Modeling the kinetics of essential oil hydrodistillation from Vietnamese ginger (*Zingiber officinale*)

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**Abstract.** *Zingiber officinale* is a frequently used herb and food flavouring agent, commonly known as ginger. *Z. officinale* belongs to the Zingiberaceae family, comprising of more than 1200 species [1]. In traditional therapeutic systems, *Z. officinale* is known for its various medicinal properties that give rise to the ability to cure a variety of diseases. Ginger oil is a potential commodity, but the extraction of these oils takes a long time to produce good quality essential oils. Thus, optimization work is required in the extraction process. In this study, the extraction was performed with the hydro-distillation method, which has been widely used to extract essential oils from natural plant and herbs due to its feasibility and green technology. The extraction was carried out over several extraction cycles from 15 minutes until the amount of essential oil recovered is almost unchanged. The maximum yield in ginger essential oil extract achieved 0.5% from 100 g starting material. This yield was obtained on optimum temperature conditions, extraction time and water to material ratio such as 200 W, 120 min, and 1:4 mL/g. The mathematical model of essential oil extraction was constructed, which is a crucial step in the industrial plant project because it helps to understand the extraction process and to achieve optimal operating conditions. The process kinetics in this study was modeled by the first and second-order kinetic models. The kinetics of the extraction of ginger essential oil by the hydrodistillation method has demonstrated that the extraction process is based on a second model as it has been done experimentally. The second order model was satisfactorily modified, with extremely high correlation coefficients ($R^2=0.99355$), demonstrating that the process was successfully described.

1. **Introduction**

Recently, the use of extraction of medicinal plants has gained considerable public attention. [7-9] *Zingiber officinale*, which is commonly known as ginger, is a slim perennial plant first grown in China and then expanded to Southeast Asia and India. The plant is 2 feet tall and has yellowish green flowers that imitate orchids of acidic pungent taste. It is a tropical herb which is used for medicinal purposes and culinary purposes [10]. Applications of ginger include diagnosis for diarrhea, improvement for joint health and aid for nausea and indigestion. Ginger oil is marketed globally in pharmaceutical and food...
application. The oil contains a wide range of volatile and non-volatile compounds which exhibit numerous biological activities, namely, zingiberene, farnesene, curcumene, gingerols and 3-dihydroshogaols [11].

There are various methods to extract the essential oils from the plant materials such as hydrodistillation, steam distillation, solvent extraction, microwave extraction, supercritical fluid extraction (SC-CO₂) [12-15]. Of these methods, the most growing method for harvesting essential oils from herbs and medicinal plants is hydrodistillation [16-18]. For this method, pure water is the key component to extraction essential oil. This method is widely used because it does not require much on the cost of extraction, post-distillation separation as solvent extraction method and its ability to apply industrial scale. However, ginger EO extraction using hydrodistillation has remained limitedly performed. For this reason, the present study has made the first attempt to employ hydro-distillation to extract the valuable EO from ginger.

Mathematical hydro-distillation modeling must be considered as an inevitable a step toward projecting industrial plants with the right operating conditions. Mathematical models are used to simulate a process without having to run experimental procedures to learn about the extraction process's behavior. So far, the model assuming instantaneous washing and diffusion is the basis used to describe the change in time of EOs yield [19-21]. Experimental models has been used to model the kinetics of extracts from various plant materials. In this analysis, the author also discusses the suitability of two models for explaining the kinetics of ginger hydro-distillation. Therefore the output of each model was evaluated by comparing experimental and calculated parameters including the rate constant, the initial extraction rate and the extraction capacity of the equilibrium.

2. Materials and methods

2.1. Raw materials
The raw material is Vietnamese ginger. An analytical grade was used for all other chemicals and solvents.

2.2. Hydro-distillation of Ginger oil
Approximately 100 g of ginger bulb was put into a 1L flask of deionized water. Using a modified Clevenger tool, the flask was set up with hydro-distillation, and a condenser was applied on top to capture the extracted EOs. The heater was operated for a period of 120 min at a power level of 204 W. This amount of time was necessary to remove all the essential oils from the material. The extraction was performed in 15 min through several extractions cycles until the amount of recovered essential oil become almost unchanged. The collected essential oil was dried over anhydrous sodium sulphate to remove vapour, weighed and stored at 4 °C in amber vials until they had been used for examination. The following equation was used for the yield of ginger oil:

\[ Y = \frac{V \times 100}{W} \]  \hspace{1cm} (1)

Y is the yield obtained from EOs (% v/w), V is the volume of ginger bulb oil extracted; (mL), and W is the amount of the plant content that is used (g).

2.3. The kinetics modeling on extraction process

2.3.1. Extraction first-order model. Lagergren's first-order kinetics equation [22] may be written as follows in differential form:

\[ \frac{dq_t}{dt} = k_1(q_o - q_t) \]  \hspace{1cm} (2)
Where \( k_1 \) (min\(^{-1}\)) is a constant of the first-order extraction rate and \( t \) (min) is the extraction time. Furthermore, Equation (2) built into the boundary condition \( q_t = 0 \) and \( t = 0 \), and \( q_t \) at \( t = t_0 \):

\[
\ln \left( \frac{q_o}{q_o - q_t} \right) = k_1 t \tag{3}
\]

The obtained equation (3) can be translated in linear form as follows:

\[
\log(q_o - q_t) = \log(q_o) - \frac{k_1}{2.303} t \tag{4}
\]

2.3.2. Extraction second-order model. The second-order kinetics equation for the Ho et al. (2005) [23] extraction rate can be written as follows:

\[
\frac{dC_t}{dt} = k_2(q_o - q_t)^2 \tag{5}
\]

Where \( k_2 \) (L.g\(^{-1}.min\(^{-1}\)) is a constant of the second-order extraction rate.

It is obtained by grouping variables into Equation (5):

\[
\frac{dq_t}{(q_o - q_t)^2} = k_2 dt \tag{6}
\]

\[
\frac{1}{C_s - C_t} - \frac{1}{C_s} = k_2 t \tag{7}
\]

\[
C_t = C_s - \frac{C_s}{1 + C_s k_2 t} \tag{8}
\]

\[
C_t = \frac{c_s^2 k_2 t}{1 + c_s^2 k_2 t} \tag{9}
\]

Equation (9) is the standardized formula for second order extraction rates

\[
\frac{t}{q_t} = \frac{1}{q_o^2 k_2} + \frac{t}{C_s} \tag{10}
\]

The extraction rate \( (q_t/t) \) can be obtained from Equation 11 as follows:

\[
\frac{q_t}{t} = \frac{1}{(\frac{1}{q_o^2 k_2})t(\frac{1}{q_o})} \tag{11}
\]

And the initial extraction rate \( h \) may be described as follows: \( q_t = t \) when \( t \) reaches 0,

\[
h = k_2q_o^2 \tag{12}
\]

Equation (9) can be changed again so that it can be finally found:

\[
\frac{t}{q_t} = \frac{t}{q_o} + \frac{1}{h} \tag{13}
\]
### Table 1: Hydro-distillation kinetics models of essential oil

| Kinetics model       | Kinetics equation          | Linearized form of equation               |
|----------------------|----------------------------|------------------------------------------|
| First-order model    | \( \frac{dq_t}{dt} = k_1 (q_0 - q_t) \) | \( \log(q_0 - q_t) = \log(q_0) - \frac{k_1}{2.303} t \) |
| Second-order model   | \( \frac{dq_t}{dt} = k_1 (q_0 - q_t)^2 \) | \( \frac{t}{q_t} = \frac{t}{q_0} + \frac{1}{n} \) |

### 3. Results and discussion

Water was used as the solvent in the ginger EOs extraction process. The amount of EOs recovered quickly at the beginning and decreased slowly once the extraction process finished. Figure 1 illustrates the resulted yield of ginger oil. The curve indicates that the oil efficiency increased proportionally with distillation time, then remained constant after 90-120 min. The maximum yield achieved 0.5% (v/w, v/100g materials) at the optimal point of the extraction process. Hydrodistillation method has also been used to extract EO from jasmine and rosemary, resulting in a lower oil yield of 0.092% and 0.44%, respectively, as compared to ginger [23, 24]. The obtained oil was used to perform kinetic study.

As can be seen from Figure 1, the initial process rate occurred quickly in the first 20 min and slowed down until it reaches the saturation state. There were two different stages in this process. Firstly, the process of rapid oil distillation (washing phase), the EOs is washed from the outside surface of the materials. The advantages of this stage was a significant increase in EOs at the beginning of the extraction process. Secondly, essential oil is then swept away by the distillation process. The characteristic of this stage is the slow increase in the extraction process until constant [25]. The ginger oil yield obtained after extraction process reached 0.5% at 90 min. From 90 min onwards, the amount of EOs obtained was insignificant change. The tendency to retrieve essential oils from the extraction phase reached 80% in the 45 min extraction period, 10% over the next 20 minutes and 10% in the last minutes of the extraction cycle.

![Figure 1. The yield of ginger oil obtain at any time t.](image)

### 3.1. First order model of extraction

The linear form of equation 2 versus time is used to evaluate the proposed kinetic models and extraction phase. The first-order kinetic model is shown through \( \log(q_0 - q_t) \) vs with \( t \). Table 2 shows the parameters of the model, such as \( k, q_0 \) and the determination coefficient were calculated from the slop and chart intercept. The results show that the determination coefficient of the model is relatively low (0.856 of \( R^2 \))
value). Moreover, Figure 2A showed that the linearization is better at the first stage than the later stage. The first-order model is therefore not appropriate for the description of the data from this extraction method. This is in close agreement with previous research in which first-ordered model was not suitable for characterizing multiple-mechanism water hydrositillation extraction process [21, 26, 27].

3.2. Second order model of extraction

The process of extraction is composed of various mechanisms. The linear form of the second kinetic model is therefore used for further study of the process. Similar to the previous survey, a graph of t/qt versus t has been established. The kinetic parameters of the process such as the initial extraction rate (h), the amount of EOs (q0), the extraction rate (k) and the determination coefficient (R²) are calculated based on the linear in Figure 2B. The slope is equal to 1/Cs, and intercept is equal to 1/h. As shown in Table 2, the second kinetic model of ginger EOs extraction process has a very high determination coefficient (0.994), which is higher than the first model (0.856). Therefore, a second model can be used to describe the experimental data of ginger essential oil extraction process. This finding was similar to citronella and *Citrus sinensis* oils [28, 29] This model fully demonstrates the mechanism of the extraction process, consisting of two stages of simultaneous washing and extraction. From Figure 1 it can be seen that at first the process performance rises quickly (phase 1), then the performance increases gradually (phase 2) before the limit or constant value is achieved. It can be concluded that the second model was chosen to describe the process kinetic with the extraction rate constant was 0.1001 L.g⁻¹.min⁻¹.

| Table 2. Linearization of first-order kinetic model of hydro-distillation of ginger |
|----------------------------------|----------|----------|----------|
|                                  | q₀       | k        | R²       |
| First-order                      | 0.2531   | 0.0308   | 0.8558   |
| Second-order                     | 0.5761   | 0.1001   | 0.99355  |

**Figure 2.** First order (A) and second order (B) extraction kinetics of ginger oil

4. Conclusions

Extraction of essential ginger oil by hydrodistillation method was experimentally tested in this study. The results were tested by using linear regression equation on two kinetic models. These models were established to assess the correlation of experimental data of the extraction process. As compared to recent studies, the results showed that the quadratic model is most suitable to describe the process of ginger oil extraction with R² coefficient of 0.99355 and extraction rate constant of 0.1001 L.g⁻¹.min⁻¹.
Acknowledgements
This research is funded by Vietnam Academy of Science and Technology with Project code NG 0001/19-20.

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