

Review

BIOPROCESS ENGINEERING FOR CIRCULAR BIOECONOMY: MODELLING, OPTIMIZATION AND VALORISATION OF AGRO-INDUSTRIAL RESIDUES AND WASTES

DOI: 10.5937/EcoTER26012B

Bojana Bajić^{1,a*}, Damjan Vučurović^{1,b}, Siniša Dodić^{1,c}

¹ Department of Biotechnology, Faculty of Technology Novi Sad, University of Novi Sad,
Boulevard cara Lazara 1, 21 000 Novi Sad, SERBIA

^a <https://orcid.org/0000-0001-9786-2376>

^b <https://orcid.org/0000-0002-0555-6089>

^c <https://orcid.org/0000-0002-3072-0549>

Abstract

Having in mind current environmental challenges and depletion of resources, the sustainable development of bioprocesses represents an important strategy for advancing a circular, bio-based economy. The integration of biological systems and engineering principles enables the creation of production processes aligned with the principles of the circular economy. While optimizing bioprocess parameters at early stages of bioprocess development significantly enhances product yield and minimizes by-products, it also reduces waste. Optimization of process parameters, such as temperature, pH value, aeration and agitation rate, medium composition, etc., in accordance with the complex needs of the biocatalysts leads to environmentally sustainable and economically feasible production. Moreover, subsequent modelling and simulation of optimized bioprocesses enable scientists to observe and examine system behaviour through different scenarios and conditions. Bioprocess modelling and simulation serve as key tools for accelerating the transition from laboratory studies to pilot-scale and industry. The generated models follow the development of the bioprocess from its inception in the laboratory until the industrial plant start-up and validation, supplemented by data that become available as the scale increases. The integration of optimization, modelling and simulation techniques contributes to faster, more efficient bioprocess development while meeting modern sustainability and circular-economy requirements.

Keywords: bioprocess, optimization, modelling, simulation, circular bioeconomy.

INTRODUCTION

Current generation of substantial quantities of agro-industrial residues, by-products, and waste materials is the result of increasing industrialization, continuous population increase, and intensive agricultural production. Traditionally, these streams have been considered waste requiring treatment and disposal. However, contemporary concepts based on the principles of circular bioeconomy view these materials as valuable renewable resources that can be valorised into biofuels, biopolymers, enzymes, microbial proteins, biosurfactants, and other value-added bioproducts [1,2].

* baj@uns.ac.rs

Large volumes of agro-industrial residues and by-products are produced annually in agriculture and food-processing industries. When inadequately managed or discharged into the environment without safe disposal, these materials might lead to the degradation of the environment and pose risk to both human and animal health. However, considering their composition and characteristics, as well as vast amounts, they have an enormous potential to generate sustainable bioproducts. For waste material to be a useful substrate, it should be abundant, non-toxic, cheap, and able to support rapid growth and multiplication of selected microorganism [1,3,4].

The development of sustainable bioprocesses based on renewable raw materials is an important prerequisite for realizing the principles of the circular bioeconomy. In this context, modelling, optimization, simulation, process scale-up, and techno-economic analysis have a key role in improving process performance and their industrial implementation. The aim of the paper is to analyse and emphasize the significance of the optimization, modelling, and simulation of bioprocesses in the development of sustainable, efficient bioprocesses for the utilization of agro-industrial residues, by-products and wastes for production of microbial biomass, biopolymers, biofuels, and high-value bioactive products.

AGRO-INDUSTRIAL RESIDUES, BY-PRODUCTS AND WASTES AS RAW MATERIAL IN BIOTECHNOLOGICAL PRODUCTION

A considerable amount of agro-industrial waste is generated from post-harvest activities and industrial processing operations. The constant, rapid population growth has transformed food production and agro-industrial systems, and, consequently, increasing productivity and, in turn, generating vast quantities of agro-industrial residues, by-products and waste. Unless treated properly, agro-industrial waste can generate significant greenhouse gas emissions, and as a result, intensify climate change through various mechanisms. Therefore, identifying efficient and sustainable management strategies for agro-industrial residues has become a key priority in the agricultural sector, emerging as one of the most urgent environmental challenges of the 21st century [5].

Due to their biodegradable nature and composition, agro-industrial residues and byproducts, represent adequate raw materials for biotechnological production, provided they fulfil all mandatory and most supplementary requirements. As with any biotechnological production process, the producing microorganism requires balanced cultivation media to grow and produce the desired product. Many agro-industrial residues are rich in carbohydrates, proteins, lipids, minerals, and other compounds suitable for microbial growth and biotechnological production. Their utilization contributes to waste reduction, environmental protection, resource efficiency, and supports the development of sustainable bioprocesses [1,2].

In recent decades, scientists around the world have been devoted to finding solutions to reduce generated agro-industrial residues and wastes through the improvement and development of the biotechnological production of various high-value products. Numerous types of agro-industrial residues, wastes, and by-products have been successfully used to produce a variety of bioproducts.

For example, soybean molasses, spent sugar beet pulp, wheat starch intermediates, and organic municipal waste have been used as substrates for bioethanol production [6–10]. Waste glycerol, vegetable oil industry wastewaters, confectionery industry wastewaters, and winery wastewaters have been utilized for biopolymer xanthan biosynthesis [11–14]. Wheat chaff has been used as a lignocellulosic substrate for cellulase and xylanase production [15].

In order to select the appropriate raw material for biotechnological production at an industrial scale it is necessary to consider several criteria, presented on Figure 1. The key criteria for assessing suitability of agro-industrial residues, by-products and wastes as biotechnological raw materials, are including carbon content, biological availability, consistency, seasonal availability, the possibility of alternative application, local technological potential and geographical location. Additionally, figure 1 shows the classification of agro-industrial residues and by-products that can serve as raw materials for biotechnological production. The agro-industrial residues and wastes are divided into four basic groups: agricultural residues from the field (stalks and straw), residues generated during agricultural processing (corn cobs, chaff and husks), industrial residues (fruit and vegetable peels, pomace, waste oils and waste water from the food industry) and industrial by-products (molasses, whey, raw glycerol, bagasse) [2,16].

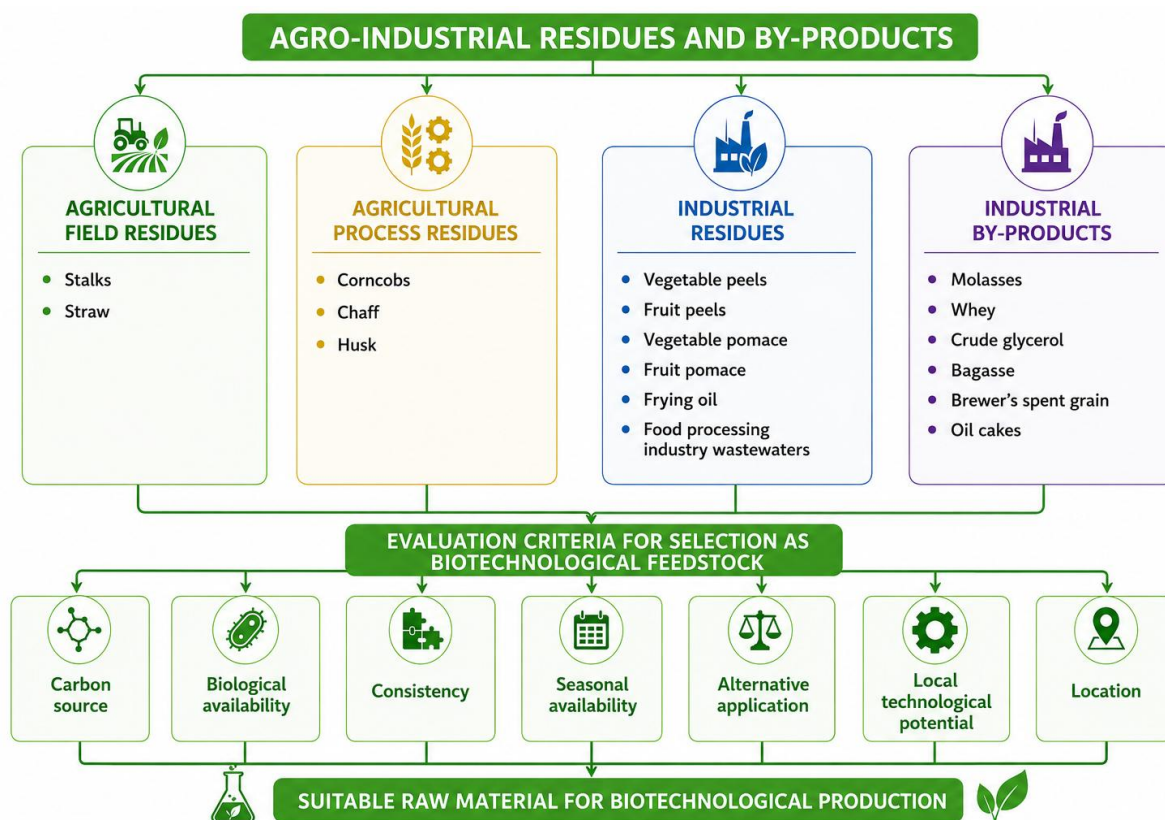


Figure 1 Classification of agro-industrial residues and by-products and criteria for their selection as raw materials for biotechnological production

OPTIMIZATION OF BIOPROCESSES FOR UTILIZATION OF AGRO-INDUSTRIAL RESIDUES, BY-PRODUCTS AND WASTES

The response surface methodology (RSM) is one of the most popular techniques for designing an experimental plan and modelling and describing interactions among many factors, which makes it particularly suitable for solving optimization problems. RSM is a statistical technique based on fundamental principles of statistics that aims to plan experiments, build empirical models, and evaluate the effects of independent variables on the desired response variable. Choosing the appropriate experimental design is a key step in applying the response surface methodology. When examining the influence of three factors on the observed bioprocess, the Box-Behnken design is most often used because it is much more efficient than other experimental designs [17–19].

Optimization of bioethanol production from soybean molasses showed that adjustment of initial sugar concentration and fermentation time significantly increased bioethanol concentration while reducing residual sugar levels [6]. In xanthan production studies, optimization of nutrient composition enabled increased xanthan yield and more efficient nutrient utilization, demonstrating the importance of medium formulation for bioprocess performance [11,13]. Agricultural residues can also serve as substrates for enzyme production. Wheat chaff was successfully utilized for simultaneous cellulase and xylanase production by *Trichoderma reesei*, while optimization of cultivation temperature, pH value, and cultivation time enhanced enzyme activities and overall process efficiency [15]. Complete bioprocess development of *Trichoderma harzianum* bioagent production included medium optimization, kinetic analysis, and economic assessment, demonstrating how optimization contributes to bioprocess development [20].

PROCESS MODELLING AND SIMULATION OF BIOPROCESSES FOR UTILIZATION OF AGRO-INDUSTRIAL RESIDUES, BY-PRODUCTS AND WASTES

When it comes to the use of modelling and simulation, they play a crucial role in the design and development of bioprocesses. They enable prediction of process performance, optimization of operational parameters, economic feasibility, and bioprocess scale-up. Additionally, modelling and simulation allow the prediction of different scenarios, and substitute experiments during the bioprocess design and development while facilitating the transition of lab- and pilot-scale systems to industrial level. Modelling involves defining a bioprocess with mathematical equations, whereas simulation refers to the solution of these mathematical equations to predict process behaviour, both improve the bioprocess understanding and help identify critical parameters in the bioprocess. SuperPro Designer is a process simulator that facilitates modelling, evaluation, and optimization of bioprocesses, and is applied for techno-economic analysis of different bioprocesses and with different raw materials. Furthermore, bioprocess simulation is a valuable tool for engineers and scientists, as it allows for the interpretation of results, analysis of the entire bioprocess, prioritization of issues, and guidance for research efforts. It also assists in identifying the most important areas for improvement as well as elimination of alternatives with little cost-effective potential [9,21–25].

Mathematical and simulation models provide detailed information regarding process performance, material flows, economic indicators, and production costs [7,9,12]. The importance of these approaches has been demonstrated in numerous studies. An example is the development of an integrated process for bioethanol and biogas production from organic municipal waste. Simulation studies showed that modelling can be used to evaluate different process scenarios, identify critical parameters, and assess economic feasibility [9]. Similarly, process and cost models developed for bioethanol production from spent sugar beet pulp enabled comprehensive analysis of capital investment, operating costs, process efficiency, and overall economic viability [7]. In research focused on bioethanol production from wheat-processing intermediates, process modelling supported evaluation of different starch hydrolysis procedures and assessment of the economic performance [8]. In addition, process modelling was successfully applied to the development of a process and economic model of xanthan gum production from confectionery industry wastewaters, demonstrating that waste-derived substrates can be successfully incorporated into economically feasible bioprocesses [12].

CONCLUSION

Bioprocess modelling and optimization plays a crucial role in the development of bioprocesses for sustainable valorisation of agro-industrial residues and wastes. Different agro-industrial residues, by-products, wastes and wastewaters, can be used as renewable raw materials for production of microbial biomass, biopolymers, biofuels, biosurfactants, enzymes, antimicrobial compounds, and other valuable bioproducts. Process modelling, optimization, and techno-economic analysis are essential tools for improving process efficiency, reducing production costs, and enabling industrial implementation of biotechnological processes. The application of statistical optimization methods and bioprocess modelling and simulation significantly contributes to development of sustainable and economically viable bioprocesses.

ACKNOWLEDGEMENT

The author is grateful to the Ministry of Science, Technological Development and Innovation of the Republic of Serbia for financial support according to the contract with registration No. 451-03-34/2026-03/ 200134.

REFERENCES

- [1] Bajić, B., Vučurović, D., Vasić, Đ., *et al.* Foods. 2023, 12(1), 107.
- [2] Vučurović, D., Bajić, B., Trivunović, Z., *et al.* Foods. 2024, 13(5), 711.
- [3] Sath, P.K., Duhan, S., Duhan, J.S. Bioresour Bioprocess. 2018, 5, 1.
- [4] Ukaegbu-Obi, K.M. J Microbiol Microb Technol. 2016, 1(1), 5.
- [5] Vigneswari, S., Noor, M.S.M., Ariffin, F., *et al.* J Renew Mater. 2026, 14(3), 6.
- [6] Rončević, Z., Bajić, B., Dodić, S., *et al.* Hem Ind. 2019, 73(1), 1–12.
- [7] Vučurović, D., Bajić, B., Vučurović, V., *et al.* Fermentation. 2022, 8(3), 114.
- [8] Katanski, A., Vučurović, V., Vučurović, D., *et al.* Fermentation. 2024, 10(3), 144.
- [9] Gegić, B., Vučurović, D., Dodić, S., *et al.* Energies. 2024, 17, 4286.

- [10] Vučurović, V., Katanski, A., Vučurović, D., *et al.* Fermentation. 2025, 11(2), 80.
- [11] Bajić, B., Vučurović, D., Dodić, S., *et al.* Chem Ind Chem Eng Q. 2017, 23(3), 329–339.
- [12] Bajić, B., Vučurović, D., Dodić, S., *et al.* J Clean Prod. 2017, 168, 169–180.
- [13] Rončević, Z., Bajić, B., Vlajkov, V., *et al.* Braz J Chem Eng. 2020, 37, 617–627.
- [14] Trivunović, Z., Mitrović, I., Puškaš, V., *et al.* J Food Process Preserv. 2021, 45, e15849.
- [15] Jovanović, M., Vučurović, D., Bajić, B., *et al.* J Serb Chem Soc. 2020, 85(2), 177–189.
- [16] Smith, J.E. Biotechnology. 4th ed. Cambridge, UK: Cambridge University Press; 2004.
- [17] Ferreira, S.L.C., Bruns, R.E., Ferreira, H.S., *et al.* Anal Chim Acta. 2007, 597(2), 179–186.
- [18] Madamba, P.S. LWT Food Sci Technol. 2002, 35, 584–592.
- [19] Esfahanian, M., Nikzad, M., Najafpour, G., *et al.* Chem Ind Chem Eng Q. 2013, 19, 241–252.
- [20] Mitrović, I., Vučurović, D., Al-Ani, L.K.T., *et al.* J Appl Microbiol. 2023, 134, lxad115.
- [21] Petrides, D., Cooney, C.L., Evans, L.B., *et al.* Comput Chem Eng. 1989, 13, 553–561.
- [22] Heinzle, E., Biwer, A.P., Cooney, C.L. Development of sustainable bioprocesses: Modeling and assessment. Hoboken (NJ): John Wiley & Sons; 2006.
- [23] Harrison, R.G., Todd, P.W., Rudge, S.R., *et al.* Bioseparations science and engineering. 2nd ed. Oxford, UK: Oxford University Press; 2015.
- [24] Canizales, L., Rojas, F., Pizzaro, C.A., *et al.* Processes. 2020, 8, 1180.
- [25] Ortiz, I., Valdez-Vazquez, I., Hernandez-Vazquez, A., *et al.* Energy Convers Manag. 2024, 306, 118319.