



Review on Prospects of Single Cell Proteins (SCPs) as a Future of Nutraceuticals

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ABSTRACT

The increasing global demand for sustainable and nutrient-dense food sources necessitates innovative alternatives. Single-cell proteins (SCPs), derived from microorganisms such as fungi, bacteria, algae, and yeast, have emerged as a promising nutraceutical resource. SCP production capitalizes on renewable substrates, including agricultural and industrial waste, aligning with sustainability goals. This review explores SCP's diverse sources, production methods, nutritional profiles, and applications. Rich in proteins, essential amino acids, vitamins, and bioactive compounds, SCP offers a cost-effective solution to address global protein shortages and malnutrition. Advancements in genetic engineering, fermentation technologies, and utilizing novel microorganisms have enhanced SCP's feasibility. Moreover, compared to traditional protein sources, SCP production reduces environmental impact by minimizing land use, water consumption, and carbon emissions. Current applications in human health, animal nutrition, and food systems illustrate SCP's versatility, while prospects include personalized nutraceuticals, functional foods, and integration into sustainable food chains. However, challenges remain in regulatory acceptance, consumer awareness, and scalability. With ongoing innovation, SCP holds the potential to revolutionize global nutrition and support a circular bioeconomy.

Keywords: Single Cell Protein, Algae, Yeast, Fungi, Bacteria, Food Waste, Nutraceuticals.

INTRODUCTION

Single-cell protein (SCP) is emerging as a promising solution to meet the increasing global demand for sustainable protein sources. With its potential to utilize various substrates, SCP can significantly contribute to nutraceuticals by providing high-quality protein while addressing environmental concerns associated with traditional agriculture. The term "nutraceutical" is derived from "nutrition" and "pharmaceutics"¹. It is employed to characterize items that are separated from natural substances, nutritional supplements, specific dietary regimes, and processed foods like beverages, cereals, and soups, which are also employed for medicinal purposes in addition to providing nutrition. Pharmaceuticals known as nutraceuticals use food phytochemicals as their active ingredients. Nutraceuticals are dietary supplements that give a condensed form of a supposed food bioactive ingredient presented in a non-food matrix and utilized to improve health in dosages greater than those that could be received from regular foods.

Single-cell Proteins (SCP) are proteins produced by the cells of microorganisms like fungi, yeast, bacteria, and algae grown using diverse sources of carbon². One crucial factor to take into account when utilizing SCP (Single-Cell Protein) is ensuring that there are no harmful or cancer-causing substances present. These substances may originate from the raw materials, be produced by the microorganisms themselves, or form as a result of the processing methods employed.

As protein constitutes the most substantial portion of microbial cells, these organisms are often called single-cell proteins, serving as a naturally concentrated source of protein. As the global population grows and protein

shortages become more prevalent, the biomass of microbes used for food and animal feed gains prominence. There is an increased food wastage globally due to the increased global population growth and subsequent rise in food production.

In this current review, we intend to examine the prospects of single-cell proteins as a future of Nutraceuticals and their broad uses in the present and future.

1. Overview of the Single Cell Protein (SCP):

Single-cell protein, which can originate from a variety of microorganisms, encompasses a wide variety of single-celled organisms, including yeast, algae, fungi, and bacteria. Beyond microorganisms, SCP can also be sourced from various wastes, such as crop waste, fruit waste, and more. Historically, SCPs have been valued for their protein content, serving as vital sources of sustenance during periods of food scarcity. However, with the advancements in biotechnology and an enhanced understanding of microbial biology, contemporary SCP production goes beyond survival strategies.

2.1 Different types of SCPs:

2.1.1 Fungi as a promising source of SCP:

Fungal species like *Kluyveromyces*, *Rhodotorula*, *Fusarium*, *Candida*, *Meyerozyma*, *Pichia*, *Aspergillus*, *Nectaromyces*, *Aureobasidium*, and *Neurospora* have been used to produce SCP because of their chemical composition³.

Fungi can achieve protein levels of 30% to 50% by optimizing fermentation processes to increase cellular protein content. Fungi are the best prospects for producing single-cell proteins (SCP), single-cell oil, and other improved substances, according to numerous research. However, due



to characteristics including their restricted cell-wall digestibility, which stands as low as 34% and increased nucleic acid content, which can reach up to 10%, the potential applicability of fungi is tempered. These considerations are crucial before incorporating them widely. Challenges related to cell-wall digestibility may result in reduced protein bioavailability, potentially leading to issues such as allergies, digestive problems, or skin-related concerns ³.

2.1.2 Fungi and substrates used for SCP production:

Different types of fungi can be used to produce SCP. Fungal SCP is typically high in protein and can also contain vitamins, essential amino acids, and minerals. Many of these fungi are efficient in converting waste products into SCP, contributing to waste reduction and sustainable production. Fungi like *Aspergillus niger* and *Trichoderma reesei* can utilize a broad variety of substrates, including complex lignocellulosic materials ⁴. Some of these fungi, beyond SCP production, are valuable in producing enzymes, organic acids, and antibiotics (Table 1)

Table 1: Fungi and substrates used for SCP production^{1,3,5}

Microorganism (Fungi)	Substrate
<i>Aspergillus fumigatus</i>	Glucose, Maltose
<i>Aspergillus niger</i> , <i>A. oryzae</i> , <i>Cephalosporium eichhorniae</i> , <i>Chaetomium cellulolyticum</i>	Cellulose, Hemicellulose
<i>Penicillium cyclopium</i>	Lactose, Glucose Galactose
<i>Rhizopus chinensis</i>	Maltose, Glucose,
<i>Scytalidium acidophilum</i> , <i>Thricoderma viridae</i> , <i>Thricoderma alba</i>	Pentose, Cellulose
<i>Paecilomyces varioti</i>	Sulphite waste liquor
<i>Fusarium graminearum</i>	Glucose, Starch

2.1.3 Nutritional Value of fungi SCP:

The composition of Single Cell Protein (SCP) derived from fungi typically includes a variety of nutrients, making it a valuable source for both human consumption and animal feed ⁵. The exact composition can range, depending on the substrate used, fungal species, and cultivation methods. The composition is included in (Table 2).

2.2.1 bacteria as a promising source of SCP:

For the rapid growth rates and versatility in thriving on diverse substrates, including sugars, starches, and organic wastes, these bacteria offer promising avenues for protein production. Recent research has specifically highlighted purple phototrophic bacteria like *Rhodospirillum Rhodopseudomonas*, and *Rhodobacter* as particularly attractive candidates for SCP production³.

Commercializing bacterial SCP requires adherence to specific criteria, Highlighting factors such as foam production, growth rate, oxygen and heat requisites during fermentation, pH resilience, chemical composition, and the purity of the final product. However, a notable drawback is the high nucleic acid content associated with bacterial SCP, coupled with the challenge of consumer unfamiliarity with this innovative material ⁶.

Table 2: Composition of fungi SCP

Component	Percentage composition of weight
True Protein	30-70a
Total nitrogen (nucleic acids + Protein)	35-50a
Lysin	6.5-7.8a
Methionine	1.5-1.8a
Fats/Lipids	5-13a
Carbohydrate	NA
Chlorophyll and Bile pigments	NA
Amino acids	54
Mineral acids	6.6
Nucleic acids	9.70
Ash	NA
Moisture	4.5-6.0a
Fiber	NA

Table 3: Bacteria and its substrates used for SCP production^{4,8,6,7}

Bacteria	Substrate for SCP Production
<i>Methylophilus methylotrophus</i>	Methanol
<i>Bacillus subtilis</i>	Various organic substrates including agricultural waste
<i>Corynebacterium glutamicum</i>	Molasses, sugary solutions
<i>Pseudomonas</i> spp.	Methanol, ethanol, and various hydrocarbons
<i>Rhodococcus opacus</i>	Glycerol, glucose, xylose
<i>Lactobacillus</i> spp.	Dairy by-products (e.g., whey)
<i>Escherichia coli</i>	Glucose, glycerol, and other sugars
<i>Clostridium</i> spp.	Starch, sugars, and cellulose-based substrates
<i>Alcaligenes eutrophus</i>	Methanol
<i>Hydrogenomonas eutropha</i>	Hydrogen gas

2.2.2 Bacteria and substrates used for SCP production:

Numerous bacterial species are capable of producing Single Cell Protein (SCP), each with its unique substrate preferences. Bacterial SCP is notable for its high protein content, comprising 50-80% of its dry weight ⁷. It is distinguished by its low density, high nucleic acid content, and diminutive cell size. These bacteria can rapidly multiply, typically within 20-120 minutes, utilizing a diverse array of substrates. Bacterial SCP can also thrive in water resources rich in nutrients and minerals ⁷. Bacteria such as *Escherichia coli* and *Bacillus subtilis* are known for their versatility, efficiently processing a diverse array of substrates. SCP production gets an advantage because of this particular adaptability (Table 3).

2.2.3 Nutritional Value of Bacteria SCP:

The composition of Single Cell Protein (SCP) obtained from bacteria fluctuates depending on, the substrate utilized for growth, cultivation conditions, and the bacterial strain ⁸. However, bacterial SCP generally contains several key components that contribute to its nutritional value, which are included in Table 4

Table 4: Composition of bacteria SCP

Component	Percentage composition of weight
True Protein	50-83a
Total nitrogen (nucleic acids + Protein)	60-80a
Lysin	4.3-5.8a
Methionine	2.2-3.0a
Carbohydrate	NA
Fats/Lipids	8-10a
Chlorophyll and Bile pigments	NA
Amino acids	65
Mineral acids	8.6
Nucleic acids	15-16a
Ash	NA
Moisture	2.8
Fiber	NA

2.3.1 Unfolding algae as a source of SCP:

Microalgae exhibit a remarkable ability to transform micro-molecules like ammonium or carbon dioxide into valuable macromolecules, particularly proteins. Their exceptional photosynthetic efficiency and swift growth rates enhance productivity concerning proteins and/or lipids. Specific strains of microalgae exhibit Single-Cell Protein (SCP) levels reaching up to 70%, rendering them advantageous options for consumption by both animals and humans ³.

Spirulina platensis and *Chlorella vulgaris* were used to partially replace fishmeal protein in the feed of African catfish, with an investigation into the impact on the body composition and growth of the catfish. Despite various microalgal species, like *Arthrospira*, *Schizochytrium*, *Haematococcus*, *Chlorella*, and *Dunaliella* being recognized as GRAS or Generally Recognized as Safe by the United States Food and Drug Administration also known as FDA, the application of microalgae in commercial formulations for food and feed demands thorough scrutiny due to potential toxicity concerns ³.

2.3.2 Algae and substrates used for SCP production:

Algae primarily use photosynthesis for growth, requiring light, carbon dioxide, and water, along with essential minerals (Table 5). But algae are also a very good source for SCP production. Algae contribute to carbon dioxide (CO₂) fixation, making them environmentally beneficial for SCP production. Algae-based SCP is protein-rich and full of fatty acids (like omega-3s), minerals, and vitamins ⁹.

Table 5: Algae and its substrates used for SCP production¹⁰⁻¹³

Algae Species	Substrate/Growth Requirements for SCP Production
<i>Spirulina (Arthrospira spp.)</i>	Carbon dioxide, mineral nutrients (nitrogen, phosphorus) in alkaline water and sunlight (photosynthesis)
<i>Chlorella spp.</i>	Carbon dioxide, mineral nutrients in freshwater and sunlight (photosynthesis)
<i>Dunaliella spp.</i>	Carbon dioxide, sunlight, and mineral nutrients; are often grown in saline conditions
<i>Haematococcus spp.</i>	Carbon dioxide, sunlight, and mineral nutrients in freshwater; are known for astaxanthin production
<i>Nannochloropsis spp.</i>	Carbon dioxide, sunlight, and mineral nutrients in the marine environment
<i>Scenedesmus spp.</i>	Carbon dioxide, sunlight, and mineral nutrients in freshwater
<i>Phaeodactylum tricornutum</i>	Carbon dioxide, sunlight, and mineral nutrients in marine environments; known for EPA (eicosapentaenoic acid) production

2.3.3 Nutritional Value of algae SCP:

The composition of SCP derived from algae varies depending on the algal species and the conditions under which they are grown ¹⁰. However, algae SCP is generally known for its rich and varied nutritional content that are shown in Table 6.



Table 6: Composition of algae SCP

Component	Percentage composition of weight
True Protein	40-60a
Total nitrogen (nucleic acids + Protein)	45-65a
Lysin	4.6-7.0a
Methionine	1.4-2.6a
Fats/Lipids	5-10a
Nucleic acids	4-6a
Bile pigments and Chlorophyll	6
Carbohydrate	9
Mineral acids	7
Amino acids	NA
Fiber	3
Moisture	6.0
Ash	3

2.4.1 Yeast as a source of SCP:

Numerous yeast species have emerged as valuable reservoirs of protein, showcasing substantial protein concentrations ranging from 50% to 80% of their dry weight. Renowned for their swift growth rates and adaptability to a diverse range of substrates, encompassing organic residues, starches, and sugars, yeast species present enticing prospects for protein production. Recent studies have specifically spotlighted well-known yeast strains such as *Saccharomyces cerevisiae* and *Candida utilis* as particularly promising candidates for SCP production¹¹.

In World War II *Candida utilis* and *Candida arborea* were employed extensively, with about 60 percent of the country substituting these yeasts as a significant part of their food intake. Yeasts are often supplemented in dog, cat, and fish feeds to enhance palatability for animals.

2.4.2 Yeast and substrates used for SCP production:

Yeast also has varying types that can be used for SCP production. Different yeasts have varying capabilities in utilizing substrates. For instance, *Saccharomyces cerevisiae* is very efficient in converting sugary substrates into protein. Yeasts like *Candida utilis* and *Kluyveromyces* spp. can turn industrial by-products (e.g., whey, molasses) into valuable protein sources, aiding in waste reduction (Table 7). Yeast-derived SCP is not only high in protein but also contains vitamins (notably B vitamins), minerals, and essential amino acids¹²

Table 7: Yeast and its substrates used for SCP production^{14,18,20}

Yeast Species	Substrate for SCP Production
<i>Saccharomyces cerevisiae</i> (Brewer's Yeast)	Molasses, sugary waste, starch-based substrates
<i>Candida utilis</i> (Torula Yeast)	Wood sugars from sulfite liquor (paper mill waste), molasses
<i>Kluyveromyces fragilis</i>	Whey (from dairy processing), lactose-rich substrates
<i>Kluyveromyces marxianus</i>	Whey, molasses, sugary solutions
<i>Pichia pastoris</i>	Methanol, glycerol
<i>Yarrowia lipolytica</i>	Industrial fats, glycerol, fatty acids
<i>Schizosaccharomyces pombe</i>	Sugarcane juice, molasses
<i>Hansenula polymorpha</i>	Methanol, glycerol

2.4.3 Nutritional Value of Yeast SCP:

The composition of single-cell protein (SCP) from yeast, like other SCP sources, can vary based on the yeast species and growth conditions¹³. However, yeast SCP generally has a consistent nutritional profile characterized by the following components shown in Table 8.

Table 8: Composition of yeast SCP

Component	Approximate Percentage in Dry Weight
Proteins	45% - 55%
Carbohydrates	25% - 40%
Nucleic Acids	8% - 12%
Vitamins (Especially B-complex)	Variable, but significant
Trace Elements and Minerals	Variable, includes selenium, zinc, magnesium, iron, calcium, and potassium
Lipids	1% - 7%
Fiber	Variable, includes beta-glucans

3. Application of Agricultural Waste for production of SCP:

In the pursuit of sustainable and eco-friendly protein sources, the use of agricultural waste for SCP production has emerged as a promising frontier. This innovative approach not only addresses the escalating challenges of agricultural residue management but also transforms waste into a valuable resource for meeting the increasing global protein demand¹⁴. Different types of agricultural waste can be used to produce SCP.

3.1 Fruit waste in the production of SCP:

A diverse array of fruit waste, like mangoes, papayas, pineapples, bananas, prickly custard apples, cashew apples, cacao, mangosteens, pomegranates, and jackfruits, as substrates to be used by *S. cerevisiae* for SCP production. SCP production and highest biomass (48.3% and 0.4 g, respectively) were achieved when the wastes of pineapple were utilized as feedstock for the fermentation. Waste of pineapple, constituting 60% v/v, also proved effective, yielding a maximum SCP of 3.0 g/L when *S. cerevisiae* was used. Various fruit wastes, including peels from Beles fruits, bananas, and sweet oranges, as well as waste from mangoes, and pomegranates, along with orange plantain, and beet pulp, have been utilized as substrates for the cultivation of *Candida tropicalis*, *Candida utilis*, and *Saccharomyces cerevisiae*¹⁵.

3.2 Use of Crop waste in the production of SCP

Crop residues stand out as economical, abundant resources, and renewable. The global production of crop residues witnessed an increase. Crop residues were generated from various crops, including cereals such as barley, millet, corn, rice, oats, wheat, and rye. These residues comprise straws, husks, bran, and hulls from crops like barley, rice, wheat, corn, and oats. Predominantly composed of lignin, hemicelluloses, and cellulose, these materials serve as promising substrates for SCP production³. However, the direct utilization of cellulose and hemicelluloses by most microorganisms is limited, necessitating enzymatic hydrolysis and pretreatment to facilitate the hydrolysis of cellulose and convert hemicelluloses into monosaccharides.

3.3 Use of Combined agricultural waste in SCP

In a recent investigation, the combination of whey and vinasse wastewaters was explored as a medium for cultivating the filamentous fungus *Neurospora intermedia* to generate biomass rich in protein. This underscores the potential of utilizing mixed substrates for SCP production, offering a sustainable approach with economic and environmental benefits. So, combined agricultural waste is a very good source for SCP production³.

3.4 Cellulosic waste in the production of SCP:

To efficiently utilize cellulose-rich waste, various pre-treatment methods are employed. Microbial cellulolysis is included among these where cellulose is broken down by cellulolytic microorganisms and mechanical thermolysis, which involves the use of steam. Other common method includes the use of acid and alkalis which are the chemical method as well as the biochemical digestion with enzymes. After pretreatment of the waste, it can be further processed which produces SCP. sed through fermentation by microorganisms¹⁶.

3.5 SCP production by Lignin waste:

The major byproduct of the paper industry is lignin, which is often used as low-value fuel. However, it can be put to many economically beneficial uses, such as microbial fermentation. Certain microorganisms possess the capability to degrade lignin for fermentation. Even though the process is slower and yields smaller quantities of Single Cell Protein (SCP) compared to other waste products¹⁷.

3.6 SCP Production by Dairy Waste:

A staggering quantity of whey, amounting to 55.5 million tons, was generated alone in Europe by the cheese manufacturing industry in 2020, which emphasizes the crucial need for effective waste treatment. Whey, comprising roughly 50% of milk residue, is rich in proteins, non-protein nitrogen, lactose, minerals, and some other trivial compounds. The effective utilization of whey hinges on identifying strains of microbes capable of metabolizing lactose and changing it into a Single-Cell Protein¹⁴.

Apart from cell mass, cheese whey has been associated with processes involving the creation of microbial cells that have substantial lipid amounts, referred to as Single-Cell Oils (SCOs). Moreover, beyond cell mass, these microbial cultures have demonstrated the production of other important metabolites, like exopolysaccharides¹⁸.

3.7 Sugar industry waste in the production of SCP:

Obtained from the sugar industry through repetitive crystallization in sugar preparation, molasses is extensively employed as a substrate for fermentation. This contributes to the generation of biotechnologically and industrially significant products such as SCP, organic acids, and biohydrogen¹⁹. *Saccharomyces cerevisiae*, also referred to as Brewer's yeast, is effectively utilized to produce SCP from sugar waste. This yeast efficiently ferments sugars present in waste materials, converting them into protein-rich biomass. Its ability to utilize sugar waste not only provides a sustainable method for SCP production but also helps in reducing environmental waste, making it a valuable tool in biotechnological applications focused on resource efficiency and sustainability¹¹.

4. Application of Industrial Waste for the Production of SCP

4.1 Waste paper for the production of SCP:

In 2014, global production of paper and cardboard reached 390 million tons, with recycling rates in developed regions like Europe and North America averaging 60-70% of total output. In other regions, however, the recycling rate is lower. This indicated the constant rise in the volume of waste paper. Unwanted microbial material poses the challenge of contamination to SCP production from waste paper. One of the solutions for bypassing such an issue is the potential use of extremophilic microorganisms, as their selective growth conditions can minimize the risk of contamination¹⁶.



4.2 SCP production by Utilizing Sulfate waste liquor:

A by-product of the sulfite is spent sulfite liquor (SSL), which is an effective substrate for microorganism cultivation. It can be utilized for the production of various products like ethanol, vanillin, and SCP. Utilizing SSL for SCP production is very advantageous economically due to its low cost and abundance; it is also environmentally beneficial as it reduces biological oxygen demand (BOD) ².

4.3 Methane in the production of SCP:

Methane is an abundant and cheap carbon source and has long been studied for SCP production. Despite its poor solubility, impurity variations, and flammability, its advantages include selectivity, low volatility, and toxicity. Natural gas, primarily methane (85-90%), is a suitable source of methane for SCP. SCP with a high concentration in microbial biomass has been successfully produced by experimenting using natural gas ²⁰.

4.4 Methanol in production of SCP:

One of the most commonly found industrial waste is Methanol, which offers a feasible option for SCP production. As a cheap and easily available carbon source, it has a cost-effective solution for SCP cultivation. The usefulness of methanol in SCP production stems from its ability to be processed metabolically by certain microorganisms, which convert it into protein-rich biomass. It offers a sustainable method to reuse industrial waste and contribute towards valuable protein resource production. By this, it helps to achieve environmental sustainability goals. Industries also seek to minimize industrial waste and maximizing its resource efficiency, the methanol-rich waste for producing SCP is a promising way. *Pichia pastoris*, *Methylophilus methylotrophus* are examples of microorganisms that are used for producing SCP ²⁰.

4.5 Glycerol in production of SCP:

The main byproduct in biodiesel production is crude or industrial glycerol which is glycerol in concentrated form containing waters with glycerol concentrations varying between 65-85% w/w. The increased production of biodiesel globally causes a decrease in its price. It also causes substantial quantities of this feedstock to accumulate in the market. Apart from this, glycerol-containing water is also significantly generated during alcoholic beverages and bioethanol production, particularly in bioethanol production ³.

Recently, numerous reports have delved into the utilization of glycerol as a renewable source of carbon in Industrial Microbiology. Many studies showed substantial dry cell weight (DCW) production employing heterotrophic-grown algal strains, fungal or yeast as cell factories. The yeast strain *Yarrowia lipolytica* (YLY) accumulated crude glycerol, resulting in 19.7 g/L of SCP. The multifaceted sources of glycerol, coupled with its effective utilization in SCP production, underscore its potential as a valuable feedstock in industrial processes ³.

5. Applications of SCPs in Nutraceuticals:

Single-cell protein (SCP) has garnered significant attention in recent years due to its potential applications in nutraceuticals, addressing the growing demand for sustainable protein sources. This review explores the current uses of SCP, potential future applications, and its advantages over traditional protein sources.

5.1 SCP a promising Nutraceutical source:

Refined or crude protein derived from bacteria, mold, algae, or yeast and utilized for human or animal consumption is known as single-cell protein (SCP) ². Large volumes of SCP can be generated in a single day. As a protein source, it holds great promise with the potential to solve the worldwide food shortage as the global population grows. Additionally, lipids and vitamins are among the supplementary nutrients present in SCP. As a result, SCP technology is very well-liked, alluring, and a speedy source of energy, nutrition, and food because of the growing demand for proteins around the world. SCP has high lipids levels as well as high protein content, carbs, vitamins, and minerals. Furthermore, SCP has significant concentrations of lysine, methionine, and threonine, three important amino acids. This protein source (SCP) is a suitable alternative to more expensive sources of protein. Sources like soybean and fish meals. Thus, it may be concluded that SCP is a simple way for humans and animals to substitute conventional sources of protein (plant and animal). These properties of SCP render them a strong candidate for utilization as a nutraceutical product ²¹.

5.2 Current Uses of SCP in Nutraceuticals:

SCP is primarily utilized as a nutritional supplement in various forms, including powders and capsules. It is incorporated into functional foods aimed at enhancing health benefits. Key applications include SCP has been shown to help control obesity and reduce body weight by providing a high-protein, low-calorie alternative to traditional protein sources. Certain SCPs can lower blood sugar levels, making them beneficial for diabetic patients. SCP is an excellent protein source for undernourished populations, particularly children, due to its rich amino acid profile and micronutrient content ¹². SCP is increasingly used in animal nutrition, particularly in aquaculture and poultry farming. It serves as a protein-rich alternative to fishmeal and other traditional feed sources, contributing to sustainable animal husbandry practices ²¹.

5.3 Potential Future Applications:

As research progresses, the potential applications of SCP are expanding, future developments may focus on extracting bioactive peptides from SCP, which could have therapeutic effects such as antioxidant and anti-inflammatory properties. Advances in biotechnology may allow for the customization of SCP formulations tailored to individual nutritional needs, enhancing their efficacy in dietary interventions. Integration into Food Systems, SCP could be more widely integrated into mainstream food



products, including snacks and meal replacements, due to its versatility and nutritional benefits ¹⁹.

5.4 Advantages Over Traditional Protein Sources:

SCP presents several advantages compared to conventional protein sources, SCP production utilizes waste materials and agricultural by-products as substrates, reducing environmental impact and promoting a circular economy. Microorganisms used for SCP have high multiplication rates, allowing for quicker biomass production than traditional livestock farming. Nutritional Quality: SCP offers a balanced amino acid profile with high digestibility, often surpassing that of plant-based proteins and some animal proteins ⁹.

Single-cell protein is emerging as a versatile and sustainable solution to meet global protein demands. Its current applications in nutraceuticals highlight its potential for improving health outcomes, while future innovations promise to enhance its role in food security and nutrition. As the industry evolves, SCP could play a crucial part in addressing the challenges posed by traditional protein sources.

6. Recent advancements in Single Cell Protein (SCP) technology :

Recent advancements in Single Cell Protein (SCP) technology have significantly enhanced its production, genetic engineering approaches, and the exploration of novel sources. This review highlights these developments, focusing on improved production techniques, genetic engineering, and emerging microbial sources.

6.1 Improved Production Techniques:

Recent innovations in SCP production have emphasized the use of second-generation substrates, which include agricultural residues and industrial by-products. This shift not only reduces competition with food crops but also promotes a circular economy by utilizing waste materials. Advanced fermentation techniques, such as continuous fermentation and cell recycling, have been shown to optimize biomass yields and enhance protein concentration in the final product. For instance, aerobic continuous fermentation has demonstrated effective protein production while simultaneously removing chemical oxygen demand (COD) from waste streams like cheese whey ³. Additionally, novel bioreactor designs are being developed to improve scalability and efficiency in SCP production processes, making them more commercially viable.

6.2 Genetic Engineering Approaches:

Genetic engineering has emerged as a powerful tool in enhancing SCP production. Techniques such as CRISPR-Cas and metabolic engineering are being employed to modify microbial strains for improved protein yield and quality. By enhancing specific metabolic pathways, researchers can increase the synthesis of desirable proteins and reduce unwanted by-products, thus improving the overall efficiency of SCP production. Furthermore, genetic

modifications can also enable microorganisms to utilize a broader range of substrates, thereby expanding the potential for SCP production from diverse feedstocks ²².

6.3 Novel Sources of SCPs:

The exploration of novel microbial sources for SCP is gaining traction. While traditional sources include yeast, fungi, and algae, research is increasingly focusing on less conventional microorganisms such as certain bacteria and microalgae that exhibit high protein content and rapid growth rates. For example, strains like *Methylophilus* spp. have been identified for their impressive generation times and high protein quality¹. Additionally, companies are investigating the use of genetically engineered microorganisms to produce specialty proteins or bioactive compounds that could serve both nutritional and functional roles in food products.

7. The environmental and sustainability aspects of SCP:

Single Cell Protein (SCP) production is gaining increasing attention as the world seeks sustainable solutions to meet the growing protein demand. This review discusses the reduced environmental impact of SCP compared to traditional protein sources, resource efficiency, and the potential for integration into a circular economy.

7.1 Reduced Environmental Impact Compared to Traditional Protein Sources:

SCP production offers a significantly lower environmental footprint than conventional protein sources such as livestock and aquaculture. Traditional animal farming is associated with high greenhouse gas emissions, extensive land use, and significant water consumption. In contrast, SCP can be produced in large-scale fermentation systems that require minimal land and water resources. For example, SCP derived from microbial fermentation can achieve net-zero carbon emissions in aquaculture feed applications, as it does not necessitate land use or contribute to deforestation. Furthermore, the cultivation of microorganisms can occur in controlled environments, shielding them from adverse weather conditions and reducing the risk of crop failures associated with climate change ²⁰.

7.2 Resource Efficiency:

SCP production is characterized by its resource efficiency. Microorganisms can utilize a variety of substrates, including agricultural waste, food processing residues, and even industrial by-products, to produce protein-rich biomass. This approach not only reduces waste but also minimizes the reliance on conventional agricultural inputs ²³. The water footprint of SCP is notably lower than that of traditional crops; while agricultural practices may require approximately 1,800 liters of water per kilogram of crop produced, SCP cultivation in closed bioreactors exhibits negligible water loss due to evaporation and runoff. Additionally, SCP production can be optimized through advanced fermentation techniques that enhance yield and reduce energy consumption ²⁴.



7.3 Potential for Circular Economy Integration:

SCP has substantial potential for integration into a circular economy framework. By utilizing waste materials as substrates for microbial growth, SCP production contributes to waste valorization, transforming what would otherwise be discarded into valuable protein sources. This process aligns with sustainability goals by promoting resource recovery and reducing environmental degradation associated with waste disposal. Furthermore, SCP can be produced using innovative methods such as autotrophic growth, where microorganisms utilize carbon dioxide (CO₂) and renewable energy sources like electricity or light to generate biomass. This not only enhances sustainability but also supports efforts to mitigate climate change by capturing atmospheric CO₂ ²⁵.

8. Future Prospects of Single Cell Proteins (SCPs) in Nutraceuticals

Advances in genomics and nutrigenomics may enable SCPs to be tailored to individual nutritional needs. Customized SCP-based products can address specific deficiencies or metabolic requirements, enhancing their appeal in the personalized nutrition market. SCP production can utilize waste streams, such as agricultural residues, industrial by-products, or CO₂, contributing to a circular economy. With an increasing global focus on sustainability, SCPs could become a cornerstone for eco-friendly nutraceutical manufacturing.

Genetic engineering and synthetic biology can be employed to enhance the nutritional profile of SCPs, such as increasing essential amino acid content, or to introduce functional properties like antioxidant, anti-inflammatory, or probiotic activity. SCPs can be integrated into functional foods and beverages, enhancing their nutritional value and creating novel products targeting health-conscious consumers. Applications could include protein-enriched drinks, bars, and dairy alternatives.

SCPs hold promise for addressing protein deficiencies and malnutrition, particularly in resource-limited settings. Their rapid production cycle, minimal resource requirements, and high nutritional value make them ideal for large-scale deployment in food aid programs.

SCPs can complement plant-based and cultured meat products, providing additional protein and enhancing the sensory and nutritional profiles of these alternative food categories. This integration could drive innovation in the nutraceutical sector. Emerging technologies, such as bioreactor optimization and fermentation process innovations, could reduce SCP production costs, making them more accessible for mass-market nutraceutical applications.

Increased consumer awareness about the environmental and health benefits of SCPs will drive their adoption. Strategic marketing, education campaigns, and collaborations with food industry giants will further promote SCPs in the nutraceutical sector. Continued exploration of diverse microorganisms, including

extremophiles and genetically modified strains, can unlock new SCP sources with unique nutritional and functional properties.

9. CONCLUSION

The review paper sheds light on the significant promise inherent in single-cell proteins (SCPs) as nutraceuticals and also shows their multifaceted potential in the realm of nutrition and health. SCPs rise as a sustainable and effective source to address the issues surrounding food security, environmental preservation, and the growing global need for nutrient-rich proteins and essential elements. When the world grappling with climate change and resource scarcity challenges, SCPs emerge as a promising solution to minimize the environmental impact of food production.

Despite the immense potential of SCP, challenges remain in terms of consumer acceptance, regulatory approval, and scaling up production to meet worldwide demands. Collaborative efforts among researchers, policymakers, and industry stakeholders to establish safety standards, improve production efficiency, and raise awareness about the benefits of SCPs as nutraceuticals are needed to tackle the discussed challenges. As research in the field of SCP is expected to evolve contentiously, SCPs are expected to play a crucial role in ensuring a more sustainable and healthier future for both the planet and human beings. SCPs have the potential to transform the way we approach nutrition and food security with ongoing innovation and investment in the research area of SCP. It also offers a brighter and more sustainable outlook for future generations.

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