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Microalgae-Derived Functional Ingredients in Food Systems: Composition, Processing Strategies, Applications and Emerging Challenges

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ABSTRACT
Microalgae have been of great interest as a viable and nutrient-based sources of functional food. They contain a good supply of proteins, essential fatty acids, vitamins and bioactive compounds and can thus be used in nutraceutical and food applications (Becker, 2007). Nevertheless, their industrial use is not quite widespread despite a great amount of research. This review is a critical assessment of nutritional value, growth and production methods, processing methods and uses of microalgae in the food system. There are also issues associated with cost, sensory properties and regulatory issues. Comparative review of literature shows discrepancies in methods and results. The views in the future include the necessity to have cost-effective technologies and better consumer acceptance strategies.

Keywords: Microalgae, functional foods, bioactive compounds, nutritional composition, cultivation strategies, processing techniques, nutraceutical applications, sensory properties, cost challenges, regulatory issues, consumer acceptance.

I. INTRODUCTION

The growing global population, coupled with increasing pressure on natural resources, has intensified the need for sustainable and efficient food production systems. Conventional agricultural practices are increasingly being challenged by climate change, land degradation and water scarcity, necessitating the exploration of alternative biological resources. Among these, microalgae have attracted considerable attention due to their rapid growth rates, high productivity and ability to synthesize a wide range of valuable biomolecules (Chisti, 2007).

Microalgae are unicellular photosynthetic organisms that utilize sunlight, carbon dioxide and nutrients to produce biomass rich in proteins, lipids and bioactive compounds. Species such as Spirulina platensis and Chlorella vulgaris have been extensively studied for their nutritional and therapeutic potential (Becker, 2007). Their ability to grow in diverse environments, including non-arable land and wastewater, further enhances their sustainability profile.

However, despite these advantages, the incorporation of microalgae into food systems remains limited. This is primarily due to challenges related to high production costs, inefficient harvesting and processing methods, and unfavorable sensory properties. In addition, variability in cultivation conditions leads to inconsistencies in biochemical composition, making standardization difficult. Therefore, a comprehensive evaluation of current research is essential to understand both the potential and limitations of microalgae in food applications.

II. NUTRITIONAL AND BIOCHEMICAL COMPOSITION

Microalgae are widely recognized for their rich and diverse biochemical composition, which varies significantly depending on species, cultivation conditions and environmental factors (Safi et al., 2014). This variability, while offering flexibility in applications, also presents challenges in terms of standardization and reproducibility.

Proteins constitute one of the most significant components of microalgae, with concentrations ranging from 40% to 70% of dry biomass in species such as Spirulina and Chlorella (Becker, 2007). These proteins possess a balanced amino acid profile, including essential amino acids required for human nutrition. However, the bioavailability of these proteins is often limited by the presence of rigid cell walls, particularly in Chlorella, which necessitates mechanical or enzymatic disruption for effective digestion. This additional processing step increases both complexity and cost, thereby affecting industrial feasibility.

In addition to proteins, microalgae are important sources of lipids, particularly polyunsaturated fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These fatty acids play a crucial role in cardiovascular health and neurological development (Pulz and Gross, 2004). However, lipid extraction processes are energy-intensive and require specialized technologies, which limits their large-scale application.

Carbohydrates in microalgae exist in the form of storage polysaccharides and structural components, contributing to functional properties such as viscosity, water retention and gel formation. These properties are advantageous in food formulation, particularly in bakery and beverage applications. Furthermore, microalgae produce a variety of pigments, including chlorophyll, carotenoids and phycobiliproteins, which exhibit strong antioxidant and anti-inflammatory activities (Plaza et al., 2008; Sathasivam et al., 2017).

Despite these benefits, a major limitation lies in the variability of composition across studies. Differences in cultivation conditions, nutrient availability and environmental factors result in inconsistent biochemical profiles, making it difficult to compare findings and establish standardized applications.

III. CULTIVATION AND PRODUCTION STRATEGIES

The cultivation of microalgae is a critical factor influencing both biomass yield and biochemical composition. Various cultivation systems have been developed, each with its own advantages and limitations.

Open pond systems are the most widely used method due to their low capital and operational costs. These systems are relatively simple to construct and operate, making them suitable for large-scale production. However, they are highly susceptible to contamination by other microorganisms, as well as environmental fluctuations such as temperature and light intensity (Brennan and Owende, 2010). These factors can significantly affect both productivity and biomass quality.

In contrast, photobioreactors provide a controlled environment that allows for precise regulation of growth parameters, including light, temperature and nutrient supply. This results in higher productivity and more consistent biomass composition (Wijffels et al., 2010). However, the high cost of installation and operation limits their widespread adoption, particularly in developing regions.

The growth of microalgae is influenced by several key factors, including light intensity, temperature, nutrient availability and carbon dioxide concentration. Optimization of these parameters is essential for maximizing yield and improving product quality. However, the lack of standardized cultivation protocols across studies leads to significant variability in results, making it difficult to draw generalized conclusions.

IV. EXTRACTION AND PROCESSING TECHNOLOGIES

The extraction and processing of microalgal biomass represent a critical step in determining its applicability in food systems. Despite the high concentration of valuable biomolecules, the recovery of these compounds is often limited by the presence of rigid and complex cell wall structures, particularly in species such as Chlorella vulgaris (Safi et al., 2014). Consequently, efficient cell disruption is required prior to extraction in order to enhance the release of intracellular components.

Mechanical disruption techniques, including bead milling, high-pressure homogenization and ultrasonication, are commonly employed for this purpose (Lam and Lee, 2012). While these methods significantly improve extraction efficiency, they are associated with high energy consumption and may lead to degradation of heat-sensitive compounds if not properly optimized (Plaza et al., 2008). In addition to mechanical approaches, solvent extraction using organic solvents such as ethanol, methanol and hexane is widely applied for the recovery of lipids and pigments (Mata et al., 2010). However, concerns related to solvent toxicity, environmental impact and residual contamination limit their suitability for food-grade applications.

To address these limitations, advanced extraction technologies have been developed. Supercritical carbon dioxide extraction has been recognized as an efficient and environmentally friendly method for extracting bioactive compounds without leaving solvent residues (Plaza et al., 2008). Similarly, ultrasound-assisted extraction and microwave-assisted extraction have been reported to enhance yield while reducing processing time (Safi et al., 2014). Enzymatic extraction techniques, which involve the selective degradation of cell wall components, offer an alternative approach with reduced environmental impact, although their cost remains a limiting factor (Koyande et al., 2019).

Despite these advancements, most extraction techniques remain confined to laboratory-scale studies and lack validation at industrial scale. Furthermore, the absence of standardized extraction protocols across studies results in significant variability in reported yields and product quality (Khan et al., 2018). This highlights the need for the development of scalable and cost-effective extraction technologies for commercial applications.

V. APPLICATIONS IN FOOD SYSTEMS

Microalgae have been investigated for their potential incorporation into a variety of food products due to their high nutritional value and functional properties. Their application in food systems can be broadly categorized into bakery products, beverages, dairy alternatives and nutraceutical formulations.

In bakery products, microalgae are primarily used as protein-rich ingredients to enhance nutritional value. The incorporation of Spirulina and Chlorella has been shown to significantly increase protein content and antioxidant activity (Gouveia et al., 2008). However, the presence of chlorophyll and other pigments often results in undesirable color changes, which may affect consumer acceptance (Bleakley and Hayes, 2017).

The use of microalgae in beverages has also gained attention, particularly in the development of functional drinks enriched with antioxidants and bioactive compounds (Suleria et al., 2015). Nevertheless, challenges such as sedimentation, phase separation and color instability limit their practical application (Khan et al., 2018). In dairy alternatives, microalgae have been incorporated into plant-based milk and yogurt products to improve protein content and nutritional profile (Yaakob et al., 2014). Despite these benefits, sensory issues such as strong odor and taste remain major obstacles.

Among all applications, nutraceuticals and dietary supplements represent the most commercially successful use of microalgae. Products such as spirulina tablets and chlorella powders are widely available due to minimal sensory constraints and high consumer acceptance (Suleria et al., 2015). However, even in this sector, issues related to standardization and quality control persist.

Overall, while microalgae offer significant potential in food applications, their widespread adoption is hindered by challenges related to sensory properties, stability and processing limitations.

VI. COMPARATIVE EVALUATION OF EXISTING STUDIES

A critical evaluation of existing literature reveals considerable variability in research outcomes, which can be attributed to differences in experimental conditions, species selection and processing techniques. Several studies have reported high protein content in microalgae; however, these findings often do not consider factors such as digestibility and bioavailability, leading to overestimation of nutritional value (Becker, 2007; Safi et al., 2014).

Similarly, research on lipid extraction highlights the presence of valuable fatty acids such as EPA and DHA, but fails to address the economic feasibility of large-scale extraction processes (Pulz and Gross, 2004; Lam and Lee, 2012). In the context of food applications, studies demonstrate improvements in nutritional profile but often neglect sensory evaluation and consumer acceptance (Gouveia et al., 2008).

Another limitation is the lack of industrial-scale validation. Most studies are conducted under controlled laboratory conditions, which do not accurately represent commercial production environments (Khan et al., 2018). Furthermore, long-term stability and shelf-life studies are rarely addressed, limiting the practical applicability of research findings.

These inconsistencies highlight the need for standardized methodologies and comprehensive evaluation frameworks that consider both technical and consumer-related factors.

VII. CHALLENGES AND LIMITATIONS

The commercialization of microalgae-based food products is constrained by a range of technical, economic, sensory and regulatory challenges. From a technical standpoint, harvesting microalgae remains a major challenge due to their small size and low concentration in culture media, resulting in high energy requirements (Lam and Lee, 2012).

Economic challenges are equally significant, as the cost of cultivation, harvesting and processing is considerably higher compared to conventional food sources (Brennan and Owende, 2010). The use of advanced technologies such as photobioreactors further increases capital and operational costs (Wijffels et al., 2010).

Sensory limitations represent one of the most critical barriers to consumer acceptance. Microalgae are characterized by a distinct taste, odor and intense green color, which are often perceived as undesirable in food products (Bleakley and Hayes, 2017). These factors significantly limit their incorporation into mainstream food systems.

Regulatory challenges also play an important role, as the approval of microalgae-based products requires compliance with safety standards and regulatory guidelines, which vary across regions (Khan et al., 2018). The lack of standardized regulations further complicates commercialization efforts.

VIII. FUTURE PERSPECTIVES

Future research on microalgae must focus on addressing the limitations identified in current studies and facilitating the transition from laboratory-scale research to industrial applications. One of the key areas of development is the optimization of cultivation systems to reduce production costs and improve biomass yield (Mohsenpour et al., 2021).

Advancements in processing technologies, such as encapsulation and nanoemulsion, offer promising solutions for improving the stability and sensory properties of microalgae-based products (Koyande et al., 2019). These approaches can help mask undesirable flavors and enhance consumer acceptance.

The integration of artificial intelligence and data analytics in microalgae cultivation and processing represents an emerging area of research. By optimizing growth conditions and predicting biomass yield, these technologies can significantly improve process efficiency (Khan et al., 2018).

Furthermore, interdisciplinary research involving food scientists, biotechnologists and engineers is essential for developing scalable and commercially viable solutions.

IX. CONCLUSION

Microalgae represent a promising and sustainable resource for the development of functional food ingredients due to their rich nutritional and bioactive composition (Becker, 2007; Pulz and Gross, 2004). However, their large-scale application is limited by challenges related to cost, processing efficiency, sensory properties and regulatory constraints (Lam and Lee, 2012; Khan et al., 2018).

Current research is largely focused on laboratory-scale studies, with limited emphasis on industrial feasibility and consumer acceptance. Addressing these gaps requires a multidisciplinary approach that integrates technological innovation, economic analysis and consumer research (Mohsenpour et al., 2021).

With continued advancements in cultivation, processing and product development, microalgae have the potential to play a significant role in sustainable food systems in the future.

REFERENCES:

[1]. Becker, E.W., 2007. Microalgae as a source of protein. Biotechnology Advances, 25(2), pp.207–210.

[2]. Bleakley, S. and Hayes, M., 2017. Algal proteins: Extraction, application, and challenges concerning production. Journal of Applied Phycology, 29(2), pp.697–710.

[3]. Brennan, L. and Owende, P., 2010. Biofuels from microalgae—A review of technologies for production, processing, and extraction of biofuels and co-products. Renewable and Sustainable Energy Reviews, 14(2), pp.557–577.

[4]. Chisti, Y., 2007. Biodiesel from microalgae. Biotechnology Advances, 25(3), pp.294–306.

[5]. Gouveia, L., Batista, A.P., Miranda, A., Empis, J. and Raymundo, A., 2008. Chlorella vulgaris in food products: A study on sensory properties and consumer acceptance. Food Chemistry, 110(3), pp.717–723.

[6]. Khan, M.I., Shin, J.H. and Kim, J.D., 2018. The promising future of microalgae: Current status, challenges, and optimization of a sustainable and renewable industry. Bioresource Technology, 255, pp.1–10.

[7]. Koyande, A.K., Chew, K.W., Rambabu, K., Tao, Y., Chu, D.T. and Show, P.L., 2019. Microalgae: A potential alternative to health supplementation for humans. Food Science and Human Wellness, 8(1), pp.16–24.

[8]. Lam, M.K. and Lee, K.T., 2012. Microalgae biofuels: A critical review of issues, problems, and the way forward. Biotechnology Advances, 30(3), pp.673–690.

[9]. Mata, T.M., Martins, A.A. and Caetano, N.S., 2010. Microalgae for biodiesel

production and other applications: A review. Renewable and Sustainable Energy Reviews, 14(1), pp.217–232.
[10]. Mohsenpour, S.F., Richards, B. and Willoughby, N., 2021. Current status and future prospects of microalgae cultivation for industrial applications. Renewable and Sustainable Energy Reviews, 148, p.111273.
[11]. Plaza, M., Herrero, M., Cifuentes, A. and Ibáñez, E., 2008. Innovative natural functional ingredients from microalgae. Trends in Food Science & Technology, 19(3), pp.162–173.
[12]. Pulz, O. and Gross, W., 2004. Valuable products from microalgae. Applied Microbiology and Biotechnology, 65(6), pp.635–648.
[13]. Safi, C., Zebib, B., Merah, O., Pontalier, P.Y. and Vaca-Garcia, C., 2014. Morphology, composition, production, processing, and applications of microalgae. Renewable and Sustainable Energy Reviews, 35, pp.265–278.
[14]. Sathasivam, R., Radhakrishnan, R., Hashem, A. and Abd_Allah, E.F., 2017. Microalgae metabolites: A rich source for food and medicine. Saudi Journal of Biological Sciences, 26(4), pp.709–722.
[15]. Suleria, H.A.R., Osborne, S., Masci, P. and Gobe, G., 2015. Marine-based nutraceuticals: An innovative trend in the food and supplement industries. Marine Drugs, 13(10), pp.6336–6351.
[16]. Wijffels, R.H., Kruse, O. and Hellingwerf, K.J., 2010. Potential of industrial biotechnology with cyanobacteria and eukaryotic microalgae. Biotechnology Advances, 28(6), pp.713–724.
[17]. Yaakob, Z., Ali, E., Zainal, A., Mohamad, M. and Takriff, M.S., 2014. An overview: Biomolecules from microalgae for animal feed and aquaculture. Journal of Biological Research, 21(1), pp.1–12.