Supplemental Material

Energy Extraction from Seaweed Waste under Low Temperatures by Using an Alkaline Fuel Cell

Li Yanga†, Ying Wanga,c†, Xianhua Liua,c\*, Chunghyok Kima, Feng Donga, Shengling Lia, Jie Dinga, Yang Lia, Muhammad Irfana and Pingping Zhangb#

aSchool of Environmental Science and Engineering, Tianjin University, Tianjin, 300072, PR China

bCollege of Food Science and Engineering, Tianjin Agricultural University, Tianjin 300384, PR China

cSchool of Marine Science and Technology, Tianjin University, Tianjin, 300072, PR China

†Both authors contribute equally to this work

\*Author for correspondence. Tel: +86-22-27402367; Fax:+86-22-27402367. Email: [lxh@tju.edu.cn](mailto:lxh@tju.edu.cn)

#Author for correspondence. Tel: +86-22-23782596; Fax:+86-22-23782596. Email: [zpp@tjau.edu.cn](mailto:zpp@tjau.edu.cn)

**Box-Behnken design (BBD) experimental design and analysis**

In the present study, the Box-Behnken design was used to obtain a proper model for the optimization of the extraction process with three process variables at three levels. Based on the preliminary studies of independent variables, the temperature (A), time (B) and concentration (C) were studied in the range of 170 ℃–190 ℃, 1.5 h–2.5 h and 0.07 mM–0.09 mM, respectively (Table S1). A total of 17 experiments were employed in this work, including 12 factorial points and 5 center points.

The general quadratic polynomial response equation was used to correlate the dependent with independent variables (Eq. 1). All variable parameters and their interactions were considered for a model for the response.

[1]

Where Y represents the responses, β is the regression coefficients, and Χ is the coded independent variables. These values were plotted to obtain contour plots that were used for the optimization process.

The experimental design matrix and the responses based on experimental runs proposed by BBD are given in Table S2. A quadratic model suggested by Design Expert is shown Eq. 2.

[2]

From Eq. 2, it was evident that the linear term A, B and interaction terms AB, AC,BC and quadratic terms A2,B2 and C2 had a negative relationship with the response, whereas the linear terms C had a positive effect on the response.

The regression (R2), adjusted R2, predicted R2, lack of fit and adequate precision were used to determine the quality of developed model. The evaluation of the statistical significance of the model by the values of F-value with prob F<0.0500 was analyzed using analysis of variance (ANOVA) (Talib et al. 2017) and shown in Table S3. The *F-value* is the ratio of the regression mean square and the real error mean. It indicates the influence of each controlled factor on the tested model (Swamy, Sangamithra, and Chandrasekar 2014). For *P-values* smaller than 0.05, the model is statistically significant (Niazi, Khorshidi, and Ghaemmaghami 2015). According to Table S3, the model F-value of 289.09 states the model is significant. In addition, the *P-value* of the model is <0.0001 which implies that the model has over 95% confidence level in terms of predictability. Also according to the calculated *P-value*, all three factors, as well as temperature, reaction time and catalyst dosage squared terms were found to be significant. The *P-value* of lack of fit is 0.1036 (non-significant), which means that the model fits well the experimental data, and the independent variables have considerable effects on the response.

Regression study shows R2 value of 0.9973, which was very high and has indicated a good correlation between the measured and the predicted values. As well, the adjusted R2 value (0.9939) was also very high to advocate the significance of the model, which ensured a satisfactory adjustment of the experimental data to the polynomial model (Zhu et al. 2014). The coefficient of variation (CV) shows the scattering of the experimental points from the predicted values of the second order polynomial model. A high coefficient of variation points out that there is extreme variation in the mean value and does not adequately develops a sufficient model (Koocheki et al. 2009). A low coefficient of variation (CV = 2.52%) denoted good accuracy and reliability of the experiments.

Figure S1 shows the effect of each two independent variables (by keeping the other at central level) and their interactions in response. The simultaneous influence of temperature and reaction time at a constant HSiW concentration (0.08 mM) on TRS yield is given in Figure S2a. High temperature and long reaction time can help the hydrolysis of *E. prolifera* and benefit the generation of reducing sugar, however, too long exposure to high temperatures can lead to breaking down of the sugars. The effect of HSiW concentration and reaction temperature on the TRS yield is shown in Figure S2b. The TRS yield increased at first by increasing the catalyst dosage and reaction temperature, and declined by a further increase of these parameters. Figure S2c illustrates the effect of HSiW concentration and reaction timeon the TRS yield. Similar to the other two parameters, the HSiW concentration also had an optimum point. This phenomena was likely due to the high concentration of HSiW can contribute to both the generation and breakdown of reducing sugars.



**Figure S1**. 3D surface and 2D contour plots of yield as a function of (a) temperature and time, (b) HSiW concentration and temperature, (c) HSiW concentration and time.

**Table S1. Experiment ranges and levels of independent variables**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Factor | Unit | Coded levels | | |
| -1 | 0 | 1 |
| Temperature | ℃ | 170.00 | 180.00 | 190.00 |
| Time | h | 1.50 | 2.00 | 2.50 |
| HSiW concentration | g | 3.70 | 4.23 | 4.76 |

**Table S2.****Box-Behnken Design of experiments and responses for TRS yield.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Run | Temperature  （℃） | Time  （h） | HSiW concentration （mmol） | Yield（mg.g-1） | |
| Experimental | Predicted |
| 1 | 190.00 | 2.00 | 0.07 | 109.21 | 108.49 |
| 2 | 180.00 | 2.50 | 0.09 | 119.33 | 114.96 |
| 3 | 180.00 | 2.00 | 0.08 | 232.10 | 232.96 |
| 4 | 180.00 | 1.50 | 0.07 | 142.50 | 146.88 |
| 5 | 180.00 | 2.00 | 0.08 | 229.83 | 232.96 |
| 6 | 180.00 | 2.00 | 0.08 | 233.23 | 232.96 |
| 7 | 180.00 | 2.50 | 0.07 | 130.71 | 129.36 |
| 8 | 170.00 | 2.00 | 0.07 | 140.50 | 138.20 |
| 9 | 170.00 | 1.50 | 0.08 | 163.25 | 161.17 |
| 10 | 180.00 | 2.00 | 0.08 | 237.21 | 232.96 |
| 11 | 190.00 | 1.50 | 0.08 | 140.32 | 136.67 |
| 12 | 180.00 | 2.00 | 0.08 | 232.41 | 232.96 |
| 13 | 190.00 | 2.50 | 0.08 | 76.19 | 78.27 |
| 14 | 170.00 | 2.50 | 0.08 | 127.75 | 131.40 |
| 15 | 180.00 | 1.50 | 0.09 | 184.25 | 185.61 |
| 16 | 170.00 | 2.00 | 0.09 | 158.75 | 159.47 |
| 17 | 190.00 | 2.00 | 0.09 | 109.25 | 111.55 |

**Table S3.** **Analysis of variance (ANOVA) for the fitted model**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Source | Sum of squares | Degree of freedom | Mean square | F value | p-Value probe>F |
| Model | 43800.55 | 9 | 4866.73 | 289.09 | <0.0001 |
| A-Temperature | 3013.98 | 1 | 3013.98 | 179.04 | <0.0001 |
| B-Time | 3886.97 | 1 | 3886.97 | 230.89 | <0.0001 |
| C- HSiW concentration | 295.97 | 1 | 297.97 | 17.58 | 0.0041 |
| AB | 204.92 | 1 | 204.92 | 12.17 | 0.0101 |
| AC | 82.90 | 1 | 82.90 | 4.92 | 0.0620 |
| BC | 705.70 | 1 | 705.70 | 41.92 | 0.0003 |
| A2 | 15373.01 | 1 | 15373.01 | 913.18 | <0.0001 |
| B2 | 8776.04 | 1 | 8776.04 | 521.31 | <0.0001 |
| C2 | 7823.06 | 1 | 7823.06 | 464.70 | <0.0001 |
| Residual | 117.84 | 7 | 16.83 |  |  |
| Lack of Fit | 88.87 | 3 | 29.62 | 4.09 | 0.1036 |
| Pure Error | 28.97 | 4 | 7.24 |  |  |
| Cor Total | 43918.39 | 16 |  |  |  |

**Table S4.** **Statistical parameters of the model equation as obtained from ANOVA model**

|  |  |
| --- | --- |
| Type of variables | |
| Standard deviation (SD) | 4.10 |
| Mean | 162.75 |
| Coefficient of variation | 2.52 |
| PRESS | 1467.16 |
| R2 | 0.9973 |
| Adjusted R2 | 0.9939 |
| Predicted R2 | 0.9666 |
| Adequate precision | 49.157 |

**Reference**

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