejuvenate the skin. They help to stimulate collagen production, improving skin elasticity and firmness. Green algae also possess anti-inflammatory and antioxidant properties that protect the skin from environmental damage and reduce the appearance of aging signs. Their hydrating abilities help to keep the skin moisturized and supple, making them a valuable ingredient in skincare formulations [53].

Incorporating algae into skincare routines can offer many benefits, from hydration and anti-aging to detoxification and soothing properties. Their rich nutrient profile and bioactive compounds make algae an invaluable natural resource for promoting healthy, youthful, and radiant skin. As the demand for natural and sustainable skincare products grows, algae-based ingredients will likely play an increasingly prominent role in the beauty industry [54]. As indicated above, the main advantage of using extracts and compounds is that they can be used to obtain advanced, viable, and environmentally friendly production techniques.

4. Conclusions

Algae-derived photoprotective substances present a promising and safer alternative to synthetic compounds in cosmetics, offering a broad spectrum of biological activities beneficial for skin health [55]. With their UV absorption, antioxidant properties, matrix metalloproteinase inhibition, anti-aging effects, and immunomodulatory capabilities, algae can significantly enhance skin protection and repair [56]. Understanding the mechanisms of skin aging and the impact of intrinsic and extrinsic factors is crucial for developing effective skincare solutions. By leveraging the unique properties of various algae species, we can create innovative products that not only address the signs of aging but also promote overall skin wellness in a sustainable and environmentally friendly manner [57].

Abbreviations

AGE	Advanced glycation end product
AMPK	AMP-activated protein kinase
DNA	Deoxyribonucleic acid
DPPH	2,2-Diphenyl-1-Picrylhydrazyl
ECM	Extracellular matrix
ELISA	Enzyme-linked immunosorbent assay
ITOA	The information theory of aging
MAPK	Mitogen-activated protein kinase
MMP	Matrix metalloproteinase
mTor	Mammalian target of rapamycin
ROS	Reactive oxygen species
SASP	Senescence-associated secretory phenotype
SAASP	Skin aging-associated secreted proteins
TGF-β	Transforming growth factor-beta
TPC	Total phenolic content
UN	United Nations
UV	Ultraviolet
UVR	Ultraviolet radiation
WHO	World Health Organization

Acknowledgments

CFE - Centre for Functional Ecology — Science for People and the Planet, Marine Resources, Conservation and Technology - Marine Algae Lab, Department of Life Sciences, University of Coimbra have technically supported this work.

Author Contributions

LMM: Conceptualization, Writing-original draft, Writing-review & editing, Supervision. Writing-review, Validation; LP: Conceptualization, Writing-original draft, Writing-review & editing, Supervision. Writing-review, Validation. All authors read and approved the submitted version.

Funding

Leonel Pereira thanks the Foundation for Science and Technology (FCT) for their support by providing institutional funding to the Centre for Functional Ecology — Science for People and the Planet (CFE; UIDB/04004/2020; https://doi.org/10.54499/UIDB/04004/2020), financed by

FCT/MCTES through national funds (PIDDAC), Associate Laboratory TERRA (LA/P/0092/2020; https://doi.org/10.54499/LA/P/0092/2020).

Competing Interests

The authors have declared that no competing interests exist.

Data Availability Statement

Data available from the authors.

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