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Changes in the Quality and Quantity of Paddy Grains by the Use of Cyanobacterial Biofertilizer as Compared to Chemical Fertilizer

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ABSTRACT: Continuous increase in global human population and depletion of natural resources of energy posing threat to environment needs, sustainable supply of food and energy. The most ecofriendly approach 'green technology' has been exploited for biofertilizer preparation. Cyanobacteria are the most successful and sustained prokaryotic organism during the course of evolution. They are considered as one of the primitive life forms found on our planet. Cyanobacteria are emerging candidates for efficiently conversion of radiant energy into chemical energy. This biological system produces oxygen as a by-product. Cyanobacterial biomass can also be used for the large scale production of food, energy, biofertilizers, secondary metabolites, cosmetics and medicines. Therefore, cyanobacteria are used in ecofriendly sustainable agricultural practice for production of biomass of very high value and decreasing the level of CO_2. This review article describes the methods of mass production of cyanobacterial biofertilizers and their applications in agriculture and industrial level.

KEYWORDS: cyanobacterial, biofertilizer, paddy, chemical, ecofriendly

I. INTRODUCTION

Cyanobacteria contribute significantly to the biogeochemical cycles of carbon, nitrogen and oxygen (Karl et al., 2002; De Ruyter and Fromme, 2008). They have undergone a series of functional and structural modifications during their evolution that permit their current distribution in diverse ecological niches (Olson, 2006). Cyanobacteria can tolerate various stresses such as ultraviolet radiation (UVR; 280–400 nm), desiccation, high or low temperatures and salinity, which contribute to their advantages over different competitors/neighbors in their natural habitats (Gröniger et al., 2000; Herrero and Flores, 2008). For example, Spirulina maxima is known to survive under high alkaline conditions (pH 11) and high salinity which provide advantage and protection from other competitors and grazers (Habib et al., 2008). The nitrogen fixing ability of cyanobacteria aids their successful growth and survival in habitats where no or little combined nitrogen is available. This trait of cyanobacteria makes them agronomically and economically important as biofertilizers (Singh, 1961, 2014; Vaishampayan et al., 2001; Singh et al., 2016).

Several cyanobacteria are known to establish symbiotic associations, and this ability could be exploited in developing the consortia of microorganisms for their application in bioremediation of affected soils or aquatic systems (Rai et al., 2000; Subashchandrabose et al., 2011; Hamouda et al., 2016). Strains of cyanobacteria which are native and adapted to local climatic conditions have a capacity to survive in wet soils. This significantly affects the nutritional status, structural stability and crop productivity of such soils (Nisha et al., 2007). Twenty five percent of the total biomass of cyanobacteria is contributed by the exopolysaccharides (EPS) (Nisha et al., 2007). The upper crust of the soil is the site of cyanobacterial activities and the EPS act as a gluing agent on soil particles. The EPS can hold soil particles together which leads to soil aggregation, organic content accumulation and increase in water holding capacity of the top layer of soil (Malamlssa et al., 2001). This increase in soil moisture and organic content can support the survival and growth of plant-growth promoting rhizobacteria (PGPR). Thus, cyanobacterial growth positively alters the chemical and physical property of soils, and PGPRs along with EPS-producing cyanobacteria may contribute to an improvement and reclamation of infertile soils (Flaibani et al., 1989; Verrecchia et al., 1995; Zulpa et al., 2003; Paul and Nair, 2008). The consortium of PGPR and cyanobacteria increases the plant growth by improving the soil fertility and nutrient utilization. In additions, this consortium also enhances the tolerance of plants against environmental stresses such as drought and salinity (Singh et al., 2011; Prasanna et al., 2012; Singh, 2014). However, community structure and diversity of cyanobacteria should be studied in depth particularly in reference to environmental conditions and ecosystem functions before devising application of a consortium under field conditions. In following sections, different properties of cyanobacteria are presented that can be utilized for the development of sustainable agriculture practice in environment friendly manner.

Cyanobacteria as Bioremediators in paddy fields

Cyanobacteria can be used for the bioremediation of several contaminants such as heavy metals, pesticides, crude oil, phenanthrene, naphthalene, phenol, catechol, and xenobiotics (Kesaano and Sims, 2014; Hamouda et al., 2016; Kumar et al., 2016; Singh et al., 2016). Synechococcus elongatus, Microcystis aeruginosa and Anacystics nidulans have shown potentials to remove organo-chlorine and organo-phosphorus insecticides (Vijayakumar, 2012). Cyanobacterial genera such as Oscillatoria, Synechococcus, Nodularia, Nostoc, Anabaena, and Microcystis break down lindane residues (El-Bestawy et al., 2007). Anabaena sp., Lyngya sp., Microcystis sp., Nostoc sp. and Spirulina sp. can utilize glyphosate as the source of phosphorus, and therefore, helps in removal of this herbicide from contaminated soil (Forlani et al., 2008; Lipok et al., 2009). Thus, an above mentioned cyanobacterial strains are potential candidates for their application in developing sustainable agricultural practice where they can be used for removing various contaminants from soil as well as water.

The consortia of cyanobacteria and chemotrophic bacteria have been effectively used to bioremediate wastewaters and oil-contaminated sediments (Abed and Köster, 2005). Cyanobacteria can oxidize oil components as well as other complex organic compounds such as herbicides and surfactants (Mansy and El-Bestway, 2002; Subashchandrabose et al., 2013). The consortium of Oscillatoria-Gammaproteobacteria can degrade phenanthrene, dibenzothiophene, pristine and n-octadecane (Abed and Köster, 2005). Similarly, consortia of Microcoleus chthonoplastes with organotrophic bacteria can fix atmospheric nitrogen and degrade aliphatic heterocyclic organo-sulfur compounds and hydrocarbons such as alkylated monocyclic and polycyclic aromatic compounds (Sánchez et al., 2005). An artificially designed biofilm consortium of hydrocarbon-degrading bacteria and cyanobacteria on gravel particles and glass plates has been developed that can be used for cleaning up crude-oil contamination of sea water samples (Al-Awadhi et al., 2003). The consortium of Anabaena oryzae and Chlorella kessleri can be used to biodegrade crude oil under mixotrophic condition (Hamouda et al., 2016). Cyanobacteria are also capable of removing heavy metals from water bodies and can reduce the excess of nitrate and phosphate from agricultural fields (Kesaano and Sims, 2014; Kumar et al., 2016). Consortia of cyanobacteria and bacteria have shown positive results in wastewater treatment. Cultures of Aphanocapsa sp. BDU 16, Oscillatoria sp. BDU 30501 and Halobacterium US 101 can be utilized for minimizing the amount of calcium and chloride in wastewater to a level that can support the survival of fishes (Uma and Subramanian, 1990). Similarly, Phormidium valderianum BDU 30501 and Oscillatoria boryana BDU 92181 can be utilized to remove phenol and melanoidin, respectively, from the effluents of distillery (Shashirekha et al., 1997; Kalavathi et al., 2001). Desertification is another challenge for sustainable agriculture practices which can be reversed by the application of cyanobacterial inoculums. Cyanobacteria together with bacteria, mosses, algae, lichens and fungi forms biological soil crusts (BSCs) in semiarid and arid areas of various geographical regions (Rossi et al., 2017). These BSCs play an important role in stabilization and primary colonization of desert soil surface by increasing the nutrient and moisture contents (Rossi et al., 2017). Thus, cyanobacteria can be ideally utilized for removing the various contaminants. However, for bioremediation of polluted sites, focus should be given to utilization of indigenous consortia that could potentially reduce the need of adding new microorganisms or fertilizers to the target site. Further improvement in bioremediation property can be achieved by genetic engineering of parent strains which can help in developing a maintenance-free and economical remediation technology while producing the biomass of high value for other purposes (Kuritz and Wolk, 1995; Cuellar-Bermudez et al., 2017).

Cyanobacteria as Bioenergy Resource in paddy fields

First and second generations of biofuels have utilized feedstocks such as rapeseed, soybean, sunflower, wheat, switchgrass, peanuts, and sesame seeds. These raw materials have been used to produce different energy sources such as ethanol, propanol, butanol, and vegetable oils (Quintana et al., 2011). However, energy crops, which are used in first and second generations of biofuels production, compete with conventional food sources for water, nutrients and fertile land. Therefore, the third generation of biofuel production using microalgae has emerged as an alternative to avoid the competition between food crops and energy crops for available resources, and furthermore, cyanobacteria are one of the most promising feedstocks for the production of third generation biofuels (Quintana et al., 2011; Al-Haj et al., 2016; Rajneesh et al., 2017). Rapid growth rate and cultivation in suitable in-house bioreactors and/or on non-arable land gives cyanobacteria an advantage over plants (Singh, 2014; Sarma et al., 2016). Furthermore, cyanobacteria show higher photosynthetic efficiency (~10%), as compared to land plants (~3–4% maximum efficiency) (Lewis and Nocera, 2006; Melis, 2009). Cyanobacteria can be easier genetically manipulated than other algae, and hence, serve as a better candidate in comparison to eukaryotic algae for the production of targeted chemicals and fuels. The genome size of cyanobacteria is relatively small and till date genomes of several genera have been sequenced (Rajneesh et al., 2017).

Therefore, cyanobacteria provide an exceptional opportunity to conduct genetic and metabolic engineering studies for improved biomass production which is comparatively difficult to do with eukaryotic algae (Rittmann, 2008). Cyanobacteria contain considerable amounts of lipids; primarily located in the thylakoid and plasma membranes, and show higher rates of growth and photosynthesis. Enhanced production of biofuel from cyanobacteria utilizing genetic engineering has been attempted mainly on Synechocystis sp. PCC 6803 and S. elongatus PCC 7942, whose genomes are fully sequenced and molecular techniques are well-established (Kaneko et al., 1996). Genetic engineering can be used for the production of various fuels such as 2,3-butanediol, acetone 1-butanol, ethylene, ethanol, fatty acids, isobutyraldehyde, isobutanol, 2-methyl-1-butanol, and isoprene in cyanobacteria. Therefore, genetically modified cyanobacteria might play a crucial role in reduction of crude oil dependency and CO2 emissions, owing to direct photosynthetic fixation of CO2 to biofuel and other valuable secondary metabolites (Ducat et al., 2011; Oliver et al., 2016).

However, cyanobacteria have some limitations for their application in biofuel production. The production of valuable chemicals in photoautotrophic cyanobacteria is always less than sugar-utilizing systems such as S. cerevisiae and E. coli (Savakis and Hellingwerf, 2014). Generally, photoautotrophic cyanobacterial chassis can produce only ~100 mg of biochemicals per liter of cell culture (Gao et al., 2016), which is far too low for any commercially viable application. Theoretical yields under heterotrophic and autotrophic growth conditions for production of several chemicals have been computed for cyanobacterial chasis to find out the limiting factors in cyanobacterial metabolic network (Gudmundsson and Nogales, 2015). However, study suggests that low yield is not due to the topology of the photosynthetic metabolic networks in cyanobacteria. Therefore, it is important to optimize the inherent biological chassis for enhancing the yield of biochemicals from cyanobacteria. In recent years, several groups have emphasized on construction, designing, and expression of the biosynthetic pathways along with development of the toolboxes for metabolic engineering in cyanobacteria which could lead to economic profitability by increasing the production of existing and novel chemicals and biofuels (Wang et al., 2012; Berla et al., 2013; Desai and Atsumi, 2013; Oliver and Atsumi, 2014; Gudmundsson and Nogales, 2015; Markley et al., 2015).

Cyanobacteria as Biofertilizers for paddy fields

It is very expensive to produce inorganic nitrogen fertilizers due to the requirement of large amount of fossil-fuel energy. This necessitated the development of alternate, sustainable and cost-effective biologically available nitrogen resources which can fulfill the nitrogen demand of agriculture in sustainable manner (Mahanty et al., 2017). For this purpose biological systems have been identified which can fix atmospheric dinitrogen (Hegde et al., 1999; Vaishampayan et al., 2001). Biological nitrogen fixation contributes ~2 × 102 Mt of nitrogen annually (Guerrero et al., 1981). According to Metting (1988), the total nitrogen fixation can be ~90 kg N ha−1 y−1. Symbiotic and free-living eubacteria, including cyanobacteria, are two groups of nitrogen-fixing organisms. The free-living cyanobacteria fix <10 kg of N ha−1y−1, however, annually ~10–30 kg of N ha−1 is fixed by dense mats of cyanobacteria (Aiyer et al., 1972; Watanabe et al., 1977). Therefore, cyanobacteria constitute an important component of naturally available biofertilizers (Vaishampayan et al., 2001; Prasanna et al., 2013). Rice production in tropical countries mainly depends on biological N2 fixation by cyanobacteria which are a natural component of paddy fields (Vaishampayan et al., 2001). In these cultivated agriculture systems, annually ~32 Tg of nitrogen is fixed by biological nitrogen fixers (Singh et al., 2016), and cyanobacteria add about 20–30 kg fixed nitrogen ha−1 along with organic matter to the paddy fields (Subramanian and Sundaram, 1986; Issa et al., 2014). Cyanobacteria also make symbiotic associations with different photosynthetic and non-photosynthetic organisms such as algae, fungi, diatoms, bryophytes, hornworts, liverworts, mosses, pteridophytes, gymnosperms, and angiosperms (Rai et al., 2000; Sarma et al., 2016).

Several heterocystous cyanobacterial genera such as Nostoc, Anabaena, Nodularia, Scytonema, Cylindrospermum, Mastigocladus, Calothrix, Anabaenopsis, Aulosira, Tolypothrix, Haplosiphon, Camptylonema, Stigonema, Fischerella, Gloeotrichia, Chlorogloeopsis, Rivularia, Nostochopsis, Westiellopsis, Wollea, Westiella, Chlorogloea, and Schytonematopsis have been shown to be efficient N2 fixers (Venkataraman, 1993). Table 1 contains a list of potential cyanobacteria which can be used as biofertilizers in agricultural fields (Vaishampayan et al., 2001). For the first time, Fritsch (1907) studied the abundance and importance of cyanobacteria with respect to maintenance of soil fertility of paddy fields through biological nitrogen fixation, which was afterwards recognized by several other workers (Singh, 1950; Fogg and Stewart, 1968; Holm-Hanson, 1968). Generally, for algalization of the rice fields, mixed cyanobacterial cultures of free-living forms are used (Venkataraman, 1972; Roger and Kulasooriya, 1980). The water fern Azolla harbors Anabaena azollae in its fronds and the cyanobacterium releases ammonium into the water when paddy fields are inoculated with foam-immobilized A. azollae strains (Kannaiyan et al., 1997). Significant increase in grain yield, biomass and nutritive value of rice can be achieved by inoculating Anabaena doliolum and A. fertilissima in paddy fields with or without urea (Dubey and Rai, 1995). Several cyanobacterial species such as Anabaena iyengarii var. tenuis, A. fertilissima, Nostoc commune, N. ellipsosporum, N. linckia, and Gloeotrichia natans are known to contribute

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|| Volume 5, Issue 6, November 2018 ||

to the productivity of rice fields in Chile (Pereira et al., 2009). Generally, application of 12.5 kg ha−1 of cyanobacterial biofertilizer has been recommended for quantitative and qualitative improvements in rice production (Dubey and Rai, 1995).

II. DISCUSSION

Cyanobacteria in Sustainable Management in Paddy grains

Beneficial microbes are an alternative to other management practices. The cyanobacteria are bestowed with ability to fix atmospheric N2, decompose the organic wastes and residues, detoxify heavy metals, pesticides, and other xenobiotics, catalyze the nutrient cycling, suppress growth of pathogenic microorganisms in soil and water, and also produce some bioactive compounds such as vitamins, hormones, and enzymes which contribute to plant growth (Higa, 1991). These bio-agents can improve the soil quality and plant growth, and minimize the crop production cost by supplementing the good crop management practices such as crop rotation, use of organic manures, minimum tillage, and the bio-control of pests and diseases. The use of cyanobacteria in agriculture promises definite beneficial effects on crop productivity, if used properly (Higa and Wididana, 1991).

The currently used traditional agriculture management practices heavily rely on the application of chemical fertilizers and pesticides, and practices like intensive tillage and excess irrigation which otherwise lead to ever increasing cost of agricultural production, over exploitation of natural resources like soil and water, and also create environmental pollution (Kumar et al., 2012). Now, there is need to adopt such sustainable agricultural practices which are not only eco-friendly, but are also cost-effective, and really help us attain the long-term food security. Some of the major objectives of sustainable agriculture include production of safe and healthy foods, conservation of natural resources, economic viability, restoration and conservation of ecosystem services. An eco-friendly management approach for complex agro-ecosystem without disturbing the interactions among number of ecological components like water, edaphic and climatic factors including the living components offers the long-term rise for sustainable increase in productivity. It may be suggested that if the four major ecosystems processes, i.e., energy flow, water cycle, mineral cycles, and ecosystem dynamics, function together without disturbing the harmony or homeostasis of individual components, can ultimately reduce the cost of agriculture production.

The application of cyanobacteria in management of soil and environment includes the economic benefits (reduced input cost), nutrient cycling, N2-fixation, bioavailability of phosphorus, water storage and movement, environmental protection and prevention of pollution and land degradation especially through reducing the use of agro-chemicals, and recycling of nutrients and restoration of soil fertility through reclamation (Shukia et al., 2008).

The following benefits to the agro-ecosystem are offered through use of cyanobacteria:

• Enhanced solubilization and mobility of nutrients of limited supply.

• Complexing of heavy metals and xenobiotics to limit their mobility and transport in plants.

• Mineralization of simpler organic molecules such as amino acids for direct uptake.

• Protection of plants from pathogenic insects and diseases as bio-control agents.

• Stimulation of the plant growth due to their plant growth promoting attributes.

• Improving the physico-chemical conditions of soils.

Cyanobacteria under Extreme Environments in Paddy field areas

Cyanobacteria commonly known as blue-green-algae, are not truly eukaryotic algae. They are Gram-negative prokaryotes, perform oxygenic photosynthesis, and also fix atmospheric N2. They are ubiquitous in ponds, lakes, water streams, rivers, and wetlands. They can easily survive the extreme environments such as hot springs, hyper-saline waters, freezing environments, and arid deserts (Singh, 2014). Cyanobacteria are able to survive at a temperature range of 45–70°C (Castenholz, 1978) and pH lower than 4–5 (Pfennig, 1969, 1974) with optimum range of 7.5–10 (Fogg, 1956). The ability of cyanobacteria to survive extreme environmental conditions can be exploited for amelioration of the salt affected soils as they can reduce the salt content and promote levels of C, N, and P including moisture content of the salt affected soils. It has been noticed that cyanobacteria induces soil aggregation and water permeability, and are quite useful in improving quality of poor structured soils of arid or sub-arid areas. Rogers and Burns (1994)

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|| Volume 5, Issue 6, November 2018 ||

investigated that inoculation of cyanobacteria enhanced the stability of soil aggregate (important characteristics of good soil and noticed the resistance of aggregates to wetting and physical disruption); that improved WHC and aeration in soils. Such organisms reduce the compaction and sodicity of soils through improvement in the level of organic carbon, WHC, aeration and support the biodiversity of other microflora.

Cyanobacteria as Bio-fertilizers for Paddy

Cyanobacteria fix atmospheric N2 by forms, i.e., free-living and symbiotic associations with partners such as water fern Azolla, cycads, Gunnera, etc. A list of free-living and symbiotic N2 fixing cyanobacteria has been described in Table 1. Some cyanobacterial members are endowed with the specialized cells known as heterocyst – thick-walled modified cells, which are considered site of nitrogen fixation by nitrogenase enzyme. The enzyme is a complex, catalyzes the conversion of the molecular N2 into reduced form like ammonia (Singh et al., 2011). The fixed nitrogen may be released in the form of ammonia, polypeptides, free amino acids, vitamins, and auxin-like substances; either by secretion or by microbial degradation after the cell death (Subramanian and Sundaram, 1986). Nitrogen-fixing ability has not only been shown by heterocystous cyanobacteria but also by several non-heterocystous unicellular and filamentous genera (Table 1). Cyanobacteria can contribute to about 20–30 kg N ha-1 as well as the organic matter to the soil, quite significant for the economically weak farmers unable to invest for costly chemical nitrogen fertilizer (Issa et al., 2014). There is a little knowledge on commercial byproducts or biofertilizers but several cyanobacterial species such as Anabaena variabilis, Nostoc muscorum, Aulosira fertissima, and Tolypothrix tenuis found to be effective biofertilizers. Many Asian countries like China, Vietnam, India, etc., have been utilizing cyanobacteria in paddy cultivation as the alternative to nitrogen fertilizers (Venkataraman, 1972; Lumpkin and Plucknett, 1982). It has been reported that N availability to plants is increased due to application of cyanobacteria in agriculture ecosystems, particularly the rice fields (Stewart et al., 1968; Peters et al., 1977; Singh and Singh, 1987). Several researchers have investigated that inoculation of cyanobacteria (in vitro) in wheat crops, could enhance the plant shoot/root length, dry weight, and yield (Spiller and Gunasekaran, 1990; Obreht et al., 1993; Karthikeyan et al., 2007, 2009), but the agronomic efficiency has not been evaluated (Gantar et al., 1991, 1995a,b; Kaushik, 2012).

It has also been suggested that cyanobacteria can improve the bioavailability of phosphorus to the plants by solubilizing and mobilizing the insoluble organic phosphates present in the soil with the help of phosphatase enzymes. Cyanobacteria have the ability to solubilize the insoluble form of (Ca)3(PO4)2, FePO4, AlPO4, and hydroxyapatite [Ca5(PO4)3OH] in soils and sediments (Bose et al., 1971; Dorich et al., 1985; Wolf et al., 1985; Cameron and Julian, 1988)

III. RESULTS

Preparing biofertilizers for paddy growing:-

On the slant, a pure culture of a potent strain of nitrogen-fixing cyanobacteria is grown on the required agar medium, a loopful of inoculum is placed in a conical flask with a capacity of 250 ml and a liquid medium, and a loopful of inoculum is placed in a conical flask with a capacity of 250 ml and a liquid medium, depending on whether the conical flask is quick or slow growing, place it on a rotary shaker or in an incubator for 3–7 days. Depending on whether the conical flask is quick or slow growing, place it on a rotary shaker or in an incubator for 3–7 days. The contents of these flasks normally contain 105–106 cells/mL, which is known as mother culture or starter culture. These mother cultures are reproduced in bigger flasks, which are then shaken on a rotary shaker for 96–120 h until the viable count per ml reaches 109–1010 cells. This broth culture with a population of 109–1010 cells/ml should not be stored for more than 24 h or at below 4 °C since the broth thickens and becomes inconsistent. Fermenters are then utilized to create microbial products such as bio-fertilizers and bio-pesticides on a big scale. The fermenter broth is immediately transferred to automatic filling equipment and packed into 250 ml, 500 ml, or 1 L bottles with a 0.5 mm thickness, leaving a 2/3rd space accessible for M.O. aeration

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|| Volume 5, Issue 6, November 2018 ||

1. Mother culture
2. Slant
3. Flasks
4. Culture in big flask
5. Fermenters for large scale production
6. Broth is mixed with sterelized carrier
7. Put in polyethelene bag
8. At room temprature 25c
9. Check culture quality
10. Store at low temprature
11. Dispatch to farmers

IV. CONCLUSION

Quality and quantity increase of paddy by blue green algae

For the generation or cultivation of algal biomass, open Pond and closed photo-bioreactor (PBR) technologies have been developed. The production of open ponds is divided into two systems 1. Natural waters (ponds, lakes, and lagoons) and 2. Artificial ponds (circular and raceway). The open pond is a less expensive method of producing large-scale algal biomass than the PBR; but, the PBR provides a superior and controlled closed culture system for growing, which prevents contamination from molds, bacteria, protozoa, and competition from other microalgae. It's frequently set up outside to take use of the free energy that sunshine provides

Biomass aggregation (flocculation and ultrasonic), flotation, centrifugation, and filtration are four ways for separating algal biomass from the growth media or harvesting it. In some circumstances, a combination of two or more strategies is utilized to boost effectiveness. Algae are chosen depending on a number of factors, including density, size, and desired end products. With the addition of flocculants to the media, such as multivalent captions and cationic polymers, algal cells are aggregated together to form a bigger particle known as a floc in this approach, which helps neutralize the cells' surface charge. Flotation is a technology that uses a micro-air bubble disperser to float algal cells on the water's surface without the use of chemicals; it is cost-effective due to its cheap operational expenses, simple operating procedure, and high biomass yield. Using a centrifuge and gravitational force, centrifugation is a method of extracting algal biomass from culture media. This technology is quick, easy, and effective, but because to the large energy input and maintenance requirements, the cost can soon climb. Another problem of this method is that it damages interior cells, resulting in the loss of delicate nutrients, whereas filtration is a way of extracting alga biomass from the liquid culture media by utilizing a porous membrane with a range of particle sizes. There are three types of filtration: ordinary, microfiltration, and ultrafiltration (isolation of metabolites) (Barros et al. 2015).

Biomass dehydration

Algae biomass is quickly processed to the next stage after being isolated from the growth medium to prevent spoiling or extend its shelf life. The three most popular types of drying or dehydration procedures are sun drying, spray drying, and freeze drying. The method used is largely influenced by the intended end results; when compared to the other two;

sun-drying is the least expensive option. Because this method relies only on solar energy, it is limited by weather conditions, long drying durations, and the size of the drying area required. Overheating, as well as changes in texture, color, and taste of the microalgae, may occur as a result of the unregulated process of drying with sunlight. Spray-drying is a method for making a dry powder from a thin spray of suspension droplets in a big vessel that is constantly in touch with heated air. This method has many advantages, including the ability to operate continuously, the fine powder produced, and the rapid drying ability to maintain a high-quality product because of its efficiency. However, some algae components, such as pigments, can deteriorate significantly, and the operation cost is high. Because large-scale production is prohibitively expensive, freeze-drying, also known as lyophilisation, is frequently employed in laboratories to dry microalgae. Freeze-drying is a dehydration method that uses the sublimation mechanism to dehydrate frozen items. The microalgae are frozen before freeze-drying to solidify the material at low temperatures. As the moisture content of the microalgae declines, the product's solid structure and quality are preserved (Balasubramaniam et al. 2016).

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