Website : www.asthafoundation.in
Progressive Research : An International Journal
Vol 18 (1) : 41-50 (January-2023), Print ISSN : 0973-6417, Online ISSN : 2454-6003
Society for Scientific Development in Agriculture and Technology, Meerut (U.P.) India

Uncovering the Potential Applications Algal Metabolites in Different Field of Science : Present Status and Future Prospects

Pushpika Udawat*, Asha Singh and Rajesh Singh Tomar
Amity Institute of Biotechnology, Amity University Madhya Pradesh
**Corresponding Author Email : pudawat@gwa.amity.edu*

Abstract

Cyanobacteria, algae and microalgae have complex photosynthetic system and can efficiently convert absorbed solar energy into chemical energy for generation of food and metabolites. They are promising future biocatalysts and can be utilised for improving the sustainable production of food, metabolites and further as a source of green energy. In the present review, an attempt has been made to uncover the importance of different metabolites such as phenolics, terpenoids, sterols, phytols, free fatty acids, phytohormones, cyanotoxins, halogenated and photoprotective compounds. Additionally, the significance of these metabolites as antibiotics, anti-tumour, anti-inflammatory, immuno-suppressant, anti-viral, anti-bacterial and anti-malarial compounds. Furthermore, metabolites isolated from these algae, micro-algae and cynobacteria have several industrial applications at commercial level in the field of biotechnology, industry, cosmetics, pharmaceutical, green fuel, agriculture, etc. Further, the review has also emphasized on role of genetically modified organisms (GMOs) and metabolite accumulation from them.

Key words *: Algae, cyanobacteria, metabolites, types, applications, future prospects.*

Introduction

An alga is a broad term used to describe a large and extraordinarily different group of eukaryotic organisms having photosynthetic capacity. They inhabit a wide range of environmental conditions from oceans, lakes, ponds to brackish water and even snow. Generally, they are green in colour but in some instances they are found in different colours viz., red and brown. The difference in colour is mainly due to difference in composition of photosynthetic pigment. For example, algae found in snow have carotenoid pigment along with chlorophyll, thus giving the surrounding snow a unique brown appearance. As a matter of fact, algae are polyphyletic in nature, as they do not share an ordinary ancestor and thus are not associated to each other. Examples of multicellular algae are giant kelp and brown algae, whereas unicellular algae include diatoms, euglenophyta and dinoflagellates. For their normal growth and development, they need a moist and humid environment and they may be fresh water or marine algae. Anatomically, they are similar to land plants, however, they lack some of the essential structural components of plants such as true stem, root and leaves. In this review article, we have summarized role of numerous metabolites like sterols, phytols, polyols, halogenated compounds, carotenoids, free fatty acids, cyanotoxins, polysaccharides and scytonemins, etc. Further, their applications are also summarised in brief in reference to different industries such as agriculture, medicine, cosmetics, phytochemical as well as neutraceuticals at commercial level. In addition, we have also dealt with development of newer and greener technologies for exploring the biofuel aspect of these metabolites. Additionally, we have also examined the functions of algae, microalgae and cyanobacteria in the production of therapeutics and green fuel.

Metabolites : metabolites are a group of intermediate products accumulated during metabolism, enzymatically produced naturally within cell, for example, antibiotics and other pigments. The term itself is denoted for small molecules showing different metabolic activities such as involved in signalling cascade, part of structural component, defence mechanism, enzymatic pathway and other cellular interactions. These metabolites are released by a set of organisms including algae, micro-algae and cyanobacteria, etc. In this review, group of metabolites released by them are discussed in detail along with suitable examples and their applications are also detailed.

Phenolics : Polyphenols include different types of secondary metabolites such as phenolic acids, flavonoids, tannins and lignins. At structural level, they possess one phenolic ring and their biological activity gets activated when halogenated. They are isolated from different types of algae such as red algae and brown algae. These phenolic compounds have shown anti-oxidant properties in biotic as well as abiotic stresses. Additionally, these metabolites have no significant role in growth but they are involved in regulating the developmental processes. However, some polyphenols such as ellagic acid, gallic

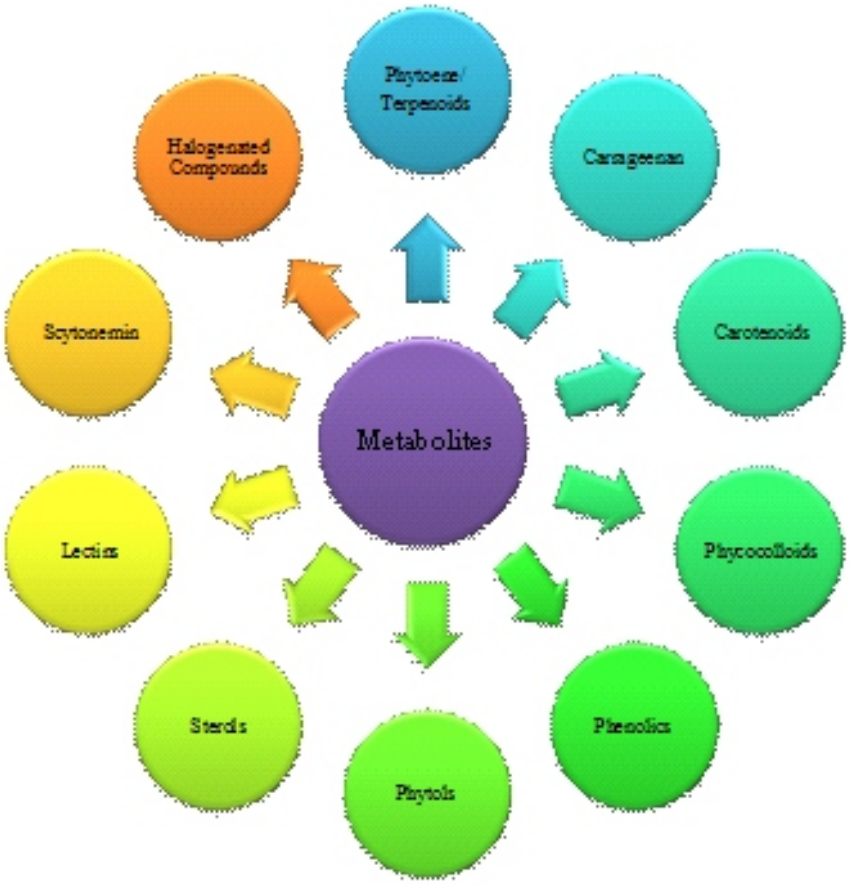
Received : October-2022; Revised : November-2022; Accepted : November-2022

acid and catechin have shown negative effect on growth. These compounds further act as free radical scavengers under oxidative stresses and thus capable of curing several diseases caused by them. Secondary metabolites of phlorotannin group such as fucols, phlorethols, fucophlorethols, fuhalols, halogenated and sulphated phlorotannins act as anti-oxidant compounds. Furthermore, some phenolic compounds such as catechol, catechin and hesperidin have anti-inflammatory activity. Secondary metabolites from some algae and cyanobacteria possess properties like anti-cancerous, anti-malarial, anti-fungal, anti-viral, anti-bacterial and anti-carcinogenic, etc (1). Phlorotannins, a collection of tannins and phloroglucinols (eight linked flavonoid rings) that have been identified from brown algae, are among the several phenolic compounds (15 percent of dry weight). In the biological system, these phlorotannins are said to exhibit antioxidant properties (2). Additionally, phenolics are classified as stress chemicals that take part in defense mechanisms against biotic stresses such as grazing, bacterial colonization (1), and abiotic stresses such as ultraviolet radiation and metal toxicity. Although secondary metabolites are not directly engaged in growth processes, several research have shown that phlorotannins may have a role in controlling brown algal development (2). When halogenated, phenolic compounds have at least one phenolic ring and exhibit powerful biological activity. Algae and cyanobacteria use metabolites such as phytoalexins, lignin, flavonoids, furanocoumarins, tannins, and anthocyanins as part of their defensive mechanism. A cyanobacterium called *Microcystis aeruginosa* has also been discovered to have growth inhibitory effects because it contains polyphenols such ellagic, gallic, and catechin, etc. Fucols, phlorethols, fucophlorethols, fuhalols, halogenated, and sulfated phlorotannins are the main compounds of the phlorotannins group and they have great potential under oxidative stress as well as the ability to treat diseases brought on by free radicals. Similar findings have been made with additional phenolic compounds such as catechin, epigallocatechin gallate, catechol, rutin, morin, caffeic acid, and hesperidin isolated from red algae (2). The existence of new substances such antioxidants, phycobilins, phenols, polysaccharides, steroids, and terpenoids was formerly thought to be the cause of the cyanobacteria and algae's antitumoral, antiviral, antibacterial, antifungal, and antiviral capabilities (3).

Phytoene/Terpenoids : Terpenoids are a group of organic compounds found in algae and cyanobacteria. They are classified depending upon five-carbon isoprene unit i.e. hemiterpenes (C5), monoterpenes (C10), sesquiterpenes (C15), diterpenes (C20), triterpenes (C30), tetraterpenes (C40) and polyterpenes (>C40). Terpenoids play an active role in initial growth and development along with they draw attraction of pollinators. They also have flavour and fragrance enhancing property. Further, they may be used as advanced biofuel precursors and may be a substitute to biosynthetic diesel in international trade. Terpenoids are a class of widely distributed chemical molecules found in cyanobacteria and algae (4). Hemiterpenes (C5), monoterpenes (C10), sesquiterpenes (C15), diterpenes (C20), triterpenes (C30), tetraterpenes (C40), and polyterpenes (>C40) are the seven classes of terpenoids based on their five-carbon isoprene unit (4). Terpenoids not only contribute significantly to early growth and development processes but also encourage pollinator attraction. They are more pertinent as secondary physiologically active chemicals because of these characteristics (5). Terpenes have reportedly been added to items to enhance their flavors and perfumes. They are also being used to replace biosynthetic diesel in the global market as emerging advanced biofuel precursors similar to linear terpenes. It has been proposed that pure monoterpenes have antiparasitic properties (6). The allelopathic properties of some cyanobacterial species are caused by the presence of a considerable amount of geranyl acetone, which prevents the growth of nearby cyanobacterial species. Terpenes can be utilized as fuels because they are hydrocarbons that are created by the cellular system. Additionally, they can be used with fossil gasoline in spark-ignition engines. Terpenoids effective functions in the pharmaceutical and pesticide sectors have recently attracted increasing commercial interest (6).

Phytols : In algae and cyanobacteria, phytols are important component of chlorophyll and act as cofactors for the photosynthesis. In cyanobacteria and algae, they are essential for the biosynthesis of chlorophyll, quinone, prenyl tails, hormones and tocopherols through methylerythroitol 4-phosphate pathway (MEP). During their biosynthetic pathway, an intermediary precursor, geranylgeranyl pyrophosphate of phytols is synthesized through the MEP pathway. In algae and cyanobacteria, the natural form of isoprenoids normally consists of phytol of chlorophyll a (6). Furthermore, limonene, which is an essential precursor of phytols is generated from the enzymatic activity of limonene biosynthase enzyme. Generally, cells may release limonene under normal atmospheric pressure and temperature. Several algae and cyanobacterial extract show anti-cancerous property due to presence of phytols in their extract, which enhances immunological response of body. Further, they act as anti-inflammatory agents thus provide cellular protection (7).

Sterols : The main function of sterols is to maintain membrane fluidity and they are a by-product of isoprenoid



biosynthesis. Previously it was believed that sterols are not synthesized by algae while with the advancements in analytical techniques, it was found that sitosterol and cholesterol are produced by *Anacystis nidulans* and *Fremyella diplosiphon*. Later on, it was discovered that both saturated and unsaturated sterols are released by cyanobacteria. Examples of some of the saturated sterols are 4 -methylsterols, 5 -cholestan-3 -ol, 24-methyl-5 -cholestan-3 -ol and 24-ethyl-5 -cholestan-3 -ol. While, some of the unsaturated sterols produced by algae and cyanobacteria are cholesterol, chondrillasterol, stigmasterol, sitosterol, brassicasterol, campesterol, 22-dehydrocholesterol, isofucosterol, 24-ethyl-cholest-7-enol, 24-methyl-cholest-7-enol, 24-ethylcholesta-2,5-dienol and 24-ethylcholesta-5,7, 22-trienol, etc. In a recent research on sterols cellular concentration, it is found around 2.25 mg/L. Biosynthesis of sterols is a multistep chain reaction that occurs in cytoplasm. They play significant functions in several cellular biochemical processes such as synthesis of steroid hormones and form an integral part of plasma membrane. Additionally, sterols are excellent sources for aqua-cultured organisms. Structurally, they consist of a plane structure with three -hydroxy tetracycle having a methyl- or ethyl-reserved hydrocarbon chain (C7-C11). They also contain C4, C14 methyl-reserved prototype in a polycyclic form showing a difference in degree and position of unsaturation at C5, C7 and C8 locations. Such fused ring architecture of sterols provides integrity, stability and rigidity to the cellular membrane and therefore holds it collectively as a single unit membrane. There are several genes and corresponding enzymes which are involved in biosynthesis of sterols. For instance, D24-sterol C-methyltransferase, sterol-C-5-desaturase or C-4 methyl sterol oxidase and sterol-C-methyltransferase, etc. However, significant progress has been made in functional validation of genes and their products involved in sterol biosynthesis (8). However, further genetic evidences are required for further identification of components involved in sterol biosynthetic pathway.

Free Fatty Acids : Out of different types of metabolites, free fatty acids are more essential due to their vital role in cellular metabolism. Some important fatty acids found in algae and cyanobacteria are linolenic, linoleic and arachidonic acids, which are indispensable for normal growth and development. Free fatty acids and alcohols are the key component of lipids and as per their configuration, a wide variety in fats, phospholipids, glycolipids and waxes may be found. Fatty acids are among the most significant metabolites because of their crucial function in metabolism. Important fatty acids including linolenic, linoleic, and arachidonic acids are

present in cyanobacteria and algae and are necessary for their optimal growth. The primary components of lipids are fatty acids and alcohols, and a wide variety of fats, phospholipids, glycolipids, and waxes can be found depending on how they are arranged. Based on the presence of essential fatty acids like C18 linolenic and linoleic acids and their C20 derivatives such as arachidonic and eicosapentaenoic acids, the structure of lipids in cyanobacteria may change. Several microalgae species have the capacity to accumulate significant amounts of lipids, which might be used as a potential source of oil output, as well as the average lipid content can vary between 1 and 70%, or even can reach up to 90% of dry weight (8, 9).

Photoprotective Compounds : **Mycosporine-Like Amino Acids (MAAs) :** Mycosporine-Like Amino Acids (MAAs) are a group of intracellular compounds involved in the safety of aquatic organisms against extreme solar radiation (10). Structurally, they possess a cyclohexenimine or cyclohexenone chromophore attached to one or two amino acids and they show absorption maxima in the UV range i.e. from 310 to 362 nm. The MAAs is produced by different types of algae such as brown, red and various other groups of cyanobacteria. They are produced by shikimate pathway and their precursors are used as an ingredient of photo-stabilising additives i.e. in sun scream and other products such as varnish, paint and plastics. They act as photo-protective compounds due to their high molar coefficient and absorption maxima in the range of UV light along with their resistance to abiotic stresses (ABs) such as extremes of temperature, pH, UV radiation and various solvents (11). The safeguarding provided by MAAs against UV-B radiation primarily depends on the type of pigment and their cellular localization. Considerable safeguarding is provided by MAAs located in the cytoplasm of cyanobacteria. In *Nostoc commune*, MAAs are located in the extracellular glycan thus they provide photo-protection. MAAs which is present in cell membrane provides extra protection against UV-B radiation due to absorption of two out of three photons. MAAs is sufficient enough to successfully scatter absorbed radiation in the form heat without generating reactive oxygen species (ROS). Additionally, these MAAs are capable of protecting different groups of organism i.e. both producer and consumer in a food chain against UVR radiation. There is a close relationship between photosynthesis and MAAs biosynthesis as observed by the inhibitory effect of 3-(3,4-dichlorophenyl)-1, 1-dimethylurea (DCMU) in *Alexandrium excavatum*. The biosynthesis of MAAs occurs in only two steps as shown in following steps.

3Dehydroquinate (Reduction of Carboxylic Group)
Methylation of Hydroxyl Group at C4

Scytonemin : Scytonemin having a molecular weight of 544 Dalton (Da) is a photo-protective compound and structurally is made up of two compounds namely., indolic and phenolic subunits. Firstly, it was discovered in a cyanobacterial species belonging to a terrestrial group. It is a yellowish brown fat soluble pigment found in exo-polysaccharide sheath. It is present in two oxido-reductive states largely in a green oxidised state (reduced is red coloured and yellow is oxidised state). Several Scytonemin pigments such as dimethoxyscytonemin, tetramethoxyscytonemin, and scytonin, etc have been isolated from *Scytonema* species (12). Scytonemin show absorption maxima at 370 nm under *in vivo* conditions whereas the purified one absorbs at 386 nm. Interestingly, it shows absorption maxima at 252, 278 and 300 nm respectively thus it helps cyanobacteria to endure extremes of UV radiation. Numerous studies have shown that scytonemin pigments are able to lower the harm caused by the most fatal UV-C radiation. Furthermore, scytonemins can efficiently reduce the inhibition of photosynthesis by UV-A radiation and additionally can diminish the photobleaching of chlorophyll a (10). The scytonemin from terrestrial cyanobacterium *Chlorogloeopsis* species are added to suns-cream in cosmetics for human beings for protection against lethal UV radiation. They are highly effective and remain stable for a very long time in presence of various abiotic stresses such as extremes of temperature and UV radiation (10).

Carotenoids : Carotenoids is an accessory photosynthetic pigment found in several microorganisms, plants, animals, algae and bacteria. Structurally, they are polymer of isoprene units having 40 carbons and maximum 15 double bonds are organized in conjugated way. Carotenoids consist of hydrocarbons only whereas xanthophylls contain oxo, hydroxyl and epoxy groups etc. Carotenoids show absorption spectra in the range of 400 to 500 nm and these spectral properties are largely defined by number and positions of double bonds (12). Two carotenoids are of more importance then other forms like -Carotene and echinenone. However, several other forms also exists such as astaxanthin, b-cryptoxanthin, zeaxanthin, canthaxanthin and 30-hydroxyechinenone show more importance in cyanobacteria and algae. They have multiple functions for example as a colorant, predecessor of visual pigments and anti-oxidants. They enhance the nutritional value, vision and cellular differentiation in humans as they act as the precursor for retinoic acid, retinal and vitamin A. Particularly, -carotene and its derivatives act as the precursor for bio-synthesis of

various biologically active compounds involved in essential biosynthetic pathways (12).

Phycocolloids : Phycocolloids are different type of polysaccharides produced by numerous seaweed species. Amongst various types of phycocolloids particularly, carageenan, agar and alginates are of great significance due to their multifunctional applications. Therefore, they may be used as anti-oxidants, anti-viral, anti-cancer, anti-coagulant and anti-coagulant, etc (13). Agar and carrageenan are sulphated polysaccharides are isolated from red algae whereas alginates are isolated from brown algae. Structurally, they are binary polyurodine made up of repetitive units of glucuronic and mannuronic acids. Furthermore, they have used like as an emulsifier, viscosifier and as a solidifying agent (13).

Agar : By boiling certain types of algae, agar may be obtained after cell wall dissolution at higher temperature and release of two structurally different polysaccharides. Structural interaction of these two polysaccharides ultimately results into agar formation, which is dehydrated in oven and stored in powdered form. Structurally, it contains (1-4)-3,6 anhydro-L-galactose and (1-3)-D-galactose glycosidic bond. Agar is synthesized from precursors like mannose and glucose *via* D- and L-galactose respectively (14). It has several applications like as an emulsifying, stabilising and gelling agent. Additionally, in pharmaceutical industries it is used as a laxative compound. Furthermore, in growth culture laboratories it is used as a semi-solid medium due to its solidifying property thus support the cell growth and development (14).

Alginate : It is found widely in algae and cyanobacteria, structurally consist of -L-glucuronic acid and -D-annuronic acid in 1,4 glycosidic linkage. They are by-product of alginic acid or alginate isolated from brown algae such as *Laminaria*. They have wide applications in industries like cosmetics, food, pharmaceutical, textile, agriculture, paint and printer's ink. Particularly, brown algae are significant source of alginates (15) and alginate derived from them is used for sizing the cotton yarns.

Carrageenan : Carrageenans are high molecular weight compounds made up of multiple units of -galacto-pyranose and anhydro-D-galactopyranose (sulfated) in 1-4 glycosidic linkage. Depending upon the location and number of sulphate groups they can create different groups of carrageenans. For example, -carrageenan has three sulphate groups on each disaccharide unit, wherein the location of third sulphate group is C6 of fourth linked residue, which is lacking 3,6-anhydride bridge (16). Widely, -carrageenan is released by different red algae such as *Chondrus* and *Gigartina*, etc. Carrageenans has multiple applications in various industries like meat processing, dairy, toothpaste, pet food and air freshener gels, etc (17).

Lectins : Lectins or agglutinins are biologically active compounds released by diverse algae and cyanobacteria. Structurally, they are complex proteins, capable of binding directly to carbohydrate moieties without altering their property (18). Therefore, they find wider applications in histo-chemical and immunological studies in addition to their ability to recognize sugar receptors located on the cell surface. In medical field, lectins find great significance due to their relatedness to blood group typing on the basis of the secretor status and tumerogenicity associated to the alteration of biosynthetic pathway of glycans. Lectins are applied as therapeutic agents due to their specific binding towards intestinal epithelium and improve diffusion of drug molecules. Hence, various lectins have been extratced from different cyanobacteria such as *Scytonema varium, Mycrocystis sp., Nostoc ellipsosporum and Oscillatoria agardhii*. Lectins which have great therapeutic value are scytovirin, microvirin, agglutinin and cyanovirin-N, etc. Furthermore, they possess huge anti-viral properties due to interaction of glycans with HIV gp120, thus lectins anticipate transmission of HIV virus (19).

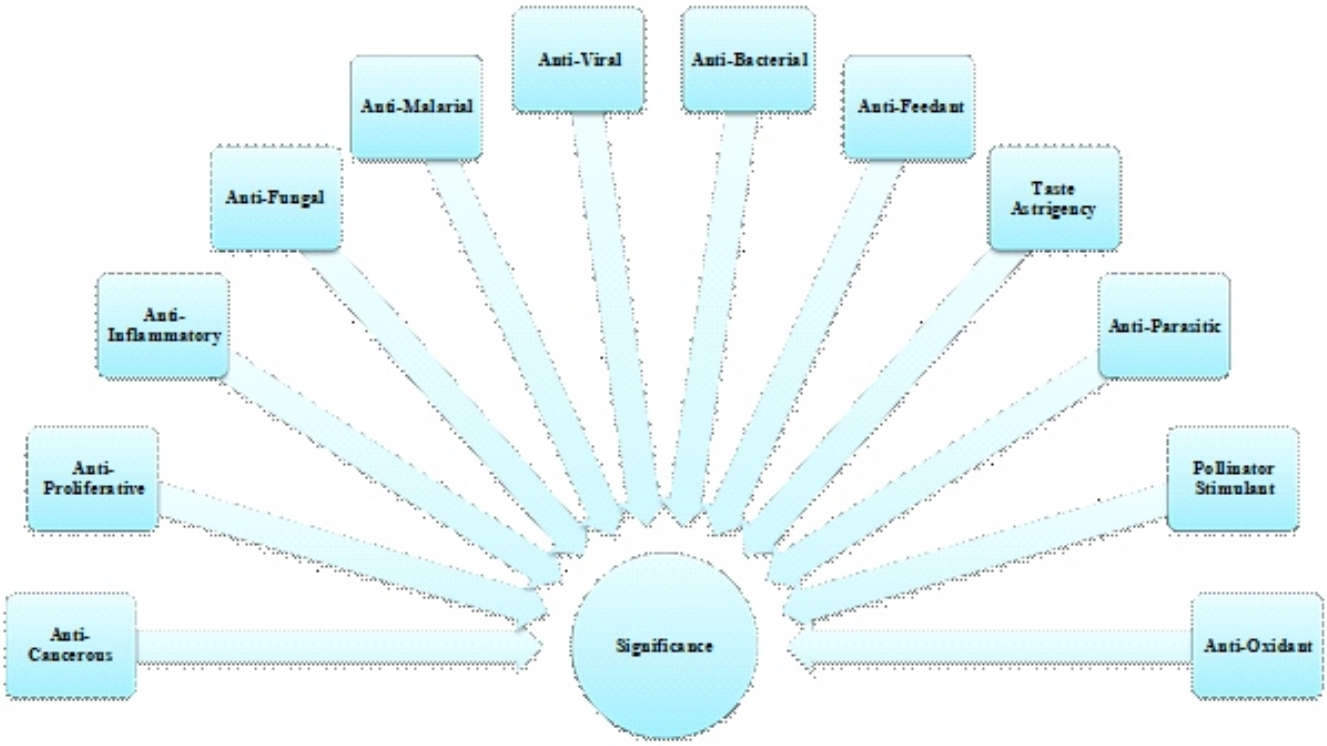
Halogenated Compounds : Halogenated compounds are mainly isolated from phaeophyceae and rhodophyceae. In algae and cyanobacteria, they are identified as acetogenins, phenols, terpenes, indoles, fatty acids and volatile halogenated compounds such as chloroform, bromoform and dibromomethane (20). They show different biological activities for instance anti-proliferative, anti-fungal, anti-cancerous, anti-viral, anti-bacterial, anti-fungal, anti-inflammatory and cytotoxic, etc. Moreover, they have applications in the field of pharmacy and agrochemistry due to their ability to inhibit proteolytic activity of some of the proteases. Brown algae such as *Eisenia arborea, Egregia menziesii, Custoseria osmundacea, Laminaria farlowii, and Prochlorococcus marinus* release a variety of halogenated compounds for example CH_3Cl, CH_3Br, CH_3I, CH_2Br_2, and $CHBr_3$.

Phytohormones : Different species of algae and cyanobacteria releases a variety of phytohormones such as those associated to cell growth, division, differentiation and overall development of plant. Phytohormones (PHs) released by them are auxins (Indole Acetic Acid), gibberellins (GAs), cytokinins (CKs) and ethylene (ET), etc (21). PHs released by symbiotic cyanobacteria is absorbed by the host plant during their different phases of growth and development. Different plant growth regulators (PGRs), which are structurally amino acids, vitamins and sugars are isolated from numerous algae and cyanobacteria. For instance, *Nostoc* sp. releasing Indole Acetic Acid (IAA) and cytokinins has shown up regulation

of *ipt* gene associated to IAA and CKs production due to homologous recombination in the background. It is observed that amongst various phytohormones only CKs and auxins perform their action at a very little concentration. For instance, Cyanophyta and Chlorophyta showed CK like activity that could be advantageous to essential agricultural crops. Furthermore, several algae, micro-algae and cyanobacteria releases ample amount of oxylipins such as jasmonic acid and its volatile methyl ester (1).

Cyanotoxins : An extensive variety of toxins which are a type of secondary metabolite are released by diverse aquatic and marine algae as well as cyanobacteria. The excessive runoff of nutrients from agricultural land leads to accumulation of nitrogen and phosphorous in the water bodies leads to algal bloom due to release of toxins, which hampers the growth of phytoplanktons. Therefore, algal bloom causes a serious threat to water quality by altering the biological and chemical oxygen demand (22). Research in recent years has shown that cyanobacteria and algae release a wide variety of toxins such as endotoxins, cytotoxins, hepatotoxins, dermato- toxins and neurotoxins, etc. This group of toxins are of great concern due to their negative effect on human health. These toxins show bioaccumulation in several aquatic and marine organisms like fish, seafood and molluscs, etc. Bioaccumulation of these toxins has deleterious effect on health of humans, animals, wildlife along with marine and aquatic organisms. They show toxicological effect on skin, nervous system, liver and different cell types. Various cyanobacterial species such as *Nostoc*, *Anabaena*, *Oscillatoria* and *Microcystis* produces very common toxins such as saxitoxins, microcystins, cylindrospermopsin and anatoxin-a, etc. A strain specific production of an alkaloid cyanotoxin is secreted by *Aphanizomenono valisporum*, *Cylindro- spermopsis raciborskii*, *Umezakia natans, Anabaena* sp. etc. Neurotoxins are classified broadly into three main categories i.e. (1) anatoxin-a, (2) saxitoxin and (3) anatoxin-a(s). All three of them have different mode of action and target different cell type. Additionally, they have negative implications on the growth of herbivorous zooplanktons and leads to dangerous health hazards by leaving water unsafe for drinking. Out of these different groups of toxins, hepatotoxins and neurotoxins are very harmful to humans along with animals due to their build up in liver and kidney (23).

Applications: Agriculture : Utilizing algal materials could help crops overcome various forms of abiotic stress in a substantial way. In vitro and in vivo testing revealed that extracts of the brown macroalgae *Ascophyllum nodosum* considerably improved *Arabidopsis thaliana*'s resistance to freezing temperatures. Reductions in damage to tissues, membranes, and chlorophyll were other characteristics of the impact. When plants were simply given the lipophilic portion of the extracts, tolerance to freezing stress was also seen, indicating that the effect



may be related to its constituent parts. Additionally, the *Ascophyllum nodosum* extract increased the fresh and dry weight of *Zea mays* shoots and roots that were cultivated in phosphorous-limited circumstances. Algal extracts gave *Vitis vinifera* plants a high level of resistance to water stress. The extract considerably boosted plant development, the accumulation of macronutrients in the plant organs, and potassium and calcium fluxes. Similar to this, *Chlorella vulgaris* promoted water stress tolerance in *Vicia faba* plants.

The cyanobacterium *Scytonema hofmanni* produced extracellular substances that protected rice plants from the effects of salt stress. In contrast to salt-stressed plants, treated plants showed increased root weight, total free porphyrin, shoot weight, and length. Exopolysaccharides from *Dunaliella salina* also had a similar effect on tomato plants by reducing salt stress. The treated plants also had longer shoots and heavier roots, higher K^+ concentrations, and a higher K+/Na+ ratio (24). Treating water-stressed whole grains of wheat plants with water extracts of *Chlorella ellipsoida* and *Spirulina maxima* resulted in increased total carotenoid, tocopherol, phenolic, and protein contents (25). Activating defense mechanisms against oxidative stress, which is brought on by an excess of reactive oxygen species (ROS) such the superoxide anion (O_2) and hydrogen peroxide, is another function of algae extracts (H_2O_2). Antioxidant substances such carotenoids, cytokinins, tocopherol, and ascorbic acid, as well as the activation of enzymes with antioxidant activity like peroxidase, superoxide dismutase, glutathione reductase, catalase, and ascorbate peroxidase, are primarily linked to this reaction (26).

Cosmetics : Algal products have been employed as antioxidants, sunscreens, thickening agents, skin sensitizers, moisturizing agents to increase the competence of skin's resistance to abrasions, tanning, etc. (27). Algae are primordial unicellular or multicellular eukaryotes that are photosynthetic, or primary producers, which means they capture solar energy and transform it into chemical energy for the creation of organic compounds like sugars. Chlorophyll, a pigment with a green hue found in certain types of algae, is a vital part of the photosynthesis process. These pigments aid in the passage of energy from the light source to the photosystems I and II reaction centres. Chlorophyll a and Chlorophyll b are the two varieties of these pigments that can be distinguished. Consequently, sunshine, water, and carbon dioxide are utilized, to convert oxygen into sugars like glucose/starch and biomass (28). Algal species are able to survive and even thrive under a variety of harsh environmental circumstances, including pH, temperature, osmotic pressure, salinity, exposure to ultraviolet light, and an aerobiosis.

Skin whitening and anti-aging : Melanin, a complex polymer pigment that gives human skin colour and serves as a protective barrier for skin cells, absorbs UV radiation when skin is exposed to it directly for an extended length of time (29). By increasing melanin levels in the skin as a result of continuous exposure to sunshine, tanning results. Sunlight's radiation contributes to the synthesis of tyrosinase, which aids in catalysing processes for the development of melanosomes, which mature into melanin and are further differentiated into keratinocytes to accelerate skin ageing. As a result, L-tyrosine is converted to 3, 4-dihydroxy-L-phenylalanine and L-DOPA, the latter of which is then oxidised to produce dopaquinone. Dopaquinone is subsequently transformed into melanin. Skin pigmentation is caused by an excessive production of melanin, which needs to be controlled. Tyranose inhibitors are thus employed to catalyse the rate-limiting phase in the pigmentation process. Tyrosinase activity and melanogenesis are inhibited by algal pigments including fucoxanthin from the brown algae *Laminaria japonica*, *Alaria, chorda* and *Macrocystis* (30).

Algae against skin aging : Skin ageing is a complex biological process that refers to the skin losing its flexibility with age, as well as the development of fine lines, ridges, creases, and skin discoloration (8). Because of the tremendous severity of the harsh environmental variables to which our skin is exposed, conditions such dryness, thinning, skin laxity, fragility, increased pores, and drooping of the skin cause premature wrinkles as the elastin fibres steadily deteriorate (31). If there is ongoing exposure to heavy metals, a vitamin shortage, and a lack of moisture on the epidermis, the natural process of skin ageing is accelerated. Reactive oxygen species (ROS), which include peroxides, superoxide, hydroxyl radicals, and singlet oxygen, are the most frequent cause of skin ageing. Protein kinase is activated by ROS, which phosphorylates activator protein 1, a transcription factor that typically regulates gene expression in response to cytokines. As a result of this transcription factor's enhanced control of matrix metalloproteinase, the skin's collagen degrades (29). Recent research has produced encouraging results on the rejuvenating and anti-aging properties of algal products including vitamin E, a fat-soluble antioxidant, and pigments like carotene, as well as the reduced risk of skin cancer in users (8). Green and red algae contain carotene, an antioxidant that slows the ageing process of the skin (30). Algal species like *Laurencia*, *Colpomenia*, *Gracilaria*, *Halymenia*, *Turbinaria ornata*, *Ahnfeltiopsis*, *Polysiphonia* are used as anti- aging agents (29).

Algae as moisturizing agent : A moisturizer is made up of a complex mixture of chemical compounds which make the epidermis of skin softer. Skin that isn't adequately hydrated is more prone to acne flare-ups and may even develop eczema. In order to avoid drying, bruising, and wrinkles, moisturisers help the skin retain moisture. Human skin can be moisturised by using water and certain acids, as hyaluronic acid. Alginate, agar, carrageenan, and fucoidans from specific algae species are polysaccharides that assist in controlling the distribution of water in the skin. These polysaccharides, which are plentiful in the algal biomass and non-toxic, can be employed in place of light oils like acetyl alcohol or silicone-derived compounds. Studies have demonstrated how the polysaccharides of some algae species, including *S. japonica*, *Chondrus crispus*, and *Codium tomentosum*, aid in the absorption of moisture while also having a calming effect that promotes normal water circulation. This keeps the skin moisturized in extremely hot and dry environments (32).

Algae as thickening agent and skin sensitizer : In lotions and other cosmetic products with high water content, thickening agents are employed to prevent consistency issues. Polyethylene glycol and vegetable gum are two thickeners used in cosmetics. In the cell walls of the red algae species Gracillaria and Gellidium, agar serves as a binder. A different form of thickening and stabilising ingredient is carrageenan, which is produced from *Chondrus crispus*. Due to the presence of skin-beneficial pigments including phycocyanin, proteins, vitamin A, carbohydrates, and carrageenan, some algae species can also be used as skin sensitizers in cosmetics (33).

Algae as antioxidants : Antioxidants are substances that help prevent skin damage while transferring electrons to an oxidising agent to give skin a healthy shine. An antioxidant aids in inflammation reduction, wrinkle reduction, and skin tightening. Retinoic acid, a form of vitamin A, improves skin suppleness while minimising wrinkles, dark spots, and dark circles. Retinoic acid is produced by cyanobacteria blooms, it has been discovered. Carotenoids are fat-soluble auxiliary pigments that assist algae in photosynthesis by assisting chlorophyll in light absorption. Natural antioxidants include vitamins A and C. Vitamins included in algae like *Spirulina maxima* and *Chlorella vulgaris* help to tone the skin, repair dark circles, purify the skin, and promote hair development by treating dandruff (30).

Flavonoids constitute a large group of plant phenolic metabolites with diverse structural compounds exhibiting multiple biological activities. Flavonoids have been utilised for ages in traditional medicine to treat a variety of human afflictions and improve human health. Flavonoids have a long history, but researchers and doctors are still drawn to them because of their potential to rethink present treatments and restore the balance to human health. The ability of flavonoids to target several clinical problems suggests that they can meet the demands of the present therapeutic strategy, which calls for the management of additional consequences associated with a sick condition. Furthermore, the abundance of flavonoids in dietary sources emphasises both their safety and their potential for usage in therapeutic settings. Flavonoids have a 15-carbon skeleton with two phenyl rings (A and B rings) and a heterocyclic ring as part of their general structure (C ring). Flavones, flavonols, flavanones, flavan-3-ols, anthocyanidins, and isoflavones are the six main subclasses of flavonoids. This classification is based on variations in the C ring's overall structure, functional groups, and the angle at which the B ring is connected to the C ring. Each subclass's individual flavonoids are distinguished from one another by the manner in which they are hydroxylated, methoxylated, glycosylated, glucuronidated, and conjugated. Numerous epidemiological studies have proposed an antagonistic relationship between the consumption of foods high in flavonoids and the advancement of a number of age-associated diseases, such as diabetes, cardiovascular disease, malignancies, and osteoporosis. The amount of flavonoids consumed daily might range from 10 to 1000 mg, depending on the dietary habits of the individual. Flavonoid-rich dietary consumption has a number of positive health effects. Due to their capacity to alter important regulatory enzymes and cellular metabolic processes, flavonoids are frequently used in nutraceutical, pharmacological, medicinal, and aesthetic applications. Due to their low molecular weight, flavonoids can operate on several cellular targets at once and mediate their positive and protective effects on the body's key organs, such as the heart, liver, brain, kidney, and colon. The main biological effects of practically all flavonoids are highlighted by their antioxidant and radical-scavenging properties. Flavonoids are being studied for their multiple health-promoting potentials (33).

Conclusion

Since ancient times, biologically active compounds particularly the active metabolites, which are collected from varying range of organisms particularly the algae, microalgae and cyanobacteria. Organisms inhabiting the diverse ecological habitat are endowed with a wide variety of metabolites to cope with extreme environmental conditions. Naturally, algae, micro-algae and cyanobacteria are rich source of several compounds such as pigments, lectins, fibers, sterols, phytols, halogenated

compounds, vitamins, free fatty acids, proteins, vitamins, polyketides and polysaccharides, etc. Hence, they find wider applications in the field of agriculture, medicine, cosmetics, neutraceutical, pharmaceutical as well as in biofuel industry etc. Metabolites derived from algae, microalgae and cyanobacteria have multifunctional role such as anti-viral, anti-malarial, anti-cancer, anti-bacterial along with immunosuppressant activities. Moreover, they are also used as biocides as an eco-friendly mechanism to control insects and pests, hence are finding greater applications in pesticide industry due to their bio-degradable nature. Certainly, in the recent past, our understanding in the area of diverse algal metabolites has greatly enhanced, but there are still many knowledge and research gaps. However, we are moving cautiously towards a blooming era of algae, microalgae and cyanobacteria to uncover the enigma of their potential metabolites. Categorically, by discovering the novel role of algal metabolites a new framework will develop with specific reference to human health and wellbeing. This review has focused on structurally and functionally diverse algal metabolites such as phytols, sterols, alkaloids, polyphenols, terpenes, halogenated compounds and many more. They have multifunctional utilities in various strategically important industries. Nonetheless, further research is required in the field of characterization of algal metabolites for compiling the metabolite profile to make them more valuable and explorable for human welfare. Furthermore, technological advancements are needed for utilising the green technology potential of these algae, microalgae and cyanobacteria. Time has come to think strategically for disseminating their commercialization at both pilot scale as well industrial scale. The pressing priority is to answer several questions such as whether the metabolite production from these is sufficient enough to meet the demand at industrial level? Whether these metabolites have unknown novel functions which are further need to be investigated? Whether the alteration generated by bioprocess and bioengineering technology can be integrated into the plant system to increase the production from different algae? Therefore, the area of algal metabolites is very promising and future research is required to be undertaken to identify their function along with associated metabolic pathways.

References

1. Lin H., Li Y. and Hill R.T. (2022). Microalgal and bacterial auxin biosynthesis: implications for algal biotechnology. *Current Opinion in Biotechnology,* 73: 300-7.
2. Gomez I., Espanol S., Veliz K. and Huovinen P. (2016). Spatial distribution of phlorotannins and its relationship with photosynthetic UV tolerance and allocation of storage carbohydrates in blades of the kelp *Lessonia spicata*. *Marine Biology,* 163(5): 1-4.
3. Chauhan J. and Kasture A. (2014). Antimicrobial compounds of marine algae from Indian coast. *Int. J. Curr. Microbiol. Appl. Sci.,* 3: 526-32.
4. Keeling C.I. and Bohlmann J. (20120. Plant Terpenoids, in Civjan, N. (ed.), Natural Products in Chemical Biology. New York: *John Wiley & Sons, Inc*. pp. 121–142.
5. Gershenzon J. and Dudareva N. (2007). The function of terpene natural products in the natural world. Nat. *Chem. Biol.,* 3: 408–414.
6. Singh R., Parihar P., Singh M., Bajguz A., Kumar J., Singh S., Singh V.P. and Prasad S.M. (2017). Uncovering potential applications of cyanobacteria and algal metabolites in biology, agriculture and medicine: current status and future prospects. *Frontiers in Microbiology*, 8: 515.
7. Kumar B.N., Mahaboobi S. and Satyam S. (2016). Cyanobacteria: a potential natural source for drug discovery and bioremediation. *J. Ind. Pollut. Control.* 32: 508-17.
8. Fagundes M.B., Falk R.B., Facchi M.M., Vendruscolo R.G., Maroneze M.M., Zepka L.Q., Jacob-Lopes E. and Wagner R. (2019). Insights in cyanobacteria lipidomics: A sterols characterization from Phormidium autumnale biomass in heterotrophic cultivation. *Food Research International,* 119: 777-84.
9. Biyyala Srinivasulu and Pradeep Kumar Singh (2022). Assessment of tomato (*Solanum lycopersicum* L.) genotypes for growth and yield traits under temperate conditions of Kashmir. *Frontiers in Crop Improvement*, 10(2): 107-111.
10. Pathak J., Pandey A. and Maurya P.K. (2020). Cyanobacterial Secondary Metabolite Scytonemin: A Potential Photoprotective and Pharmaceutical Compound. *Proc. Natl. Acad. Sci., India, Sect. B Biol. Sci.,* 90: 467–48.
11. Rosic N. (2022). Genome Mining as an Alternative Way for Screening the Marine Organisms for Their Potential to Produce UV-Absorbing Mycosporine-like Amino Acid" *Marine Drugs,* 20(8): 478.
12. Gao Xiang, Xin Jing, Xufeng Liu, and Peter Lindblad (2021). Biotechnological Production of the Sunscreen Pigment Scytonemin in Cyanobacteria: Progress and Strategy, *Marine Drugs,* 19(3): 129.
13. Hader D.P. (2021). Phycocolloids from macroalgae. In Natural Bioactive Compounds (pp. 187-201). *Academic Press*.
14. Aziz Ejaz Batool, Riffat Khan, Muhammad Usman, Rauf Abdur, Akhtar Wasim, Heydari Mojtaba, Rehman Shazia, Shahzad, Tasmeena, Malik Ayesha, Mosavat Seyed, Hamdollah Plygun Sergey and Shariati Mohammad Ali (2020). An overview on red algae bioactive compounds and their pharmaceutical applications. *Journal of Complementary and Integrative Medicine*, 17(4): 2019-2023.
15. Alfaro-Sayes D.A., Amoah J., Aikawa S., Matsuda M., Hasunuma T., Kondo A. and Ogino C. (2022). Alginate Immobilization as a Strategy for Improving Succinate Production During Autofermentation Using Cyanobacteria

Synechocystis sp. PCC6803. *Biochemical Engineering Journal,* 108681.

16. Khotimchenko M., Tiasto V., Kalitnik A., Begun M., Khotimchenko R., Leonteva E., Bryukhovetskiy I. and Khotimchenko Y. (2020). Antitumor potential of carrageenans from marine red algae. *Carbohydrate Polymers*, 246, 116568.
17. Rodrigues S., Cunha L. and Rico J. (2020). Carrageenan from red algae: an application in the development of inhalable tuberculosis therapy targeting the macrophages. *Drug Deliv. and Transl. Res.,* 10: 1675–1687.
18. Barre A., Bourne Y., Els J.M. Damme V. and Rouge P. (2019). Overview of the Structure–Function Relationships of Mannose-Specific Lectins from Plants, Algae and Fungi. *International Journal of Molecular Sciences*. 20: 254.
19. Hwang H.J., Han J.W., Jeon H., Cho K., Kim J.H., Lee D.S. and Han J.W. (2020). Characterization of a novel mannose-binding lectin with antiviral activities from red alga, *Grateloupia chiangii*. *Biomolecules.* 10(2): 333.
20. Song Y.P., Miao F.P., Fang S.T., Yin X.L. and Ji N.Y. (20180. Halogenated and nonhalogenated metabolites from the marine-alga-endophytic fungus *Trichoderma asperellum* of 44-2. *Marine drugs,* 16(8): 266.
21. Nguyen T.Q., Sesin V., Kisiala A. and Emery R.J. (2020). The role of phytohormones in enhancing metal remediation capacity of algae. *Bulletin of Environmental Contamination and Toxicology,* 105(5): 671-8.
22. Liu C., Ersan M.S., Wagner E., Plewa M.J., Amy G. and Karanfil T. (2020). Toxicity of chlorinated algal-impacted waters: Formation of disinfection byproducts vs. reduction of cyanotoxins. *Water Research,* 184: 116145.
23. Van Hassel W.H., Ahn A.C., Huybrechts B., Masquelier J., Wilmotte A. and Andjelkovic M. (2022). LC-MS/MS Validation and Quantification of Cyanotoxins in Algal Food Supplements from the Belgium Market and Their Molecular Origins. *Toxins,* 14(8): 513.
24. El Arroussi H., Benhima R., Elbaouchi A., Sijilmassi B., El Mernissi N., Aafsar A., Meftah-Kadmiri I., Bendaou N. and Smouni A. (2018). Dunaliella salina exopolysaccharides: a promising biostimulant for salt stress tolerance in tomato (*Solanum lycopersicum*). *Journal of Applied Phycology,* 2929-2941.
25. Abd A.L., Wakel E.S., Abusaief H.M., Monged A. (2016). Effect Of Fertilization by Spirulina Algal Extract on Some Wheat Varieties in Sidi Al Humree, Libya.
26. Lee J.H., Kim S.C., Lee H.Y., Cho D.Y., Jung J.G., Kang D., Kang S.S., Cho K.M. (20210. Changes in nutritional compositions of processed mountain-cultivated ginseng sprouts (*Panax ginseng*) and screening for their antioxidant and anti-inflammatory properties. *Journal of Functional Foods*. 86: 104668.
27. Wang H.M., Chen C.C., Huynh P. and Chang J.S. (2015). Exploring the potential of using algae in cosmetics. *Bioresource Technology,* 184: 355-362.
28. Croce R. and Van Amerongen H. (2014). Natural strategies for photosynthetic light harvesting. *Nature Chemical Biology*. 10(7): 492-501.
29. Thomas N.V., Diyya A.S., Ghafour D.D. and Kim S.K. (2020). Marine Algal Phlorotannins and their biological importance. *Encyclopedia of Marine Biotechnology,* 3: 1535-1558.
30. Jahan A., Ahmad I.Z., Fatima N., Ansari V.A. and Akhtar J. (20170. Algal bioactive compounds in the cosmeceutical industry: A review. *Phycologia,* 56(4): 410-22.
31. Berthon J.Y., Nachat-Kappes R., Bey M., Cadoret J.P., Renimel I. and Filaire E. (2017). Marine algae as attractive source to skin care. *Free Radical Research,* 51(6): 555-67.
32. Wang X., Zhang Z., Zhang S., Yang F., Yang M., Zhou J., Hu Z., Xu X., Mao G., Chen G. and Xiang W. (2021). Antiaging compounds from marine organisms. *Food Research International,* 143: 110313.
33. Couteau C. and Coiffard L. (2020). Phycocosmetics and other marine cosmetics, specific cosmetics formulated using marine resources. *Marine drugs.* 18(6): 322.
33. Malakar B. and Mohanty K. (2021). The budding potential of algae in cosmetics. In Algae (pp. 181-199). *Springer*, Singapore.