Sustainable Epoxidation of 1,5-Hexadiene in a Continuous Flow Reactor: Process Optimisation Using Response Surface Methodology

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Introduction

Alkene epoxidation is a vital process in organic synthesis because epoxides serve as key intermediates in the production of various industrial and commercial products, including perfumes, epoxy resins, plasticisers and pharmaceutical compounds [1]. In this work, the efficiency and sustainability of an epoxidation process were improved significantly by using a polybenzimidazole-supported molybdenum(VI) complex (PBI.Mo) as a catalyst. *tert*-Butyl hydroperoxide (TBHP) was employed as an oxidant to mitigate the environmental impacts of stoichiometric peracids, reducing waste generation and the formation of corrosive by-products. Using TBHP as an oxidant in polymer-supported heterogeneous catalysis minimises handling risks and environmental impacts, thereby enhancing the safety and sustainability of the process. The polybenzimidazole-supported molybdenum(VI) complex (PBI.Mo) showed exceptional thermal and chemical stability, which are important characteristics for an efficient catalytic process. The epoxidation process was improved further by implementing a continuous flow reactor, which allows for greater control over reaction conditions and improves heat and mass transfer efficiency.

In this study, an efficient and selective polybenzimidazole-supported molybdenum(VI) complex (PBI.Mo) was used for the continuous epoxidation of 1,5-hexadiene. Experiments were conducted to study the effect of reaction temperature, feed molar ratio of alkene to TBHP and feed flow rate on the yield of epoxide to optimise the reaction conditions in a continuous reactor. Continuous epoxidation in a FlowSyn reactor demonstrated notable gains in catalyst stability, high selectivity, and significant time savings when compared to processes conducted in a batch reactor [2, 3]. Response surface methodology (RSM) using Box-Behnken Design (BBD) was employed to study the interaction effect of different variables on the reaction response.

Materials and Methods

PBI.Mo catalyst was prepared by refluxing PBI resin and excess $MoO_2(acac)_2$ in anhydrous toluene for four days. This allowed molybdenum to be incorporated into the polymer. Within the polymer, molybdenum was found to be uniformly distributed. Brunauer-Emmett-Teller (BET) specific surface areas, specific pore volumes and mean pore diameters were determined by a nitrogen adsorption and desorption method using a Micromeritics Gemini VII instrument. Particle size measurement was performed using a Malvern Mastersizer. A PerkinElmer NexION 350D spectrophotometer was used to measure the amount of molybdenum present in the catalyst. This material characterization data was essential for evaluating the catalyst's performance.

Response surface methodology (RSM) using Box-Behnken Design (BBD) was employed for designing experimental runs and studying the interaction effect of different variables, including the effect of reaction temperature, feed molar ratio of alkene to TBHP and feed flow rate on the reaction response. Continuous epoxidation of 1,5-hexadiene has been carried out in a FlowSyn continuous flow reactor in the presence of polybenzimidazole-supported molybdenum (VI) complex (PBI.Mo) as catalyst. The investigation was conducted after the reaction conditions were optimised and the activity of the PBI.Mo catalyst for alkene epoxidation was thoroughly assessed in a 0.25 L jacketed, stirred batch reactor [1]. A specific quantity of internal standard (*iso*-octane) was added to samples with known concentrations of the components in the product mixture and analysed using an Agilent 7890A GC. To illustrate the empirical relationship between reaction variables and response, a quadratic regression model was developed.

Results and Discussion

The mathematical model was defined using the general quadratic model shown in equation (1).

$$Y = b_o + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j>1}^{n} b_{ij}\, x_i x_j + \varepsilon \qquad (1)$$

By fitting the experimental results, the generic quadratic equation shown in equation (1) was used to obtain a model of polynomial regression. The models that were developed showed the effect of each independent variable, the interactions of variables and the effect of each variable on the response. ANOVA was applied to examine the significance of the model parameters at 95% confidence level. The close agreement obtained between the predicted and actual experimental results confirms that the model accurately estimated the response values. Furthermore, the perturbation plot illustrates the influence of each variable on the reaction response.

Design Expert software was used to develop the numerical optimisation step by combining the desirability of each independent variable into a single value and then searching for optimum values for the response goals. The dependent response variable was set to be maximised to achieve the highest yield. The numerical optimisation technique concluded that the maximum yield of 1,2-epoxy-5-hexene is 55.53% at a feed molar ratio of 4.283:1, reaction temperature of 349 K, and feed flow rate of 0.1 mL/min.

Experiments were performed at optimum conditions to validate the predicted quadratic equation's optimal response values. The experimental findings revealed a response value of 56.97%, which was similar to the predicted optimal response of 55.53%, with a relative error of 2.59%. Figures 1 and 2 present 3D graphs illustrating the influence of feed molar ratio and temperature (Figure 1) and the feed molar ratio and feed flow rate (Figure 2) on the yield of 1,2-epoxy-5-hexene.

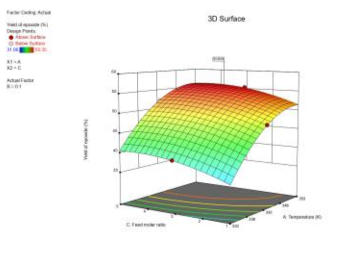

Figure 1. A 3-D graph illustrating the effect of feed molar ratio and temperature on the yield of 1,2-epoxy-5-hexene.

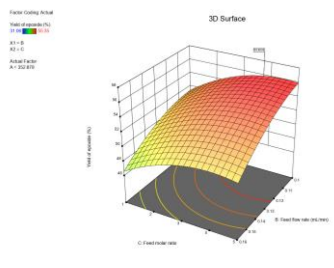

Figure 2. A 3-D graph depicting the effect of feed molar ratio and feed flow rate on the yield of 1,2-epoxy-5-hexene.

Significance

The polymer-supported Mo(VI) (PBI.Mo complex) was prepared, characterized and assessed as a catalyst for the epoxidation of 1,5-hexadiene in a continuous FlowSyn reactor using TBHP as an oxidant. A quadratic polynomial model was developed, demonstrating the yield of 1,2-epoxy-5-hexene in three independent variables. The optimisation results observed for the maximum yield of 1,2-epoxy-5-hexene were validated experimentally. The experimental results showed a 56.97% yield of 1,2-epoxy-5-hexene, which shows the adequacy of the predicted optimum conditions from the experimental results. This study demonstrates that PBI.Mo complex can be used as an effective catalyst for the greener and more efficient epoxidation of 1,5-hexadiene with TBHP as an oxidising reagent. The findings of this study indicate that a comprehensive evaluation of reaction parameters, including reaction temperature, feed flow rate, and the molar ratio of alkene to TBHP, can significantly enhance the efficiency of continuous flow alkene epoxidation in the presence of a suitable heterogeneous catalyst.

References

1. Bhuiyan, M.M.R.; Mohammed, M.L.; Saha, B. Greener and efficient epoxidation of 1,5-hexadiene with *tert*-butyl hydroperoxide (TBHP) as an oxidising reagent in the presence of polybenzimidazole supported Mo(VI) catalyst. *Reactions* **2022**, 3, 537–552.

2. Mbeleck, R.; Mohammed, M.L.; Ambroziak, K.; Sherrington, D.C.; Saha, B. Efficient epoxidation of cyclododecene and dodecene catalysed by polybenzimidazole supported Mo(VI) complex. *Catal. Today* **2015**, *256*, 287–293.

3. Patel, D.; Kellici, S.; Saha, B. Green process engineering as the key to future processes. *Processes* **2014**, *2(1)*, 311–332.