Chemical Papers
https://doi.org/10.1007/s11696-024-03509-z

ORIGINAL PAPER

Comparative simulation studies on the countercurrent multi-stage solid–liquid extraction of soybean oil by ethanol and hexane

Temitope A. Oshin[1,2] · **Kingsley E. Abhulimen**[3] · **Jerry C. Abadi**[1] · **Timothy A. Adekanye**[4]

Received: 30 December 2023 / Accepted: 6 May 2024

Abstract

This study addresses the need for a more environmentally friendly and sustainable alternative to hexane, the conventional solvent for oil extraction. Hexane, while efficient in dissolving oil, poses neurotoxicity risks and stems from nonrenewable sources. In contrast, ethanol, produced via biotechnological methods, offers a promising alternative due to its minimal environmental impact, cost-effectiveness, and safety profile. The objective of this work is to compare the performance of hexane and ethanol in the extraction of soybean oil, employing simulation techniques rather than traditional laboratory experiments. The research develops a mathematical model for a countercurrent multistage solid–liquid extraction process, specifically tailored for soybean oil extraction, and simulates the process using MATLAB/SIMULINK. The results reveal that hexane exhibits a higher initial extraction rate, especially over a 90-min simulation period, though ethanol demonstrates comparable efficiency. Moreover, ethanol consistently showcases higher extraction efficiency relative to hexane when considering solvent-to-solid mass ratios. In conclusion, both hexane and ethanol extraction prove practical with ethanol holding advantages in terms of safety and extraction efficiency. These simulation findings serve as a valuable foundation for subsequent laboratory experiments which can contribute to the validation and refinement of the simulation model.

Keywords Leaching · Soybean oil · Oil extraction · Modeling · Simulation · Ethanol · Hexane

Introduction

Solid–liquid extraction, also known as leaching, is a process whereby a solid is brought in contact with a liquid (solvent) in order to extract desired solute constituents from the solid phase. Leaching is widely used in the biological, pharmaceutical and food processing industries. In the pharmaceutical industry, many products are obtained by leaching plant roots, leaves, and stems (Gworek et al. 2021; Özçelik et al. 2024). In the food processing industries, vegetable oils (which are commonly consumed by humans every day and are used for cosmetic and pharmaceutical purposes) are extracted by solvents by leaching processes of pretreated oil seeds (Ghouila et al. 2019). Examples include the extraction of oils from peanuts, sunflower seeds, cotton seeds and soybeans.

Soybean protein has a variety of industrial applications, including wood adhesives, polymers, textile fibers, and paper coatings. Soybean oil is frequently seen as being too viscous and reactive to air oxygen to be employed in fuels, cosmetics, lubricants, and chemical additives, but not reactive enough for the majority of paint and coating applications (Johnson and Myers 1995). Continued improvement in industrial soybean processing and efficiency has helped soybeans remain an important substrate for foods, feeds, fuels, and bio-based materials (Gaonkar and Rosentrater 2019).

Globally, vegetable oils are part of the traditional food chain for humans, though some researchers are discovering growing applications for biodiesel from them by transesterification (Issariyakul and Dalai 2014; Lin et al. 2009). Soya beans or soybeans is considered in this study

✉ Temitope A. Oshin
oshin.temitope@lmu.edu.ng; temitope.oshin@mavs.uta.edu

[1] Department of Chemical Engineering, Landmark University, P.M.B. 1001, Omu-Aran, Kwara State, Nigeria

[2] Landmark University SDG 9 Research Cluster (Industry, Innovation and Infrastructure), P.M.B. 1001, Omu-Aran, Kwara State, Nigeria

[3] Department of Chemical Engineering, University of Lagos, Akoka, Yaba, Lagos, Nigeria

[4] Department of Agricultural and Biosystems Engineering, Landmark University, P.M.B. 1001, Omu-Aran, Kwara State, Nigeria

due to its health benefits, which include preventing heart attack and stroke, helping to fight cancer, aiding the digestive system, helping with good blood circulation and helping to treat insomnia. Furthermore, in the case of the development of biodiesel, vegetable oils have several advantages over petroleum fuel, which are: (i) local availability (ii) renewability (iii) relatively high heating value (iv) lower sulfur content with minimum pollution (v) lower aromatic content (vi) high biodegradability (Atabani et al. 2013). The use of vegetable oil also reduces particulate emissions from the diesel engine (Li et al. 2013).

In this study, hexane and ethanol will be considered in the soybean oil extraction process. The two solvents will be compared, via simulation, to see how they will behave in the extraction process. Other solvents that can be used for oil extraction are carbon dioxide, petroleum ether, acetone, benzene, etc. The most widely used solvent for extraction is hexane (chemically made from crude oil) due to its high stability, maximum ability to dissolve oil, and its reasonable volatility which aids easy removal using low energy. However, the major disadvantage of hexane is that it is not environmentally friendly (Hammond et al. 2005). Considering the health of the public, industries are looking for a better substitute that will reduce pollution in the environment (Rai et al. 2015). Ethanol was introduced due to its advantage from an environmental point of view. Ethanol is not harmful to the environment and it is less costly. However, one issue with ethanol is that more energy is required for the separation of ethanol from oil. Nonetheless, due to its partial miscibility with oils at room temperature, after high-temperature extraction and subsequent cooling, ethanol allows two liquid phases to be built (an alcohol-rich phase and an oil-rich phase), which is particularly beneficial for subsequent processing. Hence, it is necessary to evaluate the effectiveness and efficiency of each of these two solvents relative to the other.

Solid–liquid extraction is a fundamental process in the production of soybean oil, an essential component in the food industry. Mathematical modeling plays a crucial role in understanding and optimizing this process, aiding in the design of efficient extraction systems. Some recent studies have focused on developing comprehensive mathematical models to elucidate the complex mechanisms involved in soybean oil extraction. Comerlatto et al. (2021) proposed a mathematical model based on the mass transfer kinetics of solvent penetration into soybean seeds. The model accounted for diffusion, external and internal mass transfer resistances, and solvent solubility, providing insights into the optimal extraction conditions. Although diverse works have modeled solid–liquid extraction, the novel use of mathematical modelling for dynamic studies for the countercurrent solid–liquid extraction of soybean oil, to achieve a comparative analysis of the two solvents, hexane and ethanol, is the unique contribution of this paper which is lacking in previous works.

Although the single contact batch operation is the easiest form of solvent extraction, where the solid to be leached and the solvent are combined and the solid phases of extract and raffinate are extracted, however, to use solvent more effectively and to create a more concentrated extract, countercurrent multistage contacting is often used. Multistage leaching experiments are expensive, so the use of simulation can help minimize costs. During experiments, when hexane is used, it causes some environmental issues but simulation will help to avoid the environmental issues. Simulation is very important to solve real-world problems safely and efficiently. It provides an important method of analysis that is easily verifiable, communicated, and understood. Across industries and disciplines, simulation modeling provides valuable solutions by giving clear insights into complex systems. Hence, the use of process simulation for this comparative study.

In order to achieve the objective of comparing the performance of hexane and ethanol as viable, efficient, and effective solvents for the extraction of soybean oil, this research paper will undertake the following objectives. Firstly, the mathematical model for the dynamic countercurrent multistage solid–liquid extraction process of oil from soybean would be developed. Secondly, MATLAB/SIMULINK would be used to carry out the simulation of the process and to study its dynamics or transient behaviour. Finally, the software would be used to compare and evaluate the use of hexane and ethanol for the extraction of oil from soybean.

Materials and methods

Dynamic process modelling

The foundation of any simulation problem is a mathematical model. In this section therefore, the governing equations for the countercurrent multistage leaching process are developed.

The nth stage of a typical countercurrent leaching process is depicted in Fig. 1

The variables and parameters used in this work are as listed in the table of nomenclature (Table 1) and their units.

Taking component mass balance for the solute (soybean oil)

$$\frac{d}{dt}\left(Hx_n + hy_n\right) = V_{n+1}x_{n+1} + L_{n-1}y_{n-1} - V_nx_n - L_ny_n \qquad (1)$$

Assuming constant molar overflow and underflow such that;

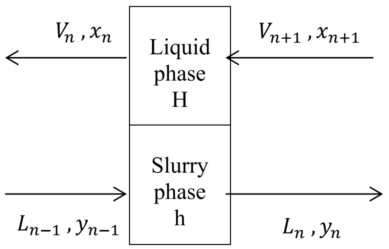


Fig. 1 Process flow diagram for stage n in a countercurrent multistage leaching process

Table 1 Nomenclature of symbols and their meanings

Symbol	Meaning	Units
n	Stage number	–
L	Underflow phase mass flow	kg/hr
V	Overflow phase mass flow	kg/hr
H	Liquid phase mass holdup	kg
h	Slurry phase mass holdup	kg
x	Mass fraction of the oil in the liquid phase	
y	Mass fraction of the oil in the slurry phase	
E	Extraction efficiency	
t	Time	hr
m	Equilibrium constant	
α	Constant defined in Eq. (12)	
β	Constant defined in Eq. (13)	
γ	Constant defined in Eq. (14)	
r_1	Solvent-to-solid mass ratio	
r_2	Liquid-to-slurry-phase-holdup mass ratio	
r_3	Underflow-to-slurry phase holdup ratio	
∀	Volume of solvent	m^3
ρ	Density of solvent	kg/m^3
ρ_{solids}	Density of soybean solids	kg/m^3

$$L_{n-1} = L_n = L_{n+1} = \mathrm{L} \tag{2}$$

$$V_{n-1} = V_n = V_{n+1} = \mathrm{V} \tag{3}$$

Substituting (2) and (3) into (1)

$$\frac{d}{dt}\left(Hx_n + hy_n\right) = \mathrm{V}x_{n+1} + \mathrm{L}y_{n-1} - \mathrm{V}x_n - \mathrm{L}y_n \tag{4}$$

Assuming constant hold-up of both the liquid and slurry phases, H and h are constant, such that

$$\mathrm{H}\frac{dx_n}{dt} + \mathrm{h}\frac{dy_n}{dt} = \mathrm{V}x_{n+1} + \mathrm{L}y_{n-1} - \mathrm{V}x_n - \mathrm{L}y_n \tag{5}$$

Assuming linear equilibrium relationship between the two phases:

$$y = mx \tag{6}$$

$$y_n = mx_n \tag{7}$$

$$y_{n-1} = mx_{n-1} \tag{8}$$

Equation (5) becomes

$$\mathrm{H}\frac{dx_n}{dt} + \mathrm{h}\frac{d(mx_n)}{dt} = \mathrm{V}x_{n+1} + \mathrm{L}(mx_{n-1}) - \mathrm{V}x_n - \mathrm{L}(mx_n) \tag{9}$$

$$(H + hm)\frac{dx_n}{dt} = Vx_{n+1} - (V + mL)x_n + mLx_{n-1} \tag{10}$$

$$\frac{dx_n}{dt} = \frac{V}{H + hm}x_{n+1} - \frac{V + mL}{H + hm}x_n + \frac{mL}{H + hm}x_{n-1} \tag{11}$$

Let

$$\alpha = \frac{V}{H + hm} \tag{12}$$

$$\beta = \frac{V + mL}{H + hm} \tag{13}$$

$$\gamma = \frac{mL}{H + hm} \tag{14}$$

Therefore, the dynamic model becomes

$$\frac{dx_n}{dt} = \alpha x_{n+1} - \beta x_n + \gamma x_{n-1} \tag{15}$$

Equation (15) is a second-order differential-difference equation expressing the mass fraction of the liquid overflow phase (containing the extracted oil) as the dependent variable.

Typically, a five-stage leaching process is the commonly adopted optimum number of stages for design purposes. As such, the model equations for each of these stages is presented below:

$$\frac{dx_1}{dt} = \alpha x_2 - \beta x_1 + \gamma x_O \tag{16}$$

$$\frac{dx_2}{dt} = \alpha x_3 - \beta x_2 + \gamma x_1 \tag{17}$$

$$\frac{dx_3}{dt} = \alpha x_4 - \beta x_3 + \gamma x_2 \tag{18}$$

$$\frac{dx_4}{dt} = \alpha x_5 - \beta x_4 + \gamma x_3 \tag{19}$$

$$\frac{dx_5}{dt} = \alpha x_6 - \beta x_5 + \gamma x_4 \tag{20}$$

where x_O can be obtained from the equilibrium relationship $x_O = y_O/m$ with y_O being the mass fraction of the oil in the feed stream (L_O) into stage 1. The exit overflow stream or extract from stage 1 (which is the product stream) has a mass fraction of x_1. Since the process is countercurrent, the solvent is fed into the process in stage 5 with a solute (oil) concentration of x_6 and the underflow raffinate leaves stage 5 with a concentration of y_5 which is in equilibrium with the overflow leaving the stage with an oil concentration of x_5. For a pure solvent, $x_6 = 0$ and for a pure feed $y_O = 1$.

Dynamic process simulation

Equations 16–20 are the differential equations which represent the soybean oil leaching process and are represented on MATLAB/SIMULINK in order to develop the computer models that will be needed for the simulation as shown in Fig. 2

Each of the sub-systems in Fig. 2 represent the differential-difference model equation representing each stage of the process. Each sub-system has two inputs as dictated by the model equations and one output. The interconnectivities of the model variables are depicted in the Figure. The inherent sub-systems' computer models are as shown in Figs. 3, 4, 5, 6 and 7

Process simulation parameters

After the models have been developed and represented on SIMULINK, it is expedient to provide values of some parameters that will be needed for simulation. Since laboratory experiments will not be carried out, the values of those parameters will be obtained from literature. Parameters for the liquid phase hold-up (H), slurry phase hold-up (h), underflow phase (L), overflow phase (V).

For ease of comparative simulations, the model parameters α, β, γ will be expressed in terms of ratios of the pertinent characteristic parameters. It will be better to work with the ratios: solvent-to-solid mass ratio (r_1), liquid-to-slurry-phase-holdup mass ratio (r_2) and underflow-to-slurry phase holdup ratio (r_3). These are defined as:

$$\frac{V}{L} = r_1 \tag{21}$$

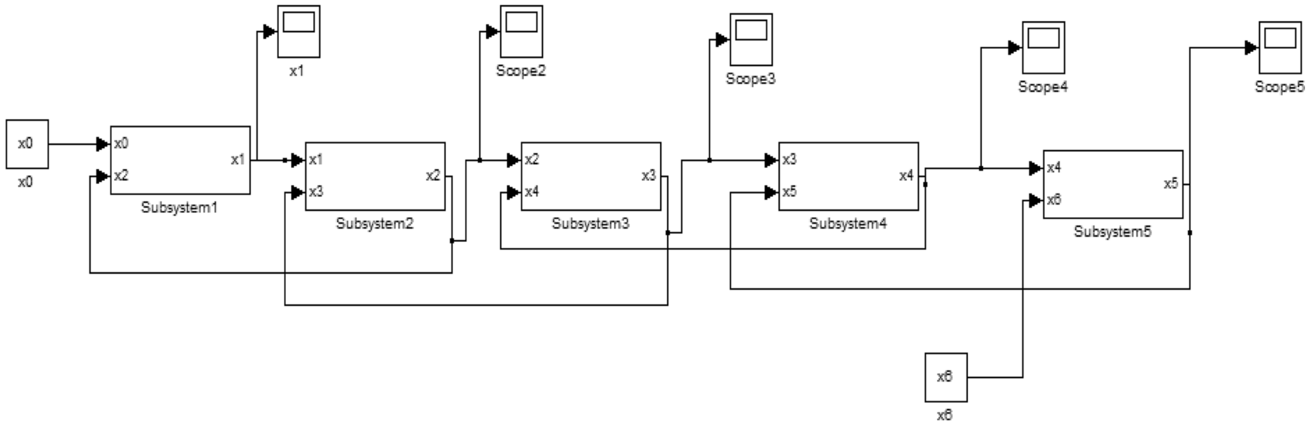
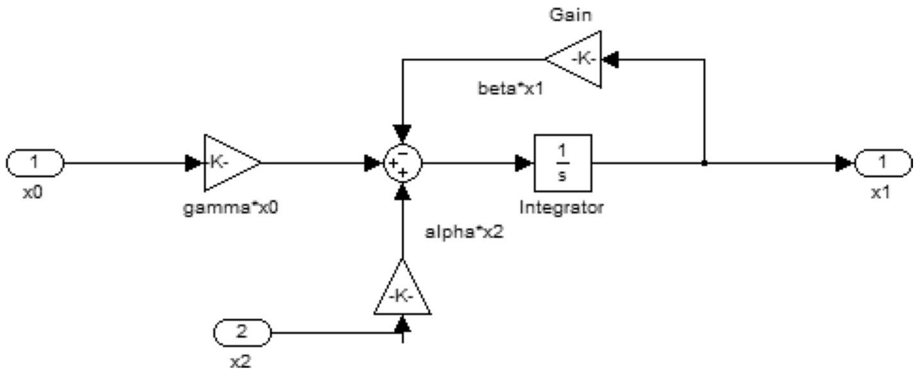


Fig. 2 A simulation model of the leaching process on SIMULINK

Fig. 3 SIMULINK model for sub-system 1



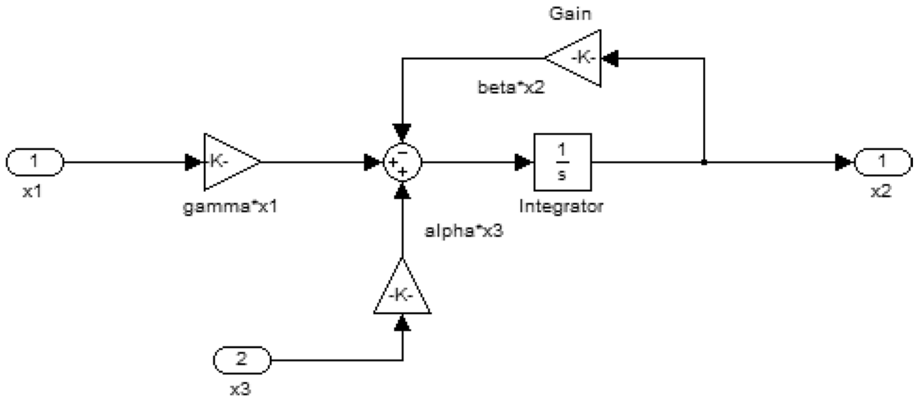


Fig. 4 SIMULINK model for sub-system 2

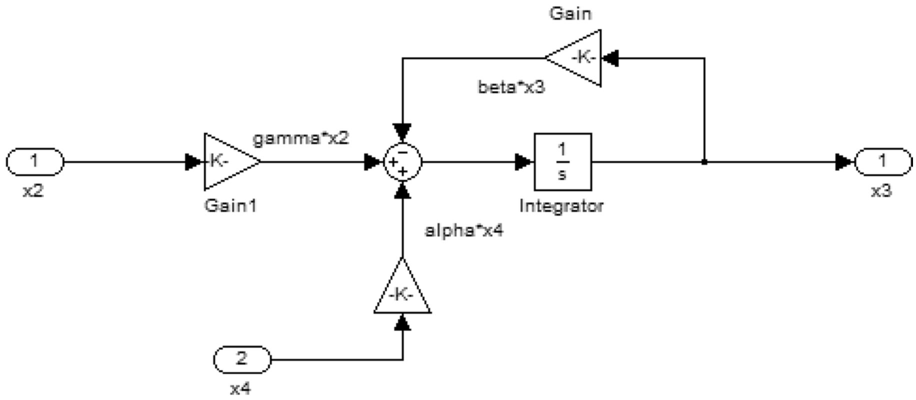


Fig. 5 SIMULINK model for sub-system 3

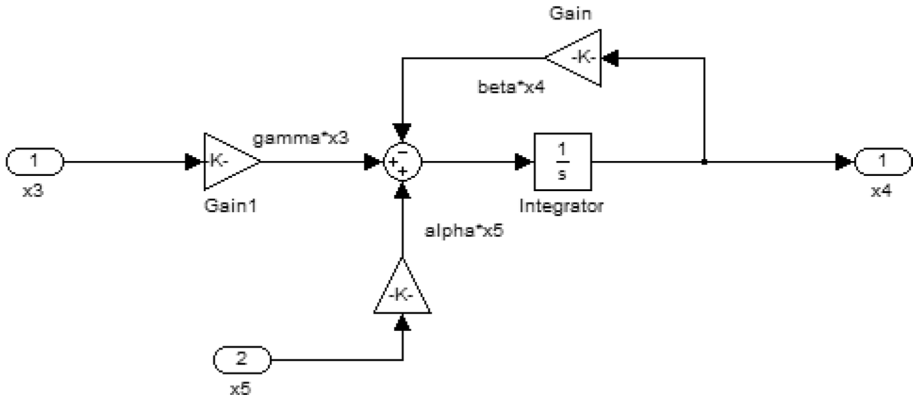


Fig. 6 SIMULINK model for sub-system 4

$$\frac{H}{h} = r_2 \tag{22}$$

$$\frac{L}{h} = r_3 \tag{23}$$

The model parameters become:

$$\alpha = \frac{\frac{V}{L} \cdot \frac{L}{h}}{\frac{H}{h} + m} = \frac{r_1 r_3}{r_2 + m} \tag{24}$$

$$\beta = \frac{\frac{V}{L} \cdot \frac{L}{h} + m\frac{L}{h}}{\frac{H}{h} + m} = \frac{r_1 r_3 + m r_3}{r_2 + m} \tag{25}$$

$$\gamma = \frac{m\frac{L}{h}}{\frac{H}{h} + m} = \frac{m r_3}{r_2 + m} \tag{26}$$

The task now is to estimate the values of the ratios for each of the solvents, and hence the parameters α, β, γ. For fair comparison of the two solvents, ethanol and hexane,

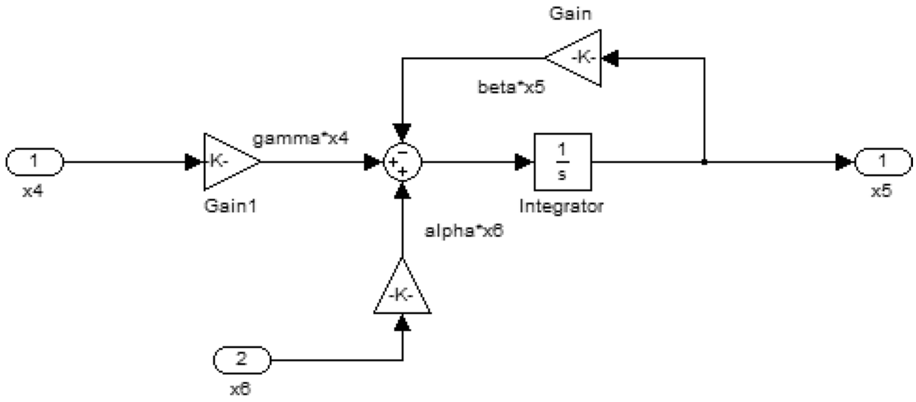


Fig. 7 SIMULINK model for sub-system 5

we will assume that the same volume of solvent is being used (∀ m^3) and that the same quantity of soybean feed solids is being processed (L kg/h).

The mass of each solvent is given as,

$$V = \rho \forall \tag{27}$$

where ρ (kg/m^3) is the density of the solvent.

For ethanol, we use a solvent to solid mass ratio of 3:1 (Bessa et al. 2017), such that

$$r_{1,ethanol} = \frac{V_e}{L} = \frac{\rho_e \forall}{L} = 3 \tag{28}$$

$$\forall = \frac{3L}{\rho_e} \tag{29}$$

where ρ_e is the density of ethanol and ∀ is the volume of ethanol to be used.

For hexane, as earlier stated, we make use of the same volume as ethanol for the extraction with hexane in order to compare fairly the use of the two solvents. Hence, the mass of hexane solvent used is:

$$V_h = \rho_h \forall \tag{30}$$

where ρ_h is the density of hexane.

Substituting the volume Eq. (29) into (30)

$$V_h = \rho_h \frac{3L}{\rho_e} \tag{31}$$

Therefore, the solvent to solids mass ratio for hexane

$$r_{1,hexane} \frac{V_h}{L} = 3 \cdot \frac{\rho_h}{\rho_e} \tag{32}$$

Now we need to find the densities of the two solvents. A correlation in Green and Perry (2008) enables the computation of these from the following expression which is dependent on the operating temperature (T) and certain empirical constants (C_1, C_2, C_3 and C_4) which are unique to each solvent.

$$\rho = \frac{C_1}{{C_2}^{\left(1+\left(1-\frac{T}{C_3}\right)^{C_4}\right)}} \tag{33}$$

The typical operating temperature for the process is 50 °C (323 K) (Oliveira et al 2012). The densities of the two solvents (ρ_h and ρ_e) were obtained at this operating temperature as: 633 kg/m^3 and 763 kg/m^3 for hexane and ethanol respectively.

If we assume a mass hold up of solids of 25% for both solvents, such that

$$\frac{h}{L} = 0.25$$

$$r_3 = \frac{L}{h} = 4$$

We can fix the value of L (the quantity of solid soybean to be processed) to be 100 kg/h as a basis. Hence, h = 0.25(100) = 25 kg.

If we further assume that 25% of the volume of each stage of the extractor is occupied by solids. That is,

$$\frac{volume\ of\ solids\ underflow}{volume\ of\ liquid\ overflow} = \frac{0.25}{0.75} = \frac{1}{3} \tag{34}$$

$$\frac{\left(\frac{h}{\rho_{solids}}\right)}{\frac{H}{\rho}} = \frac{1}{3}$$

$$\frac{H}{h} = 3 \times \frac{\rho}{\rho_{solids}} \tag{35}$$

where ρ_{solids}= density of soybean (739 kg/m^3).

For ethanol therefore,

$$r_{2,ethanol} = \frac{H}{h} = 3\frac{\rho_e}{\rho_{solids}} \tag{36}$$

For hexane,

$$r_{2,hexane} = \frac{H}{h} = 3\frac{\rho_h}{\rho_{solids}} \tag{37}$$

Summarily, Table 2 shows the parameters as evaluated for both solvents which will be used in the simulations.

Results and discussion

Extraction efficiency

After a simulation period of 90 min (1.5 h), the extraction efficiency, which is a measure of the yield of the process, was graphed for both solvents as shown in Fig. 8. By definition, the extraction efficiency is the fraction of the oil in the feed solids that was extracted by the solvent, thus

$$E = \frac{Vx_1}{Ly_0} = r_1\frac{x_1}{y_0} \tag{38}$$

Figure 8 shows that after the simulation period, ethanol has a higher extraction efficiency (94%) than hexane (91%) under the simulated process conditions. Using the same volume of solvent, and for the same given load of soybean feed solids, ethanol gives a slightly higher extraction efficiency than hexane. However, as revealed by Eq. (38), the extraction efficiency is determined by the solvent to solid mass fraction ($\frac{V}{L}$). The ($\frac{V}{L}$) for ethanol is 3 and that of hexane is 2.488 meaning that ethanol had a higher extraction efficiency than hexane as a result of its higher solvent to solid mass fraction. This result agrees with the work of Ferreira et al. (2022) in which soybean oil extraction carried out with anhydrous ethanol experimentally after a 5-stage extraction, resulted in 99.2% extraction yield which confirmed that ethanol was capable to extract soybean oil with a reasonable extraction yield with the reported minimum solvent-to-feed ratio (S/F) for ethanol (S/F = 2.62/1) which was higher than that for hexane (S/F = 0.36/1). Just as was observed herein, the solvent-to-solid feed ratio which delivered the higher yield and extraction efficiency by ethanol, was considerably higher than that for hexane, depicting that more solvent would be needed for ethanol than what would be required by hexane in order for the former to deliver a greater extractive performance.

Although the efficiency of ethanol is higher than that of hexane, consistently, the mass fraction of the extract (x_1) for hexane is higher than that of ethanol as revealed

Table 2 Parameters used for the comparative simulations for hexane and ethanol

Solvent	The quantity of solid soybean (kg/h)	$r_1 = \frac{V}{L}$	$r_2 = \frac{H}{h}$	$r_3 = \frac{L}{h}$	α	β	γ
Ethanol	100	3	3.097	4	2.928	3.905	0.976
Hexane	100	2.488	2.5697	4	2.787	3.908	1.1205

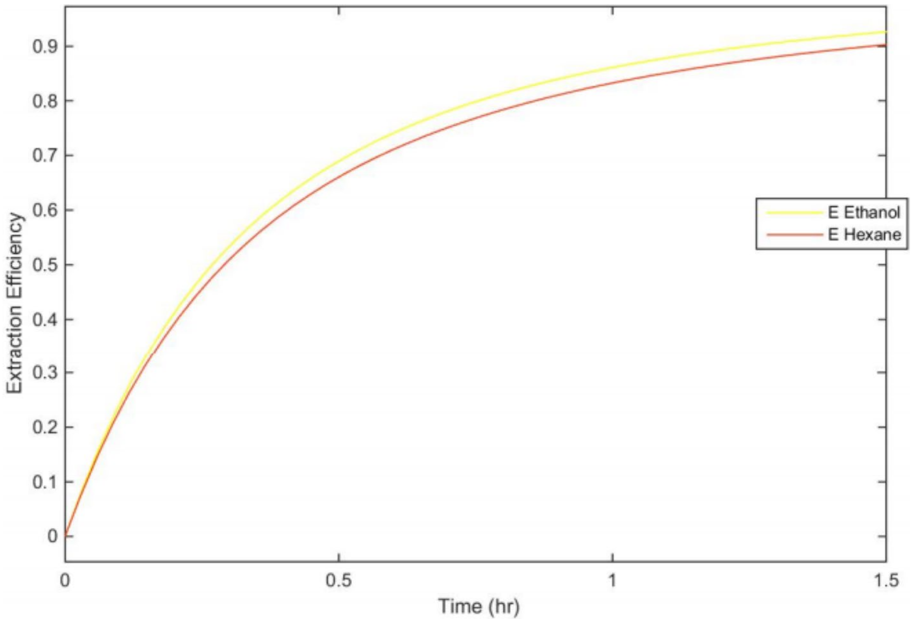


Fig. 8 Extraction efficiency of both solvents

by Fig. 9. For further comparison, the actual yield of each process, which is the mass of oil extracted by each solvent after the 1.5-h simulation time is computed (from Eq. 39) and compared. The yield of ethanol was 141 kg and that of hexane was 136.5 kg.

$$Y = Ly_0 t \cdot E \tag{39}$$

The higher the solvent-to-solid ratio, the higher the extraction yield; nevertheless, a high solvent-to-solid ratio will lead to excessive extraction solvent and a lengthy concentration time (Zhang et al. 2018).

$$E = \frac{\rho \forall x_1}{Ly_0}$$

$$E_h = \frac{\forall}{Ly_0} \rho_h x_{1h}$$

$$E_e = \frac{\forall}{Ly_0} \rho_e x_{1e}$$

Solute mass fraction in the extract

Figure 9 shows the solute (oil) mass fraction in the product (extract) against time (h). The result of the simulation shows that hexane extracted more solute than ethanol over the simulation period. Results from literature surveyed showed that hexane has a greater ability to extract oil when compared to other solvents, in this case ethanol. With a boiling point of 60–69 °C, it can retain its liquid state at all atmospheric conditions other than for extreme climates and its reasonable volatility aids easy removal from solids and oil, using low energy (Kumar et al. 2017; Sawada et al. 2014).

Hexane extraction rates for all stages

One of the objectives of this experiment is to use MATLAB/SIMULINK to study the dynamics or transient behavior of the soybean oil extraction process. Figure 10 shows the extraction rate (evidenced by the concentration of the oil in the overflow phases leaving each stage) using hexane as the solvent from stage 5 to stage 1 for over a period of 1.5 h.

To ensure sufficient contacting and high extraction yield, a 90-min simulation period was tested. Assuming that this is the contact time required to obtain optimal yield in a five-stage process, each stage should have a minimum contact time of 18 min (90÷5). Adequate contact time, on the other hand, is crucial for optimal extraction yield. At stage five when the fresh solids come in contact with the fresh solvent then the diffusion occurs then gives an extraction rate of 2.1×10^{-3} (0.22%) within 18 min extraction times. At stage 4 it gives an extraction yield of 9.6×10^{-3} (0.96%) at the same time of 18 min, it gives a higher extraction yield than stage 5 by 7.4×10^{-3} (0.74%) Stage 3 gives a higher extraction rate than that of the previous stage with an extraction rate of 0.0352 (3.52%) for an extraction time of 18 min and that of stage 2 which gives an extraction rate of 0.121 (12.1%) for an extraction time of 18 min. It shows that stage 2 gives a higher extraction rate than stage 3 which shows one of the properties of hexane which it has a greater ability to extract oil compared to other solvents. Then the final stage the extract yields and extraction rate of 0.356 (35.6%) for 18 min. For all stages its shows how hexane because of its

Fig. 9 Concentration of the extract in both solvents

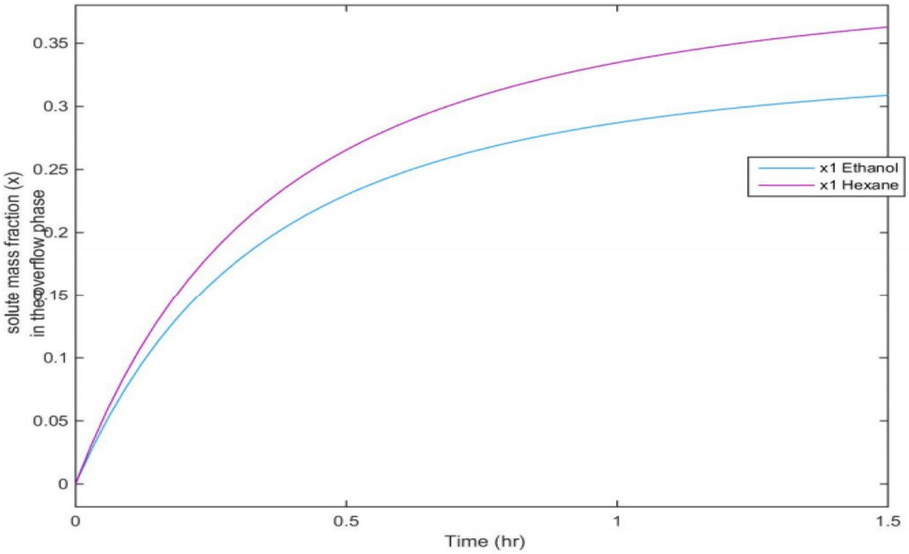
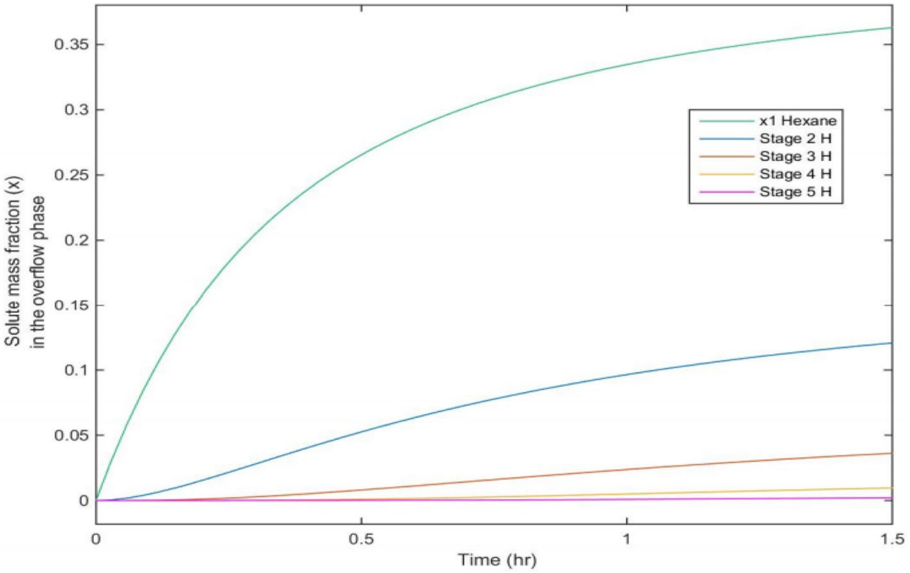


Fig. 10 Extraction rate for all stages using hexane



reasonable volatility aids easy and fast removal from solids and oil.

Ethanol extraction rates for all stages

One of the objectives of this research project is to use computer simulation to compare and evaluate the use of hexane and ethanol for the extraction of oil from soybean, to see which solvent extracts solutes more where the temperature (50 ℃) and time (90 min) are the same for both solvents. Figure 11 shows solute mass fraction in the overflow phase against time using ethanol as the solvent, the simulation was run for 90 min and the extraction was done across five stages.

At stage 5, the fresh incoming solvents come in contact with the solids entering at the other end in the underflow phase, for 18 min the solute extracted was 1.02×10^{-3} (0.102%). At stage 4, it gives an extraction yield of 5.3×10^{-3} (0.53%) giving an obvious increase than that of the first stage after been extracted for another 18 min. At stage 3 the extraction yield increases to give 0.0229 (2.29%) at constant time 18 min; then that of stage 2 gives an extraction rate of 0.088 (8.8%). At this stage the solvent gives more solutes than the other stages. Then at the extract stage, stage 1 here gives an extraction yield of 0.308 (30.8%) after running for the complete extraction time of 90 min giving the desired solute needed (soybean oil).

Comparison of extraction from stage to stage

Figures 12, 13, 14, 15 and 16 show the comparison of each stage when both solvents were used, showing the extraction rate and the same time for each stage. One of the objectives

Fig. 11 The extraction rate of all stages using ethanol

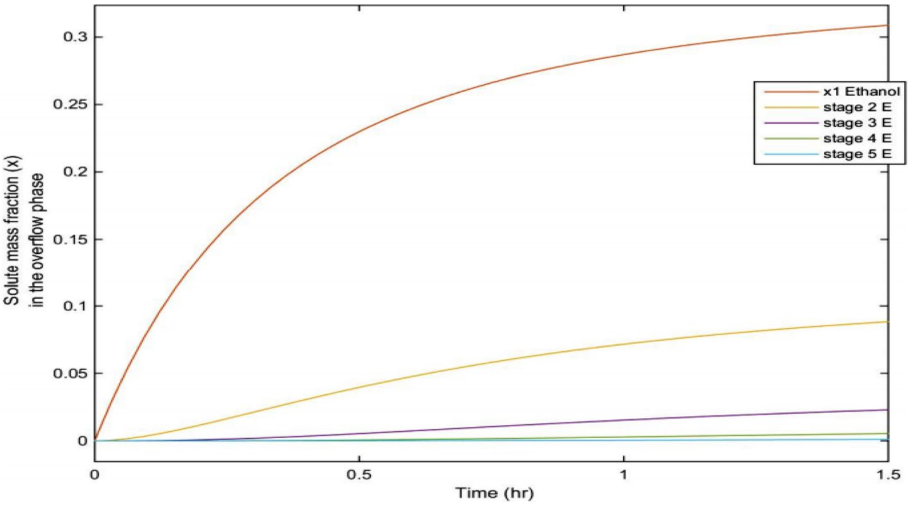


Fig. 12 Comparison of stage 5 ethanol and hexane extraction rate

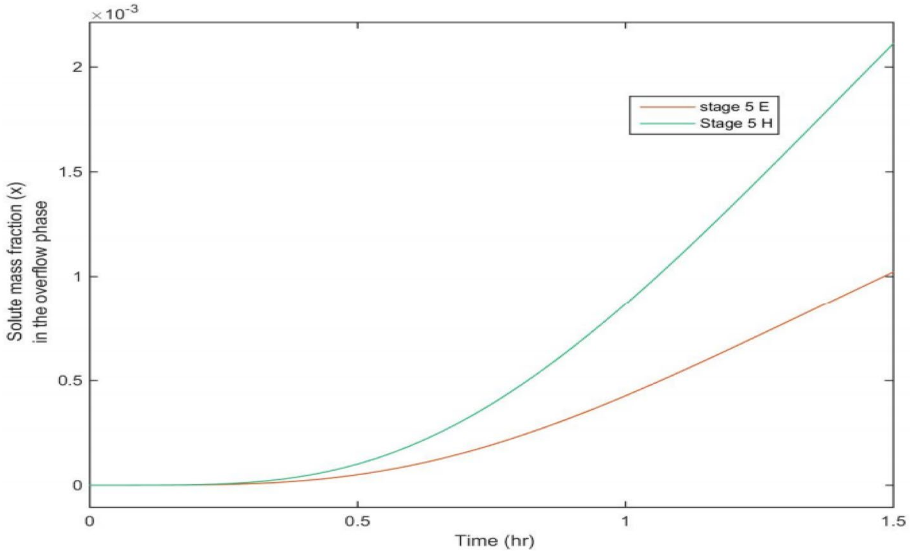
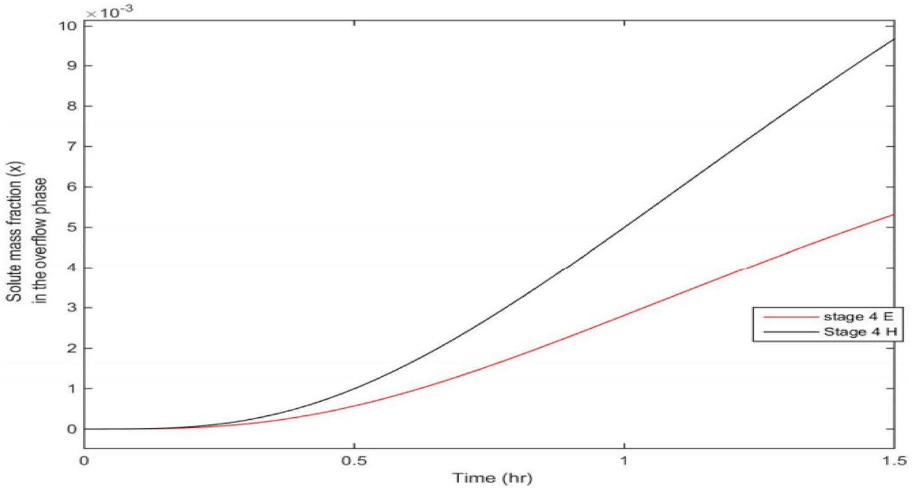


Fig. 13 Comparison of stage 4 ethanol and hexane extraction rate



of this experiment is to use computer simulation to compare and evaluate the use of hexane and ethanol for the extraction of oil from soybean. The Figures reveal that hexane extracts more solute (soybean oil) than ethanol at equal parameters like the quantity of solid soybean to be processed (100 kg/h) and operating temperature of 50 °C and mass hold up of solids of 25% for both solvents.

Conclusion

Hexane is the most-used solvent for oil extraction; although it is highly stable and has a greater throughput for oil dissolution, it is neurotoxic, resulting in environmental degradation, and is derived from nonrenewable sources (Hammond et al. 2005). For this, an alternative solvent has to be found, a solvent that has little or no environmental issues as hexane and can give an extraction rate close to hexane. Because it is generated through biotechnological techniques, the usage of ethanol provides environmental benefits. Furthermore, it is widely available at a reasonable cost, is less harmful to the environment, and is usually regarded as safe (Rodrigues et al. 2014). Therefore, it is desired to compare the performance of these two solvents for the extraction of oil from soybean. This goal is progressed in this work, by simulation means rather than by laboratory experiments.

A mathematical model for the countercurrent multistage solid–liquid extraction process of oil from soybean was derived from mass balances and simulated for five equilibrium stages which is often the optimum required for soybean oil extraction. The simulation process was carried out using MATLAB/SIMULINK to study the dynamics or transient behavior of the process. The work also highlighted

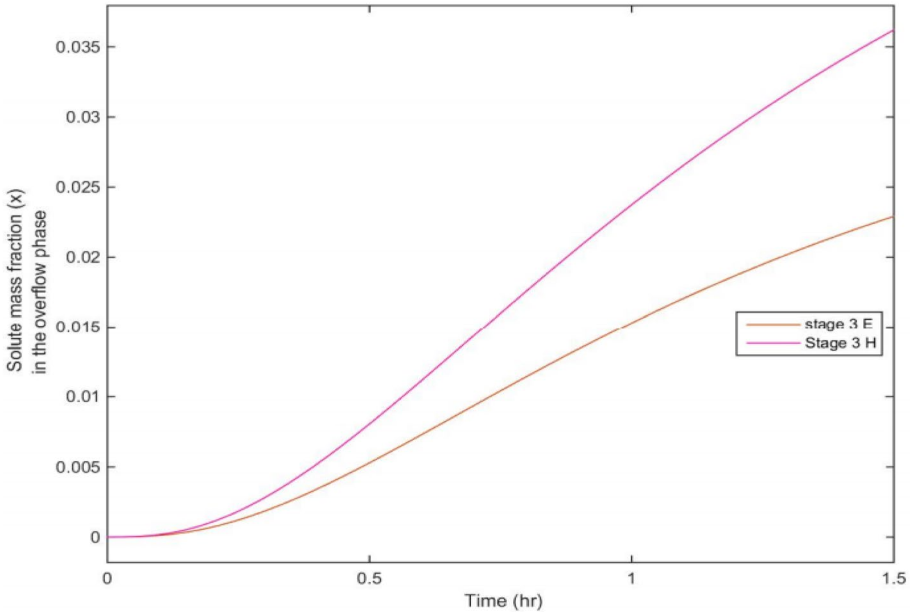


Fig. 14 Comparison of stage 3 ethanol and hexane extraction rate

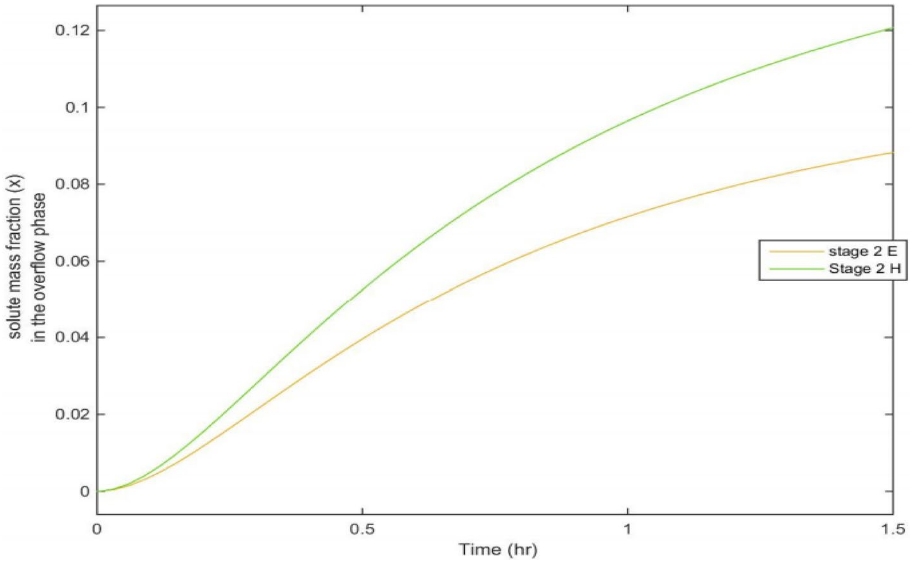


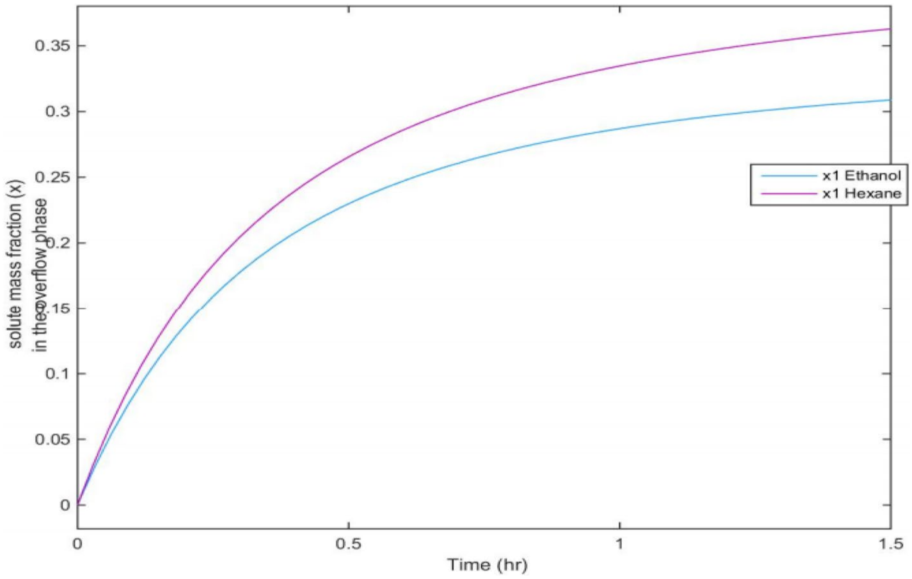
Fig. 15 Comparison of stage 2 ethanol and hexane extraction rate

the importance of simulation as a safe and cost-effective substitute to experimental investigations of promissory process routes or alternatives.

The simulation results showed that the oil extraction process utilizing hexane and ethanol as solvents is viable, with hexane providing a higher extraction rate than ethanol over the course of a simulation period of 90 min, although ethanol can be as efficient as hexane extraction wise at higher temperatures. Simulation results also showed that ethanol has higher extraction efficiency than hexane, which is affected by the solvent to solid mass ratio of which that of ethanol is higher hexane. Using the same volume of solvent, and for the same given load of soybean feed solids, ethanol gives a slightly higher extraction efficiency than hexane. It can be concluded that ethanol shows great promise as a potential substitute for hexane for soybean oil extraction in a countercurrent multistage extraction process.

The simulated results herein, can therefore provide a guide for further laboratory experiments in order to compare the simulated results with the laboratory results for the cause of validation and the drive to have better simulation results.

Fig. 16 Comparison of stage 1 ethanol and hexane extraction rate



Funding The authors did not receive support from any organization for the submitted work.

Declaration

Conflict of interests The authors have no competing interests to declare that are relevant to the content of this article.

References

Atabani AE, Silitonga AS, Ong HC, Mahlia TMI, Masjuki HH, Badruddin IA, Fayaz H (2013) Non-edible vegetable oils: a critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renew Sustain Energy Rev 18:211–245

Bessa LC, Ferreira MC, Rodrigues CE, Batista EA, Meirelles AJ (2017) Simulation and process design of continuous countercurrent ethanolic extraction of rice bran oil. J Food Eng 202:99–113

Comerlatto A, Voll FA, Daga AL, Fontana É (2021) Mass transfer in soybean oil extraction using ethanol/isopropyl alcohol mixtures. Int J Heat Mass Transf 165:120630

Ferreira MC, Gonçalves D, Bessa LC, Rodrigues CE, Meirelles AJ, Batista EA (2022) Soybean oil extraction with ethanol from multiple-batch assays to reproduce a continuous, countercurrent, and multistage equipment. Chem Eng Process Process Intensif 170:108659

Gaonkar V, Rosentrater KA (2019) Soybean. Integrated processing technologies for food and agricultural by-products. Elsevier, Amsterdam, pp 73–104

Ghouila Z, Sehailia M, Chemat S (2019) Vegetable oils and fats: extraction, composition and applications. Plant based "green chemistry 2.0" moving from evolutionary to revolutionary. Springer, Singapore, pp 339–375

Green DW, Perry RH (2008) Perry's chemical engineers' handbook. McGraw-Hill Education, New York

Gworek B, Kijeńska M, Wrzosek J, Graniewska M (2021) Pharmaceuticals in the soil and plant environment: a review. Water Air Soil Pollut 232:1–17

Hammond EG, Johnson LA, Su C, Wang T, White PJ (2005) Soybean oil. Bailey's industrial oil and fat products. Wiley, New Jersey, pp 577–653

Issariyakul T, Dalai AK (2014) Biodiesel from vegetable oils. Renew Sustain Energy Rev 31:446–471

Johnson LA, Myers DJ (1995) Industrial uses for soybeans. Practical handbook of soybean processing and utilization. AOCS Press, Urbana, pp 380–427

Kumar SJ, Prasad SR, Banerjee R, Agarwal DK, Kulkarni KS, Ramesh KV (2017) Green solvents and technologies for oil extraction from oilseeds. Chem Cent J 11:1–7

Li H, Biller P, Hadavi SA, Andrews GE, Przybyla G, Lea-Langton A (2013) Assessing combustion and emission performance of direct use of SVO in a diesel engine by oxygen enrichment of intake air method. Biomass Bioenerg 51:43–52

Lin L, Ying D, Chaitep S, Vittayapadung S (2009) Biodiesel production from crude rice bran oil and properties as fuel. Appl Energy 86(5):681–688

Oliveira R, Oliveira V, Aracava KK, da Costa Rodrigues CE (2012) Effects of the extraction conditions on the yield and composition of rice bran oil extracted with ethanol—a response surface approach. Food Bioprod Process 90(1):22–31

Özçelik A, Turgut SS, Küçüköner E, Karacabey E (2024) Solid-liquid extraction (leaching) in the food industry. Extraction processes in the food industry. Woodhead Publishing, Sawston, pp 17–44

Rai A, Mohanty B, Bhargava R (2015) Modeling and response surface analysis of supercritical extraction of watermelon seed oil using carbon dioxide. Sep Purif Technol 141:354–365

Rodrigues CE, Gonçalves CB, Marcon EC, Batista EA, Meirelles AJ (2014) Deacidification of rice bran oil by liquid–liquid extraction using a renewable solvent. Sep Purif Technol 132:84–92

Sawada MM, Venâncio LL, Toda TA, Rodrigues CE (2014) Effects of different alcoholic extraction conditions on soybean oil yield, fatty acid composition and protein solubility of defatted meal. Food Res Int 62:662–670

Zhang QW, Lin LG, Ye WC (2018) Techniques for extraction and isolation of natural products: a comprehensive review. Chin Med 13:1–26