Algae: Exploring Drug Development and Therapeutic Benefits

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Abstract - Algae have been consumed by humans for hundreds of years. Current studies have shown that algae are rich sources of bioactive compounds with excellent nutritional value, and are considered functional foods with health benefits.

Polysaccharides are the main constituents of algae; their diverse structures allow many unique physical and chemical properties that help to moderate a wide range of biological activities, including immunomodulation, antibacterial, antioxidant, prebiotic, antihypertensive, antidiabetic, antitumor, and anticoagulant activities. In this review, we focus on the major therapeutic benefits and drug development by algae. We explore how their structure leads to their health benefits, and their application prospects in functional foods and pharmaceuticals. algae have gained attention in drug development and therapeutic applications due to their rich bioactive compounds. Algae-derived compounds have shown anti-cancer properties, making them potential options for cancer therapy. Additionally, algae and cyanobacteria are being explored as natural sources

For antiviral drugs against diseases like COVID-19. Algae-derived nutraceuticals are being studied for their potential therapeutic benefits against different diseases due to their diverse nutritional components and bioactive compounds. Algae offer a promising natural resource for drug development and medical applications, showcasing their potential in pharmaceutical biotechnology and therapy. Their bioactive compounds hold promise in various fields such as cancer treatment, antiviral drugs, and nutraceuticals. Algae-derived nutraceuticals are eco-friendly, safe, and have applications in food supplements to combat various health.

Keywords- disease treatment, drug development, food and nutrition, future direction, types of algae.

I. INTRODUCTION

In the ever-evolving landscape of pharmaceutical research, the exploration of unconventional sources for novel drug compounds has become a pivotal endeavour. Among these sources, algae, often overlooked in the grandeur of marine ecosystems, have emerged as a promising reservoir of bioactive compounds with significant therapeutic potential. This review embarks on a comprehensive journey into the realms of algae-derived compounds, aiming to unravel their diverse biochemical tapestry and shed light on the transformative impact they might wield on the future of drug development [1].

Algae, diverse and omnipresent in aquatic environments, have been integral to ecosystems for eons. While renowned for their role in oxygen production and as foundational components of marine food webs, the vast biochemical diversity. Within algae has remained relatively unexplored until recent years [2]. This review seeks to bridge the gap between the understated importance of algae and the burgeoning interest in their pharmaceutical potential.

The intrigue surrounding algae lies not only in their sheer abundance but also in their ability to thrive in diverse environments, adapting to fluctuating conditions and environmental stressors [3]. It is within these adaptive responses that algae synthesize an array of secondary metabolites, ranging from polyphenols and terpenoids to polysaccharides and peptides [4]. These compounds, forged in the crucible of nature's challenges, have the potential to revolutionize drug development [5].

As we embark on this exploration, the first chapter unfolds

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in the vast expanses of marine ecosystems [6]. Algae, particularly macroalgae and microalgae, inhabit oceans, seas, and freshwater bodies, each species evolving distinct biochemical profiles [7]. The exploration of these compounds begins with an understanding of the ecological niches these algae occupy and the environmental stimuli that trigger the synthesis of bioactive molecules. By delving into the ecological context, we gain insights into the nuances of algae- derived compounds, paving the way for targeted drug discovery [8].

The review then ventures into the biochemical intricacies of algae-derived compounds. Polyphenols, known for their antioxidant properties, are prevalent in various algae species. These compounds not only serve as defensive mechanisms for the algae themselves but also present opportunities for developing pharmaceutical interventions against oxidative stress-related diseases in humans [9]. Similarly, terpenoids, with their diverse structural configurations, exhibit antimicrobial and anti-inflammatory activities, opening avenues for novel drug candidates in infectious and inflammatory diseases [10].

Polysaccharides derived from algae, such as carrageenan and alginate, are another focal point of this exploration. With their unique structural properties and biological activities, these polysaccharides hold promise in drug delivery systems and as therapeutic agents for conditions ranging from diabetes to cardiovascular diseases [11]. Peptides, often overshadowed by their counterparts in terrestrial environments, emerge as potent bioactive compounds with applications in antimicrobial, antiviral, and anticancer therapies [12].

The multifaceted nature of algae-derived compounds extends beyond conventional drug development. The review highlights the potential applications of these compounds in the realms of nutraceuticals and functional foods, underscoring their integration into preventive healthcare strategies [13]. Algae, traditionally viewed through an ecological lens, now beckon researchers and pharmaceutical innovators to envision them as reservoirs of therapeutic potential [14].

In conclusion, the exploration of algae-derived compounds in drug development stands at the intersection of ecological understanding and pharmaceutical innovation [15]. This review serves as a compass, guiding researchers through the biochemical intricacies of algae and unveiling the vast therapeutic potential that lies within. As we navigate this uncharted territory, the promise of algae-derived drugs and compounds emerges as a beacon, illuminating the path toward a future where nature's reservoirs become reservoirs of transformative medicine [16].

II. ALGAE: A COMPREHENSIVE ANALYSIS

Caulerpa racemosa and *Caulerpa lentillifera* are types of *ulvophyte* green algae that are widely consumed in the Pacific and Southeast Asian regions [17]. Asia accounted for 97.4% of global seaweed production in 2019 (99.1% of cultivation), with seven of the algae group belonging to the genus Caulerpa, especially ten largest-producing countries located in East or Southeast Asia. Until now, the main aquaculture production that has high economic value is *Caulerpa lentillifera*, which is also traded internationally in Pacific countries. Although the consumption of macroalgae is not as common in Europe as in Asia, microalgae have gained popularity due to their physiologically active components, earning them the nickname “new superfood” [18]. Groups of algae in the genus Caulerpa are recognized as functional food sources due to the presence of secondary metabolites. These algae are rich in carbohydrates, proteins, unsaturated fatty acids, and vitamin complexes, and have a much higher mineral content when compared to terrestrial vegetables [19]. However, the aquaculture-production potential of many varieties of Caulerpa sea grapes is rarely studied and has never been used in a high-density commercial-scale system [20]. The global harvest of macroalgae in 2013 was estimated at USD 6.7 billion, with more than 95% produced in sea- algae-farming countries. About two thirds of Indonesia’s territory is in the form of the sea, and it is famous as one of the world’s mega-diversity areas, with more than 555 macroalgae species having been identified in its ocean areas. In addition, most of Indonesia’s islands are located within the Coral Triangle, which has been identified as an area with a very high diversity of Caulerpa [21]. Caulerpa *lentillifera* originated in tropical areas around India and the Pacific Ocean, such as Indonesia, but today it can also be found in the Korean Peninsula due to changes in global temperatures[22]. The genus Caulerpa is famous as an edible species that has a high nutritional content, such as minerals, dietary fibres, vitamin A, vitamin C, and several essential unsaturated fatty acids. The genus Caulerpa has also been used to treat a wide variety of diseases. For instance, anti- inflammatory, antioxidant, antimicrobial, lipid-lowering, and anticancer properties, as well as cardiovascular protection, renal protection, hepatoprotection, and neuroprotection, are just a few of the previously described medicinal activities of seaweed[23]. Unlike terrestrial plants, marine algae have not been widely used as an alternative medicine or adjuvant to medicines[24]. However, technological advances and innovative engineering have allowed organisms in the marine environment to be used for scientific experiments in the last 50 years. Interestingly, natural populations of *C. lentillifera* have varying nutritional and biochemical properties due to environmental factors such as predation, sedimentation, salinity, temperature, pollution, and nutrients; thus, different geographical growing fields can contribute to varying levels of nutrients and secondary metabolites[25]. Despite its abundance, research on Indonesian *C. lentillifera’s* bioactive molecules profile and their direct biological activities is still limited[26]. Due to the uniqueness of each alga and its particular characteristics, exploration of the multifunctional properties

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of these algae has become urgent. Therefore, in this study, two different extraction methods (maceration and soxhletation) were used, with each extraction using three solvents each having different polarities, namely n-Hexane (nonpolar), ethyl acetate (semi-polar), and ethanol (polar), in order to elucidate different compounds on the basis of the degree of polarity of the compounds. To date, there have been no studies profiling and exploring the compounds or metabolites of Indonesian C. lentillifera, especially those related to bioactivity in various kinds of non-communicable diseases, such as cancer and obesity-related diseases. Therefore, this study urgently aimed to profile the metabolites and the antioxidant, anticancer, antiobesity, and cytotoxicity properties of Indonesian C. lentillifera Algae are ubiquitous; a multitude of species ranging from microscopic unicells to gigantic kelps inhabit the world's oceans, freshwater bodies, soils, rocks, and trees, and are responsible for most of the global production of organic matter by photosynthesis. They thus play a fundamental role in the world's ecosystems and a reliable and modern introduction to their kaleidoscopic diversity, systematics, and phylogeny is indispensable. In this textbook, the main groups of algae (divisions or phyla) are considered in turn. Each chapter begins with a summary of the principal characteristics of the group and interesting aspects of ecology and evolution. The final chapter is a synthesis, in which the phylogeny of the algae is discussed in relation to the evolution of other living organisms, primarily on the basis of evidence from recent molecular studies. This book is the completely revised and updated edition of a highly acclaimed German work, which was heralded for its clarity as well as its breadth and depth of information. This new edition takes into account recent re-evaluations in algal systematics and phylogeny provided by the powerful techniques of molecular genetics and electron microscopy, as well as more traditional life history studies. The book will be appropriate as an undergraduate text and as a reference for professionals in the field.

III. FUTURE DIRECION

In world, microalgae have gained popularity due to their physiologically active components, earning them the nickname “new superfood”[27]. Groups of algae in the genus Caulerpa are recognized as functional food sources due to the presence of secondary metabolites[28]. These algae are rich in carbohydrates, proteins, unsaturated fatty acids, and vitamin complexes, and have a much higher mineral content when compared to terrestrial vegetables. However, the aquaculture-production potential of many varieties of Caulerpa sea grapes is rarely studied and has never been used in a high-density commercial-scale system[29]. The global harvest of macroalgae in 2013 was estimated at USD 6.7 billion, with more than 95% produced in sea-algae-farming countries. About two-thirds of Indonesia’s territory is in the form of the sea, and it is famous as one of the world’s mega- diversity areas, with more than 555 macroalgae species having been identified in its ocean areas[30]. In addition, most of Indonesia’s islands are located within the Coral Triangle, which has been identified as an area with a very high diversity of Caulerpa[31].

Caulerpa lentillifera originated in tropical areas around India and the Pacific Ocean, such as Indonesia, but today it can also be found in the Korean Peninsula due to changes in global temperatures[31]. The genus Caulerpa is famous as an edible species that has a high nutritional content, such as minerals, dietary fibres, vitamin A, vitamin C, and several essential unsaturated fatty acids[32]. The genus Caulerpa has also been used to treat a wide variety of diseases. For instance, anti- inflammatory, antioxidant, antimicrobial, lipid-lowering, and anticancer properties, as well as cardiovascular protection, renal protection, hepatoprotection, and neuroprotection, are just a few of the previously described medicinal activities of seaweed[33]. Unlike terrestrial plants, marine algae have not been widely used as an alternative medicine or adjuvant to medicines. However, technological advances and innovative engineering have allowed organisms in the marine environment to be used for scientific experiments in the last 50 years[34].

Interestingly, natural populations of C. lentillifera have varying nutritional and biochemical properties due to environmental factors such as predation, sedimentation, salinity, temperature, pollution, and nutrients; thus, different geographical growing fields can contribute to varying levels of nutrients and secondary metabolites[35]. Despite its abundance, research on Indonesian C. lentillifera’s bioactive molecules profile and their direct biological activities is still limited. Due to the uniqueness of each alga and its particular characteristics, exploration of the multifunctional properties of these algae has become urgent[36]. Therefore, in this study, two different extraction methods (maceration and soxhletation) were used, with each extraction using three solvents each having different polarities, namely n-Hexane (non-polar), ethyl acetate (semi-polar), and ethanol (polar), in order to elucidate different compounds on the basis of the degree of polarity of the compounds[37]. To date, there have been no studies profiling and exploring the compounds or metabolites of Indonesian C. lentillifera, especially those related to bioactivity in various kinds of non-communicable diseases, such as cancer and obesity-related diseases. Therefore, this study urgently aimed to profile the metabolites and the antioxidant, anticancer, anti-obesity, and cytotoxicity properties of Indonesian C. lentillifera[38].

IV. TYPES OF ALGAE FOR HUMAN WELFARE

Algae play a critical role in the Earth's carbon cycle by converting carbon dioxide into oxygen. They provide much of Earth's oxygen, serve as the food base for almost

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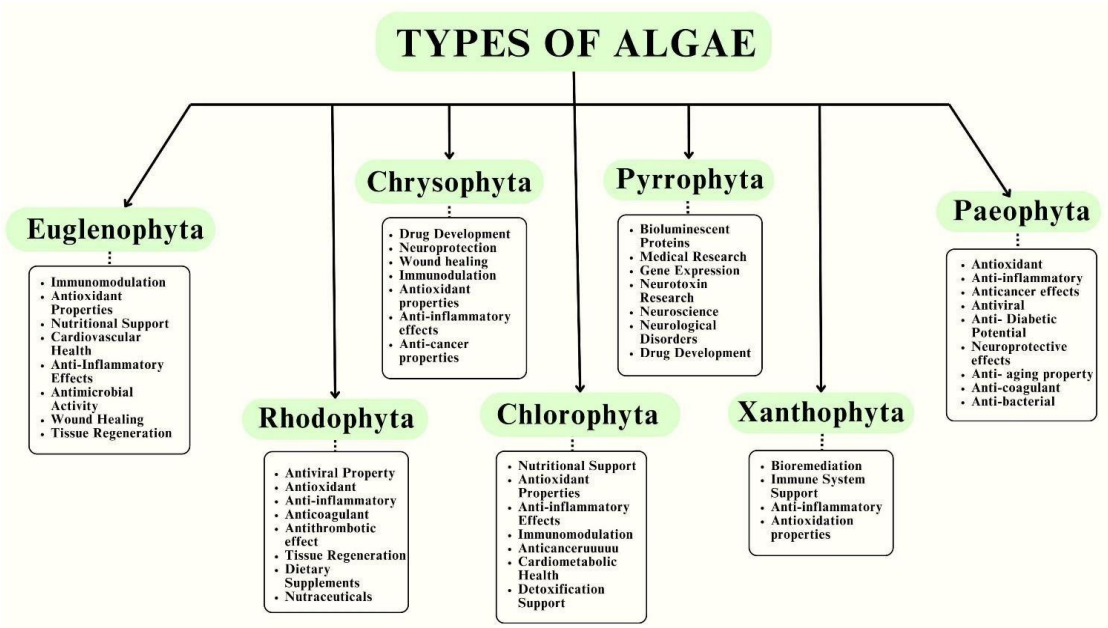
all aquatic life, and provide foods and industrial products, including petroleum products[39].

There are mostly seven types of use for drugs development and therapeutic uses.

1. EUGLENOPHYTA (EUGLENOIDS).
2. CHRYSOPHYTA (GOLDEN BROWN ALGAE AND DIATOMS).
3. PYRROPHYTA (FIRE ALGAE).
4. CHLOROPHYTA (GREEN ALGAE).
5. RHODOPHYTA (RED ALGAE).
6. PAEOPHYTA (BROWN ALGAE).
7. XANTHOPHYTA (YELLOW-GREEN ALGAE).

1- EUGLENOPHYTA (EUGLENOIDS)

1.1. Euglenophyta (Euglenoids) in Drug Development: Euglenoids are known to produce a variety of bioactive compounds, including secondary metabolites like alkaloids, terpenoids, and polysaccharides[40]. These bioactive compounds have been studied for their potential pharmacological effects, such as antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory activities[41].



1.1.1. Nutraceuticals and Dietary Supplements: Compounds derived from Euglenoids, such as paramylon (a storage polysaccharide), have been investigated for their potential as nutraceuticals and dietary supplements. Paramylon, found in Euglena gracilis, has been studied for its immunomodulatory effects and potential applications in supporting immune function and overall health[42].

1.1.2. Antimicrobial Agents: Some compounds from Euglenoids have shown antimicrobial activity against bacteria, fungi, and even viruses. Research is ongoing to explore the efficacy of these compounds as potential antimicrobial agents for pharmaceutical use, including in the treatment of antibiotic-resistant infections[43].

1.1.3. Anticancer Potential: Certain bioactive compounds from Euglenoids have demonstrated cytotoxic effects against cancer cells in preclinical studies. These compounds may be further investigated for their potential as anticancer agents, either as standalone therapies or in combination with existing treatments[44].

1.1.4. Drug Delivery Systems: The unique properties of Euglenoids, such as their ability to accumulate compounds and their cell membrane structure, make them potentially useful in drug delivery systems. Researchers are exploring the use of Euglenoids as carriers for targeted drug delivery, which could enhance the efficacy and reduce the side effects of therapeutic agents[46].

1.2. Therapeutic Benefits:

1.2.1. Immunomodulation: Paramylon, a storage polysaccharide found in Euglena gracilis, has been studied for its immunomodulatory effects. It may help modulate the immune response, potentially enhancing immune function. Research suggests that paramylon may stimulate the activity of macrophages and other immune cells, contributing to an overall improvement in immune system function[47].

1.2.2. Antioxidant Properties: Euglena gracilis contains antioxidants that can scavenge free radicals. Antioxidants play a crucial role in reducing oxidative stress, which is linked to various health issues, including chronic diseases and aging. The antioxidant properties of Euglena compounds may have potential benefits for overall health and the prevention of oxidative damage[48].

1.2.3. Nutritional Support: Euglena gracilis is rich in nutrients such as proteins, vitamins, and minerals. It provides a source of essential amino acids and may serve as a nutritional supplement. The nutritional content of

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Euglena may contribute to overall health and well-being, especially in situations where there may be nutritional deficiencies[49].

1.2.4. Cardiovascular Health: Some studies suggest that compounds from Euglena gracilis may have potential benefits for cardiovascular health. Certain bioactive compounds, such as polyunsaturated fatty acids (PUFAs), may contribute to lowering cholesterol levels and supporting heart health[50].

1.2.5. Anti-Inflammatory Effects: The compounds found in Euglena gracilis may exhibit anti-inflammatory properties.

Inflammation is associated with various chronic conditions, and the anti-inflammatory effects of Euglena comp

ounds may have therapeutic implications for managing inflammatory disorders[51].

1.2.6. Antimicrobial Activity: Euglenoids have been studied for their antimicrobial properties. Some compounds may exhibit activity against bacteria, fungi, and viruses. This antimicrobial activity could potentially be harnessed for the development of novel therapeutic agents to combat infections[52].

1.2.7. Wound Healing: Euglena gracilis extracts have been explored for their potential in wound healing. The compounds from Euglena may promote tissue regeneration and wound closure, suggesting applications in the development of wound care products[53].

2- CHRYSOPHYTA (GOLDEN BROWN ALGAE AND DIATOMS)

2.1. Chrysophyta (golden - brown algae and diatoms) in Drug Development:

2.1.1. Diatoms: Diatoms are a type of algae with a unique silica-based cell wall. Some diatom species are known to produce bioactive compounds that exhibit antibacterial, antiviral, and anticancer properties[54]. Researchers are exploring the potential of diatoms for drug delivery systems due to their nanostructured silica shells, which can be manipulated for controlled drug release[55]. Diatoms have been investigated for their potential in producing nanomaterials with applications in drug delivery, imaging, and diagnostics[56].

2.1.2. Golden-Brown Algae (Chrysophyceae): Golden-brown algae, or Chrysophyceae, are a diverse group of algae found in various aquatic environments. Some species of golden-brown algae produce polyunsaturated fatty acids (PUFAs), which have potential health benefits, including cardiovascular and anti-inflammatory effects. Golden-brown algae have been explored for their potential as a source of bioactive compounds with pharmaceutical applications[57].

2.2. Therapeutic benefits:

The therapeutic benefits of Chrysophyta, specifically golden- brown algae and diatoms, are an area of ongoing research. While these microorganisms have been studied for various potential applications, including drug development, their specific therapeutic benefits are still being explored. Here are some areas where therapeutic potential is being investigated[58].

2.2.1. Anti-Inflammatory and Antioxidant Properties: Some species of Chrysophyta, including certain golden-brown algae and diatoms, may contain bioactive compounds with anti-inflammatory and antioxidant properties. These properties could have therapeutic implications for conditions associated with inflammation and oxidative stress[60].

2.2.2. Cardiovascular Health: Certain golden-brown algae are known to produce polyunsaturated fatty acids (PUFAs), which have been linked to cardiovascular health. PUFAs, particularly omega-3 fatty acids, may contribute to reducing the risk of cardiovascular diseases and promoting heart health[62].

2.2.3. Immunomodulation: Compounds derived from Chrysophyta, such as those found in Euglena gracilis (a member of Euglenophyta), have been studied for their potential immunomodulatory effects. Immunomodulation may have therapeutic applications in supporting the immune system and managing immune-related disorders[63].

2.2.4. Wound Healing: The unique silica structures produced by diatoms have been investigated for their potential in wound healing. Diatom-derived materials may be used in wound dressings or as scaffolds to promote tissue regeneration[64].

2.2.5. Neuroprotection: Some research suggests that certain bioactive compounds from algae may have neuroprotective properties. These properties could be explored for their potential in managing neurodegenerative diseases or supporting overall brain health[65].

2.2.6. Anti-Cancer Properties: Extracts from certain Chrysophyta species have demonstrated anticancer activity in preclinical studies. Compounds with anti-cancer potential may be further investigated for their effectiveness and safety in cancer treatment[66].

3- PYRROPHYTA (FIRE ALGAE)

3.1. Pyrrophyta (Fire algae) in Drug Development:

3.1.1. Bioluminescence and Imaging: The bioluminescent properties of Dinoflagellates have been explored for their applications in imaging and diagnostics. Bioluminescent proteins from Dinoflagellates, such as luciferase, have been used as reporter genes in molecular biology and medical research[67].

3.1.2. Toxin Production: Some Dinoflagellates are known to produce toxins that can accumulate in shellfish during harmful algal blooms, leading to paralytic shellfish

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poisoning (PSP) and other toxic effects. While these toxins can be harmful, certain compounds derived from Dinoflagellates have been studied for potential medical applications, including the investigation of neurotoxins for pain management[68].

3.2. Therapeutic benefits:

3.2.1. Bioluminescent Proteins for Imaging: Bioluminescent proteins, such as luciferase, derived from Dinoflagellates have been used in biotechnology and medical research for imaging purposes. These proteins serve as valuable tools for studying gene expression, protein interactions, and various cellular processes[69].

3.2.2. Neurotoxin Research: Some Dinoflagellates produce neurotoxins, which can be harmful and cause paralytic shellfish poisoning (PSP) during red tide events. While these toxins are primarily associated with harmful effects, certain components or derivatives may be studied for their potential in neuroscience research or as leads for drug development targeting neurological disorders[70].

4- CHLOROPHYTA (GREEN ALGAE)

4.1. Chlorophyta (Green algae) in Drug development:

4.1.1. Anti-Inflammatory and Antioxidant Compounds: Some green algae species have been found to produce bioactive compounds with anti-inflammatory and antioxidant properties. These properties could be of interest in the development of drugs aimed at mitigating inflammation and oxidative stress, which are implicated in various health conditions[71].

4.1.2. Anticancer Potential: Extracts from certain green algae have shown cytotoxic effects against cancer cells in laboratory studies. Compounds derived from green algae may be investigated further for their potential as anticancer agents[72].

4.1.3. Antimicrobial Properties: Some green algae produce substances with antimicrobial activity against bacteria and fungi. Compounds with antimicrobial properties may be explored for their potential use in the development of new antibiotics or antifungal medications[73].

4.1.4. Immunomodulatory Effects: Green algae, such as Chlorella and Spirulina, have been studied for their potential immunomodulatory effects. Compounds from these algae may modulate the immune system, making them potential candidates for immune-related therapies[74].

4.1.5. Nutraceuticals and Dietary Supplements: Certain green algae are used as nutritional supplements due to their rich content of proteins, vitamins, minerals, and other bioactive compounds. While this is more related to nutrition, the bioactive components in these algae could contribute to overall health and well-being[75].

4.2. Therapeutic benefits:

4.2.1. Nutritional Support: Green algae, such as Chlorella and Spirulina, are rich in nutrients, including proteins, vitamins, minerals, and essential fatty acids. These algae are used as dietary supplements and are believed to provide nutritional support, potentially boosting energy levels and overall well-being[76].

4.2.2. Antioxidant Properties: Compounds found in green algae, such as polyphenols and carotenoids, exhibit antioxidant properties. Antioxidants can help neutralize free radicals in the body, potentially reducing oxidative stress and contributing to overall health[77].

4.2.3. Anti-Inflammatory Effects: Some green algae contain bioactive compounds with anti-inflammatory properties. Reduction of inflammation is associated with various health benefits, and the anti-inflammatory effects of green algae may have implications for conditions such as arthritis and inflammatory disorders[78].

4.2.4. Immunomodulation: Compounds from green algae may modulate the immune system, potentially enhancing immune function. Immunomodulatory effects could have applications in supporting the body's defence mechanisms and managing immune-related conditions[79].

4.2.5. Anticancer Potential: Laboratory studies have suggested that certain green algae extracts exhibit cytotoxic effects on cancer cells. While more research is needed, these findings hint at the potential of green algae compounds in anticancer therapies[80].

4.2.6. Cardiometabolic Health: Some studies have explored the impact of green algae on cardiovascular health and metabolic parameters. Compounds from green algae may have potential benefits in managing cholesterol levels and supporting heart health[81].

4.2.7. Detoxification Support: Chlorella, in particular, is known for its potential role in detoxification. It is believed to bind to heavy metals and toxins in the body, facilitating their elimination. Detoxification properties may be beneficial for individuals exposed to environmental toxins[82].

5- RHODOPHYTA (RED ALGAE)

5.1. Rhodophyta (Red algae) in Drug Development:

5.1.1. Antiviral Compounds: Certain red algae produce sulfated polysaccharides, like carrageenans, which have demonstrated antiviral activity. Carrageenans, for example, have been studied for their potential in inhibiting the replication of certain viruses, and they may have applications in antiviral drug development[83].

5.1.2. Antioxidant and Anti-Inflammatory Properties: Red algae contain phenolic compounds and other antioxidants that exhibit anti-inflammatory and antioxidant effects. These properties may be beneficial in addressing oxidative stress and inflammation, which are implicated in various diseases[84].

5.1.3. Anticoagulant and Antithrombotic Effects:

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Sulfated polysaccharides from red algae, such as carrageenans and fucoidans, have been investigated for their anticoagulant and antithrombotic activities. These compounds may have potential applications in the development of medications to prevent or treat blood clotting disorders[85].

5.1.4. Anti-Cancer Properties: Some red algae-derived compounds, particularly fucoidans, have shown promising anti-cancer activities in preclinical studies. Research suggests that these compounds may inhibit the growth of cancer cells, induce apoptosis, and interfere with tumour angiogenesis[86].

5.1.5. Anti-Infective Agents: Red algae have been explored for the production of compounds with antibacterial and antifungal properties. Extracts from red algae may be studied for their potential as novel anti-infective agents[87].

5.1.6. Wound Healing and Tissue Regeneration: Certain red algae compounds, such as carrageenans, have been investigated for their potential in wound healing and tissue regeneration. These compounds may be used in topical formulations to promote the healing of wounds[88].

5.1.7. Dietary Supplements and Nutraceuticals: Red algae are often used in the production of dietary supplements and nutraceuticals due to their rich content of minerals, vitamins, and bioactive compounds. These supplements may contribute to overall health and well-being[89].

5.2. Therapeutic benefits:

5.2.1. Cardiovascular Health: Compounds such as omega- 3 fatty acids, peptides, and phycobiliproteins found in red algae may contribute to cardiovascular health. These compounds may help regulate cholesterol levels, support blood vessel function, and have anti-inflammatory effects that benefit heart health[90].

5.2.2. Antioxidant and Anti-Inflammatory Properties: Red algae contain phenolic compounds, carotenoids, and other antioxidants with anti-inflammatory properties. Antioxidants help neutralize free radicals, reducing oxidative stress and inflammation, which are linked to various chronic diseases[91].

5.2.3. Anticoagulant and Antithrombotic Effects: Sulfated polysaccharides, such as carrageenans and fucoidans, derived from red algae have anticoagulant and antithrombotic properties. These compounds may help prevent blood clot formation and reduce the risk of thrombosis[92].

5.2.4. Antiviral Activity: Carrageenans, a type of sulfated polysaccharide found in some red algae, have demonstrated antiviral activity. Carrageenans may inhibit the attachment and entry of certain viruses into host cells, making them a subject of interest in antiviral research[93].

5.2.5. Anti-Cancer Properties: Compounds like fucoidans from red algae have shown anti-cancer activities in preclinical studies. Fucoidans may interfere with cancer cell growth, induce apoptosis (programmed cell death), and exhibit anti- angiogenic effects[94].

5.2.6. Wound Healing and Tissue Repair: Carrageenans and other polysaccharides from red algae may have applications in wound healing. These compounds may promote tissue repair, reduce inflammation, and support the overall healing process[95].

5.2.7. Skin Health: Extracts from red algae are used in cosmetic and skincare products due to their potential benefits for skin health. Compounds like carrageenans may have moisturizing and soothing effects on the skin[96].

5.2.8. Dietary Supplements and Nutraceuticals: Red algae are used in the production of dietary supplements and nutraceuticals due to their nutritional content. These supplements may provide essential minerals, vitamins, and other bioactive compounds to support overall health[97].

6- PAEOPHYTA (BROWN ALGAE)

6.1. Paeophyta (Brown algae) in Drug Development:

6.1.1. Antioxidant and Anti-Inflammatory Compounds: Algae contain polyphenols, fucoxanthin, and other compounds with antioxidant and anti-inflammatory properties. These compounds may have applications in the development of drugs targeting oxidative stress and inflammation, which are implicated in various health conditions[98].

6.1.2. Anticancer Properties: Compounds derived from brown algae, such as fucoidans, have shown potential anticancer activities in preclinical studies. Fucoidans may inhibit the growth of cancer cells, induce apoptosis (programmed cell death), and interfere with tumour angiogenesis[99].

6.1.3. Antiviral and Antimicrobial Activity: Some brown algae produce compounds with antiviral and antimicrobial properties. These compounds may be explored for their potential in developing antiviral and antibacterial drugs[100].

6.1.4. Anticoagulant and Antithrombotic Effects: Brown algae-derived sulfated polysaccharides, like fucoidans, have demonstrated anticoagulant and antithrombotic effects. These compounds may have applications in the development of medications to prevent or treat blood clotting disorders[101].

6.1.5. Anti-Diabetic Potential: Some brown algae compounds, such as alginate, have shown potential in managing diabetes by influencing glucose absorption[102].

Research is ongoing to explore the anti-diabetic properties of brown algae-derived compounds[103].

6.1.6. Neuroprotective Effects: Compounds from brown

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algae, including fucoidans, have been investigated for their potential neuroprotective effects. These compounds may have applications in the development of drugs for neurodegenerative diseases[104].

6.1.7. Skin Health: Brown algae extracts are used in cosmetic and skincare products due to their potential benefits for skin health. Compounds such as fucoxanthin may have antioxidant and anti-aging effects on the skin[105].

6.1.8. Gastrointestinal Health: Alginate from brown algae has been explored for its potential in gastrointestinal health. It may have applications in the development of drugs for conditions such as gastroesophageal reflux disease (GERD)[106].

6.2. Therapeutic benefits:

6.2.1. Antioxidant and Anti-Inflammatory Properties: Brown algae contain polyphenols, fucoxanthin, and other compounds with antioxidant and anti-inflammatory properties. Antioxidants help neutralize free radicals, reducing oxidative stress, and anti-inflammatory effects may contribute to managing inflammation-related conditions[107].

6.2.2. Anticancer Properties: Compounds such as fucoidans derived from brown algae have shown promise in inhibiting the growth of cancer cells and inducing apoptosis (programmed cell death). Fucoidans may have potential applications in cancer prevention and treatment[108].

6.2.3. Antiviral and Antimicrobial Activity: Brown algae produce compounds with antiviral and antimicrobial properties. These compounds may have applications in preventing or treating viral infections and bacterial diseases[109].

6.2.4. Cardiovascular Health: Some brown algae-derived compounds, like fucosterol, may have potential benefits for cardiovascular health. These compounds may contribute to the regulation of cholesterol levels and support overall heart health[110].

6.2.5. Anticoagulant and Antithrombotic Effects: Sulfated polysaccharides, such as fucoidans, have demonstrated anticoagulant and antithrombotic effects. These compounds may be beneficial in preventing blood clot formation and reducing the risk of thrombosis[111].

6.2.6. Anti-Diabetic Potential: Alginate, a compound found in brown algae, has shown potential in managing diabetes by influencing glucose absorption. Research is ongoing to explore the anti-diabetic properties of brown algae-derived compounds[112].

6.2.7. Neuroprotective Effects: Compounds from brown algae, including fucoidans, have been studied for their potential neuroprotective effects. These compounds may have applications in protecting nerve cells and managing neurodegenerative diseases[113].

6.2.8. Gastrointestinal Health: Alginate from brown algae has been explored for its potential in gastrointestinal health. It may have applications in managing conditions such as gastroesophageal reflux disease (GERD)[114].

6.2.9. Skin Health: Brown algae extracts, containing compounds like fucoxanthin, are used in cosmetic and skincare products[115].

7- XANTHOPHYTA (YELLOW-GREEN ALGAE)

7.1. Xanthophyta (Yellow- green algae) in Drug Development:

7.1.1. Carotenoids and Antioxidants: Carotenoids are known for their antioxidant properties, which may have potential applications in health and wellness, although specific drug development is less commonly explored[116]. Yellow-green algae contain carotenoids and other antioxidants that contribute to their pigmentation. Some yellow-green algae species may have nutritional value, providing essential nutrients like proteins, vitamins, and minerals. While more commonly used in aquaculture and animal feed, their potential as nutritional supplements for humans are an area of interest[117].

7.1.2. Bioactive Compounds: Yellow-green algae may produce various bioactive compounds, including lipids, proteins, and polysaccharides. The exploration of these compounds for potential pharmaceutical applications is an area of ongoing research[118].

7.1.3. Bioremediation and Environmental Applications: Certain yellow-green algae have been studied for their potential in bioremediation, helping to remove pollutants from water bodies. Their ability to absorb heavy metals and other contaminants may find applications in environmental cleanup efforts[119].

7.2. Therapeutic benefits:

7.2.1. Antioxidant Properties: Yellow-green algae contain carotenoids and other antioxidants, which may help neutralize free radicals in the body. Antioxidants play a role in reducing oxidative stress and are associated with various health benefits[120].

7.2.2. Nutritional Value: Some yellow-green algae species may have nutritional value, providing essential nutrients such as proteins, vitamins, minerals, and fatty acids. Incorporating these algae into the diet may contribute to overall nutritional well-being[121].

7.2.3. Anti-Inflammatory Effects: Certain bioactive compounds in yellow-green algae may exhibit anti-inflammatory properties. Managing inflammation is important for various health conditions, and compounds with anti-inflammatory effects could have therapeutic applications[123].

7.2.4. Immune System Support: The nutritional content of yellow-green algae may contribute to supporting the

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immune system. Essential nutrients play a role in maintaining immune function, and certain bioactive compounds may have immunomodulatory effects[124].

7.2.5. Cardiometabolic Health: If yellow-green algae contain bioactive compounds like omega-3 fatty acids, they may contribute to cardiovascular health. Omega-3 fatty acids are associated with heart health, and their presence in certain algae may have potential benefits[125].

7.2.6. Bioremediation and Environmental Health: While not directly related to human health, the ability of some yellow-green algae to absorb pollutants may indirectly contribute to environmental health. A cleaner environment can have positive impacts on human well-being[126].

II. BIOACTIVE COMPOUNDS FOUND IN ALGAE:

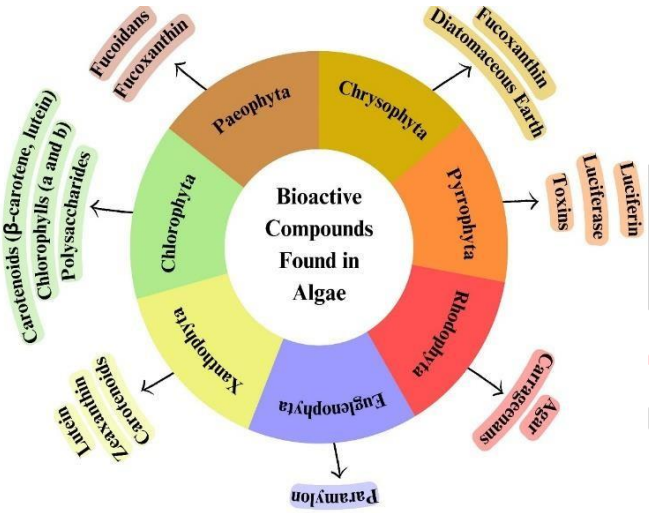

Figure 1: Bioactive Compounds Found in Algae

Bioactive compounds found in different types of algae can vary widely, and the specific compounds depend on the species and environmental conditions. Here's a general overview of potential bioactive compounds found in each of the mentioned algal groups[127]:

1. Euglenophyta (Euglenoids):

1.1. Paramylon: Paramylon is a type of β-glucan found in the cytoplasm of Euglenoids. It has potential immunomodulatory effects and may act as a dietary fibre[128].

2. Chrysophyta (Golden-Brown Algae and Diatoms):

2.1. Fucoxanthin: Fucoxanthin is a carotenoid present in brown algae, including some members of the Chrysophyta group. It has antioxidant properties and potential applications in weight management[129].

2.2. Diatomaceous Earth: Diatoms, a subgroup of Chrysophyta, have silica-based cell walls. Diatomaceous earth derived from diatoms is used in various industrial applications and as a dietary supplement[130].

3. Pyrrophyta (Fire Algae or Dinoflagellates):

3.1. Luciferin and Luciferase: Some dinoflagellates are bioluminescent and produce luciferin and luciferase for their light-emitting reactions. These compounds are used in biotechnology and molecular biology for imaging and diagnostic purposes[131].

3.2. Toxins: Certain dinoflagellates produce toxins responsible for harmful algal blooms. These toxins can have harmful effects on aquatic organisms and humans but are also studied for potential therapeutic applications[132].

4. Chlorophyta (Green Algae):

4.1. Chlorophylls: Green algae contain chlorophylls a and b for photosynthesis. Chlorophylls have antioxidant properties and may have health benefits[133].

4.2. Carotenoids: Carotenoids such as β-carotene and lutein are present in green algae. These compounds contribute to the antioxidant capacity of green algae[134].

4.3. Polysaccharides: Green algae produce various polysaccharides with potential immunomodulatory effects[135].

5. Rhodophyta (Red Algae):

5.1. Carrageenans: Red algae are known for producing carrageenans, sulfated polysaccharides. Carrageenans have applications in food, pharmaceuticals, and biotechnology due to their gelling properties[136].

5.2. Agar: Agar, another polysaccharide, is derived from red algae and is widely used in microbiology and the food industry[137].

6. Paeophyta (Brown Algae):

6.1. Fucoidans: Brown algae, including members of Paeophyta, produce fucoidans. Fucoidans have anticoagulant, antiviral, and anticancer properties[138].

6.2. Fucoxanthin: Fucoxanthin, a brown pigment, is present in brown algae. It has antioxidant properties and may have potential health benefits[139].

7. Xanthophyta (Yellow-Green Algae):

7.1. Carotenoids: Xanthophyta contain carotenoids, contributing to their yellow-green coloration. Carotenoids have antioxidant properties and potential health benefits[140].

7.2. Lutein and Zeaxanthin: Yellow-green algae may contain lutein and zeaxanthin, carotenoids important for eye health[141].

III. PRODUCTION OF PHARMACEUTICALS AND THERAPEUTIC PROTEINS :

Microalgae (especially C. reinhardtii) are viable options to be used as vaccine transporters as they are safe and contain a single chloroplast, which expresses proteins with high accumulation. Such examples of these recombinant proteins are E2 protein, which is used in the vaccines against classical swine fever virus, D2-CTB fusion protein (D2 fibronectin- binding domain of S. aureus containing cholera toxin B subunit), which is used in the oral vaccine against S. aureus, and E7 oncoprotein, which is applied in

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the human papillomavirus (HPV) vaccines. In a study in this regard, Dermutas et al. inserted the gene of HPV16 E7 protein into the genome of C. reinhardtii chloroplast, which expressed E7GGG protein for therapeutic vaccines. Therefore, the microalgae were reported to be a proper alternative of plant hosts[142].

A. Monoclonal antibodies: Today, most monoclonal antibodies are produced in Chinese hamster ovary cell lines and are highly costly and associated with the risk of contamination with human pathogens. Owing to their benefits, microalgae are considered to be effective alternative host cells[143]. These eukaryotic microorganisms are superior to bacterial cells in the post-translational modifications of human recombinant proteins. Furthermore, they are preferred to other eukaryotic hosts given their high growth rate, convenient handling, and simple culturing[144]. In research, Hampel et al. produced a monoclonal IgG antibody in engineered Phaeodactylum tricornutum against the nucleoprotein of Marburg virus, which is a leading cause of hemorrhagic fever in western Africa[145].

B. Antimicrobial agents: Several microalgae extracts have antiviral, antibacterial, antifungal, and antiprotozoal properties. Such examples are indoles, phenols, fatty acids, and volatile halogenated hydrocarbons. In addition, blue- green algae such as Ochromonas sp. and Prymnesium parvum produce toxins with pharmaceutical applications[146].

C. Antiviral activities: In general, viral infections are divided into three stages. The first stage involves attachment and the penetration of the virus into the host cell, the second stage is the replication of the virus in the host cell, and stage three is the release of the virus particles from the cell[147]. The antiviral compounds of microalgae affect different stages of viral infections. For instance, sulfated polysaccharides interfere with the first stage. In a study in this regard, Hayashi et al. could extract a monogalactosyl diacylglycerol (MGDG) from Coccomyxa sp., which caused physical changes in HPV to envelop. As a result, the virus could not attach to the host cell, indicating the antiviral effects of MGDG[148].

D. Antibacterial activities: Today, antibiotic resistance is considered to be a significant challenge in the treatment of infectious diseases. Therefore, it is essential to discover novel antibiotics[149]. In a study, Pratt et al. produced a mixture of fatty acids from Chlorella, which exerted inhibitory effects on bacteria[150]. It seems that the free fatty acids extracted from microalgae are able to kill or inhibit the growth of different gram-positive and gram-negative bacteria. In addition to the antibacterial activity of microalgae, biocompounds have exhibited antibiofilm activities, which play a key role in the treatment of infectious diseases[151]. For instance, Streptococcus mutans and Lactobacillus sp. are two bacteria that form biofilm on teeth and cause the formation of dental plaque. C. vulgaris and D. salina extracts could inhibit biofilm formation and prevent dental caries. According to the study by Santoyo et al., the short-chain fatty acids extracted from Haematococcus pelvis have antibacterial activities against E. coli and S. aureus, and the solvent used for their extraction could affect the intensity of their antibacterial activities[152]. In this regard, Bhagavathy et al. reported that Chlorococcum humicola extracts exerted different antibacterial effects on six bacteria[153]. In the mentioned study, this antibiotic activity was associated with the presence of phenol compounds and pigments such as β-carotene and chlorophyll II, which are the pigments extracted from Chlorococcum humicola with antibacterial effects against Vibrio cholera, Salmonella typhimurium, S. aureus, and Bacillus subtilis[154].

E. Anti-inflammatory and Anticancer properties: Some carbohydrates, lipids, and phycobiliproteins that are extracted from microalgae have shown antiproliferative and apoptotic effects on various cancers. Fucoidan is a sulfated polysaccharide, which is extracted from different microalgae, such as Fucus vesiculosus, Sargassum henslowianam, Cladosiphon fucoidan, and Coccophora longsdorfii, which inhibit angiogenesis and metastasis through the down- regulation of kinase activity and activation of caspase-3/7 in the human lymphoma cell line, melanoma, human colon cancer, breast cancer, lung carcinoma, and human promyeloid leukemia[155]. In research in this regard, Miceliet al. reported that the monoacylglycerides extracted from Skeletonema marinoi could induce selective apoptosis through the activation of caspase-3/7 in the colon cancer cell line (HCT-116) and hematological cancer cell line (U-937), while no apoptosis was induced in normal cells[156]. Furthermore, some microalgae lipids (e.g., polyunsaturated fatty acids) have shown antitumor activities against cervical and breast cancer[157]. Phycocyanin is a phycobiliprotein extracted from microalgae such as Arthronema africanum, Spirulina platensis, and Porphyra haitanensis, which inhibit the growth of human hepatocellular carcinoma, lung/colon cancer, and leukemia cells[158].

IV. MICROALGAE AND COVID-19 TREATMENT

Currently, coronavirus disease (COVID-19) is the most important health issue across the world, and there is an urgent need for finding effective treatments for this disease and preventing hundreds of thousands of deaths[159]. Studies have indicated that the acute respiratory distress syndrome (ARDS) resulted from the cytokine storm syndrome is a major cause of death in COVID-19 patients[160]. In cytokine storm, the level of pro-inflammatory cytokines (IL-1, IL-6, TNF-α) and chemokines (CCL2, CCL3, CXCL10, CXCL9) increase, thereby causing the hyperactivity of the immune system and acute lung injury (ALI). Astaxanthin is a carotenoid with anti-inflammatory, immunomodulatory, and antioxidative properties, as well as other therapeutic

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activities. Haematococcus pluvialis is a microalga and a natural source of astaxanthin[161]. Studies have indicated that the administration of this carotenoid to COVID-19 patients could alleviate cytokine storm, thereby preventing ARDS and ALI[162].

Lectins are proteins that attach to specific mono and oligosaccharides[163]. Cyanovirin-N is a lectin extracted from cyanobacteria (Nostoc ellipsosporum), which has exhibited anti-viral activities against HIV, influenza, and the Ebola virus[164]. Carrageenan is a sulfated polysaccharide of microalgae origin, which is able to inhibit the attachment, transcription, and replication of viruses in host cells[165]. In a study, Koenighofer et al. produced a nasal spray containing zanamivir (antiviral drug), and carrageenan was reported to exert synergistic effects on the influenza virus[166].

Spirulina is a blue-green microalgae with high protein content, several vitamins, γ- linolenic acid, and tocopherol[167]. In addition, Spirulina has nutritional and therapeutic applications and is referred to as a 'superfood'. Studies have indicated that these microalgae have potent antiviral activities. Calcium spirulan is a polysaccharide derived from spirulina, which inhibits the replication of several viruses, such as influenza, mumps, and HIV[168]. Furthermore, S. platensis could activate the immune system against viruses through the activation of immune cells and inducing the production of interferon-gamma, which is an important cytokine with antiviral activity[169]. Phycocyanin is also a pigment obtained from spirulina and an inhibitor of NADPH oxidase with anti-inflammatory activity[170]. It seems that microalgae (especially Spirulina) are effective candidates for the adjuvant therapy of COVID-19 patients[171].

V. MECHANISMS OF PHARMACHOLOGICAL ACTION AND DRUG APPLICATION:

Bactericidal and bacteriostatic compounds were first isolated from algae when chloroform and benzene fatty acid extracts of chlorellin, from Chlorella vulgaris, were found to inhibit Pseudomonas aeruginosa, Staphylococcus aureus, Streptococcus pyogenes, and Bacillus subtilis. Chlorellin was not suitable for large scale commercial use, however it heralded further research into algal antimicrobial inhibitors in genera such as Scenedesmus[172]. As discussed, several chemical functional groups in algae, such as phlorotannins, fatty acids, peptides, terpenes, polysaccharides, polyacetylenes, sterols, indole alkaloids, aromatic organic acids, shikimic acid, polyketides, hydroquinones, alcohols, aldehydes, ketones, and halogenated furanones have been reported as bacterial inhibitors[173]. The mechanism of pharmacological action for some remains uncertain, however, methods of bacterial inhibition employed by the following functional groups have been proposed[174].

1. Phlorotannins:

Phlorotannins occur in fucosan granules called physodes within algal cells and comprise 1%–15% of the thallus dry mass. The antibacterial activity of phlorotannins has been reported to be due to inhibition of oxidative phosphorylation, and their ability to bind with bacterial proteins such as enzymes and cell membranes, causing cell lysis[175]. The phenolic aromatic rings and OH groups of the phloroglucinol units bind to the -NH groups of bacterial proteins by H-bond and hydrophobic interactions. Kamei and Isnansetyo reported that the bacteriolytic activity of phloroglucinol compounds against Vibrio species increased when tertiary structures such as methyl- or acetyl-vinyl were present. However, a greater minimum inhibitory concentration (MIC) was required to penetrate the Gram-negative species, Vibrio parahaemolyticus, compared to the Gram-positive MRSA[176]. This is the case for most antibacterials, due to physiological differences in β-lactamase mechanisms, and the less penetrable nature of the outer lipopolysaccharide membrane of Gram-negative species in comparison to the peptidoglycan Gram-positive layer. reported that low molecular weight phlorotannins extracted from Sargassum thunbergii damaged the cell membrane and cell wall of Vibrio parahaemolyticus, causing cytoplasm leakage and deconstruction of membrane permeability[177]. The study suggested that low molecular weight phlorotannins from algae could potentially be used in food safety control and aquacultural drugs. Lee et al. tested a range of solvent extracts from the brown seaweed, Arame (Eisenia bicyclis) against antibiotic resistant Propionibacterium-related acne[178]. A phlorofucofuroeckol compound (phlorotannin with an alcohol substituent) exhibited the most potent antibacterial activity with an MIC of 32 μg/mL, while also significantly reversing the resistance of Propionibacterium to erythromycin and lincomycin[179]. The same research group tested the activity of phlorofucofuroeckol from Eisenia bicyclis against MRSA. Phlorofucofuroeckol suppressed mecI, mecR1, and mecA gene expression in the resistant Staphylococcus aureus cells[180]. These three genes regulate the expression of methicillin resistance in bacteria. This resulted in suppression of penicillin-binding protein 2a production, which is considered the main mechanism by which MRSA strains resist methicillin. Phlorotannins and their derivatives offer a potentially useful source of natural antibacterial agents for food and medical applications[181].

2. Fatty Acids:

Algal free fatty acids have been reported to act as inhibitors of the electron transport chain and normal oxidative phosphorylation in bacterial cell membranes. This interferes with adenosine triphosphate energy transfer, and inhibits enzymes such as bacterial enoyl-acyl carrier protein reductase, necessary for the synthesis of

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fatty acids within the bacterial cell. Lysis of the cell, and formation of peroxidation and auto-oxidation degradation products then occurs[182]. El Shafay et al. identified the antibacterial fatty acids, cyclopentaneacetic acid, and 10,13-octadeadienoic acid as principal components of ethanol extracted Sargassum vulgare and diethyl ether extracted Sargassum fusiforme. Transmission electron microscopy was used to measure the morphological changes in Staphylococcus aureus and Klebsiella pneumoniae cells treated with these brown seaweed extracts[183]. The cell walls of both bacteria were perforated, resulting in rupture of the cell wall, cytoplasmic leakage, shrinking of the protoplasm, cytoplasmic vacuolation, scattering of chromatin, distortion of the outer cell shape, and decreased cell size. Čermák et al. reported the antibacterial long-chain fatty acids in the green microalga Planktochlorella nurekis to be significant inhibitors of Campylobacter jejuni, Escherichia coli, Salmonella enterica var. Enteritidis, Salmonella enterica var[184]. Infantis, Arcobacter butzleri, and Lactobacillus johnsonii using a suspension concentration range of 0.75–6 mg/mL. The study proposed that green microalgae could be used as an alternative to in-feed antibiotics to prevent disease in livestock and poultry and to maintain the microbial safety of animal products in the human food chain[185].

3. Polysaccharides:

Polysaccharides are composed of repeating monosaccharide units linked by glycosidic bonds. They function primarily as structural storage compounds in plants and algae. Algal polysaccharides and sulphated polysaccharides have been used successfully for pharmaceutical and dietary applications[186]. Their mechanism of antibacterial action is proposed to be due to glycoprotein-receptors present on the cell-surface of polysaccharides which bind with compounds in the bacterial cell wall, cytoplasmic membrane, and DNA. This results in increased permeability of the cytoplasmic membrane, protein leakage, and binding of bacterial DNA[187]. Polysaccharides, such as fucoidan and laminarin, have been successfully used in drug delivery as oral antibiotics to inhibit the growth of Staphylococcus aureus and Escherichia coli; and to prevent the adhesion of Helicobacter pylori biofilms in gastric mucosa. They have also been incorporated into food as a dietary supplement to improve the immune response of farmed fish, and reduce susceptibility to Piscirickettsia salmonis infection[188].

Kadam et al. reported a significant inhibition of Staphylococcus aureus, Listeria monocytogenes, Escherichia coli and Salmonella typhimurium growth with ultrasound assisted extraction of laminarin from the Irish brown seaweeds Ascophyllum nodosum and Laminaria hyperborea using 0.1 M hydrochloric acid. Abou Zeid et al. demonstrated that hot and cold water-extracted polysaccharides from the red seaweed Pterocladia capillacea and brown seaweed Dictyopteris membranacea inhibit the growth of Gram- positive Bacillus cereus and Staphylococcus aureus, and Gram-negative Pseudomonas fluorescens and Escherichia coli in disc diffusion assays[189]. In the case of Staphylococcus aureus, cold water-extracted Pterocladia capillacea had an activity equivalent to 56.8% of the antibiotic standard, ampicillin[190]. Vijayabaskar et al. found that sulphated polysaccharides extracted from Sargassum swartzii inhibited both Gram-positive and Gram-negative bacteria in ten human pathogenic strains. In the case of Escherichia coli, the polysaccharide extract was more potent in the disc diffusion assay than an ampicillin antibiotic standard[191].

4. Proteins and Peptides:

The antimicrobial activity of amino acids in the form of short- chain peptides, or larger, more complex proteins, has been demonstrated in a number of recent studies[192]. The amphipathic conformation of peptides enables them to bind with polar and non-polar sites on bacterial cytoplasmic membranes, thereby interfering with cellular processes and propagation[193].

Lectins, for example, are a diverse group of proteins that occur in animals, plants, algae, bacteria, and viruses. In humans, they have multiple biological functions including carbohydrate-binding, cell adhesion, blood-protein regulation, and immune defence[194]. The ability of lectins to selectively bind with lipopolysaccharides, β-glucans, and peptidoglycans on the cell surface of bacteria affords them bactericidal properties, as normal cell processes such as nutrient uptake are blocked[195]. Several functional groups are involved. Hydrogen bonds are formed between polar moieties of amino acids in the lectins and the hydroxyl groups of polysaccharides, coupled with van der Waals interactions, and packing of hydrophobic polysaccharide regions against amino acid aromatic groups in the lectins[196]. Holanda et al. evaluated the inhibitory effect of lectin extracts from the red alga Solieria filiformis against Gram-negative and Gram- positive pathogenic bacteria. At a concentration of 1000 µg/mL, the extract inhibited growth of the Gram-negative species Pseudomonas aeruginosa, Enterobacter aerogenes, Serratia marcescens, Salmonella typhi, Klebsiella pneumoniae, and Proteus species[197]. The binding of lectin with mannan was believed to be the method by which growth was inhibited. Mannan is a linear polymer of the saccharide monomer mannose, and occurs on the cell surface of Gram- negative bacteria. Mannan acts as a hapten upon binding with the large lectin molecule, eliciting an immune response. However, no inhibition of growth was observed against the Gram-positive Staphylococcus aureus and Bacillus subtilis, possibly due to unsuitable lectin-polysaccharide binding sites on the cell surfaces of these species[198].

Enzymatic hydrolysis is the most common method used to

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isolate bioactive peptides from parent proteins for medical applications, thus avoiding toxic solvent residues. The bioactivity of individual peptide hydrolysates is often distinct from, or greater than that of the original protein. Some recently characterised peptides have been termed crypteins, due to their cryptic, or hidden, bioactivity, and are a current area of novel therapeutic study. Marine algae are good candidates for the mining of such peptides as they contain a high proportion of diverse proteins[199].

Beaulieu et al. extracted antibacterial peptides (>10 kDa mass) from the brown seaweed Saccharina longicruris by enzymatic hydrolysis with trypsin. Liquid chromatography- tandem mass spectrometry identified the sub-fractions as peptide precursors to proteins similar to ubiquitin, leucine, histone, and a ribosomal structure, which form part of the innate immune defence of the seaweed[200]. Maximum specific growth rate of the food spoilage bacterium Staphylococcus aureus was significantly inhibited by the hydrolysate at concentrations of 0.31 mg/mL to 2.5 mg/mL making it a potential agent for food preservation[20].

5. Terpenes:

Terpenes are compounds composed of repeating isoprene units, often with substituent groups. Terpenes with pharmacological activity have been successfully extracted from terrestrial plants. For example, paclitaxel (or taxol) from Pacific yew trees is used in cancer treatment, and Artemisinin from the plant Artemisia annua is an anti-malarial drug[20]. A number of terpene compounds from algae, such as diterpene-benzoate bromophycolides, have been found to inhibit bacterial growth. Lane et al. extracted bromophycolides (diterpene-benzoate macrolides) from the Fijian red alga Callophycus serratus with water, methanol, and dichloromethane. Extracts significantly inhibited MRSA and vancomycin-resistant Enterococcus faecium, with maximal inhibitory concentration (IC50) values of 1.4 µM and 5.8 µM respectively[3]. Their findings suggested that the mechanism of antibacterial action was due to the hydrophobicity and conformational rigidity of the tetrahydropyran structure. Rodrigues et al. used dichloromethane to isolate sphaerane bromoditerpenes, including a previously uncharacterised, rare dactylomelane called sphaerodactylomelol, from the red alga Sphaerococcus coronopifolius[4]. The extracts were found to inhibit Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus, and Candida albicans. The greatest antibacterial was observed against Staphylococcus aureus, with an IC50 value of 6.35 µM. Etahiri et al. isolated bromosphaerone and 12S-hydroxybromosphaerodiol from the same alga, Sphaerococcus coronopifolius[5]. Bromosphaerone and 12S-hydroxybromosphaerodiol inhibited Staphylococcus aureus with MIC values of 0.104 µg/mL and 0.146 µg/mL respectively. It was proposed that the antibacterial activity of bromosphaerone was due to its amphipathic structure of three polar alcohol groups, with non-polar aliphatic carbon and bromine atoms on the opposite side of the molecule, enabling it to bind with bacterial cell membranes [26].

Xanthophylls, such as lutein and astaxanthin, are tetraterpene oxygen-containing compounds that function as light harvesting pigments in plants and algae. They have been extensively documented for their antioxidant activity, but are also effective against bacteria[27]. Fucoxanthin is a xanthophyll that occurs predominantly in brown algae (Phaeophyceae), diatoms (Bacillariophyceae), and at lower concentrations in golden algae (Chrysophyceae) and Raphidophyceae[27]. Rajauria and Abu-Ghannam extracted fucoxanthin from the Irish brown seaweed Himanthalia elongata using diethyl ether, n-hexane, and chloroform, and purified the crude extract using preparative TLC. In disc diffusion assays, the purified extract was shown to be a potent inhibitor of Listeria monocytogenes, with an inhibition zone of 10.27 mm at a concentration of 1 mg/mL (25 µg/disc). The extract was 98.4% as effective as an analytical grade fucoxanthin standard (inhibition zone 10.89 mm)[208]. Similarly, Deyab and Abou-Dobara extracted fucoxanthin from the brown seaweed Turbinaria triquetra, the green Ulva lactuca, and the red Laurencia obtusa with chloroform and methanol. Extracts were purified by silica column chromatography and identified by nuclear magnetic resonance spectroscopy[29]. Turbinaria triquetra showed the greatest bacterial inhibition, followed by Laurencia obtusa. Ulva lactuca extracts had significantly lower antibacterial activity. Zones of inhibition for Escherichia coli, Bacillus cereus, Bacillus subtilis, Klebsiella pneumoniae, Staphylococcus aureus, and Pseudomonas aeruginosa ranged from 4.0 mm to 7.0 mm (100 µg/mL extract/disc) and in the case of some Gram-negative species, were equivalent to antibiotic standards[10].

6. Chrysophaentins:

Plaza et al. isolated eight compounds from the chrysophyte alga Chrysophaeum taylori using hexane, chloroform, and methanol. The compounds were of a new chemical structural class which they named chrysophaentins, which consisted of two polyhydroxylated, polyhalogenated ω,ω′-diarylbutene units connected via two ether bonds. The chrysophaentins exerted powerful inhibition in vitro of MRSA (MIC = 1.5 µg/mL), vancomycin-resistant Enterococcus faecium (MIC = 2.9 µg/mL), and multidrug-resistant Staphylococcus aureus (MIC = 1.3 µg/mL)[11]. The pharmacological mechanism of action of chrysophaentin is proposed to be unlike any existing antibacterial agent. The functional groups within chrysophaentin act as enzyme inhibitors by binding with guanosine triphosphatase in bacterial cells. This prevents the synthesis of a protein called FtsZ

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(filamenting temperature- sensitive mutant Z), required for bacterial cell division. The development of antibiotics and other antibacterial products from chrysophaentin continues to be an important area of marine pharmacological investigation[12].

7. Lactones:

Lactones are a chemical class of cyclic esters, which includes furanones. The Australian red seaweed Delisea pulchra has been studied for its ability to remain free of surface bacterial colonisation[13]. Halogenated furanone extracts from Delisea pulchra have been used as effective surface sanitisers in the prevention of Pseudomonas aeruginosa biofilm formation. This halogenated furanone also inhibits quorum sensing mechanisms by interfering with bacterial inter-cell communication[14]. In order for bacteria to express specific genes during quorum sensing, signalling molecules called acyl-homoserine lactones (AHLs) are required, as well as luminescence transcriptional activator (LuxR) regulatory proteins. The furanone extract from Delisea pulchra competes with AHL for the LuxR receptor site, thereby inhibiting virulence factor production and pathogenesis coli was inhibited by blocking S-ribosylhomocysteine lyase (LuxS) mediated AI-2 signalling. This influences genes and proteins involved in the normal production of flagellar synthesis, motility, and chemotaxis in the bacterium. Manefield et al. identified another mechanism of inhibition exerted by a halogenated furanone from Delisea pulchra[16]. The bacterium, Erwinia carotovora, produces carbapenem as a virulence factor during quorum sensing. A commercially available 4-bromo-5-(bromomethylene)-3-(1′- hydroxybutyl)-2(5H)-furanone was found to inhibit carbapenem production in Erwinia carotovora by disrupting the 3-oxo-C6-HSL dependent expression of the carABCDEFGH operon[17]. Castillo et al. also reported that a commercially produced furanone, similar to the Delisea pulchra extract, was effective against Gram-negative Campylobacter jejuni. When combined with epigallocatechin gallate from green tea and a citric acid extract, AI-2 activity, bacterial motility, and biofilm formation was significantly decreased[18].

Considering the efficacy of the Delisea pulchra extract against the Gram-negative Pseudomonas aeruginosa and Escherichia coli in vitro, it is not unreasonable to propose that it could also inhibit Gram-negative Campylobacter jejuni[19]. Algal furanones and other lactones may have potential as alternatives to synthetic surface sanitisers, and antibiotics. Campylobacter jejuni and Escherichia coli are two of the leading causes of food poisoning worldwide, and have developed resistance to many traditional antibiotics[20]. The demonstrated ability of algal furanone extracts to prevent biofilm formation may be useful in the treatment of Pseudomonas aeruginosa infection, which is characterised by the formation of a mucoid film in the lungs of cystic fibrosis sufferers. Pseudomonas aeruginosa is also an increasing risk to the immunocompromised, such as premature babies, and long-term hospital patients[21].

Algal polysaccharides, fatty acids, peptides, proteins, phlorotannins, terpenes, chrysophaentins, and lactones make good candidates for antibiotics, and incorporation into human food products for safety and preservation as they are edible, non-toxic, and inexpensive[22]. Further research, including in vivo toxicology studies, into these antibacterial extracts could produce very useful food preservation and pharmaceutical products[23].

VI. SUSTAINNABILITY AND COMMERCIALIZATION OF ALGAL DRUG PRODUCTS

The global commercial Potential, Market Space, and Sustainability of algae Products Apart from recognitions of algae for their nutritional importance, algae are increasingly pushed into the market as “functional foods” and/or “nutraceuticals,” which relates to the additional benefits beyond basic nutrition[24]. When compared to the total market size of food and feed products derived from all thenutraceutical. In 2009, the astaxanthin market for animal feed was $ 300 million, and for nutraceuticals was $30 million. Now, the global astaxanthin market is expected to reach USD 2.57 billion by 2025[26]. Natural astaxanthin from H. pluvialis is expected to dominate the market and reach US$ 770 million by 2024, at a robust CAGR of 7.7%. The share of H. pluvialis natural astaxanthin (in nutraceutical industry) in 2017 was noted to be the largest with 54.8% contribution, and is expected to reach the production of 190 metric tons by 2024. In 2015, the β-carotene market was estimated to be US$ 432.2 million with 35.5% revenues from algae-derived β-carotene, and has witnessed a significant growth since then[27]. Australia, due to the presence of various salt lakes and rivers, remains the major producer of natural β-carotene from D. salina. Another carotenoid- fucoxanthin production was about 500 tonnes in 2015, and it is expected to reach at 5.3% CAGR by 2021. The overall EPA/DHA market size (produced from all sources) expects gains at over 11% to exceed US$ 4 billion by 2022[28]. It is predicted that the algae oil demand of the industries dealing in EPA/DHA should witness significant gains at over 8% . Preference to the products of plant-based formulations will drive the consumption of algae oil in the segment of product formulations. Sustainability issues pertaining to the penetration and performance of the algal products into the market arise mainly due to the varying global biomass production, which can be attributed to the climate variability[229]. Various incidences such as flood and tornado especially in China have affected the production and supply of Spirulina. The climate change is affecting Spirulina market and causing reduced revenues for many companies. Various energy

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intensive processes in algal technologies can be operated through solar-powered electricity, which accounts for reduced energy footprint and improve environmental performance[30]. Further, complex cultivation and production, and lack of awareness about algal products are hindering the growth of this market to some extent. However, the market sustainability for the algal products is driven mainly due to the demand for algal ingredients in nutraceutical and pharmaceutical sectors, consideration of algae-based natural pigments over the synthetic one, and the algae as a vegan source[31]. Also, increasing healthcare awareness, use of herbal cosmetics, and the demand for plant-based nutraceuticals remains the driving factors for the sustainable growth of this industry. The sustainability of microalgal industry is also associated with the confidence of investors/promoters, which comes through the long-term market demand of algal products. Further, economically improved and environmentally sustainable processes with higher technology readiness level are necessary for sustained operation of algae possibles[32].

VII. LIMITATION AND CHALLENGES

Current Limitations and Challenges in Utilizing Algae-Derived Natural Products for Diabetes Management Despite the promising potential of algae-derived natural products in diabetes management, several limitations and challenges need to be addressed for their successful utilization. Understanding these challenges and finding suitable solutions is crucial for the future development and application of algae- based interventions[33]. Here, we discuss the current limitations and propose potential strategies for overcoming these challenges .One of the major challenges in utilizing algae-derived natural products is the lack of standardized extraction methods and quality control measures. Variations in algae species, growth conditions, harvesting methods, and extraction procedures can significantly impact the composition and bioactivity of the extracted compounds[34]. Establishing standardized protocols for algae cultivation, extraction, and quality control is essential to ensure consistent and reproducible results .

The bioavailability and pharmacokinetic profiles of algae-derived compounds are critical factors influencing their therapeutic efficacy. Some bioactive compounds may exhibit poor solubility, limited absorption, or rapid metabolism, leading to reduced bioavailability and efficacy. Strategies such as nanoencapsulation, formulation optimization, and prodrug approaches can be explored to enhance the bioavailability and pharmacokinetic properties of algae- derived compounds[35] .

1. Safety and Toxicity Assessment

While algae-derived natural products are generally considered safe, comprehensive safety evaluations are essential to determine the potential adverse effects and establish appropriate dosage guidelines. Toxicity studies, including acute and chronic toxicity assessments, should be conducted to ensure the safety of algae-based interventions [140]. Furthermore, long-term studies are needed to evaluate the potential for the accumulation of algae-derived compounds in tissues or organs[36].

Recent advances in the field of natural products derived from algae have brought about a growing awareness of their potential benefits. However, it is critical to pay attention to the importance of thorough toxicological studies. While algae-derived products are generally considered safe, contemporary research underscores the need for a nuanced understanding of their secondary metabolites and their potential effects on human health. Several studies have highlighted the intricate bioactive compounds present in algae, some of which might have physiological or toxicological implications that are yet to be discovered. Neglecting to communicate the potential risks associated with these secondary metabolites could inadvertently mislead the public into believing that algae-based interventions are entirely risk-free. Therefore, the current discourse emphasizes the necessity of comprehensive toxicological investigations to uncover any hidden adverse effects and to establish accurate risk assessments. By openly addressing these concerns, both researchers and the general public can make informed decisions regarding the utilization of algae- derived products, ensuring not only their efficacy but also their safety for human health[37].

2. Translation to Clinical Applications:

Although preclinical studies have shown promising results, the translation of algae-derived natural products to clinical applications faces several challenges. Rigorous clinical trials are necessary to validate the efficacy, safety, and optimal dosage regimens of algae-based interventions. Additionally, cost-effectiveness analyses and regulatory considerations should be considered to ensure their successful integration into clinical practice[38].

3. Sustainability and Scalability:

The sustainable production and scalability of algae-derived natural products are important considerations. Algae cultivation methods that minimize resource consumption, optimize productivity and reduce environmental impact need to be developed. Additionally, the establishment of large- scale cultivation facilities and extraction technologies is crucial for meeting the increasing demand for algae-based interventions[39].

Addressing these challenges requires interdisciplinary collaborations among researchers, industry partners, regulatory agencies, and healthcare providers. Overcoming these limitations and finding solutions will pave the way for the successful utilization of algae-derived natural products in diabetes management, ultimately benefiting patients worldwide[40].

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4. Strategies to Optimize the Therapeutic Potential of Algae-Based Interventions:

To optimize the therapeutic potential of algae-based interventions in diabetes management, several strategies can be employed. Addressing the challenges and implementing these strategies will contribute to the development of effective algae-based therapeutics. Here, we discuss potential approaches to optimize the therapeutic potential of algae- based interventions and improve their efficient[41].

5. Standardization and Quality Control:

Standardizing algae cultivation, harvesting, and extraction methods is crucial for ensuring the consistent composition and bioactivity of algae-derived natural products. Implementing quality control measures, such as standard operating procedures and rigorous testing, will enhance the reproducibility and reliability of algae-based interventions[42].

6. Formulation Optimization:

Developing appropriate formulations can improve the stability, solubility, and bioavailability of algae-derived compounds. Encapsulation techniques, such as nanoencapsulation or microencapsulation, can protect sensitive compounds, improve their delivery, and enhance their therapeutic efficacy. Formulation optimization also enables the controlled release and targeted delivery of bioactive compounds to specific tissues or organs[43].

7. Combination Therapy:

Exploring the synergistic effects of algae-derived compounds with existing antidiabetic drugs or natural products can lead to enhanced therapeutic outcomes. Combining algae-derived compounds with complementary mechanisms of action may potentiate their antidiabetic effects and improve overall glycemic control. Synergistic interactions can also help reduce drug dosage and minimize side effects[44].

8. Pharmacokinetic Enhancements:

Enhancing the pharmacokinetic properties of algae-derived compounds can improve their bioavailability and therapeutic efficacy. Strategies such as prodrug design, chemical modification, or co-administration with absorption enhancers can enhance drug absorption, distribution, metabolism, and excretion. Pharmacokinetic enhancements ensure optimal drug levels in target tissues and prolong the duration of action[45].

9. Personalized Medicine Approaches:

Taking individual patient characteristics, such as genetics, lifestyle, and comorbidities, into account can optimize the efficacy of algae-based interventions. Personalized medicine approaches can help tailor treatment regimens, dosage adjustments, and treatment durations to maximize therapeutic outcomes and minimize adverse effects[98].

Conducting well-designed translational research studies and large-scale clinical trials is essential for validating the safety and efficacy of algae-based interventions. Robust clinical evidence will enable the integration of algae-derived therapeutics into standard clinical practice and regulatory frameworks. These strategies require collaborative efforts among researchers, healthcare professionals, regulatory bodies, and industry partners to overcome the challenges associated with algae-based interventions and ensure their successful translation into clinical applications[23].

10. Future Prospects and Opportunities for Further Research and Development

The field of algae-based interventions in diabetes management holds immense potential for future research and development. Several opportunities and future prospects can further advance the utilization of algae-derived natural products. Here, we highlight the potential areas for exploration and opportunities for further research[248].

Despite significant progress, the full spectrum of bioactive compounds presents in algae and their potential effects in treating diabetes and its complications are yet to be fully explored. Further investigation into unexplored algae species and their unique metabolites may unveil novel bioactive compounds with potent antidiabetic properties. Advanced analytical techniques, such as metabolomics and proteomics, can facilitate the identification and characterization of these compounds[24].

Understanding the precise mechanisms of action underlying the antidiabetic effects of algae-derived compounds is crucial for their targeted development and optimization. Future studies should focus on elucidating the molecular pathways and cellular targets influenced by algae-derived natural products, shedding light on their therapeutic mechanisms. Advances in omics technologies and molecular biology tools can aid in unraveling the intricate mechanisms involved[50]].

11. Preclinical and Clinical Studies

Robust preclinical studies and well-designed clinical trials are essential for establishing the safety and efficacy of algae- based interventions. Future research should aim to conduct comprehensive preclinical investigations to validate the therapeutic potential of algae-derived compounds in the relevant animal models of diabetes and its complications. Subsequently, well-controlled clinical trials involving diverse patient populations will provide valuable insights into the efficacy, optimal dosage, and long-term effects of algae- based interventions[51]

12. Combination Therapies and Synergistic Approaches

Exploring the potential synergistic effects of algae-derived compounds with existing antidiabetic medications or natural products can enhance therapeutic outcomes. Combinatorial approaches involving algae-derived compounds and conventional antidiabetic drugs may lead

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to improved glycemic control and reduced side effects. Further investigation into synergistic interactions and combination therapies holds promise for enhanced therapeutic efficacy[22].

VIII. CONCLUSION

The exploration of algae in drug development has unveiled a promising avenue for therapeutic benefits that extend across various medical domains. Algae, with its rich biochemical composition and diverse bioactive compounds, has demonstrated remarkable potential in the pharmaceutical realm. From anti-inflammatory agents to antioxidants, antimicrobial compounds to anticancer substances, algae- derived drugs have showcased their versatility and efficacy. The therapeutic benefits of algae-derived drugs are not limited to just one area of medicine; instead, they span a wide spectrum, offering solutions for conditions ranging from chronic diseases to infectious ailments. The anti- inflammatory properties present in algae compounds hold promise for treating conditions such as arthritis and inflammatory disorders, while antioxidants contribute to combating oxidative stress and related diseases. Furthermore, the antimicrobial nature of certain algae compounds presents opportunities for developing novel antibiotics to counteract evolving drug-resistant pathogens. Algae's role in cancer therapy is particularly noteworthy, with compounds showing potential in inhibiting tumour growth and inducing apoptosis in cancer cells. Additionally, the immunomodulatry effects of algae-derived substances may pave the way for innovative approaches in autoimmune disease management. The sustainable nature of algae cultivation adds an environmentally friendly dimension to drug development[27]. As an abundant and rapidly renewable resource, algae stand out as a potential solution to address the growing demand for pharmaceuticals while minimizing the ecological impact. Despite these promising advancements, continued research and development are crucial to fully harness the therapeutic potential of algae. This includes refining extraction methods, optimizing drug formulations, and conducting rigorous clinical trials to ensure safety and efficacy in human subjects. Collaboration between researchers, pharmaceutical companies, and environmental advocates will play a vital role in advancing algae-derived drugs from the laboratory to the market. One of the key therapeutic avenues explored in algae-derived drugs is their potent anti-inflammatory properties. Algae compounds have demonstrated the ability to modulate inflammatory responses, suggesting their potential in treating chronic inflammatory conditions such as arthritis and inflammatory disorders. The anti-inflammatory effects may be attributed to specific bioactive molecules, opening up new possibilities for drug development in areas where current treatments fall short. Moreover, the antioxidant potential of algae-derived compounds has garnered significant attention in the pharmaceutical realm[254]. Oxidative stress plays a pivotal role in the development of various diseases, including neurodegenerative disorders and cardiovascular conditions. Algae-derived antioxidants offer a natural and sustainable source to counteract oxidative damage, providing a novel approach to prevent and manage these health challenges. In the realm of infectious diseases, algae's antimicrobial properties hold promise for the development of new antibiotics. With the rise of drug-resistant pathogens posing a global health threat, the search for alternative antimicrobial agents has become imperative. Algae, with their diverse array of bioactive molecules, present a potential source for developing effective antimicrobial drugs that can combat evolving infectious agents. Beyond therapeutic benefits, the sustainable nature of algae cultivation adds an eco-friendly dimension to drug development. Algae are abundant, rapidly renewable, and can be cultivated in various environments, making them an environmentally responsible choice for pharmaceutical production. This sustainable approach aligns with the growing global awareness of the need for greener practices in the pharmaceutical industry[255]. algae offer a diverse array of compounds with pharmaceutical potential, making them a compelling area for drug development and therapeutic exploration. Red algae, for instance, are rich in sulfated polysaccharides known for their antiviral and anti-inflammatory properties, while brown algae contain unique compounds like fucoidans, which exhibit anticoagulant and anticancer activities. Green algae, such as Chlorella and Spirulina, are recognized for their high protein, vitamin, and antioxidant content, making them valuable as functional foods and potential adjuncts in treating conditions like hyperlipidemia and oxidative stress-related disorders. Furthermore, the cultivation of algae is environmentally sustainable and scalable, offering a renewable source of bioactive compounds for pharmaceutical and nutraceutical applications. As research continues to unravel the therapeutic potential of algae and optimize production methods, they stand poised to make significant contributions to healthcare and well-being[200].

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