Optimization of garlic oil extraction via batch microwave-assisted hydrodistillation

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Abstract. The batch microwave-assisted hydrodistillation (MAHD) process has become a popular green extraction technique to extract essential oils from natural plants. The traditional hydrodistillation process is less efficient than the MAHD as the former often requires longer extraction period and higher energy consumption. This paper reports an optimization study of the batch MAHD process coupled with ethanol-water solvent in extracting garlic oil. A fundamental model of the batch MAHD process is used to simulate the extraction yield under various input conditions. The result of the model-based optimization is compared with the result from an experimental-based optimization. The objectives of the optimization are to maximize the extraction yield while simultaneously minimizing the extraction period and total energy consumption. This optimization results in the extraction efficiency and productivity equal to 90.44 µg/kJ and 3,254 µg/minute of garlic oil respectively.

1. Introduction
Garlic (Allium sativum) is a species in the onion genus and belongs to the family of Liliaceae. It has played important culinary and medicinal roles in many cultures since time immemorial. Garlic is widely used in culinary purposes around the world for its pungent flavor as a condiment. Besides of its astonishing aromatic and taste enhancement for food, it has been gaining increasing acceptance as a health supplement. Garlic has a wide range of therapeutic properties including analgesic, antibacterial, anticoagulant, antifungal, antiviral, antitumor, antimicrobial, calmative, decongestant, disinfectant, diuretic, expectorant, hypo tensor, insecticide, laxative, lymphatic toner, stimulant, tonic and vasodilator [1].

Typical contents of a fresh garlic bulb are shown in Table 1. The pharmacological effects of garlic are mainly attributed to its organosulfur compounds [2]. The organosulfur compounds, particularly γ-glutamyl-s-allyl-cysteine and S-allyl-L-cysteine sulfoxides (alliin) are the most important compounds present in the intact garlic bulb [3]. These compounds especially alliin yields characteristic flavor and acts as an “inactive” precursor of allicin [4]. Allicin also known as allyl 2-propenethiosulphinate or diallyl thiosulfate will only exist when the garlic is mechanically crushed or damaged. The injury of the garlic bulb will activate the enzyme allinase to break down the compound allii, originally present in an intact garlic, to form allicin [5]. The production of allicin is responsible for its garlic’s pungent odor and its medicinal effects [6].
Microwave refers to the non-ionizing electromagnetic radiation wave having the frequency from 300 MHz to 300 GHz with wavelength ranging from 1 mm to 1 m. In the electromagnetic spectrum, microwave falls in between the radio and infrared waves [7].

| Component                          | Percentage (%) |
|------------------------------------|----------------|
| Water                              | 65.0           |
| Carbohydrate (mainly Fructans)     | 28.0           |
| Organosulfur Compounds             | 2.3            |
| Protein (Mainly Allinase)          | 2.0            |
| Amino Acid (mainly Arginine)       | 1.2            |
| Fibre                              | 1.5            |

Recently, the microwave-assisted hydrodistillation (MAHD) process has emerged as one of the popular green extraction technologies for natural plant extraction. The principle of microwave heating in the MAHD process is based on the direct interactions between the microwave radiation and molecules of polar solvent and/or materials involved. To be effective, the electromagnetic wave has to penetrate deep (about an inch) into the plant materials. Subsequently, two phenomena will occur; firstly, the dipole rotation and secondly, the ionic migration. These phenomena cause the molecules inside the plant materials to vibrate vigorously leading to the heating of the liquid/material involved [7]. The heat produced will cause the moisture or liquid inside the plant materials to expand and evaporate, and subsequently leading to a high internal pressure [9]. This high internal pressure will then cause the cell walls to stretch out and eventually followed by cell ruptures. As a result of the ruptures, the cells release the contained oil into the bulk liquid solvent. Note that, the microwave heating efficiency can be further enhanced by soaking the plant materials in a suitable solvent that has a high dissipation factor value, or loss tangent value. The larger the loss tangent value of the given solvent, the more efficient it converts the microwave radiation into the desired thermal energy.

The effect of microwave heating greatly depends on the dielectric properties of the plant matrix and solvent used [10]. Dielectric properties including the dissipation factor, dielectric loss, dielectric constant, permittivity and conductivity are important parameters in the selection of suitable solvents [11]. The dissipation factor or loss tangent (\(\tan \delta\)), is often used as a basis to calculate the heating efficiency of solvents under microwave radiation. The loss tangent describes the ability of the solvent to dissipate the absorbed microwave energy and convert it into heat [12]. The higher the dissipation factor, the higher the capacity of the solvent to absorb microwave radiation. Therefore, it is desirable that the plant materials are soaked in a polar solvent having high dissipation factor to achieve efficient microwave heating of materials involved [10].

Also bear in mind that, the dielectric loss and dielectric constant represent the capability of materials to dissipate microwave energy into thermal energy and the capability of materials to absorb microwave energy respectively. Previous research has shown that water exhibits higher dielectric constant than ethanol, but ethanol exhibits higher dissipation factor than water. Thus, water has higher ability to absorb microwave energy than ethanol but water is less able to dissipate the absorbed microwave energy into desired heat than ethanol [13]. To achieve good absorption of microwave energy and then to effectively turn the energy into heat, several researchers have proposed to mix ethanol and water, so that the overall heating efficiency of the mixture is higher than that of water or ethanol alone [14]. Table 2 shows some commonly used solvents and their dielectric properties for microwave-assisted extraction.

The overall goal of the present work is to optimize the conditions, which include the ethanol-water ratio and volume of liquid solvent, in order to maximize the yield of oil extracted while minimizing the energy consumption. In order to achieve this goal, a multi-objective optimization will be conducted using Design Expert software. To the best of our knowledge, so far, there has been no report about a model-based optimization of the MAHD process in extracting garlic oil.
The rest of this paper is structured as follows. Section 2 presents the methodology for the optimization. Section 3 presents the optimization results as well as the simulation using the fundamental model of the MAHD process. Finally, some concluding remarks and recommended future studies are highlighted in Section 4.

Table 2. Dielectric properties of commonly used solvents in extraction [14].

| Solvents       | Dissipation factor at 2.45 Ghz (\(\tan \delta\)) | Dielectric constant (\(\varepsilon'\)) | Dipole moment (Debye) |
|----------------|-----------------------------------------------|--------------------------------------|-------------------|
| Acetone        | -                                             | 21.4                                 | -                 |
| Ethyl acetate  | -                                             | 6.02                                 | 1.88              |
| 1-Butanol      | 0.571                                         | 1.66                                 |
| Ethanol        | 0.941                                         | 25.7                                 | 1.69              |
| Methanol       | 0.659                                         | 33.7                                 | 1.70              |
| Diethyl ether  | -                                             | 4.389\(^s\)                         | -                 |
| Hexane         | -                                             | 1.88                                 | <0.1              |
| Chloroform     | -                                             | 4.8                                  | -                 |
| Water          | 0.123                                         | 80.4                                 | 1.84              |

\(^s\) value determined at 18\(^\circ\)C otherwise value at 20\(^\circ\)C

2. Methodology

2.1. Design of Experiment (DOE)
In this work, the adopted fundamental mathematical model of the MAHD process has previously been confirmed capable of giving reliable prediction of experimental data to within ±10% of error margin based on a lab-scale MAHD unit; refer to [15], [16]. In the current research, the same mathematical model is adopted to perform the model-based optimization of the batch MAHD using Design Expert software. A number of simulation runs required are first determined using the Design of Experiments (DOE) technique available in the Design Expert software.

For building a second-order response surface model, either Box-Behnken (BBD) design or the Central Composite Design (CCD) design of experiments, or their variants can be used [17]. In this research, the BBD design is selected and implemented using Design Expert 10 with three evenly spaced levels; this is less computationally expensive to run than the CCD design of experiments [17].

Four input parameters are chosen as recommended in the experimental work in [18], which are: microwave power, ethanol-water ratio, initial liquid (solvent) volume and feedstock mass. The high level (+1), medium level (0) and low level (-1) for each input parameter are set according to the specified ranges in the experiment.

Three outputs or responses are chosen in this study: extraction yield, extraction time and energy consumption. Note that, it is desired to maximize the yield whilst minimizing the extraction time and energy consumption. It is important to minimize the extraction time to reduce potential degradation of the oil quality under high temperature exposure. Also it is desirable to minimize the energy consumption to reduce the cost of production. Unfortunately, the reduction in energy consumption or extraction time tends to reduce the oil extraction yield – opposite trends of the responses. Therefore, an optimal compromise is required between the yield and the other two responses.

2.2. Response Surface Methodology (RSM)
The RSM is a collection of mathematical and statistical techniques introduced by Box and Wilson [19]. It is suitable for analyzing the effects of several input variables on the specified responses and for performing optimization of the responses [20]. In developing a RSM model, multiple regression analysis is required to obtain the coefficients of the equations involved. The RSM models are useful for the estimation of the responses involved.

A second-order (quadratic) RSM model commonly used is given by
\[ Y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum \sum_{i<j=2}^{k} \beta_{ij} x_i x_j + e_i \]  \hspace{1cm} (1)

where \( Y \) denotes the given response or output variable; \( x_i \) and \( x_j \) are input variables (\( \forall i, j = 1, 2, \ldots k \)); \( \beta_0 \) is the model intercept coefficient; \( \beta_j \), \( \beta_{jj} \) and \( \beta_{ij} \) are the interaction coefficients of linear, quadratic and second-order terms respectively; \( k \) is the number of input variables (e.g., \( k = 4 \) in this study); \( e_i \) is the model errors (assuming a zero mean).

The number of design points (\( N \)) for the BBD is defined by the expression \( N = 2k(k-1) + c_p \), where \( k \) is the number of input variables and \( c_p \) is the number of center points [20]. In this research, 4 input variables (\( k = 4 \)) will be investigated leading to a total of 24 design points plus 3 center points, which are required to estimate a RSM model. A high number of center points (\( c_p = 3 \)) is used to reduce the trace of the variance-covariance matrix. Table 3 shows the range and levels of input parameters used in the Box-Behnken design.

| Parameter          | Unit | Notation | Range and levels |
|--------------------|------|----------|------------------|
| Garlic Feedstock   | g    | A        | -1 0 +1          |
| Solvent Volume     | ml   | B        | 100 200 300      |
| Ethanol-Water Ratio| -    | C        | 0.5 1.0 1.5      |
| Microwave Power    | W    | D        | 200 400 600      |

3. Results and discussion

3.1. Optimization of MAHD

In the previous study, Yii et al. [18] conducted a lab-scale experimental work comparing the effectiveness of solvent free microwave-assisted hydrodistillation (SFME) with that of the microwave-assisted hydrodistillation (MAHD) coupled with solvent extraction. The study showed that a mixture of water-ethanol is the best extracting medium for garlic oil extraction in the MAHD process. In the present study, the optimization of the MAHD process is based on the same dimension as the lab-scale unit used in the previous study [18]. It is assumed that the fresh garlic contains 1 mg-oil/g-garlic, equivalent to 1 g-oil/100 g-garlic. The RSM models of the yield, extraction time and energy consumption are developed via quadratic Box-Behnken method. The matrix of BBD along with the observed responses are shown in the Table 4.

The RSM model of yield (\( Y_d \)) as a function of the four input parameters is given as follows

\[ Y_d = 0.033 + \Omega_{Y_0} \left[ \begin{array}{c} A \\ B \\ C \\ D \end{array} \right] + \Omega_{Y_1} \left[ \begin{array}{cccc} A^2 & 0 & 0 & 0 \\ AB & B^2 & 0 & 0 \\ AC & BC & C^2 & 0 \\ AD & BD & CD & D^2 \end{array} \right] \]  \hspace{1cm} (2)

where the coefficients for low and high order terms are

\[ \Omega_{Y_0} = 10^{-4} \left[ \begin{array}{cccc} -31.81 & 180 & -170 & 19.76 \\ 2.743 & -18.0 & -6.460 & 1.272 \\ 0 & -3.494 & -4.255 & 1.515 \\ 0 & 0 & 4.032 & 8.400 \end{array} \right] \]  \hspace{1cm} (3)

\[ \Omega_{Y_1} = 10^{-3} \]  \hspace{1cm} (4)

Meanwhile, the obtained RSM model of extraction time (\( t_f \)) is
\[ t_f = 39.98 + \Omega_{lt} \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} + \Omega_{ht} \begin{bmatrix} A^2 & 0 & 0 & 0 \\ AB & B^2 & 0 & 0 \\ AC & BC & C^2 & 0 \\ AD & BD & CD & D^2 \end{bmatrix} \] (5)

where the coefficients for the low and high order terms are

\[ \Omega_{lt} = \begin{bmatrix} -0.96 \\ 10.76 \\ -19.74 \\ -27.46 \end{bmatrix}^T \] (6)

\[ \Omega_{ht} = 10^{-1} \begin{bmatrix} 2.1 & -16.3 & 8.4 & 5.4 \\ 0 & -12.7 & -69.3 & -59.5 \\ 0 & 0 & 47.3 & 118.6 \\ 0 & 0 & 0 & 137.2 \end{bmatrix} \] (7)

**Table 4.** Box-Behnken Design matrix for four input parameters along with observed responses.

| Trail no. | Coded Value A | Yield (g/100g garlic) | Extraction Time (min) | Energy Consump. (kJ) |
|-----------|----------------|-----------------------|-----------------------|---------------------|
| 1         | -1 1 0 0       | 0.02987               | 29.376                | 705                 |
| 2         | 1 -1 0 0       | 0.006967              | 31.064                | 745.5               |
| 3         | -1 1 0 0       | 0.09872               | 51.024                | 1225                |
| 4         | 1 1 0 0       | 0.001875              | 46.196                | 1109                |
| 5         | 0 0 -1 -1     | 0.06803               | 123.959               | 1488                |
| 6         | 0 0 1 -1     | 0.01894               | 52.817                | 633.8               |
| 7         | 0 0 -1 1     | 0.06313               | 41.32                 | 1488                |
| 8         | 0 0 1 1     | 0.0174                | 17.606                | 633.8               |
| 9         | -1 0 0      | 0.02993               | 82.236                | 986.8               |
| 10        | 1 0 0      | 0.04583               | 79.024                | 948.3               |
| 11        | -1 0 0      | 0.02314               | 27.412                | 986.8               |
| 12        | 1 0 0      | 0.04413               | 26.341                | 948.3               |
| 13        | 0 -1 -1    | 0.01556               | 42.672                | 1024                |
| 14        | 0 1 -1    | 0.0597                | 78.885                | 1893                |
| 15        | 0 1 1     | 0.01045               | 21.543                | 517                 |
| 16        | 0 1 1     | 0.03757               | 30.018                | 720.4               |
| 17        | -1 0 -1   | 0.04333               | 64.455                | 1547                |
| 18        | 1 0 -1   | 0.07859               | 60.705                | 1457                |
| 19        | -1 0 1    | 0.01582               | 26.776                | 642.6               |
| 20        | 1 0 1    | 0.02524               | 26.381                | 633.1               |
| 21        | 0 -1 0    | 0.01751               | 60.267                | 723.2               |
| 22        | 0 1 0     | 0.0533                | 95.991                | 1152                |
| 23        | 0 -1 0     | 0.01009               | 20.089                | 723.2               |
| 24        | 0 1 0     | 0.05194               | 31.997                | 1152                |
| 25        | 0 0 0     | 0.03312               | 39.984                | 959.6               |
| 26        | 0 0 0     | 0.03312               | 39.984                | 959.6               |
| 27        | 0 0 0     | 0.03312               | 39.984                | 959.6               |

The RSM model representing energy consumption (\( E_{mw} \)) as a function of the input parameters is

\[ E_{mw} = 959.60 + \Omega_{IE} \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} + \Omega_{HE} \begin{bmatrix} A^2 & 0 & 0 & 0 \\ AB & B^2 & 0 & 0 \\ AC & BC & C^2 & 0 \\ AD & BD & CD & D^2 \end{bmatrix} \] (8)

with the coefficients for the low and high order terms given as follows
The results are evaluated via the analysis of variance (ANOVA) for the model fitting quality. The significance of each coefficient parameter is determined by the probability value (P value). Table V shows the results of analysis for the extraction yield.

**Table 5. Anova of response surface quadratic model for the yield response.**

| Source     | Sum of square | df | Mean square | F-Value | P-Value | Effect |
|------------|---------------|----|-------------|---------|---------|--------|
| Model      | 9.29E-3       | 14 | 6.637E-4    | 1.57    | 0.2190  | NS     |
| A          | 1.21E-4       | 1  | 1.215E-4    | 0.29    | 0.6015  | NS     |
| B          | 3.769E-3      | 1  | 3.769E-3    | 8.93    | 0.0113  | S      |
| C          | 3.431E-3      | 1  | 3.431E-3    | 8.13    | 0.0146  | S      |
| D          | 4.685E-5      | 1  | 4.685E-5    | 0.11    | 0.7448  | NS     |
| AB         | 1.367E-3      | 1  | 1.367E-3    | 3.24    | 0.0971  | NS     |
| AC         | 1.669E-4      | 1  | 1.669E-4    | 0.40    | 0.5413  | NS     |
| AD         | 6.477E-6      | 1  | 6.477E-6    | 0.015   | 0.9035  | NS     |
| BC         | 7.242E-5      | 1  | 7.242E-5    | 0.17    | 0.6861  | NS     |
| BD         | 9.181E-6      | 1  | 9.181E-6    | 0.022   | 0.8852  | NS     |
| CD         | 2.822E-6      | 1  | 2.822E-6    | 0.15    | 0.9362  | NS     |
| A²         | 4.012E-5      | 1  | 4.012E-5    | 0.095   | 0.7632  | NS     |
| B²         | 6.509E-5      | 1  | 6.509E-5    | 0.15    | 0.7014  | NS     |
| C²         | 8.672E-5      | 1  | 8.672E-5    | 0.21    | 0.6585  | NS     |
| D²         | 3.986E-5      | 1  | 3.986E-5    | 0.094   | 0.7639  | NS     |
| Residual   | 5.066E-3      | 12 | 4.222E-4    |         |         |        |
| Lack of Fit| 5.066E-3      | 10 | 5.066E-4    |         |         |        |
| Pure Error | 0.000         | 2  | 0.000       |         |         |        |
| Total (corr.) | 0.014     | 26 |             |         |         |        |
| R²         | 0.6472        |    |             |         |         |        |
| Adj R²     | 0.2355        |    |             |         |         |        |
| C.V. %     | 57.40         |    |             |         |         |        |
| Adeq       | 4.780         |    |             |         |         |        |

As shown in Figure 1, notice that the residuals are falling closely around the straight line. This means that the errors are normally distributed for the RSM model of yield. The RSM model analysis and residual plots for the extraction period and energy consumption are quite similar to that of the yield model (not shown here). Overall, all of the RSM models show satisfactory fitting quality.

The contour plots in Figure 2 represent the interactive effects of garlic feedstock, liquid solvent volume, ethanol-water volume ratio and microwave power on the scaled extraction yield of garlic oil. Each contour plot reveals the influences of any two input variables on the given response, which clearly presents the correlations between the two variables. From these plots, the optimum value range can be obtained using the Design Expert software. Please note that, in this work we choose equal values of all weighting factors used in the optimization function. Three optimization cases are compared: (1) single-objective optimization to maximize the yield, (2) multi-objective optimization to maximize the yield and simultaneously to minimize the extraction time and energy consumption, and (3) to maximize the extraction yield subject to a constraint of 60 minutes extraction period.
Figure 1. Normal Plot of Residuals (Response: Yield)

Figure 2. Contour plots (A, B, C, D) showing the interactive effects of garlic feedstock, solvent volume, ethanol-water ratio and microwave power on the yield of garlic essential oil.

Consider the case 1, in which the single-objective optimization is conducted solely to maximize the extraction yield without considering the extraction time and energy consumption. In this case, the highest yield obtained is 0.09998 g-oil/100 g-garlic. This highest yield corresponds to values of inputs as follows: garlic feedstock of 100 g, solvent volume of 300 ml, ethanol to water ratio of 0.5 and microwave power of 201.6 W. The extraction time and total energy consumption are 168 minutes and 2,038 kJ respectively. According to Yii [15], a too long extraction time beyond 60 minutes is not recommended as this can lead to serious degradation of the oil quality. In term of the energy efficiency (i.e. mass of oil extracted in µg/energy consumption), this optimized extraction condition gives an
efficiency of 48.58 $\mu$g-oil/kJ. The extraction productivity (mass of oil extraction in $\mu$g/extraction time) is 589.3 $\mu$g-oil/minute.

Next, consider the case 2 which imposes minimum extraction time and energy consumption in the maximization of the extraction yield. In this case, the highest extraction yield is 0.06835 g-oil/100 g-garlic. This extraction yield corresponds to values of inputs: 100 g garlic feedstock, 300 ml of liquid solvent, ethanol to water ratio of 1.5 and microwave power of 598.6 W. The minimum extraction time and total energy consumption corresponding to this yield are 21 minutes and 755.7 kJ respectively. In term of the extraction time, this condition is acceptable because the shorter the extraction period, the less likely the oil is degraded by exposure to high temperature. This optimization leads to extraction efficiency and productivity equal to 90.44 $\mu$g-oil/kJ and 3,254 $\mu$g-oil/minute respectively. Note that, although the absolute extraction yield in this case 2 is lower than in the previous case 1, in terms of the extraction efficiency and productivity, the case 2 optimization considering all three optimization criteria actually gives better results.

For the case 3, an optimization of the MAHD process is conducted by maximizing the absolute extraction yield whilst attempting to reduce the extraction time to less than 60 minutes (constraint imposed on the extraction time). In this case, the highest absolute yield obtained is 0.09874 g-oil/100 g-garlic. This yield corresponds to values of inputs: 100 g of garlic feedstock, 300 ml of solvent, 400 W of microwave power and ethanol to water ratio of 1. The extraction time and total energy consumption are 51 minutes and 1,225 kJ respectively. Thus, the extraction efficiency and productivity are 80.60 $\mu$g-oil/kJ and 1,936 $\mu$g-oil/minute respectively.

Upon comparing all the three cases of optimization, clearly the case 2 optimization gives the best overall results. The case 3 provides acceptable results but substantially lower performances in terms of the extraction efficiency and productivity. The single-optimization focusing on the yield only gives the worst results in terms of the extraction efficiency and productivity. Also, the case 1 optimization leads to a very long extraction period which is not recommended for garlic oil extraction, i.e., because the oil contains many thermally sensitive bioactives. As a recommendation in this study, the case 2 optimization should be adopted, which maximizes the yield while simultaneously minimizes the extraction period and total energy consumption. It is worth noting that, this case 2 optimization agrees well in term of the absolute extraction yield value with the experimental optimization value reported by Yii et al. [18]: 0.06835 g-oil/100 g-garlic in the case 2 optimization and 0.07 g-oil/100 g-garlic in the Yii et al.

However, there are marked (within 50%) differences in the values of microwave power, solvent volume and extraction time between the model-based and experimental-based optimization works. These differences are expected to be due to the different optimization approaches adopted. In the present work, a rigorous model-based optimization considering all criteria or factors simultaneously (case 2) is adopted. Meanwhile, in the experimental work of Yii et al. [18], one factor at-a-time (OFAT) approach was adopted. In the OFAT approach the extraction time was considered as one of the input parameter while in the present work, it is considered as an output response.

3.2. Model simulation

To gain some understanding of the MAHD process behaviours, simulation is performed under the conditions given by the three cases of optimization presented in previous section. Figure 3 shows the extraction yield profiles under the three different cases of optimization. For the case 1, a long delay is observed in the extraction yield which is due to the slow cell ruptures which delays the release of oil to the bulk liquid or solvent. This slow cell ruptures and therefore, slow extraction rate is caused by low microwave power, i.e., about 200 W. For the case 2 with the shortest extraction period, the delay is small because the microwave power used is larger (about 600 W) than that used in either the case 1 or case 3. The compromised optimization (case 3) also shows relatively short delay, i.e., with microwave power of 400 W.

The next Figure 4 depicts the profiles of simulated oil concentration in the bulk liquid phase. The pattern of profiles under the cases 1 and 3 are quite similar; the only major difference lies in the delay period (similar to that being observed in the yield profiles). The point to note is that, to achieve the
maximum absolute yield, the pattern of the oil concentration in the liquid must pass through a maximum point, after which a constant profile is observed for certain period of time, then finally followed by the decline of the concentration to zero, i.e., when the oil in the solid is exhausted. For the case 2, the oil concentration does not drop to zero indicating incomplete extraction of oil in the solid matrix. Note that, the extraction process stops once the liquid in the distillation vessel goes to near zero. Thus, for the case 2 the liquid dries up too quickly (because of high microwave power) which means insufficient time for the complete extraction of oil from the plant matrix – hence leading to lower absolute extraction yield than in the cases 1 and 3.

Figure 5 shows the temperature profiles under the three different cases of optimization. The important point to note is the exposure period at the maximum temperature occurring about the boiling point of pure water for the different cases. For the cases 1, 2 and 3, these high temperature exposure periods are about 80 minutes, 5 minutes and 10 minutes respectively. Thus, high degradation of oil quality is expected under the case 1 condition. The shorter the high temperature exposure period, the less likely the oil is seriously degraded. Thus, the case 2 is the best.

Figure 3. Extraction yield profiles of oil under Cases 1, 2 and 3.

Figure 4. Concentration profiles of oil (Xl) in the bulk liquid phase.

Figure 6 illustrates the liquid volume profile in the distillation flask. The fastest decrease rate of liquid volume in the case 2 is expected because of a large proportion of ethanol is used (ethanol-water ratio of 1.5) combined with high microwave power input (about 600 W). The slowest decrease in liquid volume occurs for the case 1 where larger proportion of water is used instead (ethanol-water ratio of 0.5) combined with low microwave power of about 200 W.

Overall, the simulation and optimization study suggests that, for the given garlic mass and volume of solvent, the ethanol-water ratio and microwave power play important role in the extraction
performances measured in terms of the extraction efficiency, productivity, high-temperature exposure period and total energy consumption. It is very hard to study the interplays of these several input-output parameters solely via experimental study. This is because in the experimental study, one is often presented with limited resources and time. Thus, the model-based simulation and optimization study of the process involved, e.g. the MAHD process can greatly complement the experimental works, in terms of providing extra insights into the process behaviours when exposed to different conditions.

Figure 5. Temperature (T) profiles under Cases 1, 2 and 3.

Figure 6. Liquid volume profile (Vl) under Cases 1, 2 and 3.

4. Conclusion
The model-based optimization and simulation study have been conducted on a batch microwave-assisted hydrodistillation (MAHD) combined with ethanol-water solvent extraction, with the aims to achieve optimum yield of garlic oil. Three cases of optimization have been conducted: (1) case 1 to maximize the absolute yield of extraction without considering the extraction period and total energy consumption, (2) case 2 to maximize the absolute yield of extraction and simultaneously to minimize the extraction period and total energy consumption, and (3) case 3 to strike a compromise between the cases 1 and 2. Based on the extraction efficiency and productivity criteria, the case 2 optimization provides the best overall results although it does not lead to complete exhaustion of oil in the garlic matrix, unlike in the cases 1 and 3. Simulation results help to reveals some new insights about the process behaviours under those three different cases of optimization. One suggestion for future work is to extend the current batch MAHD to a semi-batch process with solvent recycling. Another possible future work is to scale-up the current lab-scale system to a pilot- or even industrial-scale of production. In this future work, it is very useful to evaluate its technoeconomic performance against several other green extraction technologies, such as the supercritical CO2 fluid extraction.
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