



An exergetically-sustainable operational condition of a photo-biohydrogen production system optimized using conventional and innovative fuzzy techniques



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ABSTRACT

The aim of the present study was to perform an exergy-based multi-objective fuzzy optimization of a continuous photobioreactor applied for biohydrogen production from syngas via the water-gas shift reaction by *Rhodospirillum rubrum*. For this purpose, the conventional and innovative fuzzy optimization techniques coupled with multilayer perceptron (MLP) neural model to optimize the main exergetic performance parameters of the photobioreactor. The MLP neural model was applied to correlate three dependent variables (rational and process exergy efficiencies and normalized exergy destruction) with two independent variables (syngas flow rate and agitation speed). The developed MLP model was then interfaced with three different multi-objective fuzzy optimization systems with independent, interdependent, and locally modified interdependent objectives. The optimization process was aimed at maximizing the rational exergy and process efficiencies, while minimizing the normalized exergy destruction, simultaneously. Generally, the innovative locally modified interdependent objectives fuzzy system showed a better optimization capabilities compared with the other two fuzzy systems. Accordingly, the optimal syngas photo-fermentation for biohydrogen production in the continuous bioreactor corresponded to the agitation speed of 383.34 rpm and syngas flow rate of 13.35 mL/min in order to achieve the normalized exergy destruction of 1.56, rational exergy efficiency of 85.65%, and process exergy efficiency of 21.66%.

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1. Introduction

In order to cope with the growing global energy demands, and to mitigate the vast greenhouse gas emissions caused by the massive use of fossil-based fuels, rapid and widespread replacement of these fuels with alternative energy carriers is crucial [1–3]. Amongst various available renewable systems, hydrogen

has been proven as a prominent sustainable energy carrier and is also expected to play a substantial role in the future of global energy trade because of its non-pollutant and carbon neutral nature [4]. Hydrogen can be produced from various renewable and non-renewable routes such as biomass conversion, steam methane reforming, water electrolysis, coal gasification, and water splitting [5,6]. Nevertheless, the majority of current hydrogen production, i.e., 96% is environmentally-unsustainable as it is carried out by using non-renewable energy resources such as natural gas, oil and coal [7]. Therefore, in order to improve the sustainability of this unique energy carrier, it is essential to use renewable energy sources instead of the fast-depleting non-renewable resources [8].

Nowadays, biological hydrogen or biohydrogen can be produced

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from various renewable routes such as artificial photosynthesis, bio-photosynthesis, biomass gasification, and photo fermentation. Among these methods, photobiological oxidation of harmful carbon monoxide through water-gas shift (WGS) reaction via anaerobic bacteria has been found as a promising method for biohydrogen production due to its unique environmental features as well as high efficiency [9,10]. Despite these advantages, in order to proceed with the commercial application of any renewable energy production routes including biohydrogen, it is still necessary to evaluate them from the sustainability and productivity perspectives through advanced engineering tools such as energy and exergy analyses. However, it has been well agreed upon that the traditional energy analysis often fails to provide necessary and useful information on the irreversibility and subsequent sustainability aspects of thermodynamic systems [11,12]. To the contrary, exergy analysis is capable of efficiently identifying the locations, types, and magnitudes of wastes and losses occurring in energy conversion systems and offering overcoming solutions [13]. It should be noted that by decreasing exergy destruction of an energy system, its environmental impacts could be extensively diminished and its sustainability index could be enhanced and vice versa [14,15].

Accordingly, exergy analysis has also been used to design and optimize various renewable hydrogen production systems to provide a more realistic view of the process from the sustainability and renewability points of view [16–19]. For instance, Simpson and Lutz [16] used exergy analysis for the performance assessment of hydrogen production via steam-methane reforming. In another survey, five different commercial- or pilot-scale gasification systems were compared from exergetic point of view [17]. Furthermore, Modarresi et al. [18] applied exergy analysis for hydrogen production from starch and sugar as well as lignocellulosic biomass fermentation via thermophilic and photo-heterotrophic bacteria. Later, Bhattacharya et al. [19] applied the exergy concept for oxygen-blown gasification system used for hydrogen production from rice straw. In a number of recent studies, Hosseini et al. [5,8] successfully applied exergy analysis to evaluate the exergetic performance parameters of photobiological hydrogen production in batch mode. Furthermore, Dadak et al. [6] applied conventional exergy and eco-exergy approaches for decision making on acetate concentration and light intensity during CO bioconversion into molecular hydrogen in a batch photobioreactor.

Complimentary to the exergetic analysis of biohydrogen production technologies is the exergetic modeling and optimization of the processes in order to improve their exergetic-based sustainability parameters. However, these routes involve various dynamic, complex, transient, and uncertain phenomena, limiting the use of phenomenological, mathematical, statistical, and analytical techniques for their successful modeling and optimization goals. Hence, the exergetic modeling and optimization of such ill-defined systems require more advanced methods with better optimization capability such as knowledge- and evolutionary-based soft-computing techniques. Amongst these methods, the fuzzy optimization technique has been found as one of the most promising techniques for solving complex optimization problems efficiently even with conflicting objectives. Moreover, modeling of such ill-structured systems in order to develop objective functions and their subsequent optimization can be successfully carried out using the biologically-inspired techniques such as artificial neural network (ANN) [20]. Amongst ANN learning algorithms introduced, easy-to-use multilayer perceptron neural model has found many applications in various disciplines due to its ability in approximating any input/output relationship [21–24].

The main objective of the present study was to find exergetically-sustainable operational conditions of a continuous

photobiological hydrogen production system through the WGS reaction by *Rhodospirillum rubrum* using the conventional and innovative fuzzy algorithms. In this regard, an MLP neural model was trained to correlate three output parameters, i.e., normalized exergy destruction, rational exergy efficiency, and process exergy efficiency with two input variables, i.e., culture agitation speed and syngas flow rate. Subsequently, the developed MLP neural model was introduced to the fuzzy algorithms in order to find the best exergetically-sustainable working conditions of the bioreactor. To the best of our knowledge, little information is currently available on the exergetic modeling and optimization of the photobiological hydrogen production systems using advanced soft-computing techniques. Therefore, photo-biohydrogen production process from syngas using *R. rubrum* at various syngas flow rates and culture agitation speeds was exergetically optimized throughout the current survey with a focus on the crucially important phase within the whole system, i.e., the photo-fermentation step in the bioreactor. In addition, an innovative fuzzy algorithm was developed herein for targeted optimization of complex biofuel synthesizing systems with respect to the productivity and renewability issues.

2. Materials and methods

2.1. Hydrogen production and analytical procedure

The detailed information on the photo-biohydrogen production in a continuous stirred tank bioreactor from syngas using the WGS reaction can be found in our previous report [9]. Briefly, a pure culture of *R. rubrum* was purchased from the American Type Culture Collection (ATCC). The microorganism was grown in an enriched ATCC medium anaerobically at 30 °C in the presence of tungsten light. The growth medium contained 2.5 g acetic acid neutralized with sodium hydroxide at pH 6.9, 1.25 g (NH₄)₂SO₄, 1 g yeast extract, 0.9 g K₂HPO₄, 0.6 g KH₂PO₄, 0.2 g MgSO₄·7H₂O, 0.07 g CaCl₂·2H₂O, 0.02 g EDTA, and 0.01 g ferric citrate. Moreover, 7.5 mL B-Vitamin solution consisting of 0.4 g thiamine HCl, 0.2 g Nicotinamide, 0.2 g nicotinic acid, and 0.008 g biotin was added into the medium. 1 mL trace metal solution elements containing 3 g ferric citrate, 0.5 g EDTA, 0.2 g CaCl₂·2H₂O, 0.02 g (NH₄)₆Mo₇O₂₄, 0.02 g MgSO₄·7H₂O, 0.01 g ZnSO₄·7H₂O, 0.01 g H₃BO₃, and 0.01 g CuSO₄·5H₂O was also added into the medium. The continuous CO photo-fermentation was carried out in a 2 L bioreactor under anaerobic conditions. The liquid media and the syngas were continually fed into the fermenter at the atmospheric pressure and 30 °C. The molar fractions of CO, H₂, Ar, and CO₂ in inflow syngas were 55%, 20%, 15%, and 10%, respectively. The photobioreactor was equipped with temperature, pH, level, and dissolved oxygen sensors. Fig. 1 schematically shows the continuous photobioreactor used for hydrogen production from syngas using *R. rubrum*. The selected control volume for exergy analysis was also shown in this figure.

The photobioreactor was purged with nitrogen in order to establish anaerobic condition. Furthermore, the lag phase was eliminated using a 5% inoculum. Two tungsten lamps (40 W) were used to supply a uniform light with an intensity of 1500 lux on the fermenter surface. A level controller was used to control the outflow stream into the effluent tank. The photo-bioreactor was continually operated during a period of two months in order to study the effect of syngas flow rate and agitation speed in the range of 5–14 mL/min and 150–500 rpm, respectively. In general, 15 different combinations of syngas flow rate and culture agitation speed were surveyed throughout this investigation. The pH was maintained at an optimum value of 6.5 by adding 0.2 M HCl and 0.2 M NaOH solutions. The continuous operation of the photobioreactor at different syngas flow rates and agitation speeds is

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