Journal of Bioresources 11 (2): 40-46, April – June 2024

JOURNAL OF BIORESOURCES

journal webpage: https://jbr.rgu.ac.in

ISSN: 2394-4315 (Print)
ISSN: 2582-2276 (Online)

REVIEW ARTICLE

Microalgae and their diverse applications: a review

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Article No.: PKNJBR87; Received: 25.02.2024; Revised: 29.05.2024. Accepted: 11-06-2024; Published: 30.06.2024.
Doi: https://doi.org/10.5281/zenodo.12578132

Abstract

Microalgae are one of the most abundant groups of aquatics, eukaryotic microorganisms on Earth. The phenomenal biodiversity in the oceans makes these microalgae the most valuable natural resource having huge significance. Today, microalgae found in different taxonomic groups are the most sustainable natural source of production of a wide variety of carotenoids including astaxanthin, β-carotene, lutein, lycopene, canthaxanthin and zeaxanthin. These are often referred to as the prospective feedstock for commercial production of carotenoids. Further, these microbes have great potential in the healthcare industry which ranges from nutraceutical benefits to immunomodulatory effects to anti-atherogenic effects on human health. Furthermore, even in terms of environmental sustainability, these organisms have proved to be advantageous in their role in biofuels production including biodiesel, and wastewater treatment. The high content of carotenoids and other components including minerals and vitamins makes these organisms a rich ingredient for the animal feed. Thus, this review article discusses the functional aspects of these microorganisms owing to their numerous benefits in various industries.

Keywords: Bio-manufacturing; Microalgae; Carotenoids; Bioinformatics; Enzymes

1. Introduction

Microalgae are diverse microscopic photosynthetic organisms that have gained significant attention in recent years. They are capable of converting carbon dioxide into valuable compounds through photosynthesis. These remarkable microorganisms are found in different taxonomic groups and hold immense promise for addressing global challenges ranging from environmental sustainability to human health. This introductory exploration delves into the fascinating world of microalgae. It sheds light on their taxonomy, biology, and the numerous applications emerging in sectors such as biofuels, bioremediation, food and nutrition, pharmaceuticals, and cosmetics. By analyzing recent research and advancements, this essay aims to highlight the incredible potential that microalgae offers as a sustainable resource and a source of innovation that could revolutionize our future (Tan et al., 2022). Microalgae, the varied assorted group of microorganisms, are classified under several species, including Chlorophyta, Bacillariophyta, and Cyanobacteria. They are unique in their ability to perform photosynthesis. This process converts solar energy into chemical energy and, in doing so; helps mitigate the ever-increasing levels of atmospheric carbon dioxide. Chlorophyll, the green pigment in microalgae cells, plays a pivotal role in capturing sunlight and converting it into organic compounds, including lipids, proteins, and carbohydrates. This fundamental ability to harness sunlight has prompted researchers to explore various ways to harness the untapped potential of microalgae for an array of applications.

One of the most pressing challenges of our time is the need for sustainable energy sources. Fossil fuels, which have been the primary energy source for centuries, are not only finite but also contribute significantly to global warming by releasing carbon dioxide when burned. Microalgae present an innovative solution to this predicament. They have been the focus of extensive research to develop biofuels, such as biodiesel and bioethanol, which can replace conventional fossil fuels. The lipids stored within microalgae cells are of particular interest, as they can be efficiently converted into biodiesel through a process known as transesterification. This potential for biofuel production from microalgae reduces greenhouse gas emissions and addresses the concerns of energy security and resource sustainability.

Moreover, microalgae offer significant promise in the field of bioremediation. Many species of microalgae can absorb and accumulate heavy metals, toxins, and pollutants from water bodies. This ability has led to their use in wastewater treatment and environmental cleanup efforts. Microalgae can not only help remove contaminants from aquatic ecosystems but can also be harnessed to remove carbon dioxide from industrial emissions. This dual capability of environmental remediation and carbon sequestration underscores their vital role in combating pollution and climate change.

This review aims to underscore the significance of microalgae and unveil their considerable potential in promoting environmental sustainability. This comprehensive examination will emphasize their capabilities in bioenergy, biopharmaceuticals, wastewater treatment, sustainable agriculture, and creating value-added products that mitigate the biodiversity crisis. The chapter also delves into the growing global microalgae market.

2. Algal biofuel

Exhausting fossil fuels, skyrocketing prices, increasing demand, and global climate change concerns have led researchers to explore alternative options for sustainable fuels. In this quest to find potential sources of biofuels, microalgae emerged as reservoirs of diverse biofuels ranging from biodiesel, ethanol, hydrogen, lipids, and straight vegetable oil (SVO). Apart from being considered non-competitive, safer, and rapidly growing organisms, their high oil contents, high growth rates, and growth densities have been cited to be the reasons to choose microalgae as a promising biofuel option (Misra et al., 2012). Many algal strains like *Chlamydomonas*, *Chlorella*, *Euglena*, *Scenedesmus*, *Botryococcus braunii*, *Tribonema*, *Ulothrix,* and others have been reported to produce biofuels. It has been documented that to get high production of biofuel, several criteria, like the adaptability of microalgae toward high oxygen concentration, temperature variation and water chemistry, oil content, production yield, and downstream processing, are sought to select suitable algal strains (Goswami et al., 2021).

Moreover, many oleaginous microalgae like *Botryococcus braunii, Chlorella sp., Crypthecodinium cohnii, Cylindrotheca sp., Nitzschia sp., Phaeodactylum tricornutum, Schizochytrium sp. Tetraselmis suecia* have emerged as the most resourceful feedstock for the large-scale production of biofuels because these photosynthetic organisms are reported to fix solar energy into biomass at a higher productivity than terrestrial plants *and also* because they do not require freshwater (Klok et al., 2014). Additionally, many oil-rich microalgal species store generous amounts of triacylglycerol (TAG), a primary source of biofuel (Sahoo et al., 2020). Moreover, many microalgae produce a range of co-products like antioxidants, edible proteins, pigments, polyunsaturated fatty acids, and specialized bio-pharmaceuticals, thus advantageous to the biorefineries to help counterpoise the biofuel production cost (Goswami et al., 2021).

Overall, utilizing microalgae for biofuel production offers a multifaceted solution to society's energy and environmental challenges. It leverages their inherent properties and the potential for valuable co-products.

3. Algae nutraceuticals

It is evident that with the upsurging human population, the demand for nutritious products is also increasing concomitantly. Accordingly, the sources to meet this rapidly growing demand are profiled profusely. Several published reports suggest that microalgae emerged as one of the most sought-after resources, and their nutraceutical application has begun to pick up steam. Although the consumption of microalgae as food by humans has a long history (Mobin and Alam, 2017), because of their wide variety and fast growth, nowadays, microalgae are considered an effective and sustainable resource for nutritional compounds and thus accounting for a large and rapidly expanding market (Novoveská et al., 2019). It has been well documented that a balanced diet comprising essential vitamins, antioxidants, minerals, carbohydrates, polyunsaturated fatty acids (PUFAs), etc., is required for a healthy lifestyle. In addition, major commercialised health supplements include carotenoids, phycobilins, fatty acids, polysaccharides, vitamins, sterols, and other bioactive molecules for human and animal health. In addition, various microalgal species are rich in multiple vitamins, minerals, and other bioactive compounds, thus making them a potential source of health supplements (Varela et al., 2015). For example, *Spirulina plantesis*, *Chlorella sp*., *Dunaliella terticola*, *Dunaliella saline,* and *Aphanizomenon flos-aquae* are widely used algal species for health supplements because of their nutrient-rich profiles (Torregrosa-Crespo et al., 2018).

It has been well accepted that microalgal-derived nutraceuticals and food products hold an enormous potential to face the issue of malnourishment in developing nations. The abundance of proteins and other essential nutrients in microalgae can create a massive algae-based food industry that commercializes healthy and functional foods. Apart from the essential vitamins, minerals, amino acids, etc., microalgae are also known to contain many antihypertensive, antioxidative, anticarcinogenic, and hepatoprotective biomolecules (Eggersdorfer and Wyss, 2018). Additionally, the versatility of microalgae cultivation, which can be done in various environments, including arid regions and seawater, further underscores their potential to combat malnutrition on a global scale.

4. Microalgal pigment

Besides biofuels and nutraceuticals, microalgae also earn prominence as sustainable alternatives to procuring natural pigments. Microalgae are known to produce a broad range of pigments like chlorophylls (green), carotenoids (red, orange, yellow), xanthophylls (yellow), phycocyanin (blue), and phycobiliproteins (red, blue) due to which various algal species are commercially used as a potential source for natural dyes (Nwoba et al., 2020). The current scenario of increased awareness of health and environmental issues has made consumers mindful of the edible products that go in their food. Colourants and dyes that are sourced naturally have gained attention for the same reason. Moreover, pigments obtained from microalgae can be a potential substitute for artificial dyes because, besides their coloring capability, they have numerous health paybacks. Additionally, pigments (for example, astaxanthin, and beta-carotene obtained from microalgae) have also been documented to be used as food colorants (Rana et al., 2021). Microalgae are fast gaining popularity as a sustainable source for natural food-grade colorants because of their unique advantages over terrestrial plants, including their ability to grow on nonarable land, faster growth rates, and diversity in the production of various natural bioactive compounds (e.g., lipids, proteins, carbohydrates, and pigments).

Metabolites (pigments) include lutein, astaxanthin, α-, β-, and ϒ-carotene, lycopene phycoerythrin, phycocyanin, violaxanthin, allophycocyanin, chlorophyll a, canthaxanthin, and a variety of other compounds made by algal cells are among the most sought-after products. These pigments cause the color and visual characteristics of certain algae (Nwoba et al., 2019). The main factor supporting microalgae's uses in food, cosmetics, and pharmaceuticals is their variety of pigments or colors. It's interesting to note that many of these pigments, such as phycobiliproteins and fucoxanthin, are exclusive to microalgae or can be produced at concentrations more significant than those of vascular plants.

The growth and environmental conditions in which microalgae are grown directly affect their intrinsic composition and physicochemical characteristics (Benavente-Valdés et al., 2016). According to Mulders et al. (2014) and Benavente-Valdés et al. (2016), there are currently two practical methods for increasing the yield of pigments in microalgae cells. These methods include (a) modifying the growth and physical conditions of the microalgae cultures or (b) changing the metabolic pathways that produce pigments. The first alternative, commonly referred to as "stress conditions," usually entails making significant adjustments to the microalgae cultures' natural growth parameters. These adjustments can either include (a) applying sub-saturation light conditions, which have been demonstrated to raise the concentration of primary pigments, or (b) subjecting cultures to unfavourable growth conditions (stress), such as salinity, irradiance, salinity, temperature, and nutrient availability, to increase the concentration of secondary pigments (Benavente-Valdés et al., 2016; Nwoba et al., 2020).

5. Animal feed

Animal rearing and aquaculture have remarkably boosted to meet the demands of the ever-increasing human population. However, producing animal feed and agricultural products can be costly and may lead to the overutilization of available resources. Therefore, cost-effective, high-quality substitutes are required to complement conventional feedstocks to meet rising needs (Saadaoui et al., 2021). The rich nutrient profile of many microalgae makes them an ecologically viable and cost-effective alternative for animal and aquatic feed production. Moreover, it has been reported that microalgal feeds are more nourishing and palatable than traditional animal and aquatic feed sources like millet, grams, etc.

Furthermore, it has been well documented that the microalgae supplement the regular feed due to the presence of carotenoids, essential minerals, vitamins, probiotic compounds, polyunsaturated fats, pigments that improve meat colouration, disease-preventing biomolecules and their antioxidative and antimicrobial properties (Saadaoui et al., 2021). Furthermore, it has been reported that the use of even a tiny quantity of microalgae biomass in the feed can promote the overall health of the animal by boosting immunity and resistance to various diseases, enhancing intestinal function, and stimulating probiotic colonization (Kusmayadi et al., 2021). *Arthrospira sp.*, *Chlorella sp.*, *Isochrysis sp.*, *Macrocystis pyrifera*, *Nannochloropsis sp.*, *Pavlova sp.*, *Porphyridium sp.*, and *Schizochytrium sp.* are some of the important microalgal species reported to be utilized for the production of animal feed (Saadaoui et al., 2021).

Various reports suggest that microalgae not only provide dietary supplements but also reduce the burden of feed costs contribute to a balanced diet, and decrease the need for antibiotics in livestock, poultry farming, and aquaculture (Kusmayadi et al., 2021).

6. Waste water treatment

The major environmental concerns about water quality are raised because household effluents, human wastes, hospital wastes, industries, breweries, agricultural wastes, and industries are often dumped into the water bodies. It is well known that this leads to various global issues like water scarcity, unwarranted growth of detrimental microbes, and health-related snags in communities [Patel et al., 2015]. Furthermore, these consequences may lead to ecological imbalances. Therefore, a significant part of the solution is managing wastewater.

Microalgae have been identified as a potential approach to address these issues and can be used as an eco-friendly and economical water remediation method [Pandey et al., 2019]. Notably, microalgae can effectively remove the organic burden from the wastewater and provide beneficial biomass by-products. In the current scenario, wastewater treatment using microalgae and their biomass is leaping worldwide (Patel et al., 2015).

Bio-treatment of wastewater with microalgae is specifically desirable due to their photosynthetic competencies. Microalgae can translate solar energy into good biomasses and absorb nutrients like nitrogen and phosphorus, leading to eutrophication (Ren et al., 2021). Several microalgal genera like *Ankistrodesmus, Chlamydomonas, Chlorella, Euglena, Golenkinia, Oscillatoria, Micractinium, and Scenedesmus* are found to be beneficial for wastewater treatment (Pandey et al., 2019). Moreover, algal systems can treat human sewage, agro-industrial wastes, livestock wastes, industrial wastes, piggery effluents, agricultural wastes, and the effluent from food processing industries. Furthermore, algal-based water remediation systems are reported to remove toxic heavy metals (Gondi et al., 2022).

7. Microalgae in cosmetics

Algal-based uses for beauty date back centuries, and it has been reported that seaweeds were used for fat reduction, skin improvement, and anti-aging in measures similar to present thalassotherapy (Mourelle et al.,2017). Currently, microalgae are considered a treasure trove for the cosmetic industry, and many microalgal species like *Arthrospira*, *Chlorella vulgaris Dunaliella salina, Nostoc, S. platensis, Ulva lactuca* are established in the skincare market (Ariede et al., 2017). These algal species contain bioactive compounds that can be used for repairing skin aging and preventing wrinkle formation, stimulating collagen synthesis in the skin, supporting skin tissue, and augmenting the generation of new tissue (Mobin et al., 2017), promoting cell growth, improve energy metabolism. Also, some microalgae species can maintain the balance of skin flora by protecting it from various microorganisms (Wang et al., 2015).

Microalgal-based cosmetics are currently popular because it has been documented that secondary metabolites of microalgae produced by microalgae repair and heal skin, prevent inflammation, and have anti-blemish or anti-microbial effects (Ariede et al., 2017). Carotenoids, due to their anti-oxidative properties, can impart several benefits to cosmetics. Microalgal compounds have been reported to be used as anti-aging, refreshing, or regenerating products, emollients, anti-irritant products, sun protection products, and skin-whitening agents (Mourelle et al., 2017). Research on carotenoids has documented that they can stimulate fibroblasts to synthesize collagen and elastin, smoothen deep wrinkles around the eyes, and enhance the skin's firmness, elasticity, or density. Further, carotenoids have excellent regenerative and reparative properties, due to which they can regenerate and repair collagen fibers as well as elastin fibres damaged by UV radiation (Ganceviviere et al., 2012). Carotenoids have also been known to inhibit the activity of elastase, which is responsible for destroying elastin and collagen. Lycopene is frequently used in skin creams as it helps maintain skin density, elasticity, and firmness (Han et al., 2012).

Additionally, they can enhance the phenomenon of epidermal regeneration after UV damage as well as keratinization, thus making the skin smooth, soft, and elastic. For example, due to their anti-oxidative properties, lutein and zeaxanthin are known to protect the skin against premature aging stimulated by UV exposure (Guedes et al., 2011). Astaxanthin is also frequently used in skin and creams body creams as it acts as an effective UV absorber. Hence it protects against erythema, photoaging as well as changes induced in the DNA by free radicals (Li et al., 2020). Also, carotenoids are known to regularize the function of sebaceous glands, a property highly beneficial for dry and oily skin (Han et al., 2012). They are also known to bring about depigmentation by effectively reducing the size of melanocytes and decreasing the melanin levels. For example, β-carotene is usually used to treat photosensitivity in patients suffering from metabolic conditions like protoporphyria. It has been documented that the administration of β-carotene increases the yellow coloration in the skin all over the body and thus effectively reduces erythema (Ganceviviere et al., 2012).

8. Commercial application of carotenoids

Microalgae have proven to be particularly effective at producing substances of interest, such as carotenoids, fatty acids, and vitamins, sustainably. The secondary metabolites derived from microalgae are bioactive compounds having properties of being antibacterial, antifungal, antiviral, antioxidant, anti-inflammatory, antimalarial, and antitumor effectors. They have significant potential for industrial development.

Carotenoids are a class of coloured pigments found naturally in algae, photosynthetic bacteria, plants, fruits and green leafy vegetables (U.S. Department of Agriculture, 2016). These biocompounds are of great commercial value owing to their versatile, beneficial role in human healthcare, pharmaceutical, food processing, cosmetics, and the animal care industry (Saini et al., 2020). Also, because of their location in specific pigment-protein complexes, carotenoids function as photoprotectors and light-harvesting accessory pigments in algae, photosynthetic bacteria, and plants. This function is of great significance for the organisms surviving in less light environments, as carotenoids can pass on the available harvested light to the chlorophyll molecule. However, carotenoids protect chlorophyll from photodamage during bright light as they accept and dissipate the excess light energy from the chlorophyll pigment. The microalgal cells are protected from oxidative stress by the carotenoids ability to neutralize the reactive oxygen molecules and free radicals. This antioxidant ability helps in the functionality and stability of the photosynthetic system (Krinsky, 2001). Carotenoids imparting bright colour to the flowers and fruits play a key ecological and agronomical role in the propagation and survival of the species through seed dispersal pollination (Sun et al., 2022). To date, as per the last compilation, 1204 natural carotenoids from 722 organisms have been listed in the Carotenoid Data Base (http://carotenoid.jp accessed on_: September 2020) (Martínez-Cámara et al., 2021).

The study of carotenoids dates back almost 200 years, with the first study by Braconnot (1817), followed by the identification of apocarotenoid bixin by Aschoff (1818). Wackenroder (1831) isolated and described carotene in his studies on carrot juice. Later, Hans von Euler and Paul Karrer studied carotene and its similarity with vitamin A. However, further work on carotene and vitamin A structure got Paul Karrer recognition in Chemistry as he was awarded the Nobel Prize in 1937 for his work on "carotenoids, flavins, vitamin A and vitamin B2" (www.nobelprize.org, accessed on February 2022) (Britton, 2020). The identification and study of carotenoids in animal tissue was first done by Adolf Lieben (Theodore, 2009). It was in the early twentieth century that carotenoid separation using various techniques such as mass spectrometry (MS) and high-performance liquid chromatography (HPLC) was performed (Britton, 2020). This carotenoid isolation and identification helped further advance the study of carotenoids.

Commercial poultry production is vulnerable to many pathogens like fungi, bacteria, and viruses, as well as other environmental insults, including heat, stress, etc. It has been shown that carotenoids have proved to be exceptional therapeutic and health-promoting potential to augment the production performance of poultry birds (Saeed et al., 2018). For instance, it has been researched that nutritional supplementation of the poultry bird's diet with carotenoids (either natural or synthetic) can help them to achieve the required skin colour. Further, a study conducted by Nogareda et al. (2015) reported that the high carotenoid diet fed to broilers has augmented pigmentation and protective immunity against infectious bursal disease. In 2018, a research study conducted by Faruk et al. (2018) stated that the dietary supplementation of canthaxanthin 0–8 mg/kg of feed improves feed intake, feed conversion ratio (FCR), egg production, egg weight as well as egg yolk mass ($p < .001$).

Further, supplementation with canthaxanthin has been shown to effectively increase the productive and reproductive performance and reduce embryo mortality in broiler breeders (Rosa et al., 2012). Further, research studies have indicated that feeding higher concentrations of β-Cryptoxanthin to the hen could increase provitamin A and colour of egg yolk (Liu et al., 2012). In a study conducted by Krinsky (2001), it has been documented that avian species employ carotenoids as a powerful immunomodulator antioxidant agent, thus helping in the prevention of infectious diseases as well as other inflammatory and oxidation processes (Krinsky, 2001). Nutritional supplement of the feed with lycopene has been known to enhance the production performance of poultry birds, the nutritional value of the end products, and help in attaining the oxidative stability of the broiler meat (Rosa et al., 2012).

Owing to their potential benefits in various sectors such as human healthcare, pharmaceuticals, food processing, cosmetics, and even their biotechnological applications, the in vitro synthesis of carotenoids has undergone large-scale production worldwide. The molecular structure of carotenoids imparts a specialized property to carotenoids: their antioxidant property (Tamaki et al., 2021). Xanthophylls, for instance, accomplish a significant task of potent quenchers of reactive oxygen species (ROS) and reactive nitrogen species (RNS) along with functioning as free-radical scavengers and chain-breaking antioxidants (Mordi et al., 2020). Hence, xanthophylls such as astaxanthin and canthaxanthin function more effectively as antioxidants and scavengers of free radicals than carotene. Medical research in recent years has diverted attention to the understanding of ROS-induced oxidative stress mechanisms and hence the search for suitable strategies to fight oxidative stress (Mordi et al., 2020). The important biological role of the carotenoids in all living systems has gained momentum over the past few decades (Gammone et al., 2015).

One of the biggest challenges for the rising world population is health concern. The sudden outbreak of the COVID-19 pandemic has pushed the focus to conscious, healthy living. Across the globe, the trend to go natural has been the driving force for the escalation of the global carotenoid market. The global algal market for carotenoids was estimated at U.S. dollars (USD) 1.5 billion in 2019 and has been projected to grow to USD 2.0 billion by the year 2026, thus recording a compound annual growth rate (CAGR) of 4.2% (Markets and Markets, 2020). The reason attributed for this increase is the use of natural carotenoids in the preventive healthcare sector and food industry. At the same time, various technological innovations for carotenoid extraction from sources such as plants and microalgae have given impetus to carotenoid use (Saini et al., 2019). Carotenoids have long been exploited in the world commercially over, especially in markets of the USA and Europe, where there is high demand for these bioactive compounds (Torregrosa-Crespo et al., 2018). Carotenoids perform key biological functions such as photosynthesis photoprotection, light capture, excess light dissipation, and singlet oxygen quenching, making them very relevant for sustaining life on Earth (Takaichi, 2011).

Another market report predicted that the carotenoid market would grow at a rate of 7.4% of the CAGR and reach $1.9 billion by the year 2028 (Meticulous Market Research, 2021). In the forthcoming years, the demand for potential carotenoids in the global food and beverage, cosmetic, and animal feed industries will surpass the need for chemical and synthetic ingredients owing to their hazardous impact on the health (Markets and Markets, 2020). Humans, as well as animals, cannot synthesize carotenoids de novo. Hence, they are dependent on the diet for their daily requirements. The range of health benefits of carotenoids in humans includes cardiovascular health, cognitive function, and cancer prevention (Eggersdorfer et al., 2018). In animals, carotenoids help in the survival of organisms like fish larvae, increase growth performance, and are essential for the skin color in animals.

The aqua feed industry relies heavily on carotenoids as an additive in the feeds of fishes such as salmon, shellfish, trout, lobsters, and shrimp for their role in flesh pigmentation (Yaqoob et al., 2021). The Asia-Pacific region of the world ranks among the top regions for compound feed production and consumption. In 2018, in Asia, the production of pig, poultry, and cattle meat was 66,726.0, 46,468.7, 18,506.0 thousand metric tons as compared to 66,604.8, 43,444.7, 17,825.8 thousand metric tons respectively in the year 2016. Further, the increased growth of the aquaculture industry, along with increased seafood consumption, is the reason for driving the growth of the carotenoid market. Studies have estimated that by the end of 2022, cultured aquaculture will contribute more than 20 % of the catch compared to the wild growth. In the near future, the carotenoid market is expected to rise further in the aquaculture industry owing to the new interventions in scientific technology and the replacement of synthetic carotenoids with natural carotenoids (Mordor Intelligence, 2021). The carotenoid consumption of the world in 2007 was approx 4193 metric tons and rose to 5693.6 metric tons in 2017. Also, the carotenoids added to food were approximately 4020.8 metric tons in 2017 (Novoveská et al., 2019). Natural carotenoid consumption is estimated to be 2699.8 metric tons by the year 2024. The carotenoids in the cosmetics industry in the Asia-Pacific market are expected to rise at a rate of 5% CAGR in the coming years (Yaqoob et al., 2021). The world carotenoid market is divided on the basis of the source, types, application of the carotenoids and the area of utilization. The ß-carotene, which is the highest value carotenoid, is estimated to develop at the rate of 5.1% CAGR from 2019 to 2026 (Yaqoob et al., 2021). Lycopene, another vital carotenoid for its use in the pharmaceuticals and cosmetics industry, had a market share worth of USD 15 million in 2015, and is expected to grow significantly in the near future. Astaxanthin, having strong antioxidant potential, has a global market of approximately 250 tons worth $447 million, which is rising steadily (Zhang, 2018). Another carotenoid, Canthaxanthin shared the global carotenoids market with 10% in 2015. It is expected to rise owing to its prospective as an anti-tanning instrument in the cosmetics sector (Yaqoob et al., 2021).

Natural carotenoids demand in the global market is increasing owing to their multiple benefits for humans and the animal industry, however, this rampant utilization of the carotenoid calls for enhancing microalgae cultivation techniques. A sustainable and economically feasible production of natural carotenoids from microalgae must be established globally (Koller et al., 2014).

9. Biological role of carotenoids

Humans and animals acquire carotenoids through their diet as they cannot synthesize the carotenoids de novo. The carotenoid concentrations in plasma are valuable biomarkers for the total dietary intake of fruits and vegetables (Bai et al., 2009). However, these nutritional carotenoids are converted into vitamin A, along with the retinoid compounds that are also essential for morphogenesis as well as embryonic development (Saini et al., 2020). Vitamin A is a crucial nutrient for correct vision and other functions. One of the significant health problems affecting the population is Vitamin A deficiency. Severe Vitamin A deficiency leads to various health problems such as respiratory diseases, vision complications, measles and diarrhoea.

Further, severe consequences result when combined with infections, leading to an increase in morbidity and mortality. The most vulnerable group includes the pre-school children and pregnant women. Carotenoids such as beta carotene, beta cryptoxanthin, and alpha-carotene have the non-hydroxylated beta-rings that serve as the provitamin A precursors and lead to the synthesis of vitamin A in the body. These carotenoid precursors are available only through the diet and are the target for biofortification in plants (Bai et al., 2009).

Several research studies conducted in the past have indicated that carotenoids might play an essential role in cancer prevention. Studies have indicated that the consumption of carotenoids rich fruits as well as vegetables is linked to decreased risk of cancer at sites like liver, breast, lung, colon, prostate, etc. However, for other sites, conclusive results are yet awaited (Roth et al., 2020). Many mechanisms have been proposed to explain the cancer preventive properties of carotenoids. For instance, the antioxidative properties of carotenoids could avert the free-radical induced damage to macromolecules like Nucleic acids (RNA or DNA), proteins, carbohydrates, or fats. They can capture the free oxygen radicals and efficiently scavenge peroxyl radicals (Ávila-Román et al., 2021).

Further, carotenoids can enhance immunomodulatory effects, i.e., they could augment the proliferation of both T and B cells in tumorigenesis (Wang et al., 2019). Additionally, it has been well documented that retinol affects various cellular functions like cell-differentiation proliferation, and altering the membrane receptors. Retinoids have also been shown to enhance both humoral as well as cell-mediated immunity (Kundu and Kundu, 2022).

Cardiovascular diseases (CVD) are one of the leading causes of death in developing countries and, more recently, even in developed countries. Globally, more deaths (around 17.9 million) occur due to CVD as compared to other non-communicable diseases (Kundu and Kundu, 2022). According to the World Health Organization (WHO) almost one-fifth of these deaths occur in India (Kumar and Sinha, 2020). The number of people suffering from CVD worldwide has nearly doubled to 523 million in 2019 from 271 million in 1990 (Roth et al., 2020). As per the data from the American Heart Association (AHA), in the year 2020 in the United States of America, the estimated direct costs of CVD rose from $103.5 billion in 1997 to $226.2 billion in 2018 (Tsao et al., 2022). The CVD includes acute myocardial infarction

and other disorders leading to high morbidity and mortality. The main attributing factors for the pathophysiology of these disorders are inflammation and oxidative stress (Przybylska and Tokarczyk, 2022). The oxidative stress, induced by ROS, leads to the oxidation of low-density lipoproteins (LDL), one of the key factors in the pathogenesis of atherosclerosis (Przybylska and Tokarczyk, 2022). Over the last many years, various epidemiological studies have been conducted which have established an association between the carotenoids and atherosclerosis or the risk of heart diseases. Carotenoids have been found to have anti-atherogenic properties as they function to protect LDL against oxidation (Voutilainen et al., 2006).
Further, the role of carotenoids in inhibiting the process of in vivo lipid peroxidation makes carotenoids function as the stabilizing element in the cell membrane (Wieslaw, 2004). According to the WHO and the American Heart Association guidelines the critical requirement for the prevention of CVD is lifestyle modification (Eckel et al., 2013) with a healthy diet of increased consumption of fruits and vegetables. The increased content of carotenoids, with their antioxidant and anti-inflammatory properties in fruits and vegetables is the major factor helping in the prevention and treatment of CVD (Nguyen et al., 2022). Various epidemiological studies have recommended that diets rich in carotenoids protect and prevent the onset of cardiovascular diseases in humans due to the oxidizing substances and oxidative stress involvement in the progress and clinical expression of coronary heart diseases (Nguyen et al., 2022). The elevated levels of lycopene in tissues and plasma have been inversely linked to myocardial infarction, coronary heart disease, and arteriosclerosis risk (Voutilainen et al., 2006). Also, the decreased levels of lutein in plasma correlate with increased chances of myocardial infarction (Kumar and Sinha, 2020). Also, the daily supplementation of dietary beta-carotene has been observed to decrease the plasma levels of cholesterol, triglycerides and total lipids. Further, epidemiological studies on patients with acute and chronic coronary syndromes observed reduced amounts of oxygenated carotenoids (α-carotene, β-carotene, β-cryptoxanthin, lutein, lycopene, and zeaxanthin) in plasma (Voutilainen et al., 2006).
β-cryptoxanthin which is also considered as a provitamin A carotenoid, is found broadly in mangoes, peach, papaya as well as other citrus fruits. Even though, β-cryptoxanthin is yet to be investigated thoroughly, these carotenoids' potential health benefits cannot be overlooked, especially against bone-related diseases. A few research studies have indicated that consuming β-cryptoxanthin as a nutritional supplement can augment the enzymatic activity of alkaline phosphatase and increase the calcium content in metaphyseal tissue as well as cortical bone which can lessen the likelihood of osteoporosis (Yamaguchi, 2008).
The role of Carotenes, as well as xanthophylls, as antioxidative molecules has been well documented, and it has been shown that they can protect against the adverse effects of exposure to extreme sunlight due to their antioxidant properties (Varela et al., 2015). For instance, zeaxanthin, crocetin, cryptoxanthin, lutein, Neoxanthin, etc., not only prevent the production of peroxides but also hinder the attachment of chemical carcinogens like DMBA to Nucleic acids, thus inhibiting carcinogenesis (Kundu and Kundu, 2022). The antioxidant property of carotenoids is based on their capability to quench oxygen in their singlet state and further transition it to a lower energy state (Krinsky, 2001). The structure of a few carotenoids like canthaxanthin or astaxanthin comprises of a cyclohexane ring with hydroxyl substituents or ketone groups which proves to be more effective scavenger. Further, it has been shown that carotenoids can terminate the process of chain reactions (Varela et al., 2015).
Redness, pain, heat and swelling or inflammations are the common physiological responses of the body against pathogen attack or harmful stimuli or any other irritant. The defence mechanism of the body comprising both humoral as well as cell-mediated immunity can effectively eliminate the reason for the inflammatory process. A lot of health organizations have suggested that regular intake of fruits as well as vegetables, which are rich in phytochemicals like lipophilic carotenoids can lessen the chances of chronic disease (Wieslaw, 2004). These phytochemicals have been shown to block oxidative stress as well as inflammatory processes. Rubin et al. (2012) reported that nutritional supplementation of an infant's diet with carotenoids like lycopene, lutein and β-carotene can decrease the inflammatory response as well as raise the plasma concentration of carotenoids.

10. Conclusion

In conclusion, microalgae are a fascinating and incredibly diverse group of microorganisms that have captivated the scientific community and various industries alike. Their potential applications span a wide range of sectors, from energy production and environmental remediation to food and nutrition, pharmaceuticals, and cosmetics. The ability of microalgae to harness solar energy and convert carbon dioxide into valuable compounds positions them as a sustainable and innovative resource for addressing pressing global challenges. With ongoing research and technological advancements, the future of microalgae-based solutions holds great promise, not only for mitigating environmental issues but also for enhancing human health and quality of life. This essay will delve deeper into each of these applications, providing a comprehensive overview of the remarkable world of microalgae and their transformative potential.

11. Future prospects

Currently, microalgae have several applications, from human and animal nutrition to cosmetics and the production of high-value biomolecules (e.g., pigments, fatty acids, and stable isotope biochemicals). However, they are yet to gain significant attention from a biotechnological point of view, and thus, a successful discovery of the drug would be the most promising aspect of its function

Conflict of Interest

The authors declare that there is no conflict of interest, financial or otherwise.

Funding

This work did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgements

The authors (PKN and MY) thank Sri Guru Tegh Bahadur Khalsa College and Gargi College, University of Delhi, respectively for providing the resources for the completion of this work.
The authors would also like to thank Dr. Vishakha Raina, and Dr. Namrata Misra, School of Biotechnology, KIIT University, Bhubaneshwar, for providing their valuable input.

Author's contributions

MY and PKN conceptualized the review and wrote the initial draft. PKN assisted in the literature search while MY revised the manuscript. All authors read and approved the final manuscript.

Conflict of interests

The authors declare that they have no conflict of interest.

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