Algorithm of multi-criterion green process assessment for renewable raw materials bioconversion

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ABSTRACT

Green Chemistry is one of the most important and practically used tools to integrate principles of sustainable development and green economy in the field of chemistry and the chemical industry in various countries. There is a number of metrics in the field of green chemistry. The research presented is an original algorithm of multi-criterion green process assessment for renewable raw materials bioconversion. The algorithm is used when the process of obtaining the same target substance N is possible to be carried out in many ways (or under different conditions). In this case, the researcher task is to choose the best process in compliance with the principles of green chemistry. The multiple-factor complex assessment is to be used to choose the optimum process conditions. The algorithm designed was tested for efficiency in choosing the optimal processes of acid hydrolysis of deproteinized meals. The deproteinized sunflower meal preprocessing efficiency analysis was carried out during the course of its microbiological conversion into a vegetable protein and carbohydrate feed supplement taking into account the principles of green chemistry. The methodology testing was based on the experimental data obtained by chemical hydrolysis of deproteinized residues, and two-stage pretreatment process of deproteinized residues processing comprising the steps of chemical and enzymatic hydrolysis. The combination of chemical and enzymatic hydrolysis in two-stage deproteinized sunflower meal processing was justified. The proposed algorithm allowed not only to determine the effective ranges of parameters of deproteinized sunflower meal processing, but also allowed to justify the possibility of its optimization due to the both processes combined.

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1. Introduction

The impact of human activities on the environment is becoming a major socio-political problem throughout the world affecting both public policy and consumer choices. The chemical industry on the one hand has been traditionally considered one of the main sources of negative environmental impact for decades (Massey et al., 2012) and on the other hand it is considered one of the most important tools for solving environmental problems and sustainable development of society (Anastas, 2011) as mentioned in the XXI century agenda by the United Nations Conference on Environment and development (UNCED, 1992).

Developing countries have also begun to pass “green” policies (Mackey et al., 2012). Green Chemistry (Tundo et al., 2000) is one of the most important and practically used tools to integrate principles of sustainable development and green economy in the field of chemistry and the chemical industry in various countries, such as the USA (Nameroff et al., 2004), India (Chanshetti, 2014), Japan (Fujii, 2016), Russian Federation (Tarasova et al., 2010), the countries of Africa (Jumbam, 2015) and all. However, introduction of the green chemistry concept into practice depends on the availability of methods allowing to quantify the “greenness” of the process and to compare them with each other.

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There are a number of metrics in the field of green chemistry (Constable et al., 2002). These metrics are concerned with risk assessment of chemicals (Čuček et al., 2012) use of appropriate methodologies for assessing chemical footprints (Sala and Goralczyk, 2013), assess waste through the E-factor (kg/kg) (Anastas and Eghbali, 2010), the use of water and energy (NSF International, 2011) and many others (Lapkin and Constable, 2008). Mass intensity (MI) related to E-factor with ratio MI–1 = E and calculated as the ratio of the total mass of all the initial materials, solvents and other auxiliary substances used in the process to the weight of the target product (Curzons et al., 2001) is proposed to measure in addition to the E-factor. Eco-innovation compass (Fussler, 1996) is used to evaluate simultaneously multiple parameters (Brown et al., 2000). But all these methods are not adapted to the green process assessment for renewable raw materials bioconversion.

Obtaining chemicals using biotechnology is considered as one of the directions of green chemistry (Philp et al., 2013); in particular, white biotechnology aimed at the production of chemical substances that are supplements for food is considered as catalytic processes where enzymes and microorganisms act as catalysts. The green advantages of biocatalysis are obvious for both agricultural (Sheldon, 2017) and food biotechnology (Tao and Kazlauskas, 2011). The transition from an unsustainable economy to a bio-based economy (Sheldon, 2017) and renewable bio-based feedstocks as the basis for successful implementation of a new sustainable approach to manufacturing chemicals (Burk and Van Dien, 2016) are along with environmental and social pressures key drivers that provide the impetus towards green and renewable technologies for sustainable development (Singh, 2017). Valorization of waste lignocellulosic biomass is the key to sustainable production of chemicals, liquid fuels and polymers in the long term (Sheldon, 2016). The applications of enzymatic technology in the sustainable production and processing of textiles is emerging (Shahid et al., 2016).

It should be noted that the use of biotechnology in many countries seems to be a key element of bioeconomy (Philp, 2014). The state coordination “Complex programme of Development of Biotechnology in the Russian Federation until 2020 “BIO 2020” has been adopted by the Chairman of the Russian Government (№ 1853п-P8), April 4, 2012. The programme covers all the activities in this direction.

Low-waste and resource-saving technologies for the production of food products is one of the priorities in biotechnology development in the Russian Federation. Vegetable raw materials and waste products of its processing are the raw materials for products enriched with microbial protein. Animal protein deficiency in human diets of the people in Russian Federation, Asia, Africa, and Latin America is a known problem. More dietary protein will be needed to eliminate this deficit (Smil, 2002). The “BIO 2020” programme covers oilseeds secondary products processing for fodder additives enriched with microbial protein.

Sunflower seed protein is one of the most undervalued vegetable protein. The sunflower oil extraction with organic solvents such as hexane is followed by protein isolation from deoiled sunflower meal (SFM). Sustainable sunflower meal processing (Weisz et al., 2010) is based on extraction of protein with mild alkali (O’Connor, 1971) or acid solutions (Pickardt et al., 2009). Integrated sunflower meal processing (Baurin, 2014) is the part of sunflower seeds utilization. It includes enzyme assisted alkaline extraction of protein and considers utilization of both liquid residues and solid deproteinized sunflower meal (DSFM). Regardless of the isolation method the residue generated is not considered as a valuable raw material for further processing. DSFM is reach in crude fiber (McKee and Latner, 2000) and in line with sunflower hull flour is used as a dietary fiber supplement (Dreher and Padmanaban, 1983). Residual protein (12–24%) is insufficient for use in intensive livestock farming, except for feeding cattle. The DSFM is hydrolyzed for carbohydrates (Karetkin et al., 2014) and is converted to microbial protein via fermentation process. On the other hand it may be used to generate power by combustion at the end of the resource life cycle, but the use of biomass for energy generation does not contribute to green processes. Soybean meal is enriched by highly digestible protein and is used in food and animal feeds, principally as a protein supplement. Soybean complex processing is close to sunflower. Oil extraction is followed by protein isolation and the residue is converted to carbohydrates by acid hydrolysis. The hydrolysates obtained are used as the basic component for microbial fermentation. The processes of saccharification of plant raw materials are widely used in complex processing of vegetable raw materials.

Cellobiose complex hydrolysis for carbohydrates known as saccharification along with hydrothermal pretreatment (Cybulsk et al., 2013) acid hydrolysis and enzymatic hydrolysis (Kamireddy et al., 2012) in different combinations are widely used as a preliminary stage for fermentation processes (Khare et al., 2015) such as industrial ethanol production or lactic acid production. The E-factor calculated for the fermentative and chemical processes (Juodeikiene et al., 2015) demonstrates the low quantity of waste that is produced in biobased process.

The research presents an algorithm of multi-criterion green process assessment for renewable raw materials bioconversion. Energy consumption, the use of hazardous substances, waste generation and other aspects are taken into account equally and simultaneously. The application of this algorithm for renewable raw materials bioconversion results in selection of optimal process conditions taking into account several principles of green chemistry at the same time.

2. Methods

2.1. Algorithm of multi-criterion selection of the process parameters based on green chemistry principles

To compare the assessment of the similar processes the algorithm shown in Fig. 1 was proposed. The algorithm is used when the process of obtaining the same target substance N is possible to be carried out in many ways (or under different conditions). In this case, the researcher task is to choose the best process that satisfies the principles of green chemistry.

In the first stage of the algorithm proposed the 1 indicators i were selected to quantify the relevant processes to the principles of Green Chemistry (Anastas and Eghbali, 2010). For example, to assess compliance of the process with:

- Principle # 1, according to which it is need to minimize the generation of waste. Waste weight or mass intensity can be used as indicator i, and the value of the indicator “waste weight” must be minimal, and the value of indicator “mass intensity” must be the maximum;
- Principle # 3, according to which the use of hazardous substances should be minimized and may be used as an indicator of hazardous substances total weight;
- Principle # 6 (energy efficiency) – the total energy spent; etc.

In the second stage the factor (i-factor) characterizing the “Greenness” of n alternative process is calculated by normalizing...
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