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Algae: Super-Food for the Future

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ABSTRACT:

Microalgae have shown potential to meet the population's demand for increased sustainable food supply, specifically with regard to protein. The demand for microalgae and macroalgae food is growing and algae are increasingly being consumed for its functional benefits. These algae have bioactive compounds like proteins, amino-acids, lipids, pigments, antioxidants and that's the reason why they are considered as a very interesting source for the development of food products and can be used to enhance the nutritional value of conventional food products. The bioactive compounds obtained from microalgae have anti-inflammatory, antimicrobial, and antioxidant activities.

Keywords- algae, bioactive compounds, nutraceuticals, pigments, market

INTRODUCTION:

Algae are considered a broad and varied group. These are groups of photosynthetic organisms which can utilize CO2 and minerals to produce biomass; However, some species of algae are also heterotrophic. Algae can be differentiated into two groups, mainly macro algae and microalgae on the basis of cell walls, pigments, reserve substances, cellular division characteristics, and morphology. Algae can be prokaryotic (cyanobacteria e.g. Spirulina) and eukaryotic (Chlorophyta, Rhodophyta, and Phaeophyta) (Villarruel-López et.al, 2017).

The surge in the market value for algae is not only because of its conventional rumination in regards to health and nutrition, but also because of its functional benefits (Wells et.al. 2017). Products with a high nutritional value that can be produced in large quantities at reasonable prices are needed to attain sufficient amounts of nutrition for the people with rise in the world population (García, J. L. et.al, 2017). Microalgae have an upper hand in yield as compared to terrestrial crops, and they do not need large amounts of land and resources when compared to traditional crops (Koyande, A. K. et.al, 2019).

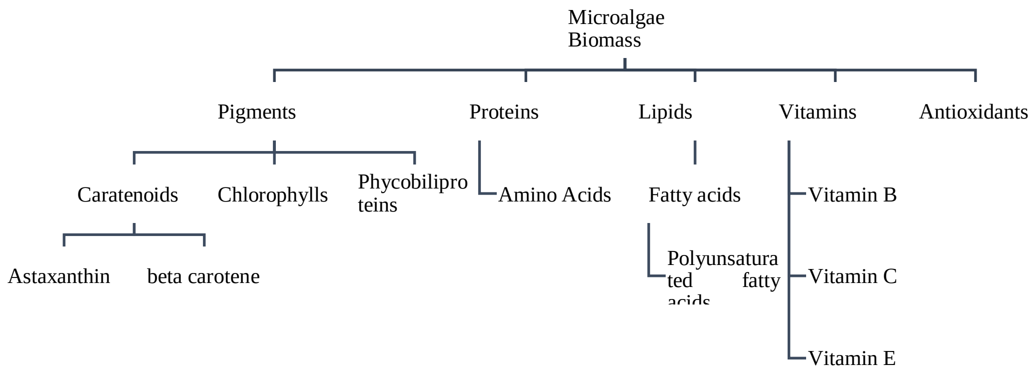

Chart 1 – The chart depicts the bioactive components of algae (Koyande, A. K.et.al, 2019).

Now, algae are marketed as "nutraceuticals," or "functional foods" which may benefit the well-being of a person beyond its root part as basic nutrition, as they contain bioactive compounds, or phytochemicals (Wells et.al. 2017).

Protein:

Proteins are formed by units known as amino acids, which are joined together by peptide bonds. Proteins are also recognized as the building blocks of the body responsible for the growth of the individual (Kusmayadi et.al, 2021). A varied content of proteins can be seen with different groups of algae (Wells et.al. 2017).

As *Chlorella* and *Arthrospira* can accumulate high-quality proteins, they have balanced amino acid profiles according to the WHO/FAO/UNU guidance for the human requirement for EAAs (Caporgno, M. P., & Mathys, A., 2018). Spirulina sp. belongs to the cyanobacteria, which is a unicellular microalgae. It has also been given the label of "Super-food" by the World Health Organization (WHO) (Koyande, A. K.et.al, 2019). Leucine, isoleucine, methionine, lysine, threonine, valine, and histidine are some of essential amino acids which the body cannot synthesize on its own, and hence these EAA have to be provided externally. (van Vliet, S. et.al, 2015). The general protein composition of *Spirulina platensis*, after complete disruption of the cell wall, is about 43-63%. It includes amino acids like leucine, asparagine, glutamine, glycine, proline, lysine, valine, and serine. In *Chlorella vulgaris*, it includes a total of 44.7% of the EAA, which includes amino acids like cysteine (0.22%) and arginine (4.5%) (Villarruel-López, A. et.al, 2017). These two species have been designated GRAS (Generally Recognised As Safe) by FDA (Wells et.al. 2017).

Microalgae like Cyanobacteria (blue-green algae), Rhodophyta (red algae), and Cryptomonads contain phycobiliproteins (Gouveia, L., et.al, 2008). Phycobiliproteins are light- capturing and water-soluble proteins, produced by cyanobacteria, and several algae. Most of these pigments are synthesized and stored intracellularly. These pigments have been explored as fluorescent tags, food coloring agents, cosmetics, and immunological diagnostic agents (Liu, L. et.al, 2016). Another protein which is extracted from microalgae and commercially used is phycocyanin. It is currently used as a natural colorant, in food products like chewing gums, candies, dairy products, ice-creams etc. (Gouveia, L., et.al, 2008).

Lipids:

Lipids are crucial parts of cell membranes, energy storage compounds, and also as cell signaling molecules (Wells et.al. 2017). Microalgae can synthesize disparate lipids such as glycolipids, phospholipids (polar lipids), glycerolipids with neutral storage lipids, and free fatty acids. The range of lipid content in microalgae is between 20% - 50% (dry weight). Considering lipids as a broad term, fatty acids are the major part of the microalgal biomass (Villarruel-López et.al, 2017). It was noted that *Haematococcus pluvialis*, *Scenedesmus obliquus, and Chlorella vulgaris* contain the highest amounts of lipid (Dolganyuk, V. et.al, 2020).

Humans cannot synthesize some fatty acids, and such fatty acids are called essential fatty acids. As they cannot be synthesized in the body, they have to be obtained from external sources like food additives, so these are often obtained from fish and fish oil (Dolganyuk, V. et.al, 2020).

The TAGS are divided into two groups: the linoleic acids (n-6 or omega 6 fatty acids) and the α-linolenic acids (n-3 or omega 3 fatty acids) (Wells et.al. 2017). Some microalgae are also considered oleaginous algae, which produce significant amounts of TAG (triacyl-glycerol).Oleaginous algae refers to those algae which can accumulate large quantities of oil>20% (weight) of their biomass.

In particular, many microalgae carry polyunsaturated fatty acids (PUFAs) such as arachidonic acid (AA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) (Villarruel-López et.al, 2017). In the synthesis pathway of ALA, the first product formed is stearidonic acid (SA, 18:4n-3), and this acid can show a notable amount of PUFAs in some edible macroalgae (sea vegetables), together with arachidonic acid (20; 4n-6), particularly in red algae (Wells et.al. 2017).

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Gamma-linolenic acid present in Spirulina can aid in heart disease, depression, & inflammatory diseases such as arthritis. For the proper development of the brain and eyes in humans. DHA is important, including cardiovascular health in adults (Dolganyuk, V. et.al, 2020). DHA as an alone molecule helps to improve brain-related disorders such as poor memory, cognitive decline, bipolar symptoms, mood swings etc. DHA in combination with EPA helps in fetal development, preventing inflammation, also dealing with cardiovascular diseases such as arrhythmia, high blood pressure, and stroke due to their ability to reduce oxidative stress and plasma triglycerides. Microalgae also synthesizes other important essential fatty acids like alpha linolenic acid (ALA), gamma linolenic acid (GLA), and arachidonic acid (ARA) which can be utilized in feed as well as in the food industry (Kusmayadi et.al, 2021).

Product	**Application**	**Microalgal Producers**
Eicosapentaenoic acid (EPA)	Nutritional supplements, aquaculture feed	Pavlova, Nannochloropsis, Monodus & Phaeodactylum
Docosahexaenoic acid (DHA)	Infant formula, nutritional supplements, aquaculture feed	Crypthecodiuimu & Schizochytrium
γ-linolenic acid (GLA)	Nutritional supplements	Spirulina
Arachidonic acid	Nutritional supplements	Porphyridium

Table 1- Use of lipids at industrial level (Chu, W. L., 2012)

Carbohydrates:

In marine algae and terrestrial plants, polysaccharides are used as energy storage and also as structural elements (Wells et.al. 2017).When compared to protein and lipid content in microalgae, polysaccharide content is low (approx. 10% of dry matter) even though it depends upon the microalgal species (Villarruel-López et.al, 2017). As microalgae have a high photo- efficiency rate, they can store high levels of carbohydrates up to 50 wt/wt% dry weight (Kusmayadi et.al, 2021). Chlorella, Arthrospira (spirulina), Dunaliella, Haematococcus, Scenedesmus, Aphanizomenon, Odontella, and Porphyridium are regarded as good dietary supplements which are rich in polysaccharides.

Levels of dietary fiber are in high amounts in edible microalgae, ranging from 23.5% (Codium reediae) to 64.0% of dry weight in Gracilaria spp. Out of dietary fiber, soluble fiber comprises 52-56% in commonly used algae like green and red macroalgae, while 67-85% in brown algae (Wells et.al. 2017).

Exopolysaccharides (EPS) which are structurally diverse compounds, are produced by many microalgae (García, J. L. et.al, 2017). Marine microalgae like Bacillariophyceae (diatoms), Chlorophyceae, Chrysophyceae, Cryptophyceae, Eustigamatophyceae, and Prasinophyceae can produce high quality EPA (Fabris, M. et.al, 2020). EPS is not only used in the food industry as a thickener and gelling agent, but it also has some pharmaceutical applications like antioxidant, antitumor, antihyperlipidemia, antibacterial, and anticoagulant activities (García, J. L. et.al, 2017). Many commercially used products also include agar, alginates, and carrageenan (Gouveia, L., et.al, 2008).

These polysaccharides have different biological properties, e.g. glucans are immune stimulators, cellulose and starch act as dietetic fibers. Sulphated Polysaccharides (SPs) like fucosylated polymers function as heparin/ heparan sulfate and have the capacity to control parameters taking part in connective tissue destruction in human skin (Villarruel-López et.al, 2017). The therapeutic application of SPs is based upon the stimulation of macrophages and modulation. *Chlorella vulgaris*, *Scenedesmus quadricauda* and *Porphyridium* sp. are some examples of SPs producing organisms (de Morais, M. G. et.al, 2015). An important unicellular red alga *Porphyridium cruentum* produces a sulfated galactan EPA that can replace carrageenans in many applications (Gouveia, L., et.al, 2008).

Vitamins:

Vitamins are important organic micronutrients. These are essential micronutrients, which cannot be synthesized inside the body and hence have to be obtained externally, i.e. from food. Algal foods contain high levels of vitamins. Laver (Porphyra umbilicalis), sea spaghetti (Himanthalia elongata), and Gracilaria changii are sea vegetables that contain vitamin C. When these sea vegetables, are compared with some common vegetables, they have a higher amount of vitamin C present in them (Wells et.al. 2017).

Microalgae shows an important source of nearly all essentials vitamins like A, B1, B2, B6, B12, C, E, nicotinate, biotin, folic acid and pantothenic acid with minerals like Na, K, Ca,, Mg, Fe, Zn and trace minerals (Koyande, A. K.et.al, 2019) (Villarruel-López et.al, 2017) (Gouveia, L., et.al, 2008).

Spirulina has a higher content of Vit B12 compared with plant or animal-based food sources. Including this vitamin in the diet can prevent a type of anemia called megaloblastic anemia, which makes people tired and weak. Also, tocopherol, a type of vitamin E, was found in the *Euglena gracilis*, as reported by Rodriguez, and colleagues (Kusmayadi et.al, 2021).Vitamin B12 deficiency is common in people who are vegetarian and people following a vegan diet. Some examples of microalgae that may contain or synthesize Vit B12 are Chlorella sp. and Pleurochrysis carterae (Dolganyuk, V. et.al, 2020).

Pigments:

Pigments are the molecules that can absorb light from the visible spectrum (Koyande, A. K.et.al, 2019). Various pigments present in microalgae are carotenoids, xanthophylls, phycobilins, and chlorophylls. Among these, carotenoids and chlorophylls are in higher amounts as compared to others (Dolganyuk, V. et.al, 2020). For production of pigments on an industrial scale, Porphyridium spp (phycoerythrin), Dunaliella salina (b-carotene, zeaxanthin, chlorophylls a, b), Spirulina spp (b-carotene, zeaxanthin, phycocyanin, allophycocyanin), Haematococcus pluvialis (astaxanthin, canthaxanthin, lutein, chlorophylls a, b), Scenedesmus spp (lutein, beta carotene), and Muriellopsis spp (lutein) are used (Kusmayadi et.al, 2021).

The presence of pro-Vit A makes beta-carotene an important pigment. It is used as an additive in multivitamin supplements and tablets (Koyande, A. K. et.al, 2019). The main carotenoid in algae is beta-carotene, which is mainly extracted from *Dunaliella salina* . Beta- carotene is regularly used in the production of butter, cheeses, margarines, and soft drinks. This pigment is considered safe and has positive health effects (Gouveia, L., et.al, 2008).

Astaxanthin, a keto-carotenoid, is produced by the freshwater algae *H.pluvialis.* This pigment is known to have strong antioxidant and anti-inflammatory activities, preventing protein degradation, rheumatoid arthritis, cardiovascular diseases, etc. (García, J. L. et.al, 2017).

Lutein is one of the important carotenoids in human serum and food. It is present in the macula lutea, in the retina and lens of the eyes. This pigment is also responsible for pigmentation in fish and poultry. The concentration of lutein in *Muriellopsis sp.* and *Scendesmus almeriensis* is high (Dolganyuk, V. et.al 2020).

Chlorophylls contain sodium-copper salt water-soluble derivatives, which are readily taken up by the body. In a report it is suggested that addition of CHL in diet has the potential to inhibit the progression of cancer (Koyande, A. K. et.al, 2019).

These carotenoids can also be used as antioxidant molecules, which can even prevent spoilage of food products (Dolganyuk, V. et.al, 2020). Pigments like beta carotene, and astaxanthin are mainly utilized for applications like colorants, pharmaceuticals, aquaculture, and nutraceuticals (Kusmayadi et.al, 2021).

Flowchart of extraction of bioactive compounds:

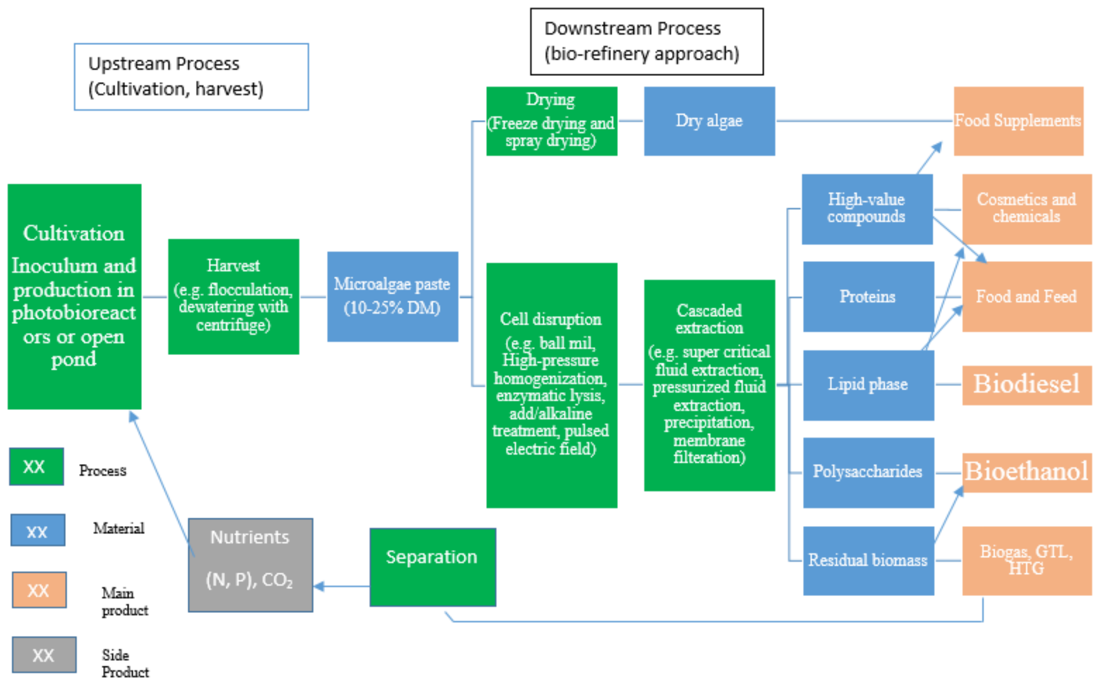

Chart 2- Extraction of bioactive compounds (Rösch, C. et.al, 2018).

Production of food from microalgae can be separated into two main-upstream processing (including cultivation and biomass harvesting) and downstream processing. There are two main systems for cultivation of microalgae, one is open pond system and second one is closed photobioreactors (PBRs).

Open pond systems have been used since the early days because of their lower cost of investment, low operating cost, and need for labour are less. In spite of having higher costs, PBRs have become favorite as they not only allow better control of cultural conditions, but also can produce more biomass and have less chances of getting contaminated. There are various types of PBRs, like tubular, flat plate, green wall, etc. PBRs are the choice for production for intergrated food and fuel production because of their upper hand in meeting the quality and safety demands for the food sector (Rösch, C. et.al, 2019).

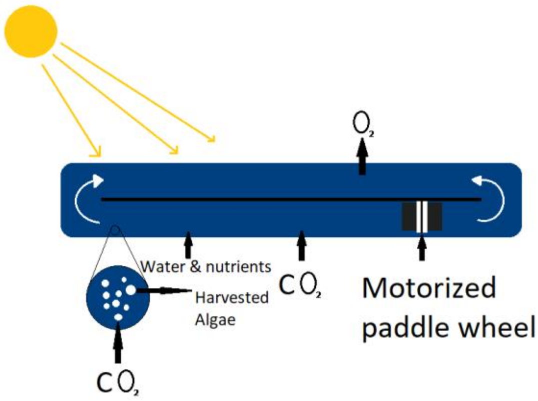

Fig 1- Schematic representation of open pond system (Pankratz, S. et.al, 2019).

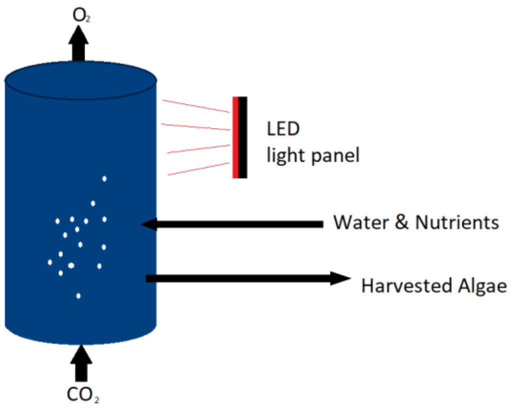

Fig 2- Schematic representation of PBRs (Pankratz, S. et.al, 2019).

Cultivation is accompanied by the separation of algal cells from the culture medium and the extraction of a lipid phase containing fatty acids, polysaccharides, proteins, and other high cost compounds. In the harvest and separation process, the dry matter content of dilute algae solution increases from a range of 0.05% to 0.075% DM (open pond system) to 0.3% to 0.4% DM (PBRs) up to 10% to 25% (Wileman, A. et.al, 2012) (Rösch, C. et.al, 2019) by flocculation, filtration, centrifugation, sedimentation, or a combining any of these techniques (Milledge, J. J., & Heaven, S., 2013) (Rösch, C. et.al, 2019).

To this end, after drying, the complex cell walls must be broken or disrupted for the release of the metabolites of interest. Several methods can be used depending on the microalgae cell wall characteristics and the product nature to be obtained, either based on mechanical or non-mechanical technologies. The mechanical methods include high-pressure and high-speed homogenization, bead mills, pulsed electric field, microwave and ultrasound assistance, or autoclave. The non-mechanical action comprises freezing, organic solvents, and osmotic shock and acid, base, and enzyme reactions.

One of the ways to use microalgae in food production is to increase the dry content by spray drying, drum drying, or and freeze drying. Step wise extraction increases the content of important compounds, like proteins, fatty acids and polysaccharides and also of high cost compounds like carotenoids, phycobillins, PUFAs, and sterols (Borowitzka, and M. A. 2013) (Rösch, C. et.al, 2019). Now, after the drying part is done, cell walls must be disrupted in order to get metabolites of interest. Mechanical and non-mechanical methods can be used depending on the cell wall characteristics and the product nature that has to be obtained. The examples of mechanical methods are high-pressure and high-speed homogenization, bead mills, and pulsed electric field, microwave and ultrasound assistance, or autoclave and that of non-mechanical methods are freezing, organic solvents, and osmotic shock and acid, base, and enzyme reactions (Rösch, C. et.al, 2019) (Demuez, M. et.al, 2015) (Gerde, J. A. et.al, 2012).

Nutraceuticals and other food products:

A functional drink product which is procured from the brown seaweed, *Sargassum binderi* tea contains fucoidan, which exhibits antioxidant activity (Al-Obaidi, J. R. et.al, 2021). Species of Wakame, Undaria pinnafitida showed presence of fucoidan having antioxidant and anticancer properties, anticoagulant (Faggio et.al, 2014) and antioxidant properties (Neri et.al, 2019). Some species have high potential to be used in nutritional supplement scales because they contain minerals like iron, cadmium, and zinc for e.g. *Gracilaria verrucosa*, *Codium tomentosum*, and *Sargassum linifolium* (El-Said et.al, 2013).

Some other groups of brown seaweed presented their ability to be an origin of functional food and nutraceutical products such as fucoidan, laminarin, and alginate (Múzquiz de la Garza et.al, 2019). Production of carrageenan from red/brown algae has the potential to be used in the food industry as a nutraceutical (Usuldin et.al, 2017). Carrageenan represents some medical application against obesity in mice, by affecting lipid metabolism; hence it can be used as an additive in the food industry (Chin et.al, 2019). *Alaria esculenta*, and *Saccharina latissima* are brown algae which can also be used in the food industry; they have high nutritional content (Stévant et.al, 2017). These two species might be good natural sources of iodine, and iron (Schiener et.al, 2015) (Circuncisão et.al, 2018). As a good substitute of protein for vegan and vegetarian diets, *Pyropia vietnamensis* can be used (Kavale et.al, 2018).

Various products of spirulina are present in the market which are used to reduce cholesterol levels by decreasing the concentration of triglycerides (Colla et.al, 2008). Chlorella is also widely used for the production of nutraceutical or pharmaceutical applications (Nabavi, S. M. et.al, 2018). Even though there are some reports related to probable side effects of spirulina and chlorella products, still these species are well studied for their antioxidant, anticancer, and anti-hyperlipidemia properties (David, S. et.al, 2018).

Specifically, seaweeds are considered good sources of vitamins (Škrovánková, S. et.al, 2011). *Saccharina latissima* (sugar kelp) in its dried and fermented form, is a good source of vitamin C (Sappati et.al, 2019) (Bruhn, A. et.al, 2019). *Undaria pinnatifida* and *Porphyra purpurea* have not only the property to lower bad cholesterol levels, but are also naturally good sources of protein and vitamins. These two species also have high content of vitamin A (Taboada et.al, 2013). Red seaweeds Gracilaria spp. (*Gracilaria edulis* and *Gracilaria corticata*) showed the presence of different forms of vitamin B and vitamin C including minerals, polysaccharides and fibers (Rosemary et.al, 2019).

Market:

The Microalgae-based market has reached a global production of 12,000 tons/year of dried Spirulina sp. (with a median price of 30 US ($/kg) followed by Chlorella sp. (5000 tons/year); Dunaliella salina (3000 tons/year); Aphanizomenon flos aquae, Haematococcus pluvialis, Crypthecodinium cohnii and Shizochytrium (Rumin et.al, 2020). A report published by Credence Research, the algae market, is expected to touch US$44.6 Billion by 2023, increasing at a CAGR of more than 5.2% from 2016 to 2023 (Koyande, A. K. et.al, 2019) (García, J. L. et.al, 2017). For instance, the global Spirulina market is predicted to register a CAGR of 10% during the forecast period and its estimated value is nearly at US$2000 Million by 2026, assuming to factors such as increased application of spirulina in cosmetics or the recent approval of phycocyanin as a natural blue color for food (García, J. L. et.al, 2017).

Product Type	Microalgae Species	Addition %(w/w)	Functions	References
Biscuits	*Spirulina platensis*	0.3, 06 and 0.9	Enhance the quality of good sensory (aroma, color, texture and flavor) and add nutritional properties to the biscuits.	Abd El Baky et.al, 2015
Bread	*Spirulina*	1 and 3	Improve protein composition and good sensory taste in the bread.	Achour, H. Y. et.al, 2014
Cheese	*Chlorella sp*	0.25	Improve the quality of processed cheese	Hanagata, N. et.al,1992
Cookies	*Haematococcus pluvialis*	5	Improve bioactive composition and decrease rate of reducing sugar released	Hossain, A. K. M. et.al, 2017
Dairy products	*Spirulina platensis*	2	Valuable impact on the viability of Acidophilusbifidus-thermophilus (ABT) milk starter bacteria apathetic storage temperature	Varga, L. et.al, 2002
Extruded snacks	*Arthrospira sp*	0.4, 1.0, 1.8, 2.6 and 3.2	Increase the amount of nutritional contents (proteins, mineral, and lipids) and the physical profiles (water solubility index, hardness, color, and expansion index)	Lucas, B. F. et.al, 2018
Pasta	*Dunaliella salina* *Isochrysis galbana and Diacronema vlkianum*	1-3 0.5, 1.0 and 2	Improve fat, protein, and Minerals content Addition of omega-3 polyunsaturated fatty acids (u3-PUFA	El-Baz, F. K. et.al, 2017 Fradique, M. et.al, 2013
Vegetables	*Spirulina*	0.1-1	Increase	Gouveia, L. et.al,

gelled desserts	*maxima and Diacronema vlkianum*		PUFA compositions with preferred texture	2008

Table 2- Different algal products (Kusmayadi et.al, 2021).

CONCLUSION:

This review tells us about how microalgae and macroalgae can be used as alternative sources of food. Algae can be grown easily and it requires less land, water etc. when compared to the traditional crops. Algae (macroalgae and microalgae) contain many bioactive compounds which can be used in not only the food industry but also in sectors like pharma and cosmetics. That's the main reason algae can be considered a Super-food for the future, as it has many health benefits and could meet the food demand of the population.

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