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RESEARCH ARTICLE

Scale-Up Extraction of *Zingiber officinale* and *Zingiber zerumbet* Using a Turbo Extractor Distillator (TED) by Applying Constant Mass Transfer Coefficient

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Abstract The scale-up studies of *Zingiber officinale* and *Zingiber zerumbet* extraction process were performed by investigating the constant mass transfer coefficient, *kLa* values in a 2L lab-scale. After determining the values of *kLa* on the 2L lab-scale by using Enhanced Diffusion Solid-Liquid Extraction (EDSLE) model , the limitations for the operating parameters in the 200L pilot-scale Turbo Extractor Distillator (TED) were computed. Impeller speeds, 200-600 rpm for 2L lab-scale and 50-500 rpm for 200L pilot-scale were manipulated to provide a condition similar to the 2L lab-scale. The optimal scale-up extraction conditions for *Zingiber officinale* were 90 minutes, 1:20 solid-to-solvent ratio, and 520 µm (powdered) particle size, while for *Zingiber zerumbet*, 90 minutes, 1:20 solid-to-solvent ratio, and 710 µm (powdered) particle size. By adjusting the operation speed, the 400-rpm speed gave the best fit with the highest R-squared above 0.9997 at the same time a constant *kLa* was kept as low as possible at both scales, 29.9769 m/min t 2L lab-scale and 28.5432 m/min at 200L pilot-scale. These results indicate that the model can be used to predict and describe the scale-up of the extraction process while maintaining process efficiency, providing a systematic approach to optimize large-scale herbal extraction with controlled operating parameters and reproducible results.

Keywords: Zingiber zerumbet, Zingiber *officinale*, scaling up, mass transfer coefficient, turbo extractor distillatory.

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Introduction

The herbal industry in Malaysia is experiencing significant growth due to increasing consumer demand for natural-based traditional medicines and wellness products. *Z. officinale* and *Z. zerumbet* are among the key medicinal plants contributing to this industry, widely utilized in health supplements, cosmetics, and functional foods. The market trend for both plants has shown positive growth, particularly in the production of essential oils and herbal extracts, driven by their broad medicinal applications and consumer preference for plant-based remedies [1,2].

Zingiber officinale (Z. officinale), also known as ginger, and *Zingiber zerumbet (Z. zerumbet),* commonly referred to as shampoo ginger, are two significant members of the *Zingiberaceae* family. *Z. officinale* contains key bioactive compounds such as gingerols (mainly 6-gingerol), shogaols, and zingerone, while *Z. zerumbet* is primarily characterized by the presence of zerumbone [3,4]. Both plants have been extensively studied for their therapeutic activities, with *Z. officinale* demonstrating anti-inflammatory, antioxidant, antimicrobial, neuroprotective, anticancer, cardiovascular protective, anti-obesity, respiratory protective, antidiabetic, antiemetic, and chemo-preventive properties [5-8]. Similarly, *Z. zerumbet* has been recognized for its anti-inflammatory, anticancer, antimicrobial, and antioxidant activities, among other pharmacological benefits [9-12].

Despite the growing demand, the extraction of herbal bioactive compounds still faces significant challenges, particularly in scaling up production. Herbal extracts are typically produced in small-scale operations due to limited scientific data, inadequate processing facilities, and high costs associated with large-scale manufacturing. Additionally, maintaining the quality and yield of extracts when transitioning from small to large-scale production remains a critical issue. Understanding the mass transfer mechanisms involved in extraction is essential to optimize the process, ensuring high-yield and high-quality herbal extracts [13,14].

One of the key aspects of improving extraction efficiency is the application of advanced extraction technologies. Turbo Extractor Distillator (TED) is an innovative device that integrates grinding, extraction, and distillation into a single system, enhancing the efficiency of essential oil production. Compared to conventional methods, TED significantly reduces processing time, improves energy efficiency, and ensures better yield consistency. The application of TED in extracting *Z. officinale* and *Z. zerumbet* bioactive compounds provides a promising approach for optimizing large-scale production [15].

An essential parameter in the extraction process is the mass transfer coefficient (*kLa*), which influences the rate at which bioactive compounds are transferred from plant material to the solvent. Understanding the mass transfer coefficient is crucial for designing efficient industrial-scale extraction processes, as it impacts both product yield and quality. Previous studies have utilized mathematical modeling to describe mass transfer dynamics in herbal extraction, providing insights into scaling-up strategies for efficient large-scale operations [16,17].

This study aims to develop a simple and reliable scaling-up approach for the extraction of crude *Z. officinale* and *Z. zerumbet* using TED. The study compares the mass transfer coefficient (*kLa*) values at different scales (2L lab-scale and 200L pilot-scale) to determine an appropriate scaling factor. A trial-and-error method was employed to refine the scaling-up parameters within the expected range, ensuring optimal extraction efficiency for large-scale production.

Materials and Methods

Preparation of Raw Materials

The rhizomes of *Z. officinale* and *Z. zerumbet* were obtained from a certified supplier. Fresh rhizomes were first washed with distilled water to remove dirt and contaminants, ensuring the purity of the raw materials. The cleaned rhizomes were then sliced into thin pieces and dried at 40°C using a hot-air oven until they reached a stable weight. Once dried, the samples were finely ground using a mechanical grinder to increase the surface area for extraction. The powdered samples were sieved to obtain uniform particle sizes of 520 μm for *Z. officinale* and 710 μm for *Z. zerumbet*, and stored in airtight containers at room temperature until further use.

Extraction Process Using TED

The extraction process was conducted using TED, a high-efficiency system designed to improve mass transfer between solid and liquid phases. The experiment used distilled water as the solvent, selected due to its safety, affordability, and effectiveness in extracting essential bioactive compounds. The solid-to-solvent ratio, particle size, and extraction duration were carefully optimized based on preliminary experiments to ensure maximum yield. The extraction time was standardized at 90 minutes for both the 2L lab-scale and 200L pilot-scale extractors to maintain consistency in the process. To achieve an efficient scale-up process, a scaling-up protocol was implemented to maintain a constant mass transfer coefficient (*kLa*) across different scales. The scale-up approach was adapted from Alam and Razali (2005) [18] with modifications to suit TED. The primary goal was to ensure that the conditions in the 2L lab-scale and 200L pilot-scale extractors remained comparable, particularly in terms of mixing efficiency and mass transfer.

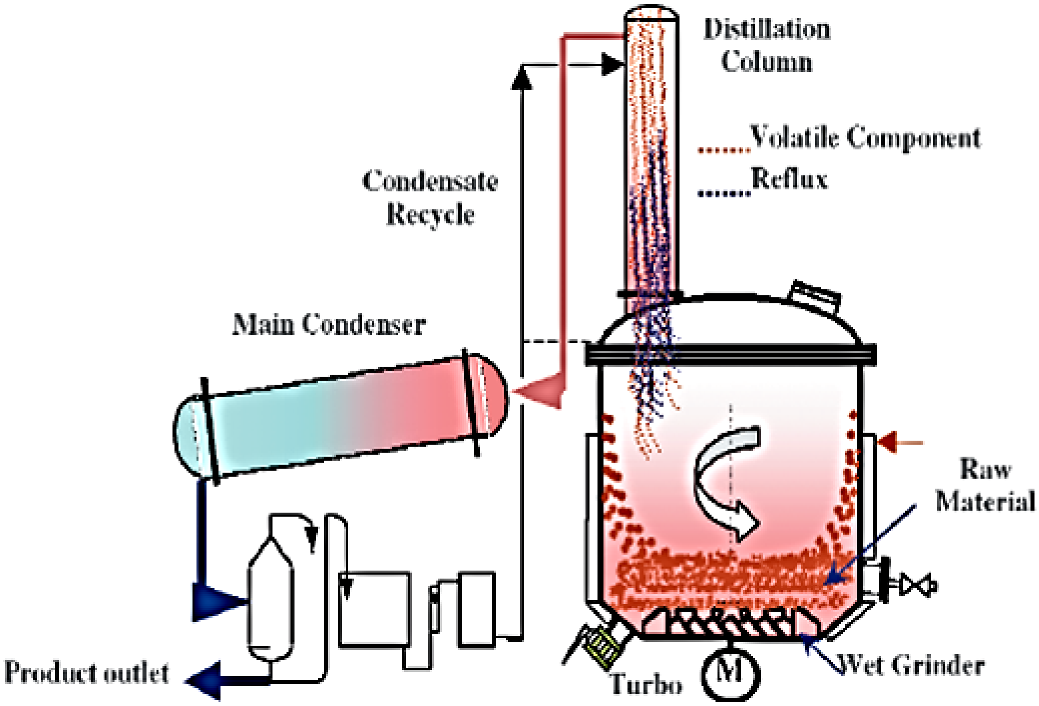

Figure 1. Mechanism/ process of turbo extractor distillator [15]

Identification of Marker Compound using High Performance Liquid Chromatography (HPLC)

HPLC analysis of zerumbone and 6-gingerol was performed using a Waters system (2487 Dual λ Absorbance Detector, 2690 Separation Module) equipped with an online degasser, binary pump, PDA detector, auto-sampler, and a Luna 5u C18(2) 100 Å column (4.6 mm × 150 mm, 5 µm). Isocratic elution was carried out for 9 minutes using a mobile phase of 0.01 M potassium dihydrogen phosphate (20%), acetonitrile (25%), and methanol (55%), which was freshly prepared, filtered (0.45 µm), and sonicated before use. The PDA detector was set at 230 nm for zerumbone and 282 nm for 6-gingerol, based on their maximum absorbance values. Stock solutions of zerumbone and 6-gingerol (purity ≥ 98%) were prepared in methanol (1 mg/mL) and diluted to 4–20 µg mL^{-1}. Essential oil samples were diluted (1:3, v/v) with methanol and filtered (0.45 µm) before injection [19-21].

Scaling-Up Protocol

Scaling up an extraction process involves maintaining similarity between the experimental prototype and its larger-scale counterpart [22]. This is achieved by ensuring that key hydrodynamic parameters, such as impeller speed and Reynolds number, remain consistent. The scale-up process began with determining the *kLa* values in a 2L lab-scale. Once these values were established, the corresponding operational parameters for the 200L pilot-scale TED were calculated. The scaling process needs the use of the rule of thumb, trial and error, interpolation, and extrapolation techniques as the scale grows and the value of *kLa* stays constant. Figure 2 shows a diagram of the protocol. To provide a similar condition to the 2L lab-scale, the impeller speeds were varied (200-600 rpm for 2L lab-scale and 50-500 rpm for 200L pilot-scale).

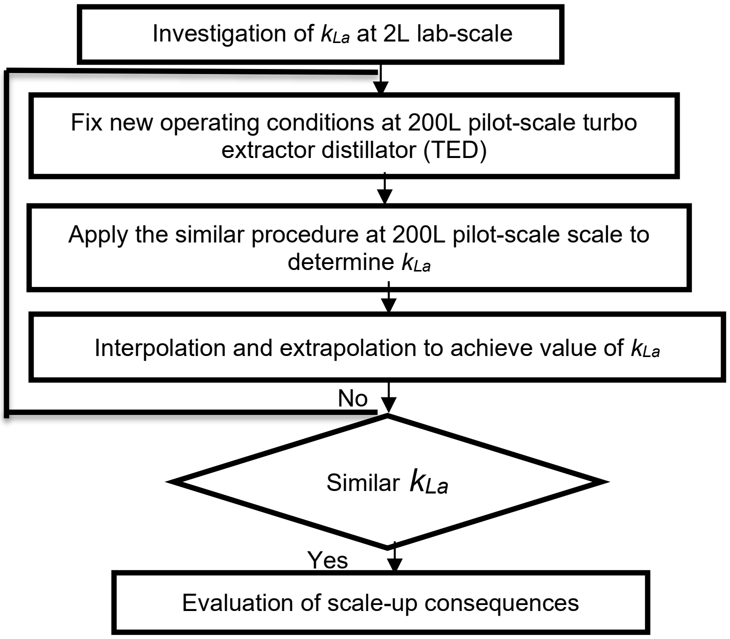

Figure 2. Protocol for scaling up based on, $k_{La.,}$ constant mass transfer coefficient Adaptation from Alam and Razali (2005) [18]

The impeller speeds were determined using the following equation:

$$\text{Impeller tip speed} = N_2 = N_1 (\frac{D_1}{D_2})^{\frac{2}{3}} \tag{1}$$

where N_1 and N_2 are the impeller speeds at 2L lab and 200L pilot-scale in rev/s, respectively, and D_1 and D_2 are the vessel diameters in meter (m). By using this equation, the impeller speeds at the 200 L scale were adjusted to match the *kLa* values obtained at the 2 L scale, ensuring a uniform mass transfer rate. To further evaluate the mixing efficiency, the Reynolds number was calculated using:

$$\text{Reynold number} = N_{RE} = \frac{\mathrm{N}D^2\rho_L}{\mu_L} \tag{2}$$

where ρL represents the density of the solvent in kg/m^3, and μL denotes the dynamic viscosity of the solvent in kg/ms^2. These calculations helped determine whether the mixing regime remained consistent across scales.

Additionally, the hydrodistillation rate was assessed using the formula:

$$\text{Hydrodistillation rate} = \frac{Weight\ of\ sample\ collected\ at\ time,t}{Time\ of\ sample\ collected,t} \tag{3}$$

where t is the extraction duration, expressed in minutes. This parameter was crucial in comparing the efficiency of the extraction process at different scales.

Dimensions and Operating Parameters

To ensure a systematic scale-up process, the dimensions and operating parameters of the extractors were carefully analyzed. The impeller type and configuration were maintained across both scales, with turbine-type impellers used in both the 2L lab-scale and 200L pilot-scale extractors. The number of impellers was adjusted accordingly, increasing from three in the 2L lab-scale extractor to six in the 200L pilot-scale extractor to maintain effective mixing. A detailed comparison of the extractor dimensions is presented in Table 1, while Table 2 summarizes the impeller speeds used during the trials.

Table 1. The dimensions of the extractor at 2L lab-scale and 200L pilot-scale

Dimension	2L lab-scale	200L pilot-scale
Total volume, V_T (m^3)	0.0020	0.2000
Working volume, V_L (m^3)	0.0016	0.0800
Vessel height, H_T (m)	0.1650	0.6850
Liquid Height, H_L (m)	0.1200	0.2740
Vessel diameter, D_T (m)	0.1150	0.6350
Surface area, a_s (m^2)	0.0804	1.9999
Impeller type	Turbine	Turbine
Number of impellers	3	6
Impeller diameters, D_i (mm)	40.0000	460.0000
Impeller thickness, T_i (mm)	1.0000	10.0000
Impeller width, W_i (mm)	8.0000	50.0000
Ratio impeller to vessel diameter	1:3	1:3
Spacing between impeller (m)	0.0150	0.1000

Table 2. Operating parameters at 2L lab-scale and 200L pilot-scale

Scale	Impeller speed, N (rpm)
2L lab-scale	200 - 600
200L pilot-scale (1st trial)	50 - 250
200L pilot-scale (2nd trial)	300 - 500

Mathematical Model for Extraction Kinetics

To describe the mass transfer process in TED, Enhanced Diffusion Solid-Liquid Extraction (EDSLE) model was used [23]:

$$V_L = \frac{dC_L}{d_t} = AkLa\,[C_e - C_L\,(t)] \tag{4}$$

where V_L represents the volume of solvent (cm^3), C_L represents the solute concentration in the liquid phase at a time, *t* (gcm^{-3}), C_e represents the equilibrium solute concentration in the liquid phase, *A* represents the total surface area of the solids (cm^2), and k_{La} represents the mass transfer coefficient (cms^{-1}). The model assumes that mass transfer occurs due to concentration gradients, with no internal diffusion within the solid particles. By rearranging and integrating the equation, the solute concentration over time is expressed as:

$$C_L(t) = C_e\,[1 - e^{\frac{-Akla}{V_L}t}] \tag{5}$$

where A is total surface area of the particles is given as:

$$A = M\sigma \tag{6}$$

with *M* represents the mass of solid particles (g) and σ represents the specific surface area of the solid (cm^2g^{-1}). The ratio of solvent to solid (R_{ss}) was also considered to ensure process consistency:

$$Rss = \frac{M}{V_L} \tag{7}$$

Model Validation and Data Analysis

To validate the model, experimental data were compared with predicted values using the coefficient of determination (R^2):

$$\boldsymbol{R^2} = \mathbf{1} - \left[\frac{\sum_{n=1}^{N}(c_{L_{exp,n}} - c_{L_{pred,n}})^2}{\sum_{n=1}^{N}(c_{L_{exp,n}} - c_{L_{pred,n}})^2}\right] \tag{8}$$

A value of R^2 near to unity indicates a better fit between the experimental and anticipated data. The model parameters (Ce and K) were estimated using Microsoft Excel's Solver function.

Results and Discussion

The scale-up equations were used to establish the minimum and the maximum value of the operating variables (impeller speeds) as the extractor scaled up from 2L lab-scale to 200L pilot-scale using a constant k_{La}. Figures 3 and 4 show the fitting plot for the 2L lab-scale model at different speed for *Z. officinale* and *Z. zerumbet* respectively. Table 3 shows the results for determining the mass transfer coefficient.

Table 3. The results for the 2L lab-scale model for different speed

Material	Speed (rpm)	k_{La} (m/min)	Ce (mg/ml)	Hydrodistillation rate (ml/min)	R^2
Z. officinale	200	17.5930	0.7219	0.0393	0.9991
	400	29.9769	0.7015	0.0470	0.9999
	600	14.9003	0.7374	0.0217	0.9995
Z. zerumbet	200	8.8293	2.8046	0.0173	0.8704
	400	21.7714	3.4523	0.0347	0.9997
	600	16.0836	3.2603	0.0280	0.9885

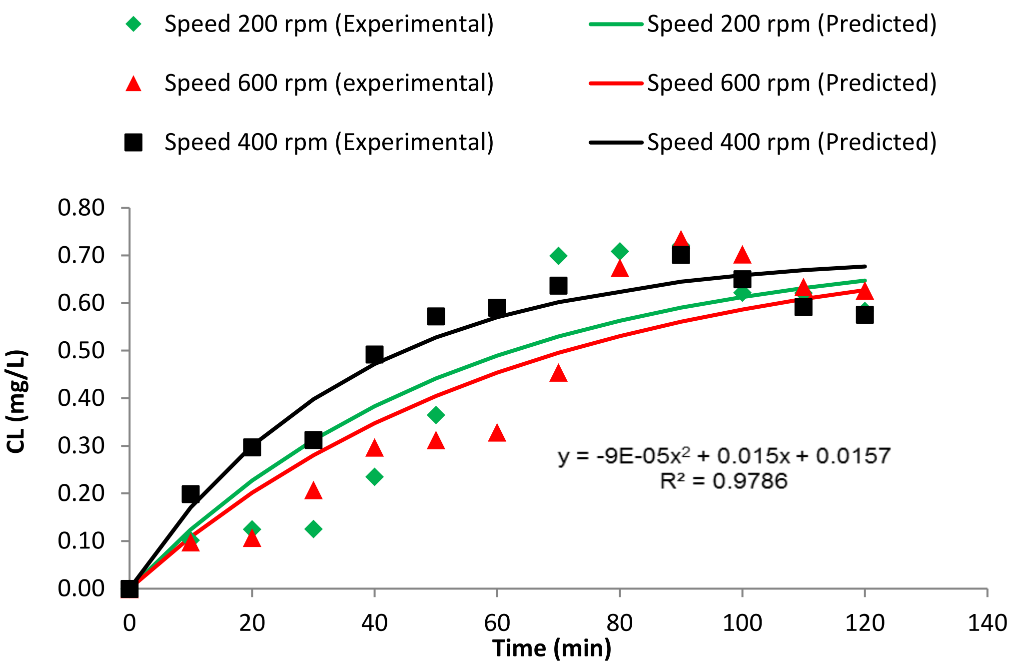

Figure 3. The fittings plot for the 2L lab-scale model for different speed (*Z. officinale*)

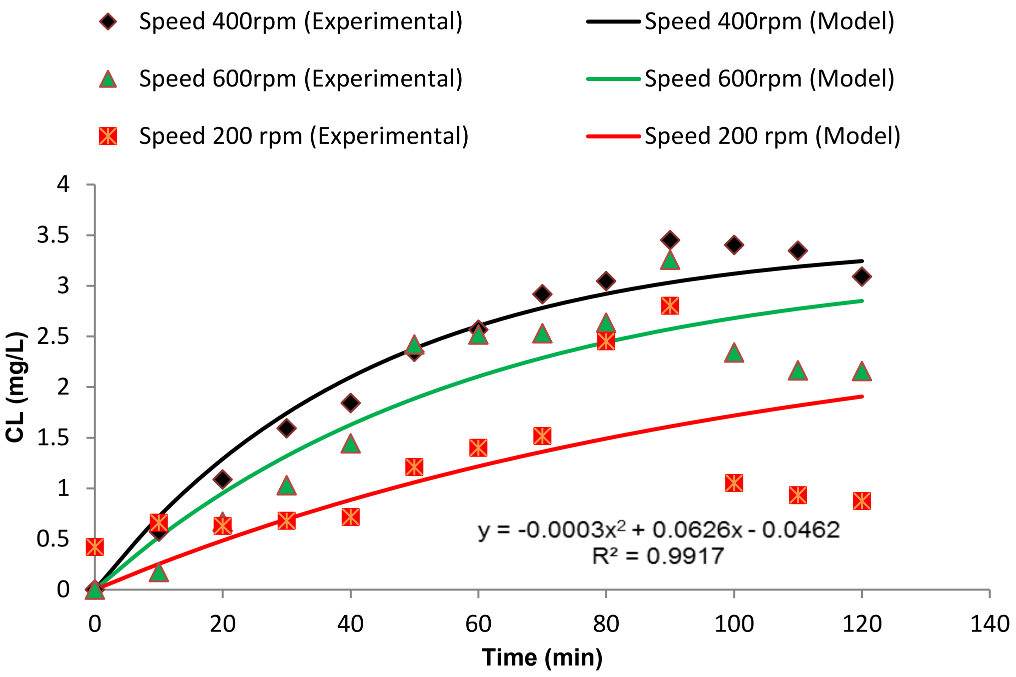

Figure 4. The fittings plot for the 2L lab-scale model for different speed (*Z. zerumbet*)

The variation in mass transfer coefficient (*kLa*), hydrodistillation rate, and equilibrium concentration (Ce) observed at different impeller speeds (200, 400, and 600 rpm) reflects the intricate balance between mixing intensity, mass transfer efficiency, and extraction kinetics. These fluctuations can be attributed to the dynamic interaction between fluid motion, turbulence, and the rate at which the solute is transferred from the solid phase to the solvent. At lower speeds, inadequate turbulence may limit the effective contact between phases, reducing mass transfer efficiency. Conversely, excessively high speeds may lead to vortex formation, increased bubble coalescence, and decreased interfacial area, which ultimately reduces the effectiveness of mass transfer [24].

The mass transfer coefficient (*kLa*) demonstrated a non-linear trend, with the highest value observed at 400 rpm (29.9769 m/min), followed by a decline at 600 rpm (14.9003 m/min). This trend is consistent with previous studies suggesting that an optimal range of agitation exists beyond which further increases in impeller speed result in a decline in mass transfer efficiency due to turbulence-induced instability. The hydrodistillation rate followed a similar pattern, peaking at 400 rpm (0.0470 ml/min) before decreasing at 600 rpm (0.0217 ml/min). This suggests that enhanced solvent penetration and contact with the solid matrix at moderate agitation speeds improve extraction efficiency, but excessive agitation can lead to particle attrition and reduced efficiency [25].

Interestingly, the equilibrium concentration (Ce) of extracted solutes did not follow a strictly linear relationship with impeller speed. Ce decreased slightly at 400 rpm (0.7015 mg/L) before rising again at 600 rpm (0.7374 mg/L). The decline at 400 rpm indicates an optimal mass transfer rate, where the system reaches equilibrium more efficiently. However, the increase at 600 rpm may be due to incomplete solute diffusion caused by turbulent flow, disrupting uniform extraction conditions [26]. These findings highlight the importance of selecting appropriate mechanical agitation parameters to balance mass transfer efficiency and extraction kinetics.

The scaling-up process from a 2L lab-scale to a 200L pilot-scale extractor required careful evaluation of operating conditions to maintain comparable *kLa* values. The initial trials at 200 and 600 rpm resulted in *kLa* values significantly lower than those at 400 rpm, indicating that the selected speed range influenced mass transfer efficiency at a larger scale. By adjusting operating speeds and employing interpolation and extrapolation techniques, similar *kLa* values were achieved at both scales. This approach aligns with previous research on scale-up methodologies, which emphasize maintaining geometric similarity and adjusting hydrodynamic parameters to ensure process reproducibility.

The scaling-up factor calculations further confirmed that similar hydrodynamic conditions could be achieved across different scales. The impeller Reynolds number and mass transfer coefficients were used to characterize extraction conditions, revealing that the process remained efficient despite changes in vessel dimensions. The consistency in *kLa* trends between the 2L lab and 200L pilot scales indicates that extraction behavior can be effectively modeled and predicted for industrial applications. These findings reinforce the importance of optimizing process parameters to enhance extraction efficiency while ensuring reproducibility at a larger scale.

As shown in Figures 5 and 6, *kLa* dependence on the operating variables was almost identical in both scales. Nevertheless, to examine the closeness of the slope between the graphs, the *kLa* in both scales was compared. A change in solute concentration in the liquid phase is illustrated in Figures 5 and 6 with respect to the extraction speed. This indicates that the extraction process was rapid at first, but slowed down as it approached equilibrium. As soon as the process reached equilibrium, the hydrodistillation rate of extraction decreased. It was found that the extraction of *Z.officinale* and *Z.zerumbet* is a rapid process that requires approximately 90 minutes to complete.

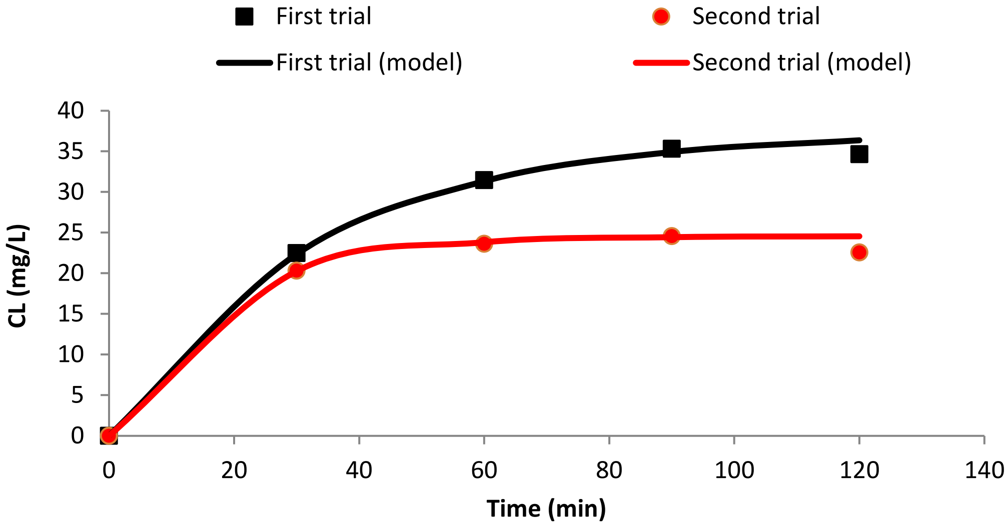

Figure 5. The fittings plot for the pilot-scale model for different impeller speed *(Z. officinale)*

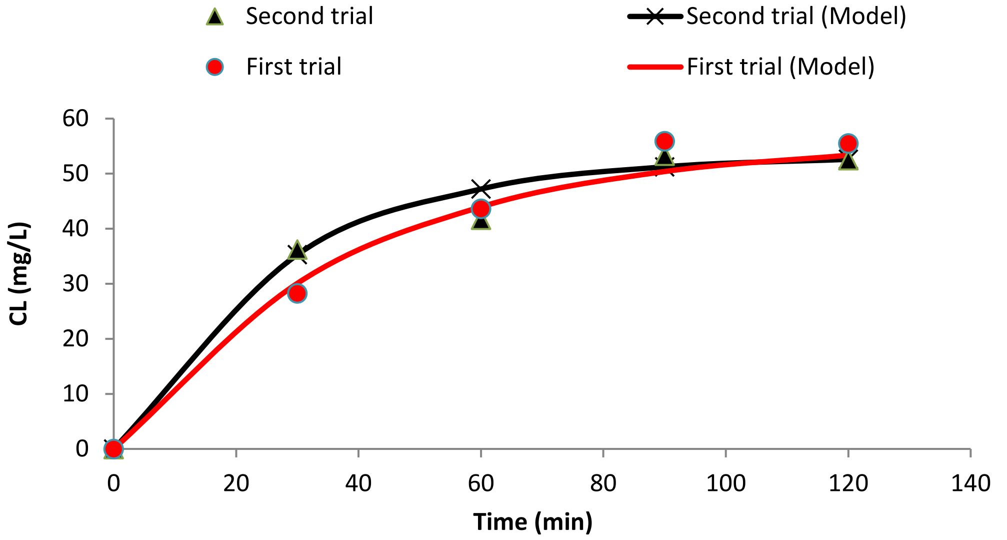

Figure 6. The fittings plot for the pilot-scale model for different impeller speeds *(Z. zerumbet)*

As shown in Table 4, the optimum values of *Ce,kLa*, and hydrodistillation rate for EDSLE are summarized with their R^2 values. The first trial (50-250 rpm) for both herbs represents a better fitting plot than the second trial (300-500 rpm) with *kLa* (28.3237 m/min for *Z. officinale* and 23.946 m/min for *Z. zerumbet*).

Table 4. The results for the 200L pilot-scale model for different speed

Material	Trial	k_{La} (m/min)	Ce (mg/L)	Hydro distillation rate (ml/min)	R^2
Z. officinale	1st (50-250 rpm)	28.3237	37.3315	0.0533	0.9990
	2nd (300-500 rpm)	53.9457	24.5758	0.0333	0.9971
Z. zerumbet	1st (50-250 rpm)	23.9460	55.9000	0.0625	0.9315
	2nd (300-500 rpm)	33.6330	53.3000	0.0517	0.9381

Table 5. Summary of scale-up calculations

Parameters	*Z. officinale*		*Z. zerumbet*	
	2L lab-scale	200L pilot-scale	2L lab-scale	200L pilot-scale
Tank diameter (m)	0.1150	0.6350	0.1150	0.6350
Impeller diameter (mm)	40	430	40	430
Mixer speed (rpm)	400	82	400	82
Particle size of (µm)	520	520	710	710
Solid-to-solvent ratio	1:20	1:20	1:20	1:20
Duration (hr)	1.5	1.5	1.5	1.5
Volume (L)	2	200	2	200
Yield of marker (%)	0.1315	0.2120	0.2158	0.3354
Reynold number	1.0616×10^5	2.5148×10^6	4.6611×10^4	1.1042×10^6
Equilibrium Concentration, Ce (mg/L)	0.7015	37.3315	3.4523	55.9
Hydro distillation rate (ml/min)	0.0470	0.0533	0.0347	0.0625
Mass transfer coefficient, k_{La} (cm/min)	29.9769	28.3237	21.7714	23.946

Conclusions

This study successfully demonstrates the scale-up of TED extraction for *Z. officinale* and *Z. zerumbet* by maintaining a consistent mass transfer coefficient (*kLa*). The developed protocol ensures process reproducibility, with minimal variation in *kLa* values between the 2L lab-scale (29.9769 m/min at 400 rpm) and the 200L pilot-scale (28.5432 m/min at 400 rpm). This consistency highlights the effectiveness of the scale-up strategy in preserving extraction efficiency. The findings imply that maintaining an optimal *kLa* is crucial in ensuring uniform extraction performance across different scales, reducing process variability, and enhancing industrial feasibility. Future studies can explore additional parameters, such as solvent selection, temperature optimization, and real-time process monitoring, to further refine and improve extraction efficiency while ensuring sustainability and cost-effectiveness in large-scale applications.This study demonstrates the successful scale-up of TED extraction for *Z. officinale* and *Z. zerumbet* by maintaining a constant mass transfer coefficient. The developed protocol ensures process consistency and efficiency, with minimal variation in *kLa* values between scales. Future studies can explore optimization of additional parameters, such as solvent type and temperature, to further enhance extraction efficiency.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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