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Single Cell Protein for Secrecy of Animal and Vegetal Protein Demand

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ABSTRACT

In the world, there is a lack of animal and plant protein, derived from environmental problems such as; the reduction of agricultural and livestock production areas, combined with the problem of global warming, and lack of water. An old but useful option, to solve this acute problem, is global demand of at all levels: humans, farm animals, livestock, fish farming, and domestic pets. It is the exploitation of microbial potential: microscopic algae, actinomycetes, bacteria, fungi and yeasts, that contain protein of nutritional value, for any of these groups, which also have the advantage, of using a wide range of waste substrates: of origin: agricultural harvest, organic fraction of urban solid, dairy industry, tequila and mezcal, food and fishing industry, etc. It requires a relatively low production cost, and minimal negative environmental impact, to convert it into a single-cell protein or SCP, that can replace its analogue, in diets for humans, domestic animals and farm. SCP was the answer to the protein shortage, in the 1950s and 1960s. Therefore, the objective of this brief review is to show the advantages of SCP synthesis, as a sustainable food option that encompasses humans and animals.

From this perspective, the biomass used for the production of biofuels, sustainable energy, bioplastics, etc. It is also useful for the growth of microorganisms as a SCP, rich in protein of nutritional quality. An analysis was carried out. Shown some of the most possible sources of waste, for the production of SCP, the quality of this protein, the diversity of production systems. As well as the inconveniences to eliminate nucleic acids, due to microbial growth, that limit the widespread substitution as SCP, by animal or vegetable protein in diets of all types. Including economic value of the SCP, compared to conventional ones. It is concluded that based on the current problems in agricultural, livestock, and fishing production, as well as the limitation of natural resources and environmental pollution, for the selection of microorganisms and carbon waste sources, of potential for SCP generation, as well as the alternatives of production systems, with methods to eliminate nucleic acids, and other drawbacks, that can be solved to consider, it a current protein option of nutritional quality for present worldwide demand.

Keywords: Food; Global Warming; Water Crisis; Limits on Agricultural and Livestock Production; Microbial Diversity

Introduction

As global food demand continues, to increase and faces resource constraints, exploring alternatives, for new and different unconventional protein sources, has become crucial (Ahmad, et al. [1]). It is estimated that by 2050, the world population will exceed 9 billion people, and based on current consumption trends, 1,250 million tons of meat and dairy, will need to be produced annually, to satisfy the global demand for source of animal or vegetal proteins, that is why the introduction of microorganisms, as a single cell protein (SCP), as tool for solving this acute problem, has opened new possibilities, terms of cost production and world benefit (Ahmad, et al. [1]). The SCP is a sustainable solution, to food challenges in a world, that is constantly changing and growing (Bajić, et al. [2]). For SCP to be effective, it must meet the nutritional requirements for animal feed and potentially human food, including appropriate protein content, a balanced amino acid composition, and good protein digestibility (Linder [3]). The quality protein obtained as a SCP, is possible from: algae (Amorin, et

al. [4]), bacteria, actinomycetes, fungi and yeast, that are cultured in fermentation to produce SCP (Forero-Ararat, et al. [5,6]).

SCP offer a solution, to this problem in quality an amount of protein production. These organisms, often overlooked compared, to conventional protein sources, such as animals and plants, with advantages in terms of efficiency in resource use, flexibility in cultivation methods, and apply to diet nutrition for all types (Chen, et al. [7,8]). It is important to consider that, the production of SCP depends, on multiple factors: chemical composition of culture media, carbon source or type substrate to oxidate, its concentration, way to add during fermentation process, growth factor, minerals salts, besides pH, agitation, oxygen supply, temperature, foam control, genetic characteristics, geographic region, environmental conditions, usually are difficult, because in holistic way these factors, are limiting of the quality and quantity of SCP (Keshav, et al. [9,10]), to the desired product as protein substitute in animal or human diets (Zepeda, et al. [11]). That is why, for its production in laboratory environments, it involves the careful selection and manipulation of microorganisms, as well as the optimization of small-scale culture conditions, where production in bioreactors stands out, that guarantees product uniformity and high yields, since it does not compete with pests and weeds (Aggelopoulosm, et al. [12]).

This process is crucial to understanding and perfecting techniques, before scaling production to industrial levels. In turn, at an industrial level, the production of SCP involves, the implementation of advanced technologies and large-scale cultivation systems (Muys, et al. [13]), there efficiency and profitability are sought, through the optimization of processes, the selection of high-performance microorganisms, and the use of diverse substrates, kind of organic waste generated mainly by the food sector (Onyeaka, et al. [6]). This conversion of waste to food, not only reduces waste and pollution, but also ensures, that the growing demand for food, by the world's population, regard to use SCP with minimal carbon footprint one the most important facts related to greenhouse gases and global warming due to agriculture and meat production by livestock (Bhatia, et al. [14]). SCP is also gaining interest in various food sectors: meat analogs, bakery, supplements, dairy alternatives, cereals, snacks, and beverages (Razzaq, et al. [15]). Thus, the industrial production of SCP stands out, for its ability to provide a sustainable, and economically viable source of protein, overcoming limitations associated with conventional agriculture (Abodunde [16]). In this sense, bacteria have the ability to grow rapidly and use a wide range of carbon source, however, bacteria have high contents of nucleic acids, that are toxic to human health, caused high concentrations of uric acid in the plasma, as a consequences formation kidney stones and gout (Okafor [17,18]).

Algae, on the other hand, offer exceptional nutritional benefits, and are positioned as a sustainable option for protein production, especially, at a time when aquaculture is looking for alternatives to fishmeal (Ribeiro, et al. [10]). Particularly noteworthy is SCP, and its application in aquafeed production, driven by the growing demand for affordable protein feeds in the aquaculture industry (Gundupalli, et al. [19]) Fungi and yeasts also play a crucial role in single-cell protein production, taking advantage of their rapid growth, ability to ferment various substrates, and their versatility in cultivation processes. These microorganisms have been the subject of numerous studies to understand and improve their performance as protein sources (Onyeaka, et al. [6]). One of the distinctive characteristics of the microorganisms to produce SCP, are able to grow in controlled culture conditions, regardless of climatic or geographical limiting factor (Al-Farsi, et al. [20]). This point does not depend environmental fluctuations, providing a constant, and predictable source of protein, compared to these from of plant, and animal, as a conventional agriculture and livestock production (Ahmed, et al. [21]). This review compiles recent advances, focused on SCP production, at laboratory and industrial scales, while emphasizing new types of applications of microbial biomass. Therefore, the objective of this brief review is, to show the advantages of SCP synthesis, as a sustainable food option, that encompasses humans and animals (Onyeaka, et al. [6]).

Origin of Single Cell Protein

All types of SCP are regard to dead and dried, microbial cells or total protein extracted, from pure microbial culture of unicellular algae, cyanobacteria, actinomycetes, bacteria, filamentous fungi, and yeast grown on different carbon sources, used as protein component for human or animal feed (Thiviya, et al. [22,23]). Production of SCP is highly efficient in terms of resource use, since these microorganisms can use diverse waste substrates, such as organic compounds or products from other industries as well as tequila and mezcal, food and fishing industry, etc growth. Compared to soy (38.60%), fish (17.80%), meat (21.20%), and whole milk (3.28%), microbial single-cell protein (SCP) offers higher production efficiency and requires less land, making it an attractive alternative (Xu, et al. [24]). In addition to high protein content, SCP contains a high relative amount of protein, which could reach 60–82% on a dry weight basis, essential amino acids. In terms of analysis of types of amino acids of these proteins, are rich in essential types such as lysine, threonine and methionine, limited in most plant and animal foods (Suman, et al. [25-28]). Since lysine and methionine concentration, are a limited in most plant and animal sources. Other nutritional components, are carbohydrates, fat, vitamins, and mineral (Wild, et al. [29-31]), SCP also contains fats, carbohydrates, nucleic acids, vitamins and minerals. the SCP origin is recognized for its bioavailability and digestibility, which makes it suitable for food and nutritional applications (Hanhart, et al. [32]). Production of SCP can occur in two ways; solid-state fermentation, which occurs with minimal free water, enhances the nutritional value of feed by breaking down proteins into bioavailable fragments, degrading antinutrient factors, and providing important nutrients, probiotics and their metabolites, while submerged fermentation, characterized by its short time and high efficiency, requires the degradation

of cellulose and hemicellulose into simple sugars for SCP production, with success dependent on the culture medium and environmental conditions (Zhang, et al. [33]) (Table 1).

Table 1: Average percentage composition on a dry basis of the main microorganisms used as a single cell protein.

Components	Fungus filamentous	Microalgae	Yeasts	Bacteria
Protein	30-50	6-62	45-55	50-65
Fat	2-8	3-45	1-6	1-3
Ashes	9-14	8-43	5-10	3-7
Nucleic acids	7-10	3-8	6-15	8-12
Amino acids	--	--	54	65

Note: (Ahmad, et al. [1]).

Microbial Genera for Single-Cell Protein

Among the most studied microorganisms for producing SCP, fungi and algae stand out, because they are a rich source of protein, they normally content 40% of crude protein as a dry weight (Patias, et al. [34]). And its production depends on several factors, as well as: simple sugars, polysaccharides, organic acids, fatty acids, hydrocarbons, lignin, including CO2 and other related (Onyeaka, et al. [6]). In order for microorganisms to use sugars as a carbon source, they need them to be pretreated. Pretreatment significantly enhances the recovery of fermentable sugars from straw biomass, increasing it from around 20% to 80%–83%, and facilitates the enzymatic and microbial conversion of the biomass into valuable sugars like glucose, galactose, xylose, and arabinose (Singhvi, et al. [35,36]). The use of microorganisms for the production of SCP, has a fundamental role, in the food industry, of current biotechnological approaches. In that sense, "Generally Recognized as Safe" (GRAS) microorganisms, for human consumption, facilitate its implementation, in various applications ranging from animal feed, to protein substitutes (Patias, et al. [34,37,38]).

Research on the applications of SCP, has revolutionized the challenges, of sustainable production. of new foods, as well as efficiency, in the exploitation of natural resources. Microorganisms to generate SCP are useful in the exploitation of organic waste of all types (Barka & Blecker, et al. [7,21,39]). In other way, currently, several industries have begun producing single-cell protein (SCP) products such as UniProtein from methane, Pro DG from methane, JUV from methanol, and FeedKind® from methane. These products are commercially manufactured by companies including Unibio (Lyngby, Denmark), String Bio (Bangalore, India), KnipBio (Lowell, MA), Calysta (Menlo Park, CA), White Dog Labs (USA), Circe Biotechnologie (Austria), RichMore® (Beijing Shoulang Bioscience and Technology Company), and Clostridium autoethanogenum protein (CAP) (Gundupalli, et al. [19]) (Table 2).

Table 2: Sources of single-cell protein and current application.

Type of microorganisms	Genus and species of microorganisms	Substrate	Application	Production level	References
Fungi	*Cladosporium cladosporioides, Aspergillus ochraceus, Aspergillus niger, Aspergillus flavus, Penicillium citrinum, Monascus ruber, Fusarium semitectum*	Potato dextrose	Improved the composition of the rice bran.	Research – Pilot scale	(Ganado, et al. [98])
Microalgae	*Dunaliella salina*	CO_2	Improved the nutritional quality of pasta.	Research – Pilot scale	(El-Baz, et al. [61])
Yeast	*Saccharomyces cerevisiae*	White grape juice	Biomarker for the occurrence of gushing in sparkling wine	Research –Pilot scale	(Kupfer, et al. [70])
Fungi	*Botrytis cinerea*	White grape juice	Biomarker for the occurrence of gushing in sparkling wine	Research – Pilot scale	(Kupfer, et al. [70])
Microalgae	*Dunaliella salina*	CO_2	Improved ovarian follicle development, plasma metabolites and hormone concentration in goats	Research- Large scale	(Senosy, et al. [91])
Bacteria	*Methylorubrum extorquen*	Methanol	Protein source for use in aquafeeds	Research- Pilot scale	Tlusty, et al. [97])
Fungi	*Aspergillus oryzae* and *Trichoderma koningii*	Orange waste	Recycling agricultural waste into valuable materials	Research - Pilot scale	Zhou, et al. [102])
Yeast	*Kluyveromyces lactis* and *Rhodotorula graminis*	Waste milk	Vitamin-enriched feed production and waste milk treatment.	Research - Pilot scale	Myint, et al. [78])

Cyanobacteria and microalgae	*Arthrospira platensis* (spirulina), Chlorella vulgaris, Tetraselmis chui,* and *Nannochloropsis oceanica*	Lipids Proteins of cyanobacteria* microalgae	Development of High-Protein Vegetable Cream	Research - Pilot scale	(Boukid, et al. [59])
Bacteria	*Methylococcus capsulatus*	Methane	Growth performance, carcass traits and gut health of broiler chickens.	Company- Large scale	(Hombegowda, et al. [67])
Yeast	*Cyberlindnera jadinii, Blastobotrys adeninivorans* and *Wickerhamomyces anomalus*	Hydrolysates of pretreated wood and chicken and turkeys cut offs	Nutrient digestibility of yeast in Atlantic salmon	Research - Large scale	Agboola, et al. [56])
Bacteria	*Methylococcus capsulatus*	Methane	Replacement for fish meal in the diets of Pacific white shrimp (*Penaeus vannamei*)	Company- Large scale	(Felix, et al. [62])
Bacteria	*Methylococcus capsulatus, Alcaligenes acidovorans, Bacillus brevis* and *B. firmus*	Methane	Diets of newly weaned piglet	Research - Large scale	(Hedemann, et al. [66])
Yeast	*Pichia pastoris*	Methanol	Economical production	Industrial – Pilot scale	(Meng, et al. [73])
Bacteria	*Clostridium autoethanogenum*	Carbon monoxide from Steel-making waste gas and ammonia	Feed utilization, growth, and intestinal histology of largemouth bass (*Micropterus salmoides*)	Research – Pilot scale	(Yang, et al. [100])
Bacteria	Methylococcus capsulatus (Bath)	Methane	Alleviates soybean meal-induced enteritis in spotted seabass (*Lateolabrax maculatus*)	Company- Large scale	(Zhang, et al. [101])
Bacteria	*Bacillus cereus*	Sago liquid waste and chicken egg white	Capsule beads	Research – Pilot scale	Mukramin [77]

Microalgae and Cyanobacteria

Algae, mostly belonging to the protista kingdom, are photosynthetic organisms as a procariot, that live in water or in humid environments. This group also includes prokaryotic cell as well as cyanobacteria (Tibbetts, et al. [40-42]). Algae are generally classified into two types i.e., macroalgae and microalgae. Macroalgae are of three types: brown, red and green whereas microalgae are majorly classified into four main types which are diatoms, green (Tibbetts, et al. [40]). Microalgal protein content and amino acid profile depend strongly on the species, and culture conditions (Muys, et al. [13,38]) it show in Table 3. But, the cellulose cell wall, that represents about 10% of the algal dry matter, it is resistence to digest enzimatic, for utilizing the algal biomass, due its chemical composition based, in polysaccharids that are not digestible for humans, and other non-ruminants. Pretreatment is essential for extracting this microbial protein, as it improves the accessibility to enzymes, that break down cellulose and hemicellulose into fermentable sugars (Meenakshisundaram, et al. [43]).

Table 3: Percent (%) of main chemical compounds of the most microalgae and cyanobacteria* used to produce single cell protein.

Genus and species of microalgae and cyanobacteria	Crude protein	Carbohidrate	Lipid	Fiber	Ash	Reference
Chlorella vulgaris	55–77	6-10	25.2	4-6	5	(Tibbetts, et al. [40]; Muys, et al. [13])
Arthrospira platensis*	60–71	11-29	15	9-17	7-8	(Tibbetts, et al. [40]; Muys, et al. [13])
Nannochloropsis granulata	18-33	12-30	20 - 50	-	6-7	(Tibbetts, et al. [40]; Wild, et al.[29])
Tetraselmis suecia	18-40	6-36	22-30	10-17	14-15	(Niccolai, et al. [37])
Tetraselmis chuii	35–40	40-50	18-22	-	14-17	(Tibbetts, et al. [40]; Anjos, et al. [41])

In Microalgae process to remove cell wall, involves several advantageous changes to the biomass, as like is increased specific surface area and porosity, structural alterations, lignin removal, hemicellulose depolymerization, and a reduction in cellulose crystallinity (Meenakshisundaram, et al. [43]). Hence, effective chemical treatments are necessary, to disrupt the cell wall to release the protein, and other chemical compounds, accessible for digestive enzymes. The digestibility of microalgae can be greatly increased by drying at high temperature under certain conditions (Wild, et al. [29,37]). However, the heat treatment needed to increase the digestibility of the cells, also affects the protein quality, and other compounds valuable of the cell wall (Muys, et al.[13]). Its chemical composition is closely related to the environment, where microalgae and cyanobacteria grow, so under laboratory conditions, the protein could be free of different toxic agents (Anjos, et al. [41]). For the industrial production of microalgae, ponds are used, in which the microbial culture is agitated, using a paddle wheel in a photobioreactor (PBR), an advantage of making the most of the availability of light, for these photoautotrophic microbes, are: temperature control, that generates high biomass yield, low harvest cost, minimal pollution, an automated process for the optimization of solar energy and temperature (Huarachi-Olivera, et al. [44]).

More than 75% of the annual microalgal biomass production, is used for the manufacture of powders, tablets, capsules, or pills (Anjos, et al. [41]). There has been an increase in the utilization of algae for SCP production, due to algal biomass contains proteins in high concentrations, with an amino acid profile composition, that compares well to protein found in conventional sources, such as soy, eggs, milk, fish or beef (Tibbetts, et al. [40]). However have cellulosic cell walls, that are not digested by human beings (Onyeaka, et al. [6]). Despite the benefits of microalgae cultivation, conditions to optimze its production, still has many problems to solve. For example, the low biomass production and the small size of cells, when microalgae are cultured in liquid medium, since harvesting process of microalgae is spencil (Tan, et al. [45]). However, extraction of high-quality protein from microalgae, remains a technological challenge due to: i) limited protein availability caused by the rigid cell wall, ii) the high concentration of anionic or nonpolar polysaccharides and iii) inherent problems linked to protein stability (Anjos, et al. [41]). Currently, a variety of cell disruption technologies, have been used for microalgae: bead milling, high-pressure, ultrasonication, microwave, pulse electric field, cavitation, thermal and chemical disruption methods, or alternatively integration of several methods, also strong acids, aqueous solvents, and surfactants, increase the permeability of the cell wall, and alkaline treatments, have most frequently been used, for microalgae cell disruption, and protein solubilization (Anjos, et al. [41]). However, based on the cost of production, nutritional value, ease of production and new methods to destroy cell walls, the future could change sooner than expected for animal feed at least (Anjos, et al. [41]) (Table 4).

Table 4: Microalgae, cyanobacteria*, substrates and percent yield obtained by single cell protein production.

Genus and species of microalgae and cyanobacteria	Substrate	Yield (%)	References
Porphyridium cruentum	CO_2	88	(Safi, et al. [86])
**Arthrospira platensis*	CO_2	41.75	(Safi, et al. [86])
**Spirulina sp.*	CO_2	59.9	(Tibbetts, et al. [40])
Chlorella sp.	Tofu waste	52.24	(Putri, et al. [82])
Tetraselmis chuii	CO_2	27	(Anjos, et al. [41])
**Spirulina platensis*	Beet filter cake extract	52.54	(Saad, et al. [84])
Chlorella sorokiniana	CO_2	52.5	(Sägesser, et al. [87])
Auxenochlorella protothecoides	CO_2	44.3	(Sägesser, et al. [87])
Chlorella vulgaris	CO_2	25.1	(Sägesser, et al. [87])

Fungi

The biological kingdom of fungi is made up of different species whose natural habitat is water, soil and decomposing organic remains. Fungi are aerobic heterotrophic, cosmopolitan, multicellular or unicellular eukaryotic organisms. Usually, fungal shape can vary from dense spherical granules to slimy mycelia. Fungi could be strict or facultative aerobes, and grow in a wide range of temperature 2 - 50°C, including pH from 1 to 8 (Azam, et al. [46]). The production of SCP from fungi, is due its high protein content, with essential amino acids for nutritional demands of humans and animals, besides a high proportion of vitamins and lipids (Ahlborn, et al. [1,6,47]). Most fungi are nutritionally undemanding, have rapid synthesis and reproduce in very basic mediums able to use single sugars, as well as polysaccharides, hydrocarbons, lignin and many other organic carbon as a only source of carbon and energy, able to grow with inorganic nitrogen salts or organic compounds of nitrogen: peptones, amino acids, urea, etc, minimal amounts of metals as a minerals salts: iron (Fe), magesium (Mg), potassium (K) zinc (Zn) , copper (Cu), magnesium (Mn) and molybdenum (Mo) (Hashem, et al. [6,48-50]. However, it has been shown that the resulting morphology and protein production, is strongly influenced by chemical composition and culture media system; energy input through stirring, aeration, mass transfer characteristics, pH value, osmolality and the presence of solid microparticles (Hashempour-Baltork, et al. [51,52]) (Table 5).

Table 5: Substrates used by microscopic fungi to produce single-cell protein and its yield.

Genus and species of	Substrate	Yield (%)	Reference
Aspergillus flavus	Rice bran	11.5	(Valentino, et al. [63])
Fusarium venenatum	Date Waste	65.3	Reihani & Khosravi-Darani, [83]
Aspergillus niger	Banana peel	61.23	(Kamal, et al.[69])
Trichoderma viride	Pineapple extract with potassium nitrate	20.31	(Anichebe, et al. [57])
Trichoderma viride	Banana peel extract with sodium nitrite	27.72	(Anichebe, et al. [57])

For SCP synthesis, the mycoprotein derived from Fusarium graminearum produced by Ranks Hovis McDougall that was grown in molasses or glucose, the fungi cells undergo heat treatment, to reduce RNA content, and the resulting mycelium is separated, using vacuum filtration, and can be further processed, to achieve suitable food textures. Recently, research has focused on producing and characterizing vegetative mycelia from fungi to enhance its protein content and develop meat alternatives for human consumption (Schweiggert-Weisz, et al. [53]). Another example of a SCP, produced with excellent quality standards, is the Quorn brand mycoprotein, that uses the fungus F. venenatum in the fermentation process, considered safe by the USA Food and Drug Administration (Hashempour-Baltork, et al. [1,51]). The approval of Quorn as a novel food shows that certain fungal-based SCPs, like mycoprotein, may not always require novel food regulation approval, especially if these proteins have a history of safe use and can demonstrate safety for human and animals consumption (Whittaker, et al. [54]).

Yeasts

Yeasts, unicellular prokaryotic microorganisms belong to the kingdom Fungi, that reproduce by budding or fission (Ahmad, et al. [1,21]). The majority of yeasts are mesophilic, a wide range growth temperature between 14 and 48ºC, the optimal growth temperatures is 20 °C – 34 °C (Azam, et al. [46]). For optimal growth, most yeasts tolerate a pH range between 3 and 10, but prefer a slightly acidic medium with a pH of 4.5 to 6.5. From a nutritional viewpoint, nucleic acids content in SCP, is one of the main factors hindering its utilization as food. Excessive intakes can lead to uric acid precipitation, causing human health disorders, such as gout or kidney stone formation (Okafor [17]). Under these conditions, yeasts have extraordinary potential to be used as a valuable source of proteins, essential amino acids and other nutrients (Forero-Ararat, et al. [5]). However, many yeast-based protein supplements lack sufficient sulfated amino acids, especially methionine, that limits its use as a primary protein source (Zhang, et al. [33]). Production of SCP involves the use of bioproducts or unconventional substrates, such as organic waste, and its versatility allows to adapt to different growing conditions, and facilitates its implementation on both a laboratory and industrial scale (Forero-Ararat, et al. [5]).

Besides, yeast offers several benefits, like has larger size, that makes it easier to harvest, high lysine content, and also able to thrive in acidic environments. Current literature reports several studies on alternative proteins by fermentation with S. cerevisiae (Aggelopoulosm, et al. [12,55,49]). A research by Pinzón-Fajardo & Hurtado-Nery in 2021 for the synthesis of SCP and S. cerevisae, in rice chaff as a source of nutrients, for feeding pigs, demonstrated up to a 10% increase, in its performance increasing amount of amino acids. For exajemple in aquaculture, the production of fishmeal, is becoming unsustainable, due to high costs, and the unsustainable action, caused by overexploitation in fishing. An alternative of solution is protein inputs, are being sought to replace fishmeal, which characteristics must be, that it is sustainable and low cost, however, the SCP of Candida utilis, Kluyveromyces marxianus and Sacharomyces cerevisae, reveals a high protein content of 30 to 50%, and high contents of nutrients and essential amino acids, that fit FAO standards. In this sense, the application of yeast biomass, in the preparation of animal feed replaces, the expensive ingredients currently used, improving the economy of the concentrates produced. This approach is a comprehensive and promising solution, to global food and environmental challenges (Gervasi, et al. [5,49]).

Substrate for Single Cell Protein

In Table 6 showed the primsary substrates used for SCP synthesis, are rich in mono and disaccharides, used as a carbon and energy sources. This preference arises because nearly all microorganisms possess the ability to metabolize glucose, along with other hexose and pentose sugars, as well as disaccharides. But, microorganisms can utilize a variety of substrate including an inorganic type like CO2, agricultural wastes and effluents, industrial wastes, biogas, ethanol natural gas like methane, n-alkanes etc; that also help in decomposing (Bajić, et al. [2]). Furthermore, the versatility in production and the ability to use diverse substrates, as well as organic waste, contribute to its sustainability and waste reduction. Other potential substrates for SCP include bagasse, citrus wastes, sulphite waste liquor, molasses, animal manure, whey, starch, sewage, molasses soybean, brewery residues, etc. Because its nutritional composition, similar or higher to conventional flours, provides essential amino acids and essential nutrients (Perez-Velazquez, et al. [56-102]). Therefore, it stands out for its advantages demonstrating efficiency, in the use of resources, lower environmental impact, and flexibility in growing conditions. This approach not only addresses problems, such as overfishing or the limitation of fertile agricultural soil, but also responds to the growing global demand for protein (Bajić, et al. [2]).

Table 6: Yeast and filamentous fungy, substrates and fermentation condition for single cell protein production.

Genus and species of yeast and filamentous fungi	Type of fermentation	Substrate	Protein concentration obtained percentage (%/g/L*)	Reference
Yeast				
Saccharomyces cerevisiae and *Kluyveromyces marxianus*	Solid state fermentation	Cheese whey and molasses	38.50%	(Aggelopoulosm, et al. [12])
Hanseniaspora uvarum KKUY-0084 and *Zygosaccharomyces rouxii KKUY-0157*	Submerged fermentation	Juice of spoiled	23.50%	(Hashem, et al. [47])
Kluyveromyces marxianus	Submerged fermentation	Cheese whey	4.5*	(Yadav, et al. [99])
Saccharomyces cerevisiae,	Submerged fermentation	Pineapple waste	15	(Akalya, et al. [54])
Saccharomyces cerevisiae	Submerged fermentation	Blend of Apples, Pears, Bananas, Strawberries, Cauliflower, Zucchini, Pepper and Molasses.	39.80%	(Gervasi, et al. [48])
Candida utilis ATCC 9950	Submerged fermentation	Potato waste water	12.2	(Kurcz, et al. [71])
Saccharomyces cerevisiae	Solid	Orange peel	1.02%	(Milala, et al. [74])
Palmyrah toddy	Submerged	Papaya	43.10%	(Rajendran, et al. [26])
Saccharomyces cerevisiae	Submerged	Pineapple peel juice, and rice washing water	0.289	(Mujdalipah & Putri [76])
Candida utilis	Submerged	Orange peel residues	6.22%	(Carranza-Méndez, et al. [60])
Saccharomyces cerevisiae	Submerged	Waste Molasses	47.34%	(Bahtiar et al. [58])
Candida sorboxylosa	Submerged	Coffe wastewater	64.4%	(Pillaca Pullo, et al. [80])
Filamentous fungi				
Fusarium venenatum	Solid state fermentation	Cane and brown sugar	49.99%	(Thomas, et al. [96])
Aspergillus niger	Submerged fermentation	Orange, pineapple, banana, watermelon and cucumber waste	0.57	(Oshoma & Eguakun-Owie [79])
Pleurotus sapidus	Submerged fermentation	Apple pomace	25.40%	(Ahlborn, et al. [46])
Neurospora intermedia	Solid state fermentation	Wheat and whole meal bread waste	33%	(Gmoser, et al. [64])
Rhizopus oligosporus	Submerged	Food waste-derived volatile fatty acids	39.28%	(Wainaina, et al. [30])
Rhizopus oligosporus	Submerged	Potato peels	5.452	(Tahir, et al. [95])
Bacteria				
Purple phototrophic bacteria	Submerged	Domestic wastewater	65%	(Hülsen, et al. [68])
Rhodococcus opacus DSM 1069	Fermentation	Orange waste	56.90%	(Mahan, et al. [72])
Rhodococcus opacus PD630	Fermentation	Lemon peel	45.80%	(Mahan, et al. [72])
Rhodopseudomonas faecalis PA2	Submerged fermentation	Domestic wastewater	64.80%	(Saejung & Ampornpat [85])

Methane Oxidizing Bacteria	Submerged	Methane	75%	(Goonesekera, et al.[65])
Purple non-sulfur bacteria (PNSB)	Submerged	Fuel synthesis wastewater	44.70%	(Shaikh, et al.[92])
Methy organophilum lobacterium	Submerged	Methanol	54.10%	(Simões, et al.[93])
Microalgae				
Chlorella sp.	Submerged fermentation	Tofu whey	52.32%	(Putri, et al. [82])
Aspergillus niger	Solid	Rice straw pulp	18.90%	(Said, et al. [88])
Trichoderma reesei	Solid	Rice straw, bagasse, and coffee husk	22%	(Said, et al. [89])
Chlorella sorokiniana	Submerged fermentation	Rice bran extract	81%	(Pruksasri, et al. [27])
Dunaliella salina	Submerged fermentation	CO_2	0.35	(Sui, et al. [94])
Galdieria sulphuraria	Submerged fermentation	CO_2	44%	(Montene-gro-Herrera, et al. [75])

Note: (Ribeiro, et al. [10]).

Future Perspectives

Single cell proteins play a central role in nearly every biological process, as well as maintaining structure, transporting molecules, promoting cell growth and attachment, transmitting signals inside cells, and catalyzing biochemical reactions. The widespread adoption of SCP processes, globally has increased propelled the progress, of modern biotechnology and spurred the creation, of new technical solutions, as well as wastewater treatment, alcohol production, enzyme technology, and nutritional science. SCP shows potential to address protein demand, under wide diversity of conditions. Although some producing microorganisms are multicellular, the efficiency and sustainability of SCP production, surpasses conventional agriculture. Processes such as the preparation of the culture medium, fermentation, extraction and yield of SCP, and its processing for food additives, show the viability and future relevance of SCP in feeding to solve World´s need to appropriated humans and animals causing no polluting problems during the process.

Conclusion

Since world's population constantly growing, and projections of the inability of conventional agriculture, to satisfy the food needs of the future, more collaborative research activities, are needed to increase food production by SCP, as it is not only option as an efficient source of nutrition, but also provides opportunities for innovation in the food industry for humans and all types animals. The versatility and short replication times of the microorganisms used, in the production of single-cell protein, has allowed us to explore various sources of nutrients, and substrates for the generating of SCP. This practice not only contributes to the reduction of pollution associated with these wastes, but also transforms materials previously considered pollution, into valuable resources from economic, nutritional and industrial perspectives for sustainable economy, health environmental that avoids greenhouse gases production and global warming.

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Conflicts of Interest

The authors declare no conflicts of interest.

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