Several biologically active secondary metabolites from aquatic plants have been extracted and identified using modern instrumental BioTechniques and used in various ways as flavors, food, additives, coloring agents, nutraceuticals, cosmetics, and also as unique source of pharma industries for the discovery or development of new drugs. From algae to aquatic macrophytes belonging to various categories, aquatic plants produce a variety of compounds such as polyketides, peptides, alkaloids, flavonoids, phenolic compounds, terpenes, steroids, quinones, tannins, coumarins, and essential oils commercially involving in antibiotic, antiviral, antioxidant, anti-fouling, anti-inflammatory, anticancer, cytotoxic, and antimitotic activities; thus making them a rich source of medicinal compounds. Moreover, they are comprehensively used in human therapy, veterinary, agriculture, scientific research, and in countless areas. Importantly these chemicals are exercised for developing new antimicrobial and cancer drugs. Furthermore, antioxidant molecules in aquatic plants and seaweeds have recently been acknowledged. This review contains a consolidated contemporary document consisting of entire knowledge available on pharmaceutical products of aquatic plants and highlights major differences among secondary metabolites found in aquatic (algae) and terrestrial plants.

Keywords: Aquatic plant’s secondary metabolites, Antioxidants, Flavonoids, Cancer, Triterpenes.

INTRODUCTION

The secondary metabolites are specialized biochemical compounds, also called a natural product which plays no apparent role in plant growth, enlargement, and reproduction but helps them in fighting under stress conditions of environment and adaptation [1, 2]. They are biologically active taxonomically extremely miscellaneous compounds produced by plants and released by plants to protect them from insects and herbivores [3]. Secondary metabolites demonstrate some kind of biological activity against few or many living organisms [4]. Secondary metabolites do not engage in any precise role in the internal organization of producers but help the plants to compete with the environment [5, 6]. They are low molecular weight compounds and have limited phylogenetic distribution [7]. Nevertheless, these natural products are used in traditional and folk medicines [8]. It is an established truth that secondary metabolites play a major role in defense mechanisms and their investigation could result in the identification of new signaling molecules [9, 10].

Plant secondary metabolites interact biologically between plants and other organisms. Their noteworthy contribution lies in plants to plant and plant to animal interaction through which they communicate, provide signals, attract pollinators, and protect themselves from enemies. Even endophytes are known to produce beneficial secondary metabolites [11].

They are also remarkable by playing a vital role as antioxidants necessary for human beings to supplement in diet to remove toxic substances from the body [12]. Antioxidant molecules in aquatic plants and seaweeds have attracted the attention of scientists globally recently for searching for new and novel antioxidants from them [13, 14].

Aquatic plants produce a variety of compounds such as flavones, flavonoids, flavonols, phenolic polyphenols, quinones, tannins, coumarins, terpenoids, essential oils, alkaloids, lectins, and polypeptides like terrestrial plants [15, 16]. Some of them can be utilized as food and feed [17]. These substances are used for developing new antimicrobial [18-20], antiviral anti-angiogenesis [21], and anticancerous drugs [22-24]. Furthermore, secondary metabolites extracted from aquatic plants have become of vital importance after realizing its role as antioxidants [25-27]. The successful in vitro production of secondary metabolites has raised the plant cell factory concept [28, 29].

Today, thousands of biologically active metabolites from terrestrial plants are available in the form of databases which are being used following modern tool for bioinformatics in silico drug discovery [30]. However, aquatic plants were ignored for the detection of natural products so far [31]. Although a large number of published information is available, reviews have not been published on secondary metabolites in aquatic plants to date. However, they have been studied earlier for its general biology, physiology, and adaptations. There have been numerous investigations on ecological productivity and dynamics in aquatic ecosystems [32]. The competition and allelopathy among aquatic plants have also been reviewed [33]. They are also being utilized in the bioremediation of soil and water [34]. This paper presents a review of the secondary metabolites of aquatic plants, their biological activity, and their application.

EXTRACTION, ISOLATION, AND IDENTIFICATION TECHNIQUES

The crude extracts of plants in various organic solvents run through column chromatography for fractional distillation. The isolated fractions were further separated using thin-layer chromatography and purified. The purified compound was tested and identified by various traditional analytical techniques such as nuclear magnetic resonance (NMR) and infrared spectroscopy methods [35]. New methods involved spectrophotometer determination and high-pressure liquid chromatography (HPLC), etc. Modern BioTechniques for the identification of secondary metabolites include HPLC-ultraviolet (UV), HPLC-mass spectrometry (MS), and HPLC-NMR [36].

AQUATIC PLANTS

Aquatic plants live in either aquatic freshwater or marine environment. They may be unicellular algae called phytoplankton or large macroalgae/macrophytes. Aquatic macrophytes in facts encompass
a different category of plants, including macroalgae, bryophytes, pteridophytes, and angiosperms that are well acclimatized to the aquatic environment [37]. Sculthorpe [38] classified aquatic angiosperms into the following four life forms, namely, submerged, floating-leaved, emergent, and free-floating.

All aquatic species belonging to angiosperm are called hydrophytes which may be monocot or dicot. These plants have specialized modified structures as an adaptation which helps them to survive in an aquatic environment.

AQUATIC PLANTS CLASSIFICATION

There are many doubts about aquatic plants. The above-mentioned references might be in context with angiosperms, that is, hydrophytes. Further, the term aquatic macrophytes are used in the perspective of angiosperm only. However, members of Phaeophyceae and Rhodophyceae are also large size and hence macrophytes. To avoid any confusion among aquatic plants, the following convenient classification is derived and presented (Fig. 1).

All kinds of aquatic plants have been classified into two, that is, I. Microphytes and II. Macrophytes. Microphytes are cyanobacteria and microalgae. The unicellular microalgae, namely, Spirulina sp. (cyanobacteria) and unicellular algae (Chlorella sp., Chlamydomonas sp., etc.), are also called phytoplankton, which are microscopic unicellular photosynthetic organisms that float with water but cannot swim against the water current. Phytoplanktons make important producer components of nearly all freshwater bodies, marine lakes, and oceans.

Macrophytes are further divided into 4, that is, (1) macroalgae, (2) aquatic bryophytes, (3) aquatic pteridophytes, and (4) aquatic angiosperms. Except for unicellular algae, all other filamentous large algae are placed in macroalgae under macrophytes. Aquatic angiosperms are classified into the following four categories, that is, (1) free-floating macrophytes, (2) floating leaves but rooted plants, (3) submerged macrophytes, and (4) emergent macrophytes.

MICROPHYTES (MICROSCOPIC)

Cyanobacteria are blue-green prokaryotes that may be unicellular (Spirulina sp.) or multicellular (Genus Nostoc, Anabaena, and Oscillatoria). The microalgae and the phytoplankton include all unicellular organisms.

Cyanobacteria

The Gram-negative Cyanobacteria, the pioneer inhabitants, are highly significant in maintaining a major role in carbon and nitrogen sources in
Euglenophycin, an alkaloid herbicidal in nature (42). In addition, they produce mycotoxins from Yessotoxins, polyether [61,64] Diterpene chlorodesmin, Bacillariophyceae Dinoflagellate domic acid, saxitoxins, Polyphenols (Phlorotannins), Planktothrix (46). This toxin enters in food chain through Nostoc commune, Nostoc spongiaeiforme, and Phormidium sp. synthesized antimicrobial compounds. An antimicrobial compound noscomin has been isolated from Nostoc commune (52) and carbonidicyclophanes, and paracyclophanes from other species of Nostoc sp. [53].

Cyanobacteria can synthesize novel biomolecules of therapeutically important (Table 1). In addition, they produce mycotoxins from cyanobacteria (Macrocystis, Anabaena), Planktothrix ( Oscillatoria sp.). Hapalosiphon, Nostoc sp. etc. It is a potent biotoxin released from cyanobacteria. Although it is persistent toxins in freshwater habitats that have attracted scientists all over the world on global health issues, ultimately enter the marine environment. Freshwater microcysts (biotoxin) entered the food chain through the intake of marine clams, mussels, and oysters of species by marine animals and finally humans. Thus, the passing of toxin from the lowest trophic level to higher in the food chain and through biomagnifications has caused serious environmental hazards. Many hepatotoxic shellfish poisoning has been reported due to Microcystin-cyanotoxins. It also provided evidence of harmful algal bloom in the Pacific coastal environment [5-4].

On receiving a huge quantity of nitrates and phosphates, water gets eutrophied and accelerates the heavy production of algal mass that floats on the water surface. This condition leads to the depletion of oxygen. The toxins produced by cyanobacteria greatly affect aquatic communities through biological interactions.

Microalgae ( unicellular algae)
It includes the following unicellular algae Botryococcus, Chlamydomonas, Chaetoceros, Chlorella, Cryptococcus, Dunaliella, Haematococcus, Ischyropsis, Schizochytrium, Spirulina, Nannochloris, Nitzschia, Phaeodactylum, Porphyridium, and Skeletonema belonging to various classes of algae. They are mostly used for inclusion in diets for keeping good health and medicines. The main secondary product of microalgae is polyunsaturated fatty acids [55]. They are also being used for nanotechnology applications [56]. Further, red microalgae are also found in acidic hot springs as benthic organisms producing mostly enzymes and hydrocolloids [57].

Chlorophyceae
Among unicellular chlorophyll-containing green algae, different species of Chlorella are prominent in producing industrial products on large scales, particularly antioxidants, whereas Dunaliella (which can tolerate higher salinity) produces vitamins, enzymes, antioxidants, and antibiotics [58]. Chlamydomonas synthesizes vitamins [59].

Bacillariophyceae (Diatoms)
Members of Bacillariophyceae, also called diatoms, occupy at the producer level in the food chain and provide food for the next trophic level. Thus, they are playing a vital role in the marine ecosystem. They produce toxic metabolites affecting reproduction potential in copepod [60].

Many diatoms belonging to the genus Pseudo-nitzschia produce a strong neurotoxin called domoic acid [61]. This toxin is responsible for causing toxicity in herbivores (Tables 1 and 2). Its toxicity increased in iron-rich waters. It can enter in food chain through contaminated shellfish [62,63]. Domoic acid was also responsible for shellfish poisoning that causes amnesic shellfish poisoning and diarrhetic shellfish poisoning. Saxitoxins are responsible for paralytic shellfish poisoning [64]. It causes nausea, vomiting, headache, dizziness, diarrhea, and coma, sometimes leading to death in humans, whereas mucus released from mouth and disorientation and death in animals [65].

Dinoflagellates
They produce yessotoxins responsible for seafood contamination (Tables 1 and 3). It is lipophilic sulfur-containing polyelectrolyte toxins secreted by several dinoflagellates, including Lingulodinium polyedrum and Gonyaulax spinifera. This toxin enters in food chain through mollusks. They are highly toxic and produce gastrointestinal disorders and accelerate cancer in the human body [66]. Polyol compound symbiodinolide isolated from dinoflagellate Symbiodinium sp.

Euglenophyceae ( Euglenophytes)
Metabolites from marine bioresources have created a center of attention for scientists all over the world from the last few years. The cells of Euglena, a unique unicellular microorganism, are nutritious and have anti-cancerous activity. It is also used in the production of trehalose from glucose, arachidonic acid, wax ester, and Vitamin E [67]. A toxin called euglenophycin is an alkaloid herbicidal in nature (Tables 1 and 4) and anticancerous [68].

MACROPHYES (MACROSCOPIC AND LARGER AQUATIC PLANTS)
The larger aquatic plants, namely, large size algae (filamentous algae, marine giant size kelp, etc.), lower seedless plants (Bryophytes and Pteridophytes), and higher aquatic Angiosperms are referred to as macrophytes.

Macroalgae ( Multicellular algae)
Large size filamentous and multicellular algae are also macrophytes but are called macroalgae.

Chlorophyceae
The green filamentous macroalg Chlorella. Halimeda, a calcareous macroalg contains less

| S. No. | Bacteria/algae | Secondary metabolites/taxins | Reference |
|-------|----------------|-----------------------------|-----------|
| 1     | Cyanophycean bacteria | Microcystins, Antioxidants | [54]      |
| 2     | Bacillariophyceae | Domoic acid, Saxitoxins     | [61,64]  |
| 3     | Euglenophyceae | Euglenophycin, an alkaloid | [68]      |
| 4     | Dinoflagellate | Yessotoxins, polyether      | [66]      |
| 5     | Chlorophyceae | Diterpene chloro desmin, Halimedata-tetraacetate, Diethylane, and trithane, mycosorine-like amino acids | [69]      |
| 6     | Rhodophyceae | Sesquiterpenoids, diterpenoids, Phlorotannin, eckol, and tocopherols | [70]      |
| 7     | Phaeophyceae | Polyphenols (Phlorotannins) terpenoids | [71,72]   |
toxic diterpene compound Halimed-tetraacetate acid which immediately converted to more active compound halimedatal upon injury [70-74]. Diterpenes are antimicrobial and anti-inflammatory compounds (Tables 1 and 5). They also possess anti-Chikungunya virus and anti-HIV potential [75].

Three fatty acids 9,12-Octadecadienoic, Tetradecanoic, and Hexadecanoic acids have been identified from Chara vulgaris which decreased the growth of major bloom-forming cyanobacteria in eutrophic freshwater. Dithiolane and thriathane were reported from the other species, Chara globularis. Nitella sp. was found to have dithiolane toxic to alga Nitzschia palea. An antitumor alkaldoid, caulerpin isolated from Caulerpa racemosa [76]. They also indicated its nutraceutical properties.

**Phaeophyceae**

Marine algae provide valuable complex industrial products, namely, alginate, carrageenan, and agar as phycocolloids [77]. Secondary metabolites obtained from marine brown algae have been extensively used as a traditional herbal medicine for a long time [78]. Furthermore, they show strong antibacterial activity. Fucales sp. and Dictyozales sp. produce the maximum content of phenolic compounds (Tables 1 and 7) like Phlorotannins. Later is also a significant source of terpenoids [79]. Besides, they also protect plants from UV radiation and defense against grazing (Table 1). Volatile compounds have also been reported from marine brown algae. Among them, b-ionone exhibited antibacterial and antifungal activity and are detrimental to some arthropods [80].

Phaeophyceae are rich sources of polyphenols. Polyphenols, particularly polyphenol oxidation, possess peculiar antioxidant properties. Phlorotannins have been isolated from Ascophyllum nodosum, Eisenia bicyclis, Sargassum kjellmanianum, Sargassum ringgoldianum, Ficus vesiculosus, and Fucus serratus in the purified form [81]. These phlorotannins are present in brown algae as chief polyphenol [82]. They are used in medicine as antiinflammatory, anti-Alzheimer disease, antimicrobial, antioxidants anti-HIV, antiproliferative activity, anti-inflamatory, radioprotective, and anti-hypertensive property [83,84].

Phlorotannins possessed therapeutic properties [85-87]. Phlorotannins are specifically present as the only group of phenolic compounds in brown algae. They are just like terrestrial tannins but unlike as phlorotannins consist of oligomers of phloroglucinol [88]; hence, in fact, scavengers in comparison to polyphenols found in terrestrial higher plants. Green tea has only 3-4 rings [89]. They are used in therapeutic medicine as a strong antioxidant.

This compound has been isolated from some brown algae, namely, Ecklonia stolonifera, Ecklonia cava, E. bicyclis, and S. kjellmanianum. Polyphenol production by Phaeophyceae has made this group very toxic to alga Nitzschia palea. An antitumor alkaldoid, caulerpin isolated from Caulerpa racemosa [76]. They also indicated its nutraceutical properties.

Two new Sesquiterpene, a halogenated C15 acetogenin compounds out of six, have been reported in Laurencia obtusa spectroscopically. Out of 34, only four genera (Placocarpus costatum, Ballia callitricha, Phaeolocarpus labillardieri, and Osmundaria colesus) possessed 20 important secondary metabolites along with five known bromophenols [94]. Eleven novel oxylipins, labillardies are reported from alga P. labillardieri and named them A to K. Most of them are macrocyclic compounds significant in therapeutic uses, particularly as antibiotics, antitumor, and antifungal compounds [95].

Different groups of compounds have been isolated and identified, such as hydrocarbons, terpenes, acids, phenols, sulfur-containing compounds, aldehydes, naphthalene skeleton, and alcohol from a diverging group of algae. Marine algae are a great choice for having huge preventive and therapeutic importance due to anticancerous compounds.

**Bryophytes**

They are pioneer land plants. They comprise the second largest group after angiosperms. The main plant body is haploid and called gametophyte which produces male and female gametes for sexual reproduction. They lack true roots. They also do not have true mechanical tissues such as xylem and phloem but have simple water and food conducting tissues such as leptoids and hadroids. Further more, their walls are not lignified.

**Freshwater Bryophytes**

Out of 15,000 plants [96], only a few are aquatic mosses (Ricciocarpus natans, Riccia fluitans, and Riella sp.) found in freshwaters. Several secondary metabolites have been extracted from liverworts (Tables 1 and 2). The synthesis of biologically active terpenoids was against cancer cells [97]. The paste made from Riccia sp. was used to cure ringworm skin disease [98]. Flavonoids Apigenin 7-o-glucuronide, lucerin, luteolin 7-o-glucuronide, and lucerin 2,7-o-rhamnoside have been identified from R. fluitans [99]. The latter is also present in tea, coffee, fats, and oils.

**Marine Bryophytes**

Sphagnum a peat moss marine bryophyte Sphagnum magellanicum produced hydroxyl hydroxybenzoic acid [100]. Polysaccharides extracted from this species possessed antibacterial and antifungal properties [101]. It produces stenols, terpenoids, and polyphenols [102].

**Pteridophytes**

The common aqueous pteridophytes are referred to as aquatic ferns. The common genus is represented by genus Equisetum, Marsilea, Salvinia, and Azolla. Few compounds have been isolated from pteridophytes (Table 2).

Two compounds isooqueretin and flavonoid have been ascribed from Equisetum arvense. The total phenolic content of N-butanol was 96.4 mg/g of dry extract of E. arvense. It showed antibacterial activity against the growth of test bacteria [105]. Flavan-4-ol glucosides identified in Equisetum arvense [106].

### Table 2: Secondary metabolites extracted from bryophytes and pteridophytes

| S. No. | Bryo/ Pteridophytes | Secondary metabolites | References |
|-------|---------------------|-----------------------|------------|
| 1.    | Bryophytes          | Polyphenols, sterols, terpenoids | [103,104] |
| 2.    | Pteridophytes       | Alkaloids, sterols, tannins, flavonoids, terpenoids, cardiac glycosides, phenolic compounds, and terpenoids | [105-110] |

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Saxena et al. Asian J Pharm Clin Res, Vol 14, Issue 1, 2021, 48-63

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S. kjellmanianum, S. ringgoldianum, E. bicyclis, and S. kjellmanianum. Polyphenol production by Phaeophyceae has made this group very toxic to alga Nitzschia palea. An antitumor alkaldoid, caulerpin isolated from Caulerpa racemosa [76]. They also indicated its nutraceutical properties.
Alkaloids, phenolic compounds, flavonoids, saponins, and tannins have been extracted from ferns Azolla pinnata, Marsilea minuta, and Salvinia molesta [107,108]. The former exhibited antibacterial [109] and anti-diabetes properties [110]. Alkaloids, steroids, tannins, flavonoids, terpenoids, cardiac glycosides, phenolic compounds, and terpenoids have been reported from the crude extract of Cyclosorus interruptus [111]. Alkaloids, arbutin, and tannin are identified from this fern [112]. A paste of aquatic fern Ceratopteris thalictroides is used as a poultice for a skin disorder and to stop bleeding.

Gymnosperm
A conifer species Retrophyllum minus is the only obligate inhabitant of aquatic habitats [113], but this is an endemic species to New Caledonia and not much is known about their chemical profiling. This category of plants is not included in the classification of aquatic plants in this paper.

Angiosperms
These are higher plants and the highest evolved. Macrophytes (Angiosperms) are aquatic vascular plants also known as hydrophytes. These specialized plants are adapted to live in the presence of an excess of water in aquatic communities.

Free-floating aquatic plants
These plants float on the water surface. They are also called amphibians because they can also survive on moist soil. Their leaves are exposed to air. Pistia stratiotes and Eichhornia crassipes are medicinal plants known from the ancient system of Indian medicine and used in Ayurveda [114]. Alkaloids, phytosterols, Phenols, flavonoids, and tannin are detected in P. stratiotes [115-117]. Phenolic compounds exhibited antiplatelet activity. Antibacterial and anticancer activity was found in this plant [118-120].

Linolenic acid, β-sitosterol, 24-Ethyl-cholest-4-ene-3,6-dione, sterols (24-Methylphenol), flavanol glycosides (isorhamnetin-3-o-glucoside, Quercetin-3-o-neohesperoside, and Isorhamnetin-3-o-neohesperoside) have been identified from P. stratiotes [121,122]. All these allelochemicals possessed antialgal properties. A compound isolated from Pistia altered the physiology and ultrastructure of Selenastrum capricornutum [123-129]. Stratiotes aloides were found to have lipophilic compounds active against some algae (Table 3).

Tannin, phlobatannin, saponin, steroids, terpenoids, alkaloids, flavonoids, quinines, anthraquinones, cardiac glycosides, sterols, anthocyanins, phenols, carotenoids, polyphenols, carbohydrates, resins, etc., have been recently reported from E. crassipes. Moreover, studies on exudation from the roots in freshwater plants are few. Bioactive sterols have been reported from this plant [130]. He identified five allelochemicals as 24-Methyl cholesta, 24-Ethyl cholesta, 22 -dien, and Methyl-22, -dien- β, α-diol. These allelochemicals were bioactive against Chlorella emersonii of Chlorophyta. The first two compounds also exhibited toxicity against Synecococcus leopoldiensis, Muriella aurantica, and Chlorella vulgaris, whereas 3rd and 4th compounds against Navicula pellicula and C. vulgaris and last one against N. pellicula. The following four bioactive sterols have been identified from E. crassipes as alpha-asarone, γ-linolenic 12 hydroxy 9, 13, 15-octadecatrienoic, and 9 hydroxy 10, 12, 15 octadecatrienoic).

They were toxic to microalgae belonging to the group Cyanochloronta, Rhodophycophyta, Chrysophycophyta, and Chlorophycophyta. Further, most of them inhibited the growth of another green alga Selenastrum capricornutum. Flavonoids are involved in pharmaceutical activities, namely, anti-allergic, anti-inflammatory, antimicrobial, and anticancer activity. Terpenoids are especially used as therapeutic agents in Alzheimer’s disease and liver cancer [131,132].

Rooted aquatic plants with free-floating leaves
These plants are rooted, but their leaves float on the water surface. Genus Nuphar, Nymphaea, and Nelumbo are common plants of the water lily family Nymphaeaceae. All these three species are potent medicinal herbs. They are used to cure, particularly diabetics, liver disorders, etc. Antimicrobial activity of the Members of Nymphaeaceae has been documented. High antibacterial activity of root exudation of Nuphar luteum has been reported [133]. Nymphaea tuberosa exhibited high antibacterial activity against Mycobacterium smegmatis and Staphylococcus aureus. It also possessed anti-fungal properties and inhibited fungi Alternaria sp. and Fusarium roseum [134]. They have reported tannic acid, gallic acid, and ethyl gallate from other species N. tuberosa. Alkaloids such as nupharidine, 7-epideoxynupharidine, and nupharolutine and sesquiterpenes like nupharides have been identified from N. luteum. All these compounds exhibited anticance, anti-diabetes and antioxidant potential [135]. The former plant possessed antinumor and anti-diabetic properties [136]. Lotus pedunculatus (Fabaceae) contained nitro toxin compounds [137]. These nitro compounds identified as a mixture of 3 nitro m-monaloyl-D-glucopyranoses, karatin, co-nation, and cibarian present in the roots. N. stellata declined the growth of water hyacinth; both aboveground and underground parts of the former plant harmed the later [138].

Nymphaea caerulea is used in traditional medicine to treat diabetes, cardiotonic for palpitation of heart, and liver disorders [139,140]. Many compounds were isolated from four Nymphaea species. Further, triterpenes have been reported in all [141-145]. They recommended 5-glycosyl isoflavones as a taxonomic character to identify plants of this group (Table 4).

Total phenolic contents were observed 7.61% (w/w) in Nelumbo nucifera. The seeds contain alkaloids, saponins, phenolics, and carbohydrates. Significant antioxidant activity is reported in this plant [146]. Secondary metabolites alkaloids, flavonoids, phenols, and sesquiterpenes, 2, 3, 4, 5- tetrafaloyl-D-glucose have been identified from Nuphar sp. [147]. Phenols [148] and flavonoids have been reported from Limnophila geoffroyi [149].

Submerged macrophytes
These aquatic plants remain inside water under submerged conditions [150]. Ceratophyllum demersum, Hydrilla sp., Vallisneria sp., and Potamogeton sp. are commonly found in freshwater lakes. Most of them produce phenols and flavonoids. Ceratophyllum demersum synthesized 52

| S No. | Aquatic macrophytes | Secondary metabolites | References |
|-------|---------------------|-----------------------|------------|
| 1. | Pistia stratiotes | Fatty acids – α-linolenic acid, linolenic acid, β-sitosterol, 24-Ethyl-cholest-4-ene-3,6-dione, sterols (24-Methylphenol), flavanol glycosides Isorhamnetin-3-o-glucoside, Quercetin-3-o-neohesperoside, Isorhamnetin-3-o-neohesperoside, Alkaloids, phytosterols, Phenols, flavonoids, and tannin | [124] |
| 2. | Stratiotes aloides | Lipophilic compounds | [125] |
| 3. | Eichhornia crassipes | 24 –Methylcholest 4-ene-3,6-dien, 24-Ethylcholesta – 4, 22-diene-3,6, diene, 24-Methyl cholesta-5, 22-dien-38 -ol, 24 -Ethyl-Cholesta – 5, 22 –dien-3 β -ol, and 24-Methyl Cholesta–22, diene-3 β, α-diol Sterols- alpha-asarone, γ-linolenic 12 hydroxy 9, 13, 15-octadecatrienoic, 9 hydroxy 10,12,15 octadecatrienoic. | [126-129] |
| 4. | Azolla pinnata | Flavonoids | [107] |
Myriophyllum spicatum
Aquatic macrophytes
and
Aquatic macrophytes
Sesquiterpene- Coryan-17-ol, 18,19-di dehydro-10-methoxy-acetate, Phenolics and flavonoids
References
N. ampla
Triterpenes, saponins
N. ampla, N. pulchella, N. gracilis, 3 nitro propanoyl-D-glucopyranoses, karatatin, coronarian, and cibarian
Secondary metabolites
Nelumbo nucifera
Potamogeton natans
[160]
Ent-labdane diterpene
Secondary metabolites
Hydrilla verticillata
References
α-asarone, phenylpropane glycoside
Nuphar lutea
an attractive fast-growing aquarium plant
Gallic acid, myricitrin, myricetin, 1,2,3,4,6- pentagalloyl-D-glucose
Myriophyllum alterniflorum
Nuphar
Ruppia maritima
Elodia sp.
3,4,5-trimethoxyallylbenzene [1] and three lignoids: β-apopicropodophyllin [2]; [−]- [3,3,4,6-R]-[3,3′,4′-methylenedioxy-α-hydroxybenzyl]-4-[3′,4′-dimethoxybenzyl]butyrolactone [3]; and [−]-hibalactone [4]
Tannins, ellagic acid, polyphenols eugenin, phenolic acid, nonanoic acid, flavonoid glycosides, apigenin-7-O-glucoside, sterols-sitosterol, Volatile- paraffins, benzyl 2 5-glycosyl isoflavones, 7,3' , 4' –trihydroxy-5-O-β-D-[2"-Antioxidants
Micranthemum umbrosum
Ceratophyllum demersum
Diterpenes
in limited nitrogen.
4-oxo-β-ionone, dihydroactinidiolide,2 ethyl 1-3-methylmaldeimide
Oxygenated fatty acids have been reported in submerged plants,
derived from Asian grass carp (Osteochordys argus).
might suppress the growth of cyanobacteria. Besides, phenylpropanoid glucosides (α-asarone, β-asarone, 1-o-coumaroyl-6-o-galloyl- β-D-glucopyranose) were identified from Myriophyllum verticillatum (N-hexadecanoic acid). These biomolecules have the potential to clean water in shallow lakes.
Micranthemum umbrosum an attractive fast-growing aquarium plant contained four compounds: 3,4,5-trimethoxyallylbenzene [1] and three lignoids [158]. These compounds played an important role in herbivores against Asian grass carp (Ctenopharyngodon idella).

Table 4: Secondary metabolites extracted from free-floating rooted macrophytes

| S. No. | Aquatic macrophytes | Secondary metabolites | References |
|-------|---------------------|-----------------------|------------|
| 1. | N. ampla and N. pulchella | 2 5-glycosyl isoflavanones, 7,3′, 4′-trihydroxy-5-O-β-D-[2′-acetyl]-xylopyranosylisoflavanone, 7,3′-trihydroxy-5-O-α-L-rhamnopyranosylisoflavanone, 3-glycosyl flavones | [141] |
| 2. | N. ampla, N. pulchella, N. gracilis, and N. elegans | Triterpenes, saponins | [141] |
| 3. | Myriophyllum spicatum | Tannins, ellagic acid, polyphenols eugenin, phenolic acid, nonanoic acid, tetradecaenoic acid, palmitic acid, octadecaenoic acid, octadecaenoic acid, cis-6-octadecaenoic acid, cis-9-octadecaenoic acid, gallic acid, pyrogallic acid, (+)-catechin, polyphenolic compound | [142,143] |
| 4. | Myriophyllum alterniflorum | α-asarone, phenylpropane glycoside | [144] |
| 5. | Nuphar sp. | 3 nitro propanoyl-D-glucopyranoses, karatatin, coronarian, and cibarian | [145] |
| 6. | Nelumbo nucifera | Alkaloids, saponins, phenolics, and carbohydrates | [146] |
| 7. | Nuphar lutea | Gallic acid, myricitrin, myricetin, 1,2,3,4,6-pentagalloyl-D-glucose, 2,3,4,5-tetraflavoyl-D-glucose, 6,6′-dihydroxythiobinupharidine | [147] |

Table 5: Secondary metabolites present in submerged aquatic macrophytes

| S. No. | Aquatic macrophytes | Secondary metabolites | References |
|-------|---------------------|-----------------------|------------|
| 1. | Vallisneria spiralis | 4-oxo-β-ionone, dihydroactinidiolide,2 ethyl 1-3-methylmaldeimide | [152] |
| 2. | Bacopa monnieri | Antioxidants | [153] |
| 3. | Ceratophyllum demersum | flavonoid glycosides, apigenin-7-O-glucoside, sterols-sitosterol, Volatile-paraffins, benzyl acetate and a sesquiterpene | [154] |
| 4. | Hydrilla verticillata | Sesquiterpene-Coryan-17-ol, 18,19-di dehydro-10-methoxy-acetate, Steroids- Ergost-5-en-ol, 22, 23-dimethyl acetate, 1,2-benzene dicarboxylic acid butyl octester, Linoleic acid-10-Octadecenoic acid, methyl ester, stearic acid-Pentadecanoic acid, 1,4-methyl, methyl ester, Diterpene compound, Phthalic acid-1,2-benzenedicarboxylic acid diisocystal ester, Dibuty phthalate, 1,2-hydroxydilaic acid-1,2-12-hydroxydodecanoic acid, 11,14-12-Octadecenoic acid, β-sitosterol acetate, β-sitosterol, ethyl palmitate, 1,14-tetradecanediol acid, 1,2-hydroxydodecanoic acid, 6,10,14-trimethyl-2-pentadecanone, 1-[5'-Hydroxy-4'-hydroxymethyl-1'-methyl-1'H-pyrrol-2'-yl]-henicosa-2,12,15-trien-1-one, dicarboxylic acid-Octadecanediol acid, phenolic acid-Ferulic acid, Chlorogenic acid, Caffeic acid, 3,4,5-trimethoxyallylbenzene [1] and three lignoids: β- apopicropodophyllin [2]; [−]-[3,3,4,6(R)]-[3,3′,4′-methylenedioxy-α-hydroxybenzyl]-4-[3′,4′-dimethoxybenzyl]-butyrolactone [3]; and [−]-hibalactone [4] | [155-157] |
| 5. | Micranthemum umbrosum | 4-oxo-β-ionone, dihydroactinidiolide,2 ethyl 1-3-methylmaldeimide | [158] |
| 6. | Myriophyllum verticillatum | Phenylpropanoid glucosides [α-asarone, β-asarone, 1-o-coumaroyl-6-o-galloyl-β-D-glucopyranose] | [159] |
| 7. | Potamogeton natans | Diterpenes | [160] |
| 8. | Elodia sp. | Phenolics and flavonoids | [161] |
| 9. | Ruppia maritima | Ent-labdane diterpene | [162,163] |
Most of the herbivore does not eat aquatic plants due to the presence of flavonoids. Submerged plants are rich in antioxidants, which provide them antibacterial, antifungal, antialgal, and antitumor properties [173].

Emergent aquatic plants

The Emergent macrophytes are mostly C4 plants and known to produce huge biomass in wetlands. Phenols are the most known secondary metabolites in emergent aquatic plants than any other substance. These phenolic compounds released from aquatic plants help in carbon sequestration by delaying their decay [16]. Further, they have recorded wetland emergent grasses such as Scirpus sp., Typha sp., and Phragmites sp. produced very high phenolic contents of more than 10 g/kg DW [10 g/kg, 15 mg/kg, and 27 g/kg DW, respectively]. However, in Phragmites karka and Arundo donax, the phenolic contents in the dry leaves were measured as 4.45 mg/g and 3.95 mg/g, respectively [110].

An emergent grass A. donax was found toxic to the growth of duckweeds and S. molesta. Both plants died within 7 days due to the presence of phenolic compounds [174]. They proved that phenolic extract was toxic to the growth of duckweeds. Thus, emergent plants also possess a high potential for biocontrol due to the presence of phenolic compounds. Many phytotoxic compounds produced by higher plants are phenolic compounds in Table 6 [175-191]. Flavonoids, the phenolic compounds, are the chief ingredients of this plant.

The medicinal values of reed, Phragmites sp., have been explored from the ancient days for herbal medicine. Long-chain fatty acids, flavonoids such as luteolin and apigenin-7-0-glucoside, cyanidin-3,5-diglucoside, delphinidin-3-glucoside, and quercetin from flowers of Polygonum orientale have been reported. Anthocyanins, delphinidin-3-0-glucoside, and cyanidin-3,5-diglucoside possessed anti-cancer property and induced cancer cell death in human (máze). In addition to these polyphenols and flavonoids, alkaloids have also been isolated from Phragmites vallatoria [192]. They have detected the highest radical scavenging activity (IC 50=735 μg/ML) in this plant. Further, Phragmites plants are an abundant natural source of flavonoids. Their Gas chromatography–mass spectrometry (GC-MS) analysis is emphasized the presence of fatty acids and antioxidants. Out of seven, the main compound was Hexadecanoic acid (30.88%). Others were 9, 12, 15-Octadecatetraenoic acid (alpha-Linolenic acid) and 9, 12-Octadecadienoic acid, two unsaturated methyl esters, and two fatty acids, diisoocetyl ester, 3, 7, 11, 15-Tetramethyl-2-hexadecan-1-ol, and phytol. It tends to reduce wound, fever, vomiting, and sickness after chemotherapy. Furthermore, treat arthritis, rheumatoid arthritis, diabetics, diaphoretic problems, etc. Its antiviral properties have also been well described [188].

The plant is rich in proteins and edible. The Phragmites sp. contained phenol and gallic acid as a prominent compound. Gallic acid and the organic acid ethyl 2-methyl acetoacetate (EMA) methyl acetoacetate were isolated from root exudates, whereas taraxerol and taraxeron from the leaves [193]. High cellulose and lignin were also reported in the aqueous solution of Phragmites australis [194]. Naturally occurring glucosides have been isolated from P. australis flower [195]. A compound EMA was discovered from P. communis, which was found allelopathic to green algae [196].

It has been used for the treatment of diabetes and other diseases such as arthritis and rheumatism in various preparations of different plant parts. Its paste is also used to heal any external injury. Ethanol extract of P. vallatoria has been reported efficient anti-diabetic potential in rats [197]. Phragmites plants are an abundant natural source of flavonoids. A flavone Apigenin-7-O-glucoside and luteolin present in this plant have much therapeutic importance as antioxidants, anti-inflammatory, antioxidant, Alzheimer’s disease, and various types of cancers [198]. These compounds have been reported both from Phragmites sp. and P. orientale. Lutein is a very good source of eye tonic. Flavone, luteolin and apigenin are the chief ingredients of this plant.

| S. No. | Aquatic macrophytes | Secondary metabolites | References |
|-------|---------------------|-----------------------|------------|
| 1.    | Arundo donax       | Alkaloids, N-{4-[Bromophenyl]-2,2-Diphenylacetanilide, Cumarimimetic indoles | [175,176] |
| 2.    | Bacopa monnieri    | Alkaloids, saponins, sterols, betulinic acid, stigmasterol, beta-sitosterol, and bacopa saponins. | [177] |
| 3.    | Cyperus rotundus   | α-cyperone, β-selinene, cyperene, cypertotundone, patchoulenone, sgeunol, kobusone and isokobusone, sesquiterpene-rotundone, flavonol glycoside, saponin, vitamin-in-C, sesquiterpenoids and essential oils, polyphenol, cyperine | [178,179] |
| 4.    | Eclipta alba       | Resin, alkaloid eclitine, vedelactone, triterpenoid | [180,181] |
| 5.    | Eleocharis microcarpa | Fatty acid-trihydroxy cyclopentenyl, phenolic acids, linoic acid, α-linoic acid, p-coumaric and vanillic acids, cycloartane triterpenes cycloartane glucosides, and 9,10-dihydrophenanthrene glucosides | [182] |
| 6.    | Juncus sp.         | 3'-O-glucosides and 3'-O-gentiobioside, ethyl 2-methylacetoacetate, ferulic acid, p-coumaric acid, syringic acid, vanillic acid, p-hydroxy benzoic acid, p-hydroxybenzaldehyde, aurantiamide acetate, 2,3-dihydroxy-1-[4-hydroxy-3,5-dimethoxyphenyl]-1-propano, palmitic acid, heptadecanoic acid, β-sitosterol, stigmasterol, methyl gallate, [-]+l-lyoniresinol, and [-]+l-lyoniresinol-3a-0-D-glucopyranoside | [183-185] |
| 7.    | Phragmites australis | Flavonoid-luteolin and apigenin-7-0-glucoside, cyanidin-3,5-diglucoside, delphinidin-3, 5-diglucoside, quercetin | [186,187] |
| 8.    | Polygonum sp.      | Alkaloids, flavonoid quercetin | [188] |
| 9.    | Polygonum orientale | Flavonoid-luteolin and apigenin-7-0-glucoside, cyanidin-3,5-diglucoside, delphinidin-3, 5-diglucoside, quercetin | [189] |
| 10.   | Schoenoplectus sp. | 11 free and glycosylated low-molecular polyphenols, 17 cinnamic acid and Hydrocinnamic acid derivatives, flavonoids, and 10 C13 nor-isoprenoids,1-benzoyl-glycerol-2-a-1-aminobiphenyloxirane, [-]-catechin | [190] |
| 11.   | Typha domingensis  | Alkaloids, sterols, and flavonoids (noacosalol, lupeol acetate) | [191] |
to the presence of alkaloids. About 12 different alkaloids were identified from *A. donax*. Besides, N-4′-(Bromophenyl)-2, 2-Diphenylacetanilide and curaminic indoles were reported from flowers of giant reed *A. donax*.

The biochemicals have been isolated and identified from *Juncus effusus* plant which had the allelopathic potential for interactions [203]. Various glucosides have been reported from the pith of culms [204]. Allelochemicals present in *Juncus sp*. alelo pathy was demonstrated [205]. These allelochemicals were, namely, antioxidant phanethrones from *Juncus acutus* [206], carotenoids, coumarins, steroids [207]. A triterpene, cykortanes [208], and phenol Juncunol [209] have been isolated and identified from *Juncus sp*. The biological activities of these compounds revealed their cytotoxic and antioxidant properties, and help to protect neurotransmitters, that is, anti-acetylcholinesterase [210].

Higher quantities of phenolic compounds and flavonoids have been do cumented in this macrophyte [211]. Antieptic potential of J. acutus was reported due to the presence of phenolic glycosides, caneoside B, and caffeic acid. The rizome of *J. acutus* exhibited antioxidant potential due to the presence of 8.8′-di-hydroxybiscoumucol, juncunol, 5, 7-dihydroxydihrocone, and flavone products (apigenin, luteolin, chrysonerol, luteolin-7-O-glucoside, and hydrocarbon) [206]. These antioxidant compounds acted as anti-inflammatory, anti-oxidative, and anti-leukemic elements. Moreover, Rodrigues [212] detected a significant *in vitro* cytotoxic effect of phenol, juncunol on human cancer cells (HeP2, MDA-MB468, and Hela), possibly due to the radical scavenging activity of *J. acutus* species.

A perennial emergent tall grass of genus *Typha* possessed several natural products such as saponins, coumarins, and flavonoids. The phenolic compounds-typhaphthalide, typharin, flavonoids-azalchelin, epazafichelin, -1-catechin, and -epicatechin and phytosterol-sitosterol were isolated from rizomes of *Typha capensis* Rohrb. [213,214], fatty alcohol nonacosenol, and triterpene-lupenol acetate were detected in dry flowers and leaves of *Typha angustifolia*. Further, the cerebrosides, 1-O-(beta-D-glucopyranosyl)-(25,3S,4R,7E)-2-(1′(R)-2′-hydroxy-tricosanoyl-amino)-8-nonadecane-3,4-diol and 1-O-(beta-D-glucopyranosyl)-(2S,3R,4E,8Z)-2-(1′(R)-2′-hydroxy-nonadecanoylamino)-4,13-nonadecane-3-diol have been reported from pollen grains of the same species [215].

*Typha* species being medicinal grass have health benefits. Roots and rhizome are rich in starch and used as flour. They have observed significant antioxidant, cytotoxic [216], and immunosuppressive activity from pollen grains [217] in *T. angustifolii* while leaves and flower extracts of *Typha sp*. exhibited strong antibacterial potential against *Salmonella typhimurium*, *Pseudomonas aeruginosa*, *Escherichia coli*, and *S. aureus* [218]. Moreover, silver nano-sized particles made using *T. angustifolia* leaf extract harmed bacteria *E. coli* and *Klebsiella pneumonia* with greater antibiotic efficiency [219].

The phytochemical studies of *Cyperus rotundus* rhizomes have revealed the presence of polyphenol, a flavonol glycocode, saponin, sesquiterpenoids, essential oils, and Vitamin C. The most important biologically active compound reported from *C. rotundus* is cyperine. This volatile compound is used in Ayurveda as a tonic, diuretic, diaphoretic, and stimulant, hypotensive and anti-inflammatory. Alkaloids and terpenes have also been reported from rhizomes [220]. They have isolated 10 alkaloids and 25 phenolic compounds from this plant by GC-MS analyses. These compounds demonstrated inflammatory, anti cancer, anti diabetic, and antioxidant anti-antimicrobial properties [221,222]. Further, it contained a huge amount of tannins [223]. Its roots and rhizome have multidimensional therapeutic potential, including a diuretic and digestive juice and appetizer [224]. Acetone and methanol extract (70%) of the rhizome of *C. rotundus* possesses a good source of antioxidants [225]. Secondary metaboltes such as phenols, flavonoids, and alkaloids produced by *C. rotundus* are valuable sources of modern drug design for chronic diseases such as cancer [226,227].

*Eleocharis* sp. was used in Chinese folk medicine for the treatment of pharyngitis, laryngitis, enteritis, cough, hepatitis, and hypertension [228]. It also inhibits natural acrylamide formation during food processing. It has diverse pharmacotherapeutic applications such as antioxidant, anti-depressant, and neuro disorders [229], a phenolic glucoside, leonuride A, 2-hydroxyethyl-6-(5-hydroxy-2-methylphenoxymethyl)-6-tetrahydro-pyran-3,4,5-triol, and 1,4 dihydroxy-3-methoxy-phenyl-4-O-J-D-glucopyranoside showed good acrylamide formation activity.

Aquatic medicinal herbaceous plant *Bacopa monnieri*, a creeping small tropical plant with oblong leaves and light purple flowers, is known for its pharmacological effects due to the presence of chemical constituents isolated in India (*B. monnieri* Monograph 2004). It contains beta-sitosterol and linoleic acid. The former reduces inflammation in prostate, whereas the latter is an antitumor compound. Another medicinal plant *Eclipta alba* is a moisture-loving herb with small white flowers. Leaves of this plant contain resins, an alkaloid called eclairine, chemical wedelolactone, etc. Wedelolactone, luteolin, and apigenin are antioxidant compounds isolated from this medicinal aquatic plant active against hepatitis C Virus [230].

The strong fungicidal effect of *B. monnieri* was illustrated due to the presence of high antioxidant activity [231]. They have identified flavonoids, glycosides, phenols, tannin, phlobatannin, saponin, and alkaloids from this medicinal plant. Major compounds were 9,12-octadecadienoic acid (36.96%), 9,17-octadecadienoic acid (26.65%), 9-octadecenoic acid (7.79%) and *in vitro* roots yielded 9,12-octadecadienoic acid (25.62%), 9-octadecenoic acid (2.3%), and 9,17-octadecadienoic acid (16.08%). In *vitro* roots subjected to salicylic elicitation comprised of 1,3-dihydroxycetone dimmer (15.6%), 1-hexadecena (7.7%), 1-tetradecena (6.7%), 1-ocadecena (5.9%), 1-decena (4.6%), E-15-heptadecenal (4.4%), and heptacosene (3.4%). In *vitro* elicited roots showed 36 compounds and an increasingly higher percentage of sesquiterpenoids and higher alkenes.

*Schoenoplectus* belonging to the family Cyperaceae, Bulrush (New World species) is closely related to Genus *Scirpus*. Secondary metabolites of this species have been isolated and identified. The biological activity test revealed that they exhibited toxicity to unicellular. More than 50 biocheamicals have been reported from emergent *Schoenoplectus lacustris*. Mostly they are phenolic compounds.

*Nasturtium officinale*, one of the oldest known leaf vegetables for human beings harvested from a fast-growing aquatic plant belonging to family Brassicaceae, released 2-phenyl isothiocyanate which discouraged feeding by freshwater amphipods, cattle fish, and snails [232]. *Habenaria repens*, an aquatic orchid, contained a compound *Habenaria* (bis-p- hydroxybenzyl 2- alkyl-2 hydroxysuccinate) that protects the plant from crayfish [233]. Antioxidant activity is found highest in the aquatic tree *Neptunia oleoacra* [234,235].

**JOURNEY OF SECONDARY METABOLITES FROM AQUATIC TO TERRESTRIAL**

Tracing the journey of secondary metabolites from early ancient plants to contemporary angiosperms is rather a difficult task. It is a universal truth that early land plant communities consisted of prokaryotic organisms, namely, bacteria and blue-green algae (*Cyanophyceae*). Later, being prokaryotic organisms, green algae were placed in photosynthetic bacteria in Monera by Whittaker [236] under five-kingdom classifications. Their secondary metabolites include polyketides, peptides, amino acids derivatives, fatty acids, and some terpenoids. Nevertheless, pathways like flavonoid biosynthesis were completely absent in prokaryotic organisms. The presence of oxidized sterols and xanthophylls in prokaryotes suggests that they were evolved under less availability of oxygen. Alkaloids were also absent in lower organisms.
Secondary metabolites covered a vast journey from primitive antibiotics in ancient groups to complexed flavonoids in higher terrestrial plants. In biological interactions, the most important secondary metabolite is terpenoid. Terpenoids are produced both by lower organisms as well as higher plants in aquatic and terrestrial habitats. They are highly significant in the identification of a taxonomic group in angiosperms. However, no particular secondary metabolite was a marker of a particular phylogenetic group of algae; nevertheless freshwater toxins were reported only from cyanobacteria from selected genera [236].

Volatile monoterpenoids and sesquiterpenoids are major components of essential oils characteristics of many terrestrial families, particularly Asteraceae and Verbenaceae. Like higher plants, terpenoids are also common in marine algae [237].

Besides terpenoids, algae can synthesize fatty acids, simple nitrogen compounds from amino acid pathways, polyketides, some simple phenolic compounds, tri-tetra terpenoids, and majority as steroids, sesqui, and diterpenes are also common. Mono terpenes are rare [238,239]. Carotenoids from marine algae are more complex and variable than present in terrestrial algae [240]. Tri-terpenes are not very common in marine alga [241]. Only green algae produce some halogenated compounds. Phaeophyceae algae predominate in temperate water bodies. These brown algae only produce polyphenolic compounds. Alkaloids, condensed tannins, and lignins which are peculiar in terrestrial plants are absent in all algal groups.

Land plants originated in the Silurian period from amphibian algae [242]. The former faced environmental stresses in terrestrial dry habitat particularly UV radiation harmful for DNA and protein cofactors [243]. In aquatic organisms, these wavelengths are largely attenuated by water hence did not influence significant mortality in aquatic organisms.

In aquatic environment, plants are suspended in the water column; hence, they require less protection from UV radiation. The evolutionary trend of biochemical products in lower aquatic plants is not evident [244]. They demonstrated that lower organisms (bacteria and algae) produced mycosporine-like amino acids (MAAs) as UV-absorbing compounds while higher plants synthesized flavonoids to protect themselves from ultraviolet rays. Ancestors of present-day land plants were cyanobacteria. They were exposed to a higher UV-B level[245].

Aquatic cyanobacteria and algae produce MAAs as UV absorbing compounds when exposed to UV-B fluxes, whereas upon migration to land, land plants such as pteridophytes, gymnosperms, and angiosperms instead of MAAs synthesized a complex flavonoid in terrestrial plants [245]. They reported that moss, however, does not produce flavonoids on an elevated quantity of UV-B radiation. Nevertheless, both compounds are equally efficient in absorbing UV-B radiations, indicating clearly a demarcation in the type of UV absorbing compounds synthesized by lower (algae) and higher aquatic plants (Hydrophytes). This difference in UV absorbing compounds corroborates the migration of higher aquatic plants from the terrestrial environment to aquatic.

Fig. 2: Classification of aquatic plants
Land plants originated from charophycean lineage of green algae [246,247]. All algae and cyanobacteria produced MAAs as UV-absorbing compound except *Chara aspera*. All land plants possessed flavonoids from bryophytes to higher plants. As *Chara* (Charophycean) algae are being considered a link between algae and land plants, it does synthesize neither MAAs nor flavonoids [247]. Furthermore, an alga, *C. aspera*, belonging to Charophyceae serves an important link in between primitive aquatic algae and land plants as evidenced by the fact that neither MAAs is present in this species nor flavonoids, both were absent in *C. aspera*.

Importantly, aquatic submerged angiosperms (*C. demersum, Batrachium trichophyllum*, and *Potamogeton alpines*) synthesized flavonoids just like higher terrestrial plants. It has been established fact that higher aquatic plants, that is, angiosperms are more advanced than terrestrial plants [248]. It is documented here that higher aquatic plants are not producing MAAs as found in lower aquatic plants (algae). Similarly, monocot plants are more advanced and developed later than dicot plants. This is also evidenced by the fact that in monocot tissues, five but in dicot, only two flavonoids responded at higher UV-B.

The aquatic environment does not provide a vast variety of pathogens and predators as present in the terrestrial environment. That may be the reason aquatic plants have been screened less in search of defense molecules. The terrestrial habitats on the other hand expose more competitive conditions that support a greater number of bioactive biomolecules [249].

Temperature and moisture patterns affect the production of biomolecules. They may be secondary metabolites or allelochemicals. Under hot and dry environment, plant species produce aromatic compounds, whereas in the presence of water species produce phenolic

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*Fig. 3: Biological activity of various natural products isolated from aquatic plants*
CONCLUSION AND FUTURE PROSPECTS

Cyanobacteria produce characteristic toxins. Planktons and microalgae synthesize toxins like Microcystins, Domoc acid, Saxatoxins, and Yessotoxins. Chlorophyceae are rich in terpenes, whereas Rhodopcheae and Phaeocheae produce phlorotannins and polyphenols, respectively (Fig. 2). The first land plants, bryophytes, are known to synthesize polyphenols, tannins, flavonoids, phenolic compounds, and terpenoids. In addition to this, pteridophytes also produce alkaloids. Flavonoids and carotenoids are identifiable markers of vascular aquatic plants and may serve as sunscreen for early land plants. The flavonoids of bryophytes are relatively complex and resemble those of many vascular plants. Terpenoids and phenolics are common secondary metabolites.

Eukaryotes originated from prokaryotes [251]. Therefore, genes for secondary metabolites have been introduced into the eukaryotic genome through prokaryotes called horizontal transfer. Aquatic macrophytes (angiosperms) are evolved from terrestrial plants [252]. It is believed that they somehow migrate to aquatic conditions and used to survive thereafter, developing some adaptation mechanisms in their structure. This is also evidenced by the secondary metabolites present in aquatic macrophytes [alkaloids, phenols, and flavonoids]. However, in submerged plants such as Ceratophyllum and Hydrilla species, alkaloids are absent as plants are not exposed to the aerial environment. All algae and cyanobacteria produced MAAs as a UV-absorbing compound except Chara. All land plants possessed flavonoids from bryophytes to higher plants as a UV absorbing compound.

Further, aquatic plants are a potent source of natural bioactive molecules that can be used for the ailment of chronic diseases (Fig. 3). They are a natural source of antioxidants and are used to cure cancer, viral fever, diabetics, etc., without any side effects. Most of them are highly productive. They synthesize huge biomass in water bodies; therefore, efforts should be made to isolate medicinally important compounds from them. It will be cheaper and safe for human health.

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AUTHORS' CONTRIBUTIONS

MKS prepared overall concept of this review, drafted the manuscript and all aquatic informations and discussion part; NS compiled biochemical part of the script. SK performed all computational and designing work. MPD managed all chemical part of natural products and SD supervised overall written document and final editing.

CONFLICTS OF INTEREST

We all five have no conflicts of interest, neither financial nor personal or any other kind.

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Asian J Pharm Clin Res, Vol 14, Issue 1, 2021, 48-63

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