Journal of Scientific & Industrial Research
Vol. 71, January 2012, pp. 13-20

Potential applications of blue green algae

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Received 30 March 2011; revised 05 November 2011; accepted 15 November 2011

Blue green algae (BGA) possess immense morphological and metabolic diversity and can be used in economic development and environment management like wastewater treatment, land reclamation, production of fine chemicals, atmospheric fixation of nitrogen, production of methane fuel, conversion of solar energy, therapeutic functions and so on. This review presents applications of BGA in agriculture, food and industry.

Keywords: Agriculture, Blue green algae (BGA), Cyanobacteria, Industry

Introduction

Cyanobacteria (CB), known as blue-green algae (BGA), are a group of gram negative photosynthetic bacteria that have colonized earth surface for nearly 3.5 billion years and are considered as the predecessors of modern day chloroplast. BGA possess a great deal of morphological and metabolic diversity, which makes CB an extraordinary repertoire of a vast array of chemical products with applications in the feed, food, nutritional, cosmetic, pharmaceutical and even fuel industry. BGA utilization is centuries old (*Nostoc* in Asia and *Spirulina* in Africa and Mexico), purposeful cultivation of BGA started only a few decades ago. During 20th century, several cultivation technologies have been developed and are in use to produce CB biomass as a source of valuable products.

Agriculture

Most promising feature of CB is the ability to photosynthesize and fix atmospheric nitrogen (N) in rice fields. Inherent fertility of tropical rice field soils was attributed to the activity of diazotrophic cyanobacteria[1]. Virtually all dominant CB inhabiting rice fields are diazotrophic and it gives an indication how rice has been grown for centuries without any external supply of N[2]. Most paddy soils have a natural population of CB, which provides free of cost, a potential source of combined nitrogen. CB particularly inhabit the lowland rice fields which provide an ideal environment for their luxuriant growth. Basic significance of ecological observations on the abundance of BGA in Indian rice field soils became apparent when it was recognized that heterocysts were N-fixing stations of heterocystous BGA and that various non-heterocystous forms fixed N anaerobically[3]. Agronomic trials conducted with rice crop commonly show that N contributed by BGA is of the order of 20-30 kg/ha[4]. Thus, using BGA in rice field, a farmer can save to the extent of 20-30 kg N/ha without compromising with the normal yield. Nitrogen fixed by CB may become available to rice plants only after its release extracellularly into the surrounding, either as extracellular products or by mineralization of their intracellular contents through microbial decomposition of fresh or dry algal mass incorporated into the soil, but N fixation by CB vis-à-vis its release in the soil water system may be more useful for crop production during vegetative growth stages of rice than later stage[5,6]. Beneficial effect of CB inoculation has also been reported in other crops (barley, oat, tomato, radish, cotton, sugarcane, maize, chilli and lettuce). Besides contribution of N, growth promoting substances liberated by BGA play an important role in sustaining the crop yield. A number of growth promoting substances [amino acids, sugars, polysaccharides, vitamins (B_{12}, nicotinic acid, pantothenic acid, folic acid etc.), growth hormones (IAA)] have been documented[7,8].

BGA also have tremendous potential in environmental management as soil conditioner. Organic amendments not only act by improving soil structure, but also strongly influence soil microflora[9]. A well developed continuous

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layer of colonies of different CB species in rice fields generally yield a significant amount of biomass. Biomass of some algae decomposes quickly while those of others last longer[10]. Inoculation of rice fields with BGA may help to quickly regenerate and improve soil structure. BGAs during growth in soil excrete extracellularly a number of compounds (polysaccharides, peptides, lipids etc.)[11-13], which possibly diffuse around soil particles and hold/glue them together as microaggregates. Besides, polysaccharides can also entangle clay particles and form clusters. These clusters or microaggregates, in turn, grow and take the shape of macroaggregates and subsequently of larger soil aggregates. Interwoven nature of algal filaments may also help in binding soil particles along with organic carbon added through algal biomass. A significant increase has been observed in soil aggregate stability due to an increase in polysaccharide content of soil as a result of algal inoculation[14,15].

CB also hold potential to reclaim salinity affected soils. A biological approach to the problem of saline soils using BGA was proposed in 1950's, wherein natural populations of N fixing CB were employed for reclamation of saline/alkaline lands typical of certain North Indian States[16,17]. Potential of a brackish-water CB, *Anabaena torulosa*, to grow and enrich N status of moderately saline coastal (*Kharland*) soils have been demonstrated. Most of the sodium removed by CB remains extracellularly trapped in their mucopolysaccharide sheaths[18]. No evidence was found for the incorporation of Na^+ into any biomolecule, especially proteins or carbohydrates. Therefore, permanent removal of Na^+ from saline soils using CB may not be possible, since Na^+ is released back into the soil subsequent to the death and decay of cyanobacteria. Removal of top soil containing CB mats significantly decreased soil salinity (26-38%). But such practice removes all fixed N and carbon. CB are also known to solubilize and mobilize phosphorus (P) and make it available to plants. N fixing CB, *Tolypothrix tenuis*, *Hapalosiphon fontinalis* solubilize Mussourie rock phosphate (MRP), a source of P_2O_5. Similarly, *Westeillopsis prolifica* and *A. variabilis* showed good growth and N fixing ability in presence of mineral phosphate sources (MRP and TCP) in addition to solubilizing these insoluble phosphate sources[19,20]. Such microorganisms can be exploited for efficient utilization of low cost, low grade rock phosphate fertilizers.

Food

BGA are being used as food for a long time. According to legend, Hung Ge, an alchemist, physician and Taoist theoretician of Eastern Jin Dynasty (317-420 AD) used *Nostoc commune* as a staple food during periods of famine when he was a hermit in Southern China. *Nostoc* is a common dietary supplement for the indigenous populations of Thailand, Peru, China, Ecuador, Fiji, Java, Japan, Mexico, Mongolia and Siberia who have long appreciated the nutritional value of different forms of *Nostoc* like *N. commune* var. *flagelliforme*, *N. edule*, *N. ellipsosporum*, *N. verrucosum* and *N. pruniforme*[21]. *N. commune* has high amount of fibre with moderate protein and is considered as a new dietary fibre source.

Spirulina has been eaten for centuries by Kanembu people, who live along the shores of Lake Chad in north-central Africa. It has the highest protein of any natural food (65%); far more than animal and fish flesh (15-25%), soybeans (35%), dried milk (35%), peanuts (25%), eggs (12%), grains (8-14%) or whole milk (3%). *Spirulina* also contains a considerable amount of carbohydrate (~20%), lipid (~5%), mineral (~7%). It is a very rich source of β-carotene, thiamine, riboflavin and is one of the richest source of vitamin B_{12}. Due to its high protein content and various possible health promoting effects (alleviation of hyperlipidemia, suppression of hypertension, protection against renal failure, growth promotion of intestinal lactobacilli and lowering of elevated serum glucose level), *Spirulina* has been exploited commercially. Pharmaceutical preparations from *Spirulina* are also recommended as protein supplement. Hainan Simai Enterprising located in the Hainan province of China, is the largest producer of *Spirulina* in the world. On the other hand, Earthrise Company (Caliptera, CA, USA) has the largest *Spirulina* production plant and their products are distributed in over 20 countries. Besides, some other companies selling BGA products across different countries in the world are listed (Table 1). Commercial preparations like "Zyrulina" and "Recolina" (Zydus Cadila), "Nuclina" (Mapra Laborarories), "Vitalinaa" (Hydrolina Biotech), "GAIA Spirulina" (Cosmic Nutracos), "Spiru Power" (Antenna Nutritech) and "Sunova" (Sanat Products Ltd.) containing dry powder of *Spirulina* are available in the Indian market. Capsules containing dry powder of *Aphanizomenon flos-aquae*, under the trade name of Kalmath's Best ® Blue Green Algae by Kalmath Valley Botanicals LLC, USA have gained popularity in USA, Germany, Canada, Korea, Japan and Austria. It contains 20 antioxidants, 68 minerals and 70 trace elements, all amino acids, B vitamins and important enzymes.

Table 1—Companies selling blue green algae or blue green algal products from different countries

Countries	Companies
USA	Earthrise Nutritionals, California; Cyanotech, Hawaii; Kalmath Valley Botanicals LLC
Italy	BioEarth Spirulina
Germany	Green Valley Spirulina
France	Natésis Spirulina
Thailand	Boonsom Spirulina Farm
UK	All Seasons Health
Switzerland	NaturKraftWerke Spirulina
Germany	Sanatur Spirulina
Netherlands	Marcus Rohrer Spirulina
Monacco	Exsymol S.A.M.
Japan	DIC Lifetec
China	Fuqing King Dnarmsa Spirulina Co. Ltd; Hainan Simai Pharmacy Co. Ltd; Jiangsu Cibainian Nutrition Food Co.Ltd; Jiangxi Boyuan Spirulina Co. Ltd; Nanjing General Spirulina Developing Corporation; and Bluebio Bio-Pharmaceutical Co. Ltd
Taiwan	Far East Bio-Tec Co. Ltd; and Far East Microalgae Ind Co. Ltd
Mayanmar	Mayanmar Spirulina Factory
Thailand	Siam Nostoc
India	Zydus Cadila, Ahmedabad; Mapra Laboratories Pvt Ltd, Mumbai; Cosmic Nutracos Solutions Pvt Ltd, New Delhi; Hash Biotech Limited, Chandigarh; Sanat Products Ltd, New Delhi; Parry Neutraceuticals, Oonaiyur; Hydrolina Biotech Pvt Ltd, Chennai; Ecotech Technologies India Pvt Ltd, Mumbai; Essar Biotech, Hindupur; Miraculous Mushroom, Pune; Admark, Vijayawada; Care

Feed for Animals and Aquaculture

Apart from use of BGA as human food, it can also be incorporated in feeds for a wide variety of animals ranging from fish to pets, farm animals and birds. Of current world algal production, 30% is sold for animal feed applications[22] and over 50% of *Spirulina* is used as feed supplement[23]. When soy protein in feed for pigs was replaced by *Spirulina*, there was no sign of diarrhoea, loss of appetite, toxicity or gross histopathological lesions of gastro-intestinal tract[24]. Better digestibility was obtained with *Spirulina* constituting 20% of a complete sheep diet[25]. As a tonic for horses and cows, ½ ounce may be used twice a day for each 100 pounds of body weight by mixing in slightly dampened feed. Canary, finch, parrot, lovebird and other breeders use *Spirulina* to increase coloration, accelerate growth and sexual maturity and improve fertility rates. It is used by ostrich and turkey breeders to increase fertility and reproduction rates. It enhances desirable yellow skin coloration in chickens and increases the deep yellow color of egg yolks[26]. BGA increases feather color and shine, healthy beaks and skin, and promotes good bacteria in the digestive tract. *Spirulina* is being used as feed for Penacide shrimp larvae, bivalve molluscs, brine shrimps, marine rotifers etc. *Spirulina* added to feed ration of brine shrimp at 1-10% levels increases survival rates, allowing fish to reach market size sooner[26]. It is the best food for tiny brine shrimp. Species (22) of *Nostoc*, *Anabaena* and *Calothrix* increase body weight of Telapia hybrid fish with excellent food conversion ratio. Feed containing 5-20% *Spirulina* enhances color pattern of Champion Koi fish, thereby increasing its demand and value in market by several folds[26].

Pigments and Natural Colours

Apart from chlorophyll, CB produce two major groups of pigments (phycobiliproteins and carotenoids). Phycobiliproteins are assembled into particles named Phycobilisomes that are attached in regular arrays to external surface of thylakoid membrane and act as major light harvesting pigments in CB. These are accessory photosynthetic pigments and may comprise 40-60% of the total soluble protein in these cells[27]. Phycobiliproteins are covalently attached linear tetrapyrrole chromophoric group called bilins or phycobilins because of their close structural relationship to well-known bile pigments of human bilirubin and biliverdins[28]. Among them, Phycocyanin (PC) and Phycoerythrin (PE) are commercially valuable. PC has been extracted and purified from *Spirulina* sp., *Synechococcus* sp., *Oscillatoria quadripunctulata*, *Aphanizomenon flos-aquae* etc. and produced commercially from *Spirulina platensis* and *Anabaena*. PC as natural colorants are gaining importance over synthetic colours as they are environment friendly, non toxic and non-carcinogenic. Dainippon Ink & Chemicals (Sakura, Japan) has developed a product called "Lina blue" (PC extract from *S. platensis*), which is used in chewing gum, ice sherbets, popsicles, candies, soft drinks, dairy products and wasabi. Besides, there are number of other companies commercializing following products based on phycobiliproteins: Cyanotech, C-Phycocyanin (C-PC); PROzyme, C-Phycocyanin (C-PC), GT5 Allophycocyanin, PhycoLink® Biotinylated C-Phycocyanin, Phycolink® Goat "-Human IgG (Fc-specific)-Allophycocyanin; AnaSpec Inc., C-Phycocyanin (C-PC); Europa Bioproducts Ltd, PhycoPro™ C-Phycocyanin; Innova Biosciences, Lightning-Link C-PC conjugation kit; and Sigma-Aldrich, C-Phycocyanin (C-PC). Use of Phycobilins in cosmetics (lipstick, eyeliners etc.) is also gaining momentum. Properties like high molar absorbance coefficients, high fluorescence quantum yield, large Stokes shift, high oligomer stability and high photostability make Phycobiliproteins very powerful and highly sensitive fluorescent reagents. Purified native Phycobiliproteins and their subunits fluoresce strongly and since 1982, have been widely used as external labels for cell sorting and analysis and a wide range of other fluorescence based assays[29]. A large number of patents (up to 2008) on fluorescence based applications of Phycobiliproteins[30] are as follows: fluorescent labels, tags and markers, 122; as a moiety in fluorescent energy transfer, 25; signal generators and image contrast agents, 13; diagnostic tools, 12; in bioluminescent novelty items, 4; recombinant constructs, 13; and intact phycobilisome preparation for fluorescent applications, 3.

Among health-promoting properties and pharmaceutical applications of Phycobiliproteins, as an antioxidant, Phycocyanin is able to scavenge alkoxyl, hydroxyl and peroxyl radicals *in vitro* and inhibited microsomal lipid peroxidation induced by Fe^{+2} –ascorbic acid or free radical initiators 2, 2′ Azobis (2- amidinopropane) dihydrochloride (AAPH). Phycocyanin has also been reported to reduce the levels of tumor necrosis factor (TNF-α) in blood serum of mice-treated with endotoxin. Phycocyanin from *Aphanizomenon flos-aquae* is reported as a strong antioxidant[31,32] and its protective nature against oxidative damage has also been demonstrated *in vitro*[33]. Carotenoids present in CB protect cells from damage by reactive oxygen molecules, hence, act as antioxidants and these pigments can boost immune system and lower risk of heart disease, prevent onset of cancers and protect against age related diseases (cataracts and macular degradation, multiple sclerosis). *Spirulina*, a rich source of β-carotene, has been used in aquaculture and poultry to improve colour of fishes and egg yolks respectively. Chlorophyll-a extracts from *Spirulina* having iron oxide and higher alcohols (cetyl and stearyl) is patented as strong deodorant. Alcohol moiety of Chlorophyll is a precursor for synthesis of Vitamin A, E and K_2.

Cosmetics

As natural colorants, Phycobiliproteins of CB are non-toxic and non-carcinogenic. Some CB species (mainly *Spirulina*) have established in skin care market. A protein-rich extract from *S. platensis* repairs signs of early skin aging, exerts a tightening effect and prevents stretch mark formation (Protulines, Exsymol S.A.M., Monaco). Spirulina Firming Algae Mask by ODA (Optimum Derma Aciditate) improves moisture balance of skin and its turgor strengthens skin's immunity; Spirulina Whitening Facial Mask by Ferenes Cosmetics contains proteins from *Spirulina* and herbal extracts, which improve skin complexion, and reduce wrinkles without any allergic effect. Spirulina Facial Moisturizer by Ferenes Cosmetics contains natural proteins, essential fatty acids and β-carotene from *Spirulina* and other herbal extract. Similarly, Spirulina Facial Scrub by Ferenes Cosmetics contain quality ingredients from *Spirulina* and other herbs that remove dead skin cells and act as a cleanser to energize the face. Codif Recherche & Nature (Paris, France) has marketed a *Phormidium persicinum* product Phormiskin Bioprotech G, which has unique photo-protective property.

Antibiotics and Other Potential Drugs

CB are known to produce a vast array of toxic or otherwise bioactive metabolites. BGA like *Anabaena*, *Nostoc* and *Oscillatoria* produce a great variety of secondary metabolites. The only comparable group is *Actinomycetes*, which has yielded a tremendous number of metabolites including many important therapeutic agents. Medicinal qualities of CB were first appreciated as early as 1500 BC when *Nostoc* species were used to treat gout, fistula and several forms of cancer. Noscomin, a diterpenoid from *N. commune*, showed antibacterial activity against *Bacillus cereus*, *Staphylococcus epidermidis*, and *Escherichia coli*[34]. Natural products of *Nostoc* sp. are effective against *Cryptococcus* sp. as a causal agent of secondary fungal infections in patients with AIDS[35]. Fibre [oxalate oxalic acid soluble substances (OOSS)], extracted from *N. commune*, possesses hypocholesterolemic effect in rats. *Lyngbya majuscula*, a marine CB, produces a wide variety of polyketides, lipopeptides, cyclic peptides and many others. *L. majuscula* show antibacterial activity against *B. cereus*, *B. subtilis*, *Mycobacterium balnei* etc.[36]. Majusculamide-C, a micro filament depolymerizing agent from *L. majuscula*, has shown potent fungicidal activity and may find application in the treatment of resistant fungal-induced diseases of plants and agricultural crops. Lipophilic and hydrophilic extracts of over 900 strains of cultured CB were examined *in vitro* for their ability to inhibit enzyme Reverse Transcriptase (RT) of Avian Myeloblastosis Virus (AMV) and HIV type 1. Maximal level of RT inhibition achieved by some of the active extracts was equivalent to that measured for 3′ -azido-2′ ,3′ -dideoxythymidine (AZT) at 668 ng/ml. An extract of two CB *Phormidium tenue* BDU 20571 and *Pseudoanabaena schmidlei* BDU 30313 have shown anti-viral activity against Hepatitis B virus[37]. Chlorine containing β-carotenes (Bauerines), isolated from terrestrial BGA *Dichothrix baueriana* GO-25-2, showed anti-viral activity against Herpes Simplex Virus type 2. *Fischerella ambigua* and *Haplosiphon hybernicus* produce Ambiguines, which show anti-fungal activity on *Aspergillus oryzae* and *Candida albicans*[38]. Tjipanazoles, N-glycosides of indolo-[2,3-a] from *Tolypothrix tjipanasensis*, exhibited appreciable fungicidal activity against phytopathogenic fungi. Calothrixins A and B derived from *Calothrix* sp. inhibit FAF6 strain of *Plasmodium falciparum*[39]. Symplocamide A obtained from a CB *Symploca* sp. was found to be active against parasite of malaria (*P. falciparum* W2), Chagas disease (*Trypanasoma cruzi*) and leishmaniasis (*Leishmania donovani*)[40].

An anti-cancer factor has been identified in *Scytonema* sp., *Phormidium tenue* and *Anabaena variabilis*. Curacin A, an antimitotic agent, has been isolated as a major component (8-10%) from organic extract of marine CB, *Lyngbya majuscula*. Cryptophycin-1, isolated from a *Nostoc* sp., showed cytotoxic activity against KB nasopharyngeal carcinoma and human colorectal adenocarcinoma cell lines[41]. Tylotoxin isolated from *Scytonema ocellatum* depolymerized actin to disturb cell division and seems to be a potent anti-cancer drug. Structural novelties of CB natural products can serve as structural templates for synthesis of highly potent synthetic analogues with reduced toxicity. This is exemplified by the successful modifications of Dolastatins 10 and 15 (produced by certain marine CB) to provide synthetic analogues, such as TZT-1027 and ILX-651, currently in phase II clinical trials as anticancer drugs[42].

Enzymes

CB produce a battery of enzymes that can be exploited commercially. *Microcystis aeruginosa* possesses a large capacity to mineralize organic P per unit of biomass due to alkaline phosphatase activity. Both cell bound and extracellular phosphatase activities of CB isolates are reported. A number of studies report detection of enzymes (phosphatase, arylsulfatase, chitinase, L-asparaginase, L-glutaminase, amylase, protease, lipase, cellulase, urease and lactamase) produced by CB[43,44]. An anti-fertility enzyme, elastase, has been purified from *Oscillatoria* sp. Several unique sequence specific restriction endonucleases are produced by CB with potential use in recombinant DNA technology (Table 2).

Table 2—Major restriction enzymes obtained from blue green algae

Restriction enzyme	Source
Acy I	*Anabaena cylindrica*
Ani I	*Anacystis nidulans*
Ava I	*Anabaena variabilis*
Ava II	*A. variabilis*
Ava III	*A. variabilis* UW
Asu I	*Anabaena* sp. PCC 6309
Afl I	*A. flos-aquae*
Afl III	*A. flos-aquae*
Mla II	*Fischerella* sp. PCC 7414
Mst II	*Microcoleus* sp. UTEX 2220
Nsp CI	*Nostoc* sp. PCC 7524
*Sp*1 I	*Spirulina platensis*
*Sp*1 II	*S. platensis*
Ttn I	*Tolypothrix tenuis*

Carbohydrates

Fresh water CB accumulate osmotically active low molecular weight carbohydrates (glucose, trehalose, sucrose etc.) while marine species accumulate glucosyl-glycerol, sucrose, trehalose etc. *Synechococcus* sp. contain up to 0.25 M glucosyl-glycerol. Intracellular content of osmoregulatory carbohydrates can be modified by changing salinity of growth medium. Levels of other intracellular carbohydrates can also be modified by changing nutrient levels (N and P) in medium. Many species of unicellular and filamentous CB produce extracellular polymeric substances consisting mainly polysaccharides; especially edaphic forms, which produce extracellular polymers of diverse chemical composition. Mucilaginous material excreted by *Aphanothece* and other cyanobacteria helps to seal porous bottom of the evaporation ponds and thus reduces the loss of brine to ground water[45]. EPS produced by marine *Cyanothece* sp. ATCC 51142 has been characterized for physical, thermal and gelling properties and its exploitation towards metal removal, food and packaging industries[46]. CB EPS are a promising alternative to polysaccharides of plant and algal origin due to higher growth rates, reproducible physico-chemical properties of their EPS, easier genetic manipulation of producing microorganisms, presence of novel functionalities and economic costs of production.

Ammonia and Amino Acids

Ammonia generation by photo-biological energy transduction system in CB has also been found industrially feasible. A number of amino acids are produced by CB. *Spirulina* produces 18-20 amino acids, whereas other CB produce different amino acids in appreciable amount. Important amino acids produced by CB include serine, arginine, glycine, aspartic acid, glutamic acid, cystein, lysine, isoleucine alanine, methionine, phenylalanine etc[7]. With appropriate physiological and genetic manipulations, CB species can either accumulate economically valuable amino acids in their cells or release them into the medium. Amino acids are used extensively in food industry, medicine and in chemical industry as starting material for manufacture of cosmetics.

Fatty acids

CB lipids (2-23% dry wt basis) contain neutral lipids, glycolipids and phospholipids. CB fats, oils and hydrocarbons have been commercially exploited with a wide range of applications like liquid fuels, waxes, biosurfactants, phospholipids & lecithins, essential fatty acids and prostaglandins. A number of lipids produced by these organisms have surface active properties and can be potentially used as biosurfactants (phosphatidyl glycerol, phosphatidyl choline, phosphatidyl ethanolamine and a range of galactosyl diglycerides) in flocculation and emulsification. Among various fatty acid constituents of CB lipids, the most important are PolyUnsaturated Fatty Acids (PUFA) and within these essential fatty acids. These fatty acids are precursors of prostaglandins, prostacyclins, thromboxanes and leucotrienes and as such are becoming increasingly important in pharmaceutical industry. Gamma linolenic acid (GLA), an essential fatty acid, is a precursor for the body's prostaglandins, the master hormones that control many functions. PGE1 is usually formed from dietary linolenic acid and GLA progresses to PGE1. Prostaglandin PGE1 is involved in regulation of blood pressure, cholesterol synthesis, inflammation and cell proliferation. *Spirulina* is a rich source of this rare essential fatty acid[47] and 10 g of *Spirulina* has over 100 mg of GLA. Studies show dietary intake of GLA can help in arthritis, heart disease, obesity and zinc deficiency. Alcoholism, manic-depression, aging symptoms and schizophrenia have been ascribed partially to GLA deficiency. In Spain, GLA in *Spirulina* and evening primrose oil is prescribed for treatment of various chronic health problems

Vitamins and Special Biochemicals

Some marine CB are potential source for large scale production of vitamins of commercial interest such as vitamins of B-complex group and vitamin E. *Spirulina* contains β-carotene an analogue of vitamin A and has the potential to produce two molecules of vitamin A. *Spirulina* is also the richest known natural source of vitamin B_{12}. Panmol Company (Austria) has commercialized vitamin B_{12} from *Spirulina*. Some of the CB producing different vitamins are as follows: *Anabaena flos-aquae*, B_{12}; *Anabaena hassali*, biotin; *Chroococcus minutes*, B_{12}; *Oscillatoria jasorvensis*, B_{12}, pantothenic acid; *Spirulina platensis*, A, B_1, B_2, B_{12}, C, E, pantothenic acid; *S. maxima*, vitamin A, B_1, B_2, B_{12}, C; and *Nostoc* sp., B_{12}, B_1, biotin, nicotinic acid[48]. CB are suited as a source of stable isotopically labeled compounds because their photosynthetic nature allows them to incorporate stable isotopes like ^{13}C, ^{15}N and ^{2}H from $^{13}CO_2$, $^{15}NO_3$, $^{2}H_2O$ respectively to highly valued organic compounds like amino acids, carbohydrates, lipids and nucleic acids. Stable isotope biochemicals after their incorporation into different biomolecules may facilitate their structural determination at atomic level and metabolic studies. *Spirulina* is being exploited to produce ^{13}C incorporated DHA.

Hydrogen (H_2) and Other Biofuels

Cost of photobiological produced H_2 (\$25/m^3) is lower compared to that produced by photovoltaic splitting of water (\$170/m^3)[49]. H_2 production is reported under a vast range of culture conditions from a number of CB genera, which include some unicellular non-diazotrophic CB *Gloeocapsa alpicola* (shows increased H_2 production under sulphur starvation), *Spirulina platensis* (can produce 1 μmole H_2/12 h/mg cell dry wt in complete anaerobic and dark condition), diazotrophic CB *Anabaena variabilis* etc.[50]. CB H_2 production is poised to be a very useful commodity, provided effective utilization of produced H_2 is devised. Direct conversion of carbon dioxide to biofuels in photosynthetic CB can significantly improve the efficiency of biofuel production. A theoretical calculation shows that productivity of ethanol in a photosynthetic organism can reach 5,280 gal/acre/y[51]. Algenol Biofuels Inc. has developed an innovative CB-based technology to produce ethanol at a rate of 6000 gal/acre/y. In contrast, annual yield of ethanol from corn is 321 gal/acre/y, from sugarcane 727 gal/acre/y[52], from Switch grass 330-810 gal/acre/y, and from corn stover 290-580 gal/acre/y[53]. Clearly, ethanol production from CB is significantly more efficient than is ethanol production from plant feedstocks.

Conclusions

Role of CB in agriculture and industry has both promise and potential. The effect of BGA has so far been studied mainly in rice fields, under flooded conditions that are ideal for the growth of BGA, but their effect on dry crops like wheat, maize etc. need experimentation and will further boost their role in agriculture. Effective utilization of CB biofertilizers will not only provide economic benefits but also improve and maintain soil fertility and sustainability in natural ecosystem. Similarly, biotechnological applications of BGA like human and animal nutrition, cosmetics and production of high value molecules (fatty acids, pigments, stable isotope biochemicals etc.) have also gained importance in recent years. The use of transgenic CB with properties of overproduction and of newly discovered metabolites holds significant promise and could be seen as gateway to all human needs. Development of different cultivation systems implying varied kind of sophisticated bioreactors can lead to quality biomass production and further enhance their use in functional foods and pharmaceuticals. Nevertheless, BGA have great potential and their use will extend to new areas in near future.

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