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Single cell protein production from waste biomass: review of various agricultural by-products

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Abstract. Agricultural waste constitutes for most of the manmade waste streams. Processing of biodegradable waste materials ensures the treatment of harmful substances and allows to reduce environmental pollution. In addition, conversion of these waste materials in value-added products makes these recycling methods more economically viable. Single-cell protein is one of the value-added products that can be produced by microbial fermentation of waste materials. In this review various biodegradable agricultural by-products as substrates for production of SCP are categorized and compared.

Key words: single cell protein, waste biomass, agricultural by-products, resource availability, aquaculture, fish feed, fish meal.

INTRODUCTION

The recycling of biodegradable waste into environmentally harmless compounds is one of the bases for waste management. However, simply treating biodegradable waste is no longer considered efficient waste management practice. Depending on the type of waste used, nowadays it is possible to produce a range of value added products that make waste management not only an environmentally friendly endeavour, but also a promising business activity. However, a large proportion of biodegradable waste is currently being processed into products with a relatively low added value, such as biogas (Kost et al., 2013), bioenergy and biofuels (Lipinsky, 1981; Browne et al., 2011). Thanks to the development of various waste recycling technologies, an increasing number of technological solutions are emerging today that provide the opportunity to extract high value-added products such as enzymes (El-Bakry et al., 2015), single-cell oil (Finco et al., 2016), building block chemicals (Werpy & Petersen, 2004; FitzPatrick et al., 2010) and others. One such high-value added product is single-cell protein (SCP).

SCPs are known as dietary single-cell microorganisms whose biomass or protein extracts are derived from pure or mixed microscopic algae, yeasts, mushrooms or bacterial cultures (Anupama & Ravindra, 2000). These microorganisms can be used as protein-rich foods or food ingredients or dietary supplements (Ritala et al., 2017), but they are mainly used as food for human and animal consumption (Ugalde & Castrillo, 2002). SCPs are a good alternative to replacing protein of agricultural origin, since SCP production is not characterized by high water consumption (Mekonnen & Howkstra, 2014), it does not cover large areas of land, does not endanger environmental diversity (Tilman, 1999), does not contribute to climate change and does not produce high greenhouse gas emissions (Vermeulen et al., 2012), as it is the case with agriculture.

To reduce the cost of production of SCP, it is essential to use biodegradable agroindustrial by-products and waste as a source of nutrients for the cultivation of microorganisms. In this context, currently known agricultural waste products suitable for the cultivation of microorganisms synthesizing SCP will be reviewed and compared. Industrial wastes applicable for SCP production will be compared in another review.

In other reviews (Anupama & Ravindra, 2000; Nasseri et al., 2011; Ritala et al., 2017), which summarize the reported findings on the waste products suitable for the cultivation of SCP producing microorganisms, information mainly focuses on the used microorganisms (fungi, bacteria, algae, etc.) and not so much on the properties of the waste products themselves. However, nowadays, for both research and industrial applications, access to various strains of microorganisms is relatively simple, but availability of waste products is very specific for every local economy. Consequently, in order to further facilitate the finding of the most suitable waste products, this review seeks to categorize and describe waste products suitable for the production of SCP.

WASTE TYPES

Finco et al. (2016) described the most suitable waste products for the production of single-cell oils and divided them into four groups: mono and disaccharide-rich waste products; starch rich waste products; glycerol-rich waste products; lignocellulose-rich waste products. This distribution was used as bases for the division of four groups of agricultural wastes. The proposed agricultural waste groups for SCP production are: Mono and disaccharide rich sources; Starch rich sources; Structural polysaccharides rich sources; Protein or lipid rich sources (Fig. 1).

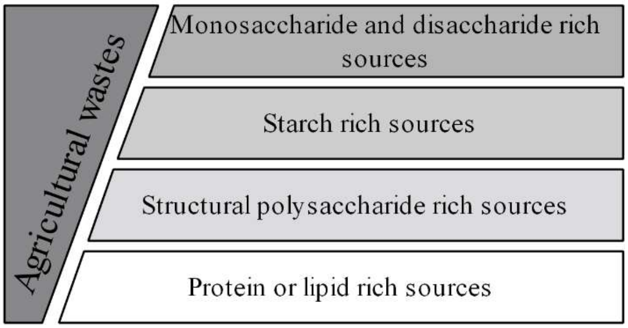

Figure 1. Categorization of agricultural wastes applicable for cultivation of SCP producing microorganisms.

COMPARISION OF WASTE RESOURCES

Monosaccharides and disaccharides rich sources

Monosaccharides and disaccharides rich sources such as molasses, dairy (lactose rich) and fruit processing wastes can be directly processed by microorganisms with good

SCP yields. Consequently, this waste group requires much less pre-treatment prior to its use in the cultivation of microorganisms, which significantly reduces the overall SCP production costs.

Molasses

Molasses is a rich source of carbohydrates suitable for the cultivation of various microorganisms without the need for pre-treatment of the waste material (Kopsahelis et al., 2007; Aggelopoulos et al., 2014). Molasses are mainly a by-product of the production of sugar from sugar cane and sugar beet or by-product from soy protein concentrate production. From all potential sources soy molasses, a by-product of soy protein concentrate (SPC) production, has become more accessible in recent years due to rapid increase in the production of SPC (Deak & Johnson, 2006; Gao et al., 2012). Depending on the extraction method, plant species and plant age, molasses usually contain about 45–60% fermentable carbohydrates, 10% nitrogen compounds, 20% fat and 10% minerals (Kinney, 2003; Gao et al., 2012). The use of molasses in SCP production is determined by its availability, price, composition, and whether it contains impurities of fermentation inhibitors and toxic compounds that could be transferred from culture medium to the final SCP product (Bekatorou et al., 2006; Aggelopoulos et al., 2014).

Dairy waste

Whey and other dairy wastes have high levels of chemical oxygen demand (COD) and biological oxygen demand (BOD), as well as high concentrations of oils and fats and nitrogen and phosphorus compounds (Braio & Taveres, 2007; Singh et al., 2011), which can lead to ecological problems if such wastes enter local environments without prior treatment. From cheese production alone, the global dairy industry generates around 139 million tonnes of whey every year (Ghaly et al., 2007; Yadav et al., 2013; Yadav et al., 2014), of which about 50% are simply dumped in sewage systems or in local water bodies (Ghaly et al., 2007; Yadav et al., 2014). Consequently, the dairy industry needs to develop effective solutions for the processing of whey and other waste products, in order to remove organic and nitrogen compounds from the wastes. Depending on the technology used in milk processing, dairy waste can have high levels of either lactose or protein (Kim & Lebeault, 1981; Singh et al., 2011; Aggelopoulos et al., 2014), therefore whey can be categorized as monosaccharides and disaccharides rich source or protein or lipid rich source (see Tables 1, 4). If dairy waste is high in lactose, these by-products can be used as suitable substrate for SCP production using microorganisms capable of fermenting lactose (Singh et al., 2011).

Fruit waste (simple sugar rich)

The content of fruit processing waste is highly dependent on the type of fruit and the part of the fruit that forms the main mass of the waste. If the waste is mainly whole fruit, then a large amount of monosaccharides and disaccharides will be available in the waste, as it is in the case with banana wastes, where 5 to 30% of harvested bananas are discarded as waste due to export regulations (Baldensperger et al., 1985). A similar situation exists for figs where, due to incorrect transport, storage and market changes, large quantities of figs are not realized, and they need to be disposed of when they begin to deteriorate (Hashem et al., 2014).

Table 1. Monosaccharides and disaccharides rich sources. Recent reports of protein content (% of biomass after fermentation) from mono and disaccharide rich wastes

Mono and disaccharides rich sources	Microorganisms	Protein content (%)	References
Molasses	*Kluyveromyces marxianus*	50.5	Anderson et al., 1988
Soy molasses	*Candida tropicalis*	56.4	Gao et al., 2012
Sugarcane juice	*Phaffia rhodozyma*	-	Fontana et al., 1996
Whey (lactose rich)	*Penicillium cycloplum*	54	Kim & Lebeault, 1981
Cheese whey	*Kluyveromyces marxianus, Candida krusei*	43.4	Yadav et al., 2014
	kefir microorganisms	53.9	Paraskevopoulou et al., 2003
Cheese whey filtrate	*Trichoderma harzianum*	34.2	Sisman et al., 2013
Banana wastes	*Aspergillus niger*	18	Baldensperger et al., 1985
Spoiled date palm fruits	*Hanseniaspora uvarum, Zygosaccharomyces rouxii*	48.9	Hashem et al., 2014

Table 2. Starch rich sources. Recent reports of protein content (% of biomass after fermentation) from starch rich wastes

Starch rich sources	Microorganisms	Protein content (%)	References
Sorghum hydrolysate	*Candida krusei*	47.5	Konlani et al., 1996
Wheat bran	*Rhodopseudomonas gelatinosa*	66.7	Shipman et al., 1975
Rice bran	*Aspergillus flavus*	11.5	Valentino et al. 2016
Starch hydrolysate	*Fusarium graminearum*	-	Anupama & Ravindra, 2000
Starch	*Schwanniomyces alluvius*	52.8	Calleja et al., 1986
	Schwanniomyces occidentali	-	Deibel et al., 1988
Leaf juice	*Saccharomyces cerevisiae*	45.6	Chanda & Chakrabarti, 1996
	Torula utilis	54.3	
	Candida lipolytica	50.5	

If fruit processing waste mainly consists of outer and inner shells, peels and seeds, as it is the case with juice producing wastes (Bhalla & Joshi, 1994; Scerra et al., 1999; De Gregorio et al., 2002), then there will be more fibres and hence the waste can be categorized as structural polysaccharides rich sources (see subsection 3.3.4. and Table 3).

Starch rich sources

Starch rich waste products, such as grains and tuber residues, account for a large proportion of agricultural waste. Starch rich substrates need to be hydrolysed to monosaccharides prior to use them in cultivation, which may increase the cost of production of SCP, if microorganisms that are capable of dissolving and metabolising starch are not used in fermentation. However, expenses can be reduced if associative fermentation is ensured, where amylolytic microorganisms with SCP synthesizing microorganisms are used in tandem (Calleja et al., 1986; Deibel et al., 1988). In this way amylolytic microorganisms digest starch and provide SCP producing microorganisms with the simple carbohydrates they require.

Bran

Bran is a by-product of grain processing, which is commonly used in oil extraction, animal feed or as a food additive (Hanmoungjai et al., 2000; Valentino et al., 2016). In general, all types of grain bran have a high content of starch, fibre and protein (Shipman et al., 1975; Konlani et al., 1996) and bran is also a good source for lipids, iron, vitamin B, phenolic acid, phytosterol and antioxidants (Godber & Juliano, 2004; Kahlon, 2009; Valentino et al., 2016). Consequently, bran should be used as a substrate for SCP production only if it is not possible or it is economically unprofitable to use bran in animal or human consumption.

If bran is deoiled, then during this process starch content in the bran is significantly reduced, which leaves only proteins and fibres in the by-product (Revinder et al., 2003); therefore, use of starch fermenting microorganisms in deoiled bran is no longer effective and it is necessary to use cellulolytic microorganisms instead (see Table 3).

Table 3. Structural polysaccharides rich sources (agricultural waste). Recent reports of protein content (% of biomass after fermentation) from structural polysaccharides rich wastes

Structural polysaccharides rich sources	Microorganisms	Protein content (%)	References
Corn cobs	*Aspergillus niger*	30.4	Singh et al., 1991
Maize stalk Cotton stalk	*Aspergillus niger,* *Sporotrichum pulverulentum*	-	Anupama & Ravindra, 2000
Wheat straw	*Pleurotus florida*	62.8	Ahmadi et al., 2010
Rice bran (deoiled)	*Aspergillus oryzae*	57	Revinder et al., 2003
Soy bean hull	*Bacillus subtilis*	12.3	Wongputtisin et al., 2014
Potato starch processing waste (cellulose rich)	*Bacillus licheniformis*	38.2	Liu et al., 2014
	Bacillus pumilus, Candida utilis, Aspergillus niger	46.1	Liu et al., 2013
Sugarcane bagasse	*Pleurotus eryngii*	-	Zadrazil & Puniya, 1995
	Candida tropicalis	31.3	Pessoa et al., 1996
Beet-pulp	*Trichoderma reesei, Kluyveromyces marxianus*	54	Ghanem, 1992
Apple pomace	*Aspergillus niger*	20	Bhalla & Joshi, 1994
Citrus pulp (pectin rich)	*Trichoderma viride*	31.9	De Gregorio et al., 2002
Citrus fruit peel	*Penicillium roquefort*	5.7	Scerra et al., 1999
Poltry manure (fibre rich)	*Pseudomonas fluorescens*	59.1	Shuler et al., 1979
Poultry litter (fibre rich)	*Candida utilis*	29	Jalasutram et al., 2013
Brewery's spent grains hemicellulosic hydrolysate	*Debaryomyces hansenii*	31.8	Duarte et al., 2008
Pawn shell waste	*Candida species*	70.4	Rhishipal & Philip, 1998
	Pichia kudriavzevii	40	Revah-Moiseev & Carroad, 1981

Leaf juice

Deproteinized leaf juice (DIJ) is a vegetable protein production by-product from leaf juice. This waste product has high COD and BOD and low pH levels. Consequently, DIJ discharges without prior treatment can cause damage to the environment (Chanda et al. 1984; Pirie 1987; Chanda & Chakrabarti, 1996). Thus, microbiological pre-treatment of DIJ is desirable and in combination with SCP production, this treatment may also serve as a good business perspective, since SCP yields reported so far on using DIJ as substrate are high (see Table 2). The amount of starch and other substances in DIJ are affected mostly by used plant species and applied extraction methods for production of vegetable protein. The starch content in leaves of legumes, peas and beans (*Papilionoideae* family) is high (Pirie, 1987), but in general, other carbohydrates (both monosaccharides and polysaccharides), amino acids, fats, vitamins and minerals are found in the DIJ as well (Pirie, 1987; Chanda & Chakrabarti, 1996; Choi & Chung, 2003).

Structural polysaccharides rich sources (agricultural waste)

Lignocellulosic agricultural waste is the most widely available waste in the world. According to the International Grains Council, in 2015, 737 million tonnes of wheat, 984 million tonnes of maize and 474 million tonnes of rice (IGC, 2018) were harvested globally. Rice, wheat and corn straw-to-grain ratio varies from 0.7 to 1.7 (Skidmore, 1988; Nelson, 2002; NLA, 2013), which means that straw and stover volumes are usually equal or greater than actual produced grain volumes. This alone indicates that cereal straws are available in enormous quantities in virtually all regions of the world where crops are grown. Consequently, the use of these residues in the production of SCP is highly desirable, both economically and ecologically. However, the use of lignocellulosic agricultural waste is much more complicated than using starch or simple sugar-rich waste because lignocellulose is more difficult to process, and lignocellulosic substrates need to be subjected to extensive mechanical and chemical or biochemical pre-treatments, which greatly increase the total cost of production.

Lignocellulose essentially consists of 30–56% cellulose, 3–30% lignin, 10–24% hemicellulose and 3–7.2% protein, but its applicability, for example in animal feed, is limited due to low digestibility and low protein content (Ahmadi et al., 2010).

In order to reduce the costs associated with the use of straw, researchers have explored the possibilities of using cellulolytic microorganisms that are able to delignify and ferment lignocellulose-rich waste materials (Singh et al., 1991; Valmaseda et al., 1991; Vares et al., 1995; Agosin et al., 1999; Ahmadi et al., 2010; Brijwani & Vadlani, 2011).

Soybean hull

Soybean hull (SBH) is an agricultural by-product from the extraction of soybean oil and production of soybean meal (Zervas et al., 1998). SBH accounts for about 8–10% of the total soybean mass (Wongputtisin et al., 2014), and given the fact that around 350 million tonnes of soybeans (IGC, 2018) are harvested annually globally, then the amount of available SBH is significant. In small amounts, SBH is used to regulate the protein content of soy bean meal used as animal feed (Wongputtisin et al., 2014). SBH is suitable and also used as a source of fibre for ruminants, but unprocessed SBH cannot be used as feed for monogastric animals as they cannot digest cellulose and hemicellulose compounds (Zervas et al., 1998). In general, SBH contains about 36% fibres, about 12% protein and 3% fat (Wongputtisin et al., 2014). So far, SBH fermentation studies have succeeded in increasing simple sugar and protein content and reducing fibre concentrations, but the overall increase in protein concentration has been relatively small (Wongputtisin et al., 2014).

Starch and sugar processing waste

Similarly, as for other previously described by-products, also liquid wastes from starch and sugar production have high COD and BOD values, therefore these wastewaters have potential of being harmful to environment if released into natural water bodies (Lettinga et al., 1980; Frostell, 1983; Rajeshwari et al., 2000). Environmentally friendly starch and sugar refineries are too expensive; therefore, they need to be combined with the production of other products (Cibis et al., 2006; Krzywonos et al., 2009; Lasik et al., 2010; Lui et al., 2014). Multiple studies have been carried out on the use of potato starch processing residues using microbial fermentation in the production of biologically active compounds and animal feeds (Suzuki et al 2010; Wang et al 2010; Lui et al., 2013; Lui et al., 2014). Studies have also been carried out on how to obtain high-quality SCP from sugarcane bagasse and beet pulp (Ghanem, 1992; Zadrazil & Puniya, 1995; Pessoa et al., 1996). Additionally, sugarcane bagasse and beet and potato pulp can be used in limited amounts as feed additive for ruminants (Zadrazil & Puniya, 1995; Wang et al., 2010). Despite being a by-product of starch or sugar processing, potato starch processing waste, sugarcane bagasse and sugar beet pulp itself are low in starch and sugar and other non-structural carbohydrates, but high in energy and fibre. These residues, similarly as cereal straws, contain large amounts of cellulose and hemicellulose, which is the reason why potato, sugarcane and sugar beet wastes need to be pre-treated before SCP producing fermentation stage. Fermentation process can be divided in two stages, where in the first stage cellulolytic microorganisms are used for pre-treatment of the substrate and SCP synthesizing microorganisms are used in the second stage (Ghanem, 1992; Lui et al., 2013; Lui et al., 2014). By doing so it is possible to ensure a good SCP yields, while at the same time limiting the pollution created by sugar and starch industries.

Fruit waste (fibre rich)

Similarly, as for sugar and starch production waste, also fruit processing residues can be used as feed for cattle, however, this is often not possible, or the transportation of the residues is too expensive (Bhalla & Joshi, 1994; Scerra et al., 1999; De Gregorio et al., 2002). Consequently, in order to reduce the production costs, usually the waste from fruit processing is simply discarded (Upadhyay & Sohi 1988, De Gregorio et al., 2002). Mainly dietary fibre rich fruit processing wastes come from juice and essential oil production factories (De Gregorio et al., 2002). Pomace and juice pulps make up to about 25 to 65% of the total fruit volume used for juicing (Walter & Sherman, 1976; Bhalla & Joshi, 1994; Scerra et al., 1999). Considering that about 25% of the harvested fruits are used in industrial processing (Bhalla & Joshi, 1994), the global annual amount of pomace and juice pulp produced from apples and citrus fruits is estimated at around 15 million tonnes (FAO, 2018a). From a nutritional point of view, fruit remnants are not suitable for monogastric animal feeds because of their low digestibility and low protein content (Bhalla & Joshi, 1994). Due to the large amount of generated waste and the limited use of it, researchers have looked at ways to improve the nutritional value of fibrous fruit wastes by using them as substrates for the production of SCP (Bhalla & Joshi, 1994; Scerra et al., 1999; De Gregorio et al., 2002; Aggelopoulos et al., 2014).

Poultry waste

Disposal of poultry waste has always been problematic because of the price of this waste is too low to be used as a cost-effective fertilizer, and its direct use without destroying pathogens is potentially dangerous for public health (Shuler et al., 1979; Jalasutram et al., 2013). Consequently, SCP production is a good alternative to the processing of poultry wastes because of the relatively high concentrations of micro and macroelements and the high composition of organic compounds compared with other animal wastes (Mitchell & Tub, 2003; Stanely et al., 2004; Kargi et al., 2005; Jalasutram et al., 2013). In general, poultry waste has a high content of nitrogen compounds (5–7% of which 60–70% is uric acid nitrogen, 10–15% is protein nitrogen, 10% is ammonia nitrogen) (Shuler et al., 1979) and fibre, thus appropriate pre-treatment needs to be performed, which hydrolyses polysaccharides and eliminates potential pathogens (Jalasutram et al., 2013). Microorganisms such as *Candida*, *Saccharomyces* and *Rhodotorula spp*. are suitable for the conversion of nitrogen-rich materials into SCP (El-Deek et al., 2009; Jalasutram et al., 2013).

Spent grains

The composition of brewery's spent grains (BSG) can be very different from one beverage plant to the other, and the composition can also vary within a single production unit, depending on which type of beverage is being brewed at that moment (Duarte et al., 2008). Consequently, before using the BSG in the fermentation of microorganisms, it is necessary to find out the concentrations of simple sugars, polysaccharides and proteins in order to choose the most suitable pre-treatments and microorganisms. Usually BSG has high concentration of hemicellulose, lignin and proteins (Duarte et al., 2008), and BSG can be rich in various minerals and vitamins (Mussatto et al., 2006), which makes BSG a potentially complete culture for the cultivation of microorganisms. By hydrolysing BSG, it is possible to significantly increase the concentrations of simple sugars such as xylose and glucose (Duarte et al., 2008).

Pawn shell waste

According to FAO, in 2015, crustacean production from aquaculture and wild capture was 13.9 million tonnes (FAO, 2018b), of which 70–80% constitutes as processing waste (Mauldin & Szabo, 1975; Anderson et al., 1978; Revah-Moiseev & Carroad, 1981). Consequently, the amount of crustacean processing waste is huge. Those wastes that cannot be fed to aquaculture or farm animals are simply dumped into the ocean, burned or landfilled (Revah-Moiseev & Carroad, 1981). These are generally environmentally unfriendly solutions, that considerably increase overall production expenses due to transportation of the waste materials (Kreag & Smith, 1975). In crustacean processing waste chitin content ranges from 13–27% of the dry mass (Ashford et al., 1977; Revah-Moiseev & Carroad, 1981). Chitin is a structural polysaccharide that is a glucose derivate. The high concentration of chitin in crustacean waste limits its options for recycling if economically sound and environmentally friendly operation principles are considered (Revah-Moiseev & Carroad, 1981). Hydrolysis of chitin results in the production of carbohydrates available to SCP synthesizing microorganisms, therefore it is possible to utilize the already developed enzymatic lignocellulose hydrolysis technologies for pre-treating of crustacean processing wastes (Revah-Moiseev & Carroad, 1981). By using hydrolysed crustacean waste as source of nutrients for SCP production, it is possible to obtain very high protein concentrations in microbial biomass (Rhishipal & Philip, 1998).

Protein or lipid rich sources

By using protein-rich waste products in the production of SCP, it is possible to obtain very high protein concentrations in the final biomass (Table 4). In order to break down the fibrous protein compounds in the waste, they need to be hydrolysed using enzymes from proteolytic microorganisms. The hydrolysis of proteins usually complicates and raises the cost of the SCP production. If it is possible to hydrolyse the waste products by providing associative fermentations (Atalo & Gashe, 1993), then protein-rich waste products can become one of the most suitable waste products for the production of SCP due to their high protein yields.

Wastewaters (protein rich)

Protein rich wastewaters usually have high levels of COD and BOD, therefore expensive waste treatment is required to ensure that it will not cause serious pollution (Kam et al., 2012).

Stickwater

Stickwater is a liquid by-product from fish feed production (Kam et al., 2012). The volume of fish feed production has been relatively constant since the 1980s (6–7 million tonnes a year) (Stickney & McVey, 2002). In comparison, soybean protein production, which produces soy whey wastewater as by-product, has increased in production volumes more than 4-fold in the same time period (Wang et al., 2013; FAO, 2018a). Therefore, there has been no ecological or economical pressure to look for solutions to stickwater treatment and the use of stickwater in the production of SCP was first described relatively recently (Kam et al., 2012). In general, stickwater, as a substrate, can provide high protein concentrations in microbial biomass (Kam et al., 2012). Stickwater has high concentrations of protein, phosphorus and calcium (Kam et al., 2012).

Waste liquor from glutamic acid factory

Approximately 4 tonnes of wastewater are produced from each tonne of L-glutamate (Chiou et al., 2001). Around 1.5 million tons of L-glutamate per year are produced globally (Perosa & Zecchini, 2007), therefore L-glutamate industry generates a huge amount of wastewaters. Solid particles of the waste liquor are rich in protein (around 20%) (Chiou et al., 2001), and therefore this by-product can be used in pig and ruminant nutrition (Yang & Lee, 1982; Chen et al., 1983). However, so far studies on the use of L-glutamate production wastes in animal nutrition have shown that the use of these wastes should be limited in order to avoid metabolic disorders (Yang & Lee, 1982; Chen et al., 1983). Therefore, use of glutamic acid rich wastewaters in SCP production is a promising alternative that can improve the nutritional quality of the waste products and treat created wastewaters at the same time.

Waste capsicum powder

Paprika oleoresin is a natural pigment that is usually obtained from plants of *Capsicum* genus (Uquiche et al., 2004). This pigment is widely used in the food industry and annually around 1,400 tonnes of paprika oleoresin are produced globally (Buckenhusks, 2001; Topuz & Ozdemir, 2003). Waste capsicum powder is a by-product of pigment extraction (Zhao et al., 2010). Approximately 98.6% of the used peppers turn into wastes during pigment extraction (Zhao et al., 2010). Waste capsicum powder contains capsaicin (Perva-Uzunalic et al., 2004), which is irritant for mammals that produces a sensation of burning, therefore, while waste capsicum powder has high protein content, it is not usable as additive in animal feeds and is usually simply dumped in landfills (Zhao et al., 2010). In recent studies, waste capsicum powder has shown good protein yields after fermentation (Zhao et al., 2010).

Slaughterhouse waste

Horns, feathers, nails and hair make up large part of the waste products from slaughterhouses (Lehninger, 1975; Baden & Kubilus., 1983; Dalev, 1990). These fibrous protein rich wastes are suitable for bioconversion using proteolytic microorganisms, which can produce protein or amino acid concentrates (Atalo & Gashe, 1993). For example, ram horns are rich in cysteine and other amino acids (Kurbanoglu & Algur 2002), and by using ram horn hydrolysate as a medium for SCP production it is possible to obtain very high protein concentrations in microbial biomass (Kurbanoglu & Algur 2002) (see Table 4). This suggests that slaughterhouse waste products are a very promising raw material for the production of SCP.

Table 4. Protein or lipid rich sources. Recent reports of protein content (% of biomass after fermentation) from protein or lipid rich wastes

Protein or lipid rich sources	Microorganisms	Protein content (%)	References
Stickwater	*Aspergillus niger*	48.7	Kam et al., 2012
	Lactobacillus acidophilus	68.4	
Glutamic acid waste liquor	*Aspergillus niger*	50.2	Chiou et al., 2001
Waste capsicum powder	*Candida utilis*	48.2	Zhao et al., 2010
Combined agricultural waste (mostly protein rich)	*Saccharomyces cerevisiae*	38.5	Aggelopoulos et al., 2014
	Kluyveromyces marxianus	33.7	
	Kefir microorganisms	23.6	
Ram horn	*Escherichia coli*	66	Kurbanoglu & Algur, 2002
	Bacillus cereus	68	
	Bacillus subtilis	71	
Soy bean meal	*Bacillus subtilis*	-	Wongputtisin et al., 2012

Soybean meal

Soybean meal (SBM) is one of the most widely used sources of protein for farm animals. SBM is a by-product of soybean oil extraction and contains about 50% proteins, 35% carbohydrates and 2% fat, as well as various minerals (Wongputtisin et al., 2007). SBM can be with and without shell, and as we previously discussed, soy bean hull is polysaccharide rich soy processing by-products that can be used with SBM to regulate its protein concentration (Wongputtisin et al., 2012). SBM fermentation greatly improves its nutritional value, increases feed conversion ratios and neutralize compounds that are not desirable in animal feeds (Feng et al., 2007; Wongputtisin et al., 2012).

Combined agricultural wastes

A good approach to waste utilization for SCP production is combination of different wastes. In this way it is possible to ensure that the medium contains all nutrients and elements necessary for the cultivation of microorganisms. Aggelopoulos et al. (2014) managed to produce good SCP yields by using a combination of agricultural waste feedstocks containing simple sugars-rich molasses, fibre-rich orange and potato pulps, and protein-rich brewer's spent grains, whey and malt spent rootlets.

CONCLUSIONS

In this review, most of the agricultural wastes that can be used in the production of SCP have been categorized and discussed more closely. Each agricultural waste group has its own advantages and disadvantages if used as substrate for SCP production.

Monosaccharides and disaccharides rich sources require minimal pre-treatment, which give these wastes distinct technological and economical advantage over other waste types, since simpler bioreactor designs can be used, and no sophisticated pre-treatment processes are required.

Fermentation of polysaccharides, protein or lipid rich sources improve the overall digestibility of these by-products, which makes them more applicable as animal feeds. More extensive pre-treatment of these wastes can result in higher SCP yields, but cost effectiveness of applied pre-treatments needs to be considered in order to justify the expenses.

Structural polysaccharides rich wastes are available in huge quantities all over the world; therefore, using these wastes have limited competition with other industries which use waste as resource for production of other value-added products. In comparison, competition over monosaccharides, disaccharides and starch rich sources is greater, since those wastes are not so abundant and are more easily used. If other waste types have limited local availability and efficient and economically reasonable pre-treatment process can be used for hydrolysis, structural polysaccharides rich wastes can be used extensively for production of SCP.

In general, the key considerations for choosing the most suitable waste product for SCP production are: (1) local availability of the particular waste product; (2) pre-treatment costs of the waste product before using it in fermentation; (3) the costs of transportation of the waste product; (4) SCP concentrations in the final microbial biomass after fermentation.

In the future, it is also necessary to thoroughly review and compare the different industrial wastes in regard to their use as substrates for SCP production.

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