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SIMULATION OF ENERGY CONSUMPTION IN STERILISATION PROCESS USING ASPEN PLUS AND RESPONSE SURFACE METHODOLOGY

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ABSTRACT

*Improving energy consumption in the palm oil milling process is regarded as one of the sustainable palm oil elements. Thus, this study highlights the use of ASPEN Plus-response surface methodology (RSM) approach to simulate and optimise the energy consumption of sterilisation process based on exergy analysis (*i.e. *exergy destroyed) and chemical reaction. ASPEN Plus V8.6 was employed to simulate the sterilisation process and then optimised using RSM. The validation of simulation results with experimental results demonstrating error values of less than 5.0%. Comparison of outlet stream simulation results with mill's data also showed deviation values less than 10.0%. These indicated that the actual values were in good agreement with model prediction. For optimisation, three variables were considered, namely pressure, steam mass flow and sterilisation time. For conventional steriliser operated at 2.8 bar, 90 min and 14 580 kg/hr steam mass flow, the exergy destroyed was 5259.3 MJ/hr. Under optimised conditions at 5 bar pressure, 70 min and 17 550 kg/hr steam mass flow, the exergy destroyed was 3493.9 MJ/hr. In comparison to conventional conditions, the heat loss was reduced by 33.6%. This approach is considered sustainable as it could predict the performance of industrial process without impacting processing time, cost and resources consumption.*

Keywords: ASPEN Plus, exergy analysis, optimisation, simulation, sterilisation.

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INTRODUCTION

In palm oil milling process, the fresh fruit bunches (FFB) sterilisation process uses the highest amount of steam (Aziz *et al*., 2015), thereby becoming a major contributor to high energy consumption. According to Kong *et al.* (2018), vegetable oil production is an energy-intensive process. In recent years, palm oil research has been directed towards sustainable development across the oil palm supply chain (Parveez *et al*., 2021). Hence, the issue of energy consumption in the crude palm oil (CPO) production process in Malaysia should be given attention so as not to compromise its sustainability.

Fundamentally, FFB sterilisation efficiency is often evaluated based on the ability of the fruits to detach from the bunch. Higher percentage of fruit detachment can be achieved via higher degradation rate of lignocellulosic fibres to sugars (Thang *et al*., 2021). It is vital to ensure that all fruits are detached from the bunch to successfully implement subsequent operations, which means more oil can be extracted from the fruits. Inefficient sterilisation may result in unstripped bunches (USB) which contribute to oil loss (Nadzim *et al.,* 2020; Thang *et al.,* 2021). This is due to poor heat distribution to the FFB which impairs carbohydrate degradation, and is also usually influenced by the operating conditions (*e.g.* pressure, temperature, time) during FFB sterilisation. Consequently, the sterilisation operating conditions should be improved.

However, it is a question of whether using different operating conditions such as high/low pressure, longer/shorter sterilisation period and

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decrease/increase steam amount is efficient in terms of energy consumption. Therefore, this concern should be addressed through the exergy analysis concept based on the ideal requirement. Exergy analysis is the maximum obtainable work that brings a system into equilibrium with its surroundings and helps identify the energy degradation in a process (Gharagheizi *et al.,* 2018; Martínez *et al.,* 2016). Exergy analysis is primarily used in industry to measure the amount of usable energy and calculate how efficiently the process uses the available energy.

Nevertheless, any improvement made to complex industrial processes will incur additional costs, and consume considerable resources and energy. This is where simulation software could be used to replicate complex processes such as palm oil milling process. In a previous study, Kamarden *et al.* (2018) successfully simulated and integrated palm oil milling, refinery and oleo-chemical processing using ASPEN Plus version 8.6. The use of materials and energy from one process unit to another and the sharing of energy supply from a centralised utility system were integrated to minimise waste and emission generation. The study demonstrated the applicability of simulation software in making the best possible decision for process improvement. To embark advancement in industrial processes, ASPEN Plus combined with response surface methodology (RSM) is expected to serve the purpose. RSM could be used to identify variables that could potentially affect the desired outputs. The integration of ASPEN Plus into RSM to combine both experimental and simulated data is seen as a powerful tool for process assessment and improvement (Cifuentes *et al.,* 2017). Several previous studies have employed this approach for energy studies in various fields, such as refinery operations (Braimah *et al.,* 2016), catalytic steam reforming of ethanol (Cifuentes *et al.,* 2017), acetic acid production (Feyzi and Beheshti, 2017) and gas-to-liquid (GTL) condensation (Hosseini and Iranshahi, 2017).

However, no recent studies have been reported on the application of ASPEN Plus-RSM on palm oil milling process focusing on energy consumption. Exergy analysis also has received little attention in palm oil milling, particularly the sterilisation process. This approach has not been adopted in palm oil mills due to a lack of relevant expertise and information. Moreover, previous studies have yet to examine extensively the role of carbohydrate degradation in sterilisation process, which is the most important stage for oil productivity as it reflects the ability of fruits to detach from the bunch. Thus, this study employed ASPEN Plus-RSM to simulate and identified significant variables which affected the energy consumption in FFB sterilisation based on exergy analysis and carbohydrate degradation. All simulated results were validated and compared with experimental results and mill data. This article will provide beneficial information to palm oil millers to improve the current processes and promote opportunities to learn more about palm oil milling.

MATERIALS AND METHODS

Steady-state Simulation in ASPEN Plus

Input specification for simulation. The steady-state simulation of the FFB sterilisation process was performed for conventional horizontal steriliser using ASPEN Plus V8.6. The operating conditions of the simulated sterilisation process were 2.8 bar pressure (130°C temperature) and 90 min sterilisation time in accordance with the conditions used in selected palm oil mill located in Selangor, Malaysia. Other inputs included in the simulation were the compositions of main components in FFB and steam estimated from Ariffin (1984), Keshvadi *et al.* (2012) and Simarani *et al.* (2009) as presented in *Table 1*.

In addition, chemical reactions of carbohydrate and triglycerides (*Table 2*) were also included as simulation inputs together with reaction kinetics estimated from previous studies.

Model selection. The simulation model of the sterilisation process was represented by a continuous-stirred tank reactor (RCSTR) and a flash block. *Figure 1* exhibits the schematic diagram of a typical sterilisation process in a palm oil mill and flowsheet diagram in ASPEN Plus.

After inserting all the inputs in the simulator, the thermodynamic model was selected. This study

TABLE 1. INPUTS OF STEAM AND FFB USED IN SIMULATION

	Fresh fruit bunches (FFB)	Steam
Condition		
Temperature (°C)	32	131
Pressure (bar)	1.0	2.8
Total mass flow (kg/h)	54 000	14 580
Component mass fraction		
Tripalmitin	0.1480	-
Triolein	0.1480	-
Glucan	0.2540	-
Xylan	0.1490	-
Water	0.3000	1.0
Palmitic acid	0.0045	-
Oleic acid	0.0045	-

TABLE 2. KINETIC PARAMETERS USED IN SIMULATION OF STERILISATION PROCESS

Reactions	Temperature (K)	Rate constant, k (s^{-1})	Activation energy, E (kJ/mol)	Reference
Tripalmitin + water → Palmitic acid + Glycerol	404	9.974	232.90	Anozie and Dzobo (2006)
Triolein + water → Oleic acid + Glycerol	404	9.974	232.90	Anozie and Dzobo (2006)
Glucan + water → Glucose	404	0.011	106.58	Husin (2016)
Xylan + water → Xylose	404	0.010	56.04	Husin (2016)

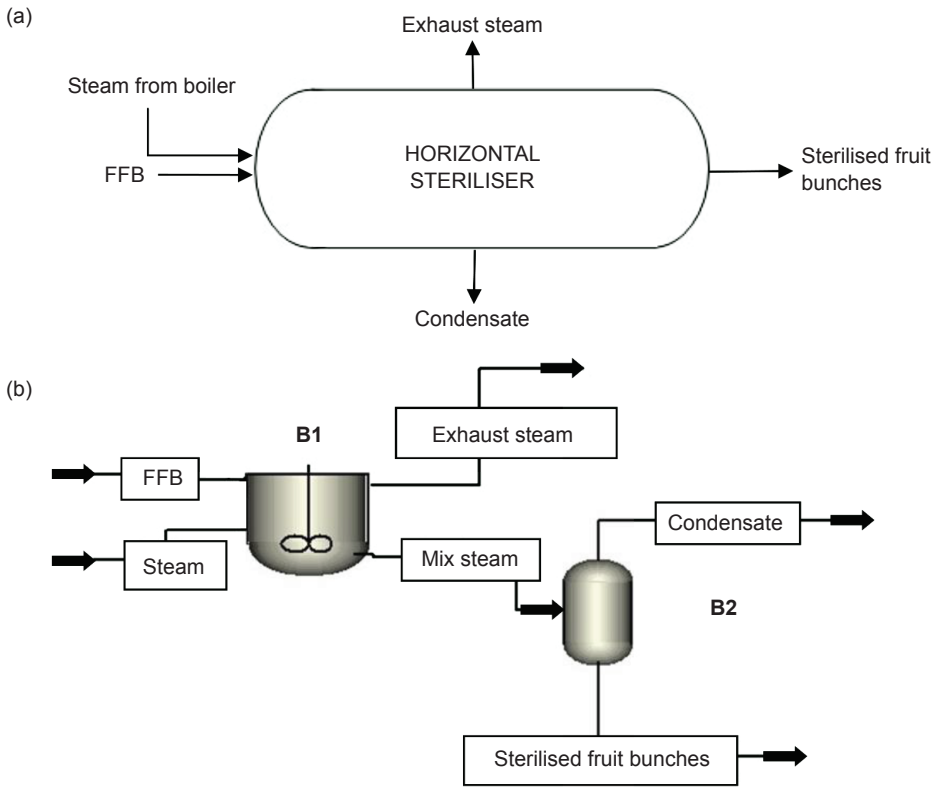


Figure 1. Sterilisation process; (a) schematic diagram and (b) flowsheet diagram in ASPEN Plus.

used non-random two-liquid (NRTL) for immiscible components (oil and water) and steam table (STEAM-TA) for saturated steam.

Model Validation and Comparison

The simulation results of the sterilisation process were validated in terms of component composition in streams, namely oil, glucan, xylan and moisture content. The streams involved for validation were condensate and sterilised fruit bunches. The oil contents in the sterilised fruits and condensate were determined using the Soxhlet extraction method according to MPOB Test Method (2005), while glucan and xylan contents were measured via proximate analysis. The moisture contents of the samples from sterilised fruits and condensate were determined using the oven drying method in accordance with MPOB Test Method (2005). The differences between simulation and actual results were expressed as absolute error (Equation 1). Moreover, the mass balance of the simulated sterilisation process was compared with the data obtained from the palm oil mill. Absolute relative deviation in Equation (2) was used to determine the differences between the simulation and mill's data.

$$\text{Absolute error (AE)} = \text{Simulation value} - \text{Actual value} \quad (1)$$

$$\text{Absolute relative deviation (ARD)} = \frac{\text{Simulation} - \text{Actual}}{\text{Actual}} \times 100 \quad (2)$$

Exergy Analysis

This study adopted the method from Hinderink *et al.* (1996) for exergy analysis calculation as it

was developed appropriately for application in flowsheeting simulators such as ASPEN Plus. The total exergy of a stream is presented in Equation (3).

$$Ex = Ex_{chem} + Ex_{phys} + \Delta_{mix}Ex \quad (3)$$

where Ex is total exergy of a stream; Ex_{chem} is total chemical exergy of a stream; Ex_{phys} is total physical exergy of a stream; and $\Delta_{mix}Ex$ denotes the exergy change of mixing. The unit is expressed in Watts (W) or Joules (J). Each term has to be calculated separately and systematically.

Chemical exergy is defined as a minimum work needed to synthesise a pure chemical compound at an environmental reference state from its constituent elements at the same state (Gharagheizi *et al.*, 2018). In this study, the chemical exergy was calculated using Equation (4) adopted from Gharagheizi *et al.* (2018) with a slight adjustment on the symbol used to represent chemical exergy.

$$Ex^{o}_{chem,i} = \Delta_f G^{o}_i - \sum \eta_j Ex^{o}_{chem,j} \quad (4)$$

where $Ex^{o}_{chem,i}$ denotes standard chemical exergy of any species i, $\Delta_f G^{o}_i$ denotes Gibbs energy of formation of species i, $Ex^{o}_{chem,j}$ denotes standard chemical exergy of the element j in species i, and η_j denotes the number of atoms of elements j in species i. To evaluate consistent results of standard chemical exergy, the thermodynamic values ($\Delta_f G^{o}_i$) were retrieved from the internal database of ASPEN Plus.

Since standard chemical exergy is phase-dependent, the phase at which a species component is present at a reference state should be considered when dealing with mixtures (Hinderink *et al.*, 1996). Therefore, Equation (5) was used to determine the standard chemical exergy of species i expressed in phase α from the value in phase β.

$$Ex^{o\alpha}_{chem,i} = Ex^{o\beta}_{chem,i} + \Delta_{\beta\rightarrow\alpha} G^{o}_i \quad (5)$$

in which

$$\Delta_{\beta\rightarrow\alpha} G^{o}_i = \Delta_f G^{o\alpha}_i - \Delta_f G^{o\beta}_i \quad (6)$$

The Gibbs energy formation of species i in its unstable phase at reference state was retrieved from the ASPEN Plus database. Hence, the chemical exergy of a multi-component stream is given by Equation (7) at the reference state (T_o and P_o).

$$Ex_{chem} = L_o \sum_{i=1}^{n} x_{o,i} Ex^{ol}_{chem,i} + V_o \sum_{i=1}^{n} y_{o,i} Ex^{ov}_{chem,i}[T_o, P_o] \quad (7)$$

Physical exergy is defined by Equation (8) which can be obtained from ASPEN Plus simulation for each stream as EXERGYFL (exergy flow rate). It is calculated as a function of enthalpy and entropy difference.

$$Ex_{phys} = (H - H_o) - T_o (S - S_o) \quad (8)$$

Calculation of exergy change of mixing from enthalpy and entropy of mixture and pure components is shown in Equation (9), while Equation (10) denotes total exergy flow rate of a material stream at actual conditions (Hinderink *et al.*, 1996).

$$\Delta_{mix} Ex = \Delta_{mix} H - T_0 \Delta_{mix} S \qquad [T,P] \quad (9)$$

$$Ex_{tot} = F (Ex_{chem} + Ex_{phys} + \Delta_{mix} Ex) \quad (10)$$

The main focus of this study was to obtain the exergy destroyed by the process. Exergy destroyed, known as irreversibility, shows how much exergy is lost through the process unit as shown in Equation (11).

$$Ex_{destroyed} = \sum Ex_{in} - \sum Ex_{out} \quad (11)$$

Sensitivity Analysis

Sensitivity analysis is useful to study the sensitivity of process performance to modification in process feeds and operating variables prior to optimisation. In this study, sensitivity analysis was conducted to study the effect of reactor pressure (3-7 bar), sterilisation time (20-120 min) and steam mass flow (10 800-24 300 kg/hr) on the degradation of glucan and xylan to produce glucose and xylose, respectively, which later on would be used in RSM as variables. The purpose was to determine whether the selected variable ranges have significant effect on degradation. The selection of variables were made based on that reported by Ariffin (2011) where temperature/pressure, water equilibrium and period of reaction are three predominant factors that can influence the efficiency of degradation. Ranges of the operating variables of sterilisation process used for sensitivity analysis are given in *Table 3*.

Optimisation

Using similar ranges of operating variables as presented in *Table 3*, the energy use in sterilisation process was optimised using central composite design (CCD) through response surface methodology (RSM) in Design Expert software version 11. About 16 sets of experimental designs were established and run in ASPEN Plus to obtain the responses.

TABLE 3. RANGES OF OPERATING VARIABLES USED FOR SENSITIVITY ANALYSIS

Parameter	Lower range	Upper range	Points
Pressure (bar)	3	7	5
Steam flow rate (kg/hr)	10 800	24 300	5
Reaction time (min)	20	120	5

RESULTS AND DISCUSSION

Simulation and Model Validation

Simulation. The sterilisation process is of utmost importance in the palm oil milling process, typically performed in a horizontal pressure vessel as a batch process with steam supplied from the boiler. The FFB sterilisation uses pressurised steam in an enclosed vessel at a steam pressure between 40-45 psig (equivalent to 2.8-3.1 bar) and at a sterilisation time of around 1.0-1.5 hr (Wondi *et al.*, 2021). Sterilisation is imperative for fruit detachment from the bunch, softening fruit structures, and inhibiting lipase enzyme (Wondi *et al.*, 2021) to prevent free fatty acids (FFA) formation. The process generates sterilised fruit bunches, condensate as liquid discharge and exhaust steam to evacuate air from the vessel.

To ensure simulation is possible, several simplifications were made to overcome the constraints inherent in the simulation. This study used simple triglycerides (tripalmitin and triolein) to represent complex mixed triglycerides (carbon chains between C46 to C58) due to the absence of mixed triglycerides in the ASPEN Plus component database. This was followed by selecting palmitic and oleic acids to represent FFA. Hemicellulose was represented by xylan in the simulation as the component was also absent in the database, and its properties were estimated by ASPEN Properties. Similar to cellulose, it was represented by glucan. Due to model limitation in ASPEN Plus, the steriliser was represented by two blocks, namely continuous-stirred tank reactor (B1) and flash block (B2) (*Figure 1b*). The reactor works based on the kinetic reaction of a process, while the flash block runs based on the separation of a single vapour phase and a single liquid phase. To connect B1 and B2, an additional stream was included in the simulation. Conventionally, the sterilisation process is operated mostly in a triple-peak pressure pattern for uniform steam heat distribution to the FFB, but this was excluded in the simulation to reduce convergence constraints.

The results obtained from the steady-state simulation of the sterilisation process using ASPEN Plus are shown in *Table 4*. The simulation results showed that the sterilised fruit bunches stream was mainly composed of oil, water, glucan and xylan with a small amount of glucose, xylose, palmitic acid and oleic acid. The degradation of glucan and xylan to simple sugars, namely glucose and xylose, respectively, was evidenced after sterilisation as observed in the sterilised fruit bunches stream (*Table 4*). Moreover, the simulation results showed that the amount of xylose (0.03 kg/hr) produced in sterilised fruit bunches stream was higher than glucose ($1.5x10^{-8}$ kg/hr). This was because glucan (represented cellulose) has a more stable structure which was challenging to degrade at low sterilisation temperature (130ºC). Unlike xylan (represented hemicellulose), its unstable structure easily degraded under such conditions.

Generally, palm fruit is majorly composed of fleshy mesocarp fibre and kernel. Mesocarp fibre contains mainly oil, carbohydrate and water. The primary constituents of carbohydrate are hemicellulose, cellulose and lignin, which contribute to the structure of the fruits and bunch stalk. Hemicellulose, for instance, holds the oil cells in the fruits together and attaches the fruits to the bunch stalk by the abscission layer. *Figure 2* illustrates the components in the FFB. During sterilisation at high temperatures, hydrolysis in palm fruit will degrade the semi-stable hemicellulose (Nadzim *et al.*, 2020). The deformation properties of both the abscission and mesocarp layers of the fruits are significantly affected by the thermal softening process (Thang *et al.*, 2021) via sterilisation. Therefore, the presence of glucose in the sterilised fruit bunches stream, as indicated in *Table 4*, was more likely due to glucan degradation, whose molecular structure was shorter and less stable than cellulose. The chemical breakdown of cellulosic materials, particularly hemicellulose during sterilisation process will result in the fruits being detached from the spikelets of the bunch stalk.

Moreover, the simulation results obtained for the sterilised fruit bunches stream showed that the oil content of 15 187.8 kg/hr (represented by tripalmitin and triolein) was similar to that of the FFB stream. This proved that oil was not degraded at the given conditions. The oil breakdown process requires a higher temperature (~250ºC) and pressure around 3000-5000 kN/m^2 (30-50 bar) (Siew, 2011). The actual sterilisation process inactivates oil-splitting enzymes and prevents the formation of FFA (Shehu *et al.*, 2019). However, small amounts of palmitic acid and oleic acid representing FFA found in the sterilised fruit bunches stream were not caused by oil degradation but due to the initial simulation input. This study assumed that the initial condition of fruits in the bunches received at the palm oil mill might contain FFA slightly. This was justified by Ariffin (1984) that oil palm fruit mesocarp considered intact and undamaged has an FFA of 0.025%.

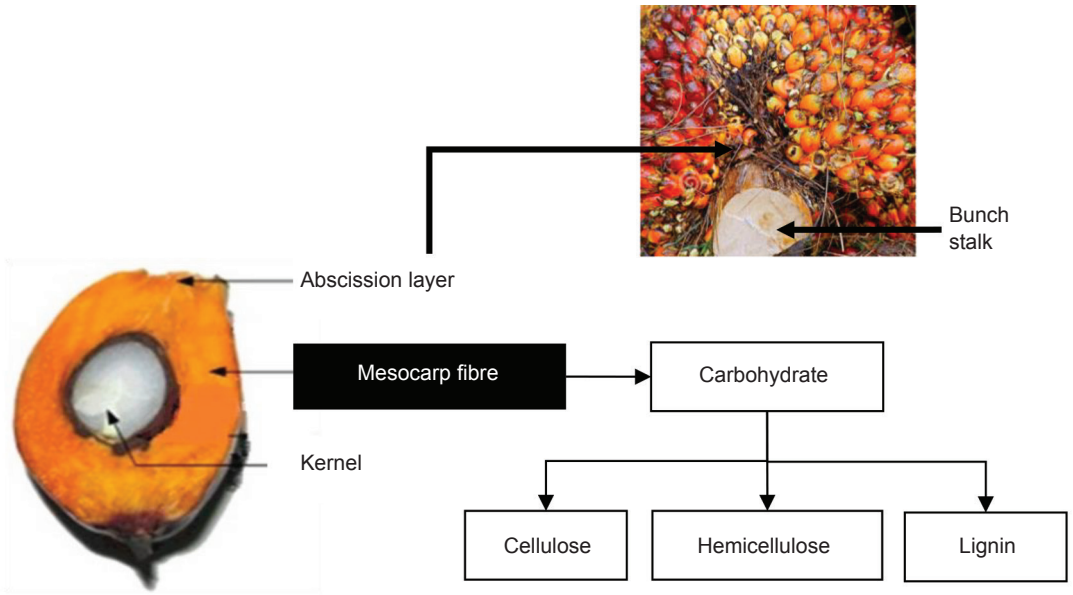


Figure 2. Illustration of components in fresh fruit bunches.

TABLE 4. SIMULATION RESULTS OF STERILISATION PROCESS

Components	Stream mass flow (kg/hr)					
	Steam	FFB	Mix stream	Exhaust steam	Sterilised fruit bunches	Condensate
Tripalmitin	-	7 593.90	7 593.90	$7.2x10^{-8}$	7 593.90	$1.9x10^{-7}$
Triolein	-	7 593.90	7 593.90	0.00	7 593.90	0.00
Glucan	-	13 032.80	13 031.00	1.90	13 025.20	5.80
Xylan	-	7 645.20	7 645.10	0.10	7 645.00	0.20
Water	14 580.00	15 393.10	20 761.20	9 211.90	10 229.00	10 532.20
Glucose	-	-	$1.5x10^{-8}$	$1.5x10^{-15}$	$1.5x10^{-8}$	$4.0x10^{-15}$
Xylose	-	-	0.03	$7.1x10^{-8}$	0.03	$1.8x10^{-7}$
Palmitic acid	-	20.50	19.60	1.00	19.00	0.50
Oleic acid	-	20.50	19.80	0.70	19.50	0.30
Glycerol	-	-	0.00	0.00	0.00	0.00
Trash	-	2 700.00	0.00	0.00	0.00	0.00
Total flow rate (kg/hr)	14 580.00	54 000.00	48 368.30	9 215.50	46 125.60	10 539.00

In comparison with the initial composition of FFB as shown in *Table 1*, it was found that the composition of oil in the sterilised fruit bunches stream indicated in *Table 4* increased from 29.6% to 32.9% and water decreased from 30.0% (15 393.1 kg/hr) to 22.2% (10 229.0 kg/hr). Although the mass flow rate of oil in both streams was similar, their compositions differed due to the reduced total mass flow rate of each stream. The reduction of water content in sterilised fruit bunches stream was influenced by water dehydration of FFB during sterilisation, which increased the composition of oil. In the real process, loss of moisture in FFB occurs when the steam is blown off during sterilisation (Ropandi *et al.*, 2017).

Meanwhile, condensate and exhaust steam streams (*Table 4*) have water as their main component. Condensate is generated from the condensation of water vapour from the steam or evaporated moisture in FFB due to the temperature effect, consisting of oil, water, fibrous material and sand (Ropandi *et al.*, 2017). From *Table 4*, the loss of oil in the condensate was insignificant at only $1.8x10^{-7}$ kg/hr, almost no oil loss. This was probably affected by the kinetic parameters of oil estimated from the literature used in the simulation. As the estimated value was small (*Table 2*), thus simulation predicted slight oil loss in the condensate. According to Garcia *et al.* (2017), the selection of kinetic parameters used in ASPEN Plus will significantly influence the model prediction.

On the other hand, the total amount of condensate produced from the simulation of sterilisation was 19.5%. This value was close to the reported values by Menon (2016), which is 20.0%/ FFB.

Model validation and comparison. After obtaining the simulation results, the sterilised fruit bunches and condensate streams were then validated with the experimental results in terms of oil, moisture (water), glucan and xylan content, as exhibited in *Table 5*. The errors obtained for condensate and sterilised fruit bunches between simulation and actual results were in the range of 1.1%-3.8%, signifying that the experimental results were in good agreement with model prediction. From previous studies, the reported oil content in condensate is 0.07%-0.64% per FFB (Corley and Tinker, 2016) and the moisture content of sterilised fruits is nearly 28.00% of total fruit composition (Wondi *et al.*, 2021). According to Thang *et al.* (2021), the compositions of the mesocarp of the sterilised fruit are as follows: 56.68% total oil content, 2.89% soluble sugars, 8.27% glucan and 4.52% xylan. These values differ from those obtained in this study as they depend on the type of fruit, sterilisation techniques and conditions.

Based on the simulation results, the oil content in condensate was insignificant, contradicting with the experimental results. As mentioned above, the simulation of the sterilisation process employed kinetic parameters of triglyceride estimated from literature, which most likely influenced the oil content present in the condensate. In the actual process, oil in the condensate is very significant, which commonly stems from the sterilisation of overripe and bruised fruits. Oil from the bruised fruits will be released to the steam and floated through steam condensation (Oi-Ming *et al.*, 2012). Furthermore, *Table 6* presents the total mass flow for outlet streams of the sterilisation process compared with the palm oil mill data. The deviation values between the simulated and actual results were below 10%, signifying that the actual results were in good agreement with model prediction. As exhaust steam stream is immeasurable in the real process, thus, it was excluded from this validation study.

Sensitivity Analysis

Effect of reactor pressure. *Figure 3* displays the effect of varying pressure on the degradation of glucan and xylan into glucose and xylose in sterilised fruit bunches, respectively. It showed that as the pressure increased from 3 to 7 bar, the glucose and xylose production increased as well. According to Ariffin (2012), the hydrolysis rate is proportional to temperature. For saturated steam, temperature is corresponding to pressure. Moreover, Yulianto and Panji (2012) revealed that the higher the temperature, the hemicellulose residues in fibres are most likely to decrease. This means that sugar production increases as the temperature increases. Production of high sugar in fruits after sterilisation could reflect the possibility of high fruit detachment from the bunch. According to Menon (2013), the detachment of fruits from bunches and oil extraction are closely related. If fruit detachment is not efficient, thus, it will result in low oil extraction and high USB. In addition, Thang *et al.* (2021) emphasized that the composition of sugars in sterilised fruits or condensate could be used as an indicator to optimise the sterilisation parameters to achieve full detachment of fruits without USB.

TABLE 5. VALIDATION OF SIMULATION AND EXPERIMENTAL RESULTS

Parameter	Sterilised fruit bunches		AE (%)	Condensate		AE (%)
	Actual	Simulation		Actual	Simulation	
Oil content (%)	34.0	32.9	1.1	1.9	$1.8x10^{-7}$	1.9
Moisture content (%)	23.8	22.2	1.6	96.1	99.9	3.8
Glucancontent (%)	26.2	28.2	2.0	N/A	N/A	-
Xylan content (%)	15.2	16.6	1.4	N/A	N/A	-

Note: AE - Absolute error; N/A - Not available.

TABLE 6. COMPARISON OF TOTAL MASS FLOW RATE OF STREAMS BETWEEN SIMULATION AND MILL'S DATA

Stream name	Simulation (kg/hr)	Mill (kg/hr)	*ARD (%)
Sterilised fruit bunches	46 125.6	47 055.6	2.0
Condensate	10 539.0	11 577.6	9.0

Note: *ARD - Absolute relative deviation.

Effect of sterilisation time. The effect of sterilisation time on glucose and xylose production is shown in *Figure 4*. It can be observed that glucose and xylose productions increased as the sterilisation time increased from 20 min (0.3 hr) to 120 min (2 hr). According to Hadi *et al.* (2012), sufficient sterilisation time is crucial for efficient degradation process or detachment of fruits to take place to

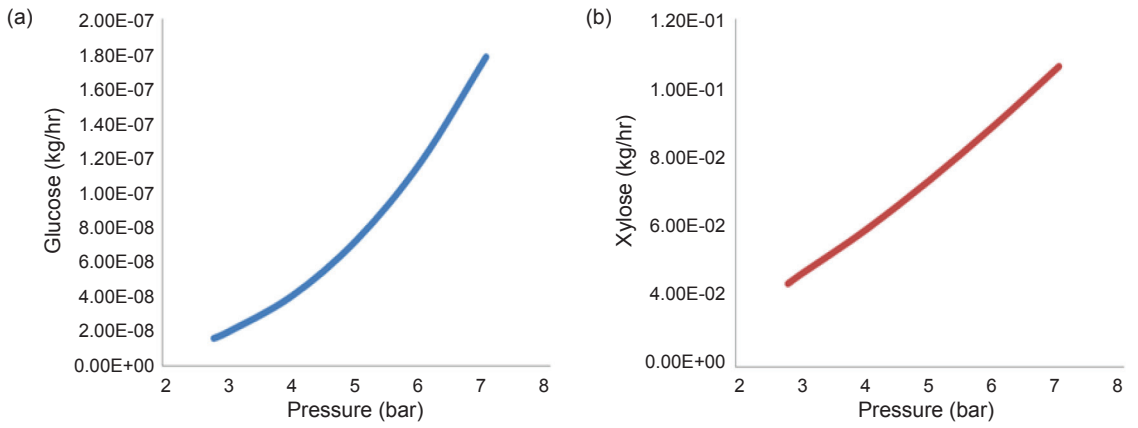


Figure 3. Effect of pressure on production of (a) glucose and (b) xylose in sterilised fruit bunches.

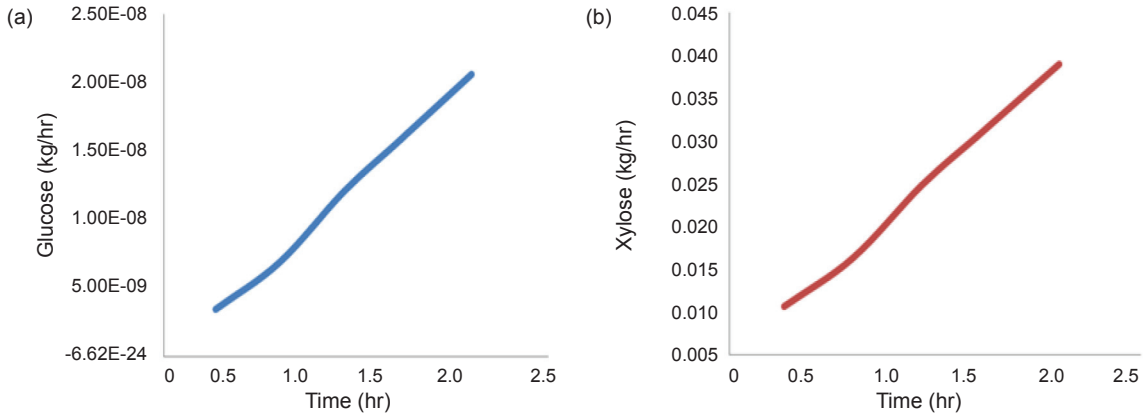


Figure 4. Effect of sterilisation time on production of (a) glucose and (b) xylose in sterilised fruit bunches.

ensure every fruit on the bunch is detached. High temperature/pressure sterilisation reduces the period for complete detachment of fruit in one sterilisation consignment.

Effect of steam mass flow. Another crucial variable involved in the degradation of glucan and xylan to produce glucose and xylose is the amount of water present in the sterilised fruit bunches. Hadi *et al.* (2012) mentioned in their study that prolonged steaming period and large quantity of steam are compulsory to ensure complete heating up till the inner layers of the bulky FFB. Unlike previous variables, increment of steam mass flow into the steriliser exhibited declining trend of glucose and xylose production in sterilised fruit bunches (*Figure 5*). Apparently, the degradation of glucan and xylan to produce glucose and xylose, respectively, was not proportional to the increase of water (steam) to the bunch. This is because glucose and xylose production increased in condensate stream as the amount of steam increased during sterilisation as exhibited in *Figure 6*. Glucose and xylose are soluble in water, thus more sugar dissolved in condensate as the amount of steam increased. This is supported by Yan *et al.* (2014) revealing that more glucose dissolves with presence of high amount of water.

Optimisation of Operating Conditions and Exergy Destroyed

Owing to the engineering and operational considerations, various constraints were also considered to obtain optimum results for this study. In the actual process, the applied pressure for sterilisation process should not be more than 5 bar and longer sterilisation time is not favourable as the minor components in palm oil, namely carotene, will deteriorate as well as affect the conditioning of palm nuts, thereby affecting the palm kernel oil production.

Prior to optimisation, the exergy destroyed of sterilisation process at conventional operating conditions of 2.8 bar pressure, 90 min sterilisation time and 14 500 kg/hr steam mass flow were determined based on Equations (3)-(11). The use of ASPEN Plus simulator can help evaluate and

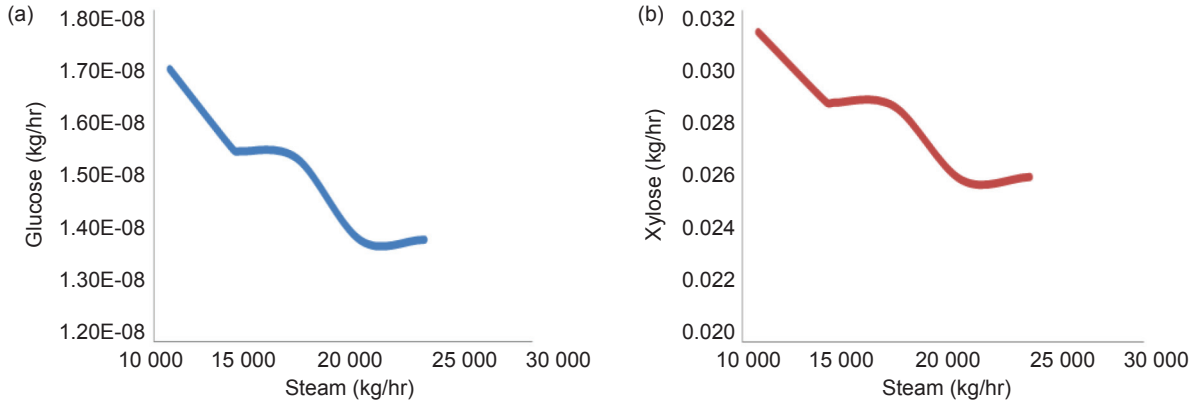


Figure 5. Effect of steam flow rate on production of (a) glucose and (b) xylose in sterilised fruit bunches.

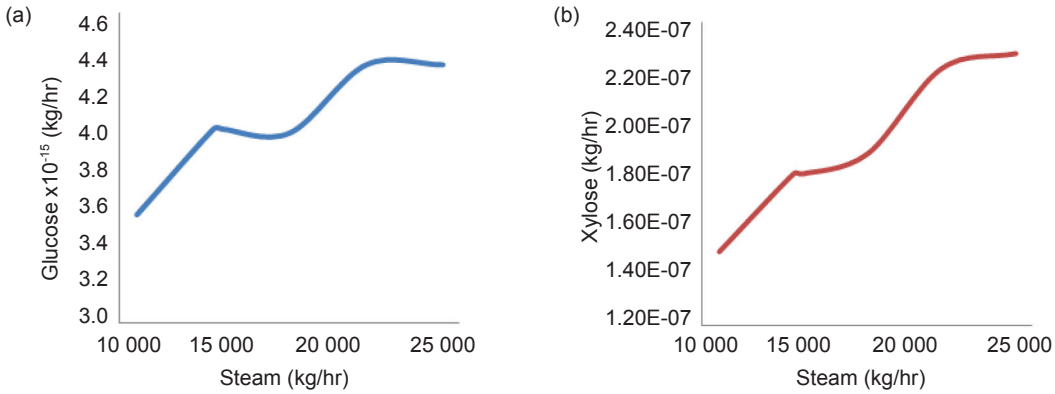


Figure 6. Effect of steam flow rate on production of (a) glucose and (b) xylose in condensate.

identify energy inefficiency by providing crucial parameters for exergy analysis, namely enthalpy, entropy and Gibbs free energy. It also provides thermo-physical properties of process stream flows and validates mass and energy balances which are essential for exergy analysis (Dogbe *et al.*, 2018). Using these data, the software computes the chemical and physical exergy of process streams (Ruiz-de la Cruz *et al.*, 2015). *Table 7* summarises the exergy analysis for the sterilisation process.

From Equation (11), it was found that 5259.3 MJ/hr of exergy was destroyed or energy was wasted during the conventional sterilisation process, indicating an opportunity for improvement. The factors that contributed to high exergy destroyed could be large steam consumption and high heat losses to the environment during the blow-down step. In addition, steriliser produces a large amount of condensate as liquid waste, which becomes the main water contributor for palm oil mill effluent. Generally, the sterilisation process consumes about 30%-60% of total process steam, which depends on the technology used and sterilisation pattern (single-peak, double-peak and triple-peak cycles utilised) (Reese, 2009). Therefore, it is essential to predict the possibility of conducting sterilisation process of FFB at optimum operating conditions with minimum energy consumption at the mill.

In this study, the effects of varying operating conditions of steriliser were evaluated in terms of hydrolysis of carbohydrate and exergy destroyed through optimisation via response surface methodology (RSM). According to Montgomery (2001), RSM is one of the statistical methods that can model and analyse the response of interest influenced by several variables. RSM selects the optimum operating conditions among a group of variables by efficient quantitative methods and provides a better understanding of the process, effect of control variables and interactions between all variables (Braimah *et al.*, 2016). The results obtained from RSM are presented in *Table 8*.

The proposed mathematical models from RSM for the glucose and xylose production in a steriliser, as well as exergy destroyed, are given by Equations (12)-(14).

Glucose =

+5.74076E-08		
+6.13520E-08	Pressure	
-1.37400E-09	Steam mass flow	
+5.24720E-08	Sterilisation time	
-1.15750E-09	Pressure * Steam mass flow	
+4.50475E-08	Pressure * Sterilisation time	
-1.05750E-09	Steam mass flow * Sterilisation time	
+2.03386E-08	Pressure^2	
-1.11379E-10	Steam mass flow^2	
-2.56138E-09	Sterilisation time^2	
-8.42500E-10	Pressure * Steam mass flow * Sterilisation time	(12)

Xylose =

+0.051372		
+0.027779	Pressure	
-0.000521	Steam mass flow	
+0.037817	Sterilisation time	
-0.000280	Pressure * Steam mass flow	
+0.020365	Pressure * Sterilisation time	
-0.000385	Steam mass flow * Sterilisation time	
+0.002416	Pressure^2	
+0.000036	Steam mass flow^2	
-0.002134	Sterilisation time^2	(13)

Exergy destroyed =

+8010.68621		
+503.38000	Pressure	
+4868.56000	Steam mass flow	
-9.01812E-13	Sterilisation time	
+320.17500	Pressure * Steam mass flow	
-1.08370E-12	Pressure * Sterilisation time	
-1.01137E-12	Steam mass flow * Sterilisation time	
-207.57931	Pressure^2	
+153.42069	Steam mass flow^2	
-109.47931	Sterilisation time^2	(14)

The values of coefficient of determination (R^2) for these models were close to 1, indicating the high accuracy of the developed model. Analysis of variances (ANOVA) was used to evaluate the adequacy of the developed model and to examine the interaction of each operating variable which exhibited a significant effect on the production of glucose and xylose as well as exergy destroyed as responses. The ANOVA results are summarised in *Table 9*. The significance of each variable or interaction between variables was indicated by *p*-values and *f*-values. The corresponding variables are considered more significant if the magnitude of the *f*-value is greater and *p*-value is smaller (less than 0.05) (Feyzi and Beheshti, 2017). Based on the ANOVA results, it can be inferred that the production of glucose and xylose in sterilised fruit bunches during sterilisation was mostly affected by pressure and sterilisation time. In contrast, exergy destroyed was affected significantly by pressure and steam mass flow. *Figure 7* shows the interactions between operating variables and responses.

From the results predicted by ASPEN Plus, the production of glucose and xylose in the sterilised fruit bunches during sterilisation was affected mainly by pressure and sterilisation time, whereas exergy destroyed was affected by pressure and steam mass flow. Pressure (or temperature) and time are among the main contributing factors for hydrolysis efficiency (Ariffin, 2012), which can be associated with water evaporation from the fruit and steam condensation on the bunch due to differences in temperature inside and outside. According to Ariffin (2012), both evaporation and condensation activities will stop if the temperature within the bunch and surrounding is the same, achieving an equilibrium state. Thus, the remained water in the fruits will be used to degrade the unstable carbohydrate. Ariffin (2012) also explained that the hydrolysis process takes time to ensure that each fruit on the bunch is detached. At low pressure (<40 psi), the required sterilisation time is 90 min, but the period will be shortened at high sterilisation pressure.

On the other hand, exergy destroyed refers to the irreversibilities in the process, of which the potential of a system to produce work that is not used (Martínez *et al.*, 2016). In other words, exergy destroyed indicates the loss of heat to the environment. As calculated, the conventional sterilisation process had 5259.3 MJ/hr of exergy destroyed, signifying that the conventional operating conditions contributed to high heat loss to the environment. Minimising heat loss is crucial for high-temperature industrial processes. For the palm oil milling process, steam consumption for the heating process has the greatest implication on energy utilisation at the mill (Energywise, 2013). Steam supplies heat for FFB sterilisation as a heating medium in a pressure vessel, either horizontal or vertical. Pressure is the key player for ensuring the process feasibility owing to fruits detachment and enzyme inactivation. The contributing factor to high exergy destroyed or heat loss could also be attributed to the blow-down step, which evacuates air from the steriliser to facilitate uniform heat distribution to the FFB consignment.

Considering the process constraints mentioned earlier, it can be deduced that the degradation process is the best in terms of glucan and xylan degradation at 5 bar, 17 550 kg/hr of steam and 70 min with minimum exergy destroyed of 3493.9 MJ/hr. The optimised conditions reduced the exergy destroyed by 33.6%. In other words, the predicted heat loss to

TABLE 7. PHYSICAL, CHEMICAL AND MIXING EXERGY OF STREAMS FOR STERILISATION PROCESS

Stream no.	Stream name	Physical exergy (ASPEN Plus) (MJ/hr)	Chemical exergy and mixing exergy (calculated) (MJ/hr)	Total exergy (MJ/hr)
1	Fresh fruit bunches	0.0	1 002 292.6	1 002 292.6
2	Steam (steriliser)	8 926.0	7 669.1	16 595.1
4	Exhaust steam	553.7	5 645.1	6 198.8
5	Sterilised fruit bunches	1 298.7	999 008.1	1 000 306.8
6	Condensate	6 461.1	661.6	7 122.7

TABLE 8. EFFECT OF PRESSURE, STEAM MASS FLOW AND STERILISATION TIME ON GLUCOSE AND XYLOSE PRODUCTION IN STERILISER

Run	Factors			Responses		
	Pressure (bar)	Steam mass flow (kg/hr)	Sterilisation time (min)	Glucose mass flow (kg/hr)	Xylose mass flow (kg/hr)	Exergy destroyed (MJ/hr)
1	3	10 800	20	$3.76x10^{-9}$	0.00636	2 745.7
2	3	24 300	20	$3.62x10^{-9}$	0.00623	11 923.4
3	7	10 800	120	$2.41x10^{-7}$	0.13920	3 112.1
4	5	17 550	20	$1.46x10^{-8}$	0.01299	7 937.7
5	5	17 550	70	$5.72x10^{-8}$	0.05132	7 937.7
6	7	24 300	120	$2.32x10^{-7}$	0.13641	13 570.5
7	7	17 550	70	$1.41x10^{-7}$	0.08250	8 343.0
8	3	10 800	120	$2.51x10^{-8}$	0.04239	2 745.7
9	3	24 300	120	$2.41x10^{-8}$	0.04155	11 923.4
10	3	17 550	70	$1.47x10^{-8}$	0.02513	7 336.2
11	7	10 800	20	$3.61x10^{-8}$	0.02088	3 112.1
12	5	17 550	120	$9.53x10^{-8}$	0.08554	7 937.7
13	5	10 800	70	$5.85x10^{-8}$	0.05195	3 493.9
14	7	24 300	20	$3.47x10^{-8}$	0.02046	13 570.5
15	5	24 300	70	$5.63x10^{-8}$	0.05092	12 907.2
16	5	17 550	70	$5.72x10^{-8}$	0.05132	7 937.7

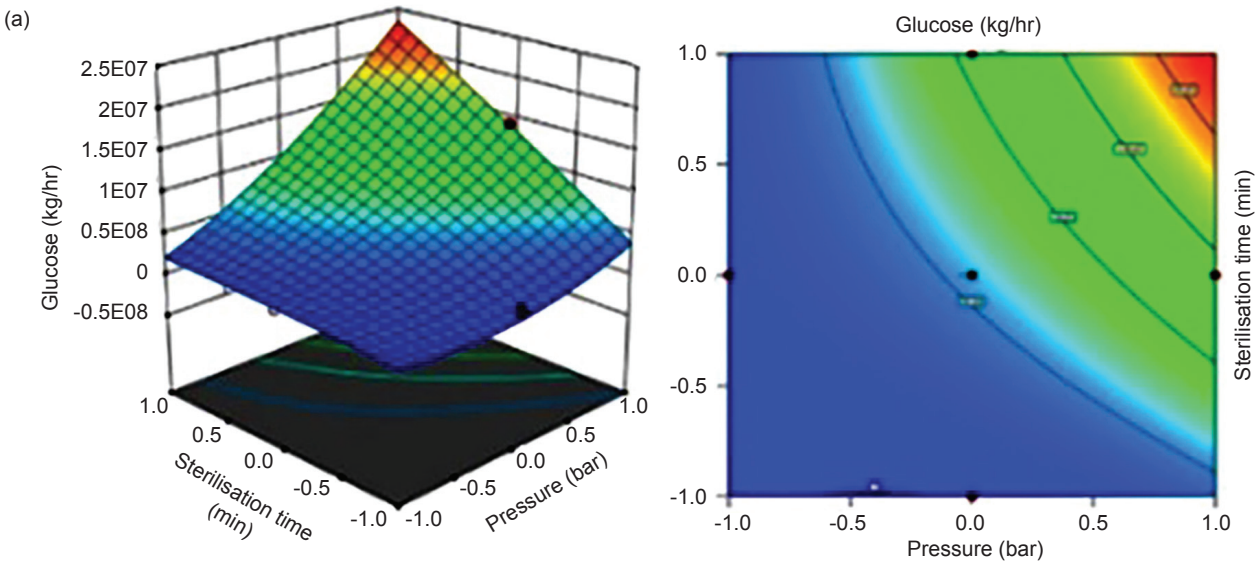
the environment is minimum when the steriliser vessel is operated at 5 bar pressure and 70 min with 17 550 kg/hr steam supplied to the vessel. The use of high-pressure sterilisation may create uniform heat distribution of steam to the inner part of the bunch, facilitating the fruits to easily detach from the bunches due to the high carbohydrate degradation rate, which possibly reduces the occurrence of USB during threshing. Importantly, efficient energy use at palm oil mills is the predominant factor that may reduce the carbon footprint and impact global warming trends (Energywise, 2013), thus creating a sustainable palm oil production operation.

CONCLUSION

Steady-state simulation of the FFB sterilisation process was successfully conducted using ASPEN Plus V8.6, where the deviation values between the simulation and experimental results were less than 5%. The comparison of mass balance between simulation and mill also showed deviation values of less than 10%. Overall, the actual values were in good agreement with the model predictions. Based on the exergy calculated for conventional sterilisation, 5259.3 MJ/hr of energy was estimated to be wasted when operated at 2.8 bar and 1.5 hr (90 min). However, based on the RSM results, the energy loss to the environment was reduced to 3493.9 MJ/hr when the FFB was sterilised at 5 bar (pressure), 70 min (sterilisation time) and 17 550 kg/hr (steam mass flow), 33.6% lower than the conventional conditions. Thus, the RSM-ASPEN Plus approach can assist industry players in minimising energy consumption for palm oil milling process. Future research should extend this study at palm oil mills using actual data so that process improvements do not affect the use of mill resources.

TABLE 9. ANOVA RESULTS OF THE DEVELOPED MODELS FROM RSM

Source	*f*-value	*p*-value
Glucose		
Quadratic	144.7600	<0.0001
A-Pressure	592.0500	<0.0001
B-Steam mass flow	0.2969	0.6055
C-Sterilisation time	433.0700	<0.0001
AB	0.1686	0.6956
AC	255.3500	<0.0001
BC	0.1407	0.7205
A^2	17.1500	0.0061
B^2	0.0005	0.9826
C^2	0.2721	0.6206
R^2 = 0.9954, R^2 (adj) = 0.9885, R^2 (pred) = 0.9603		
Xylose		
Quadratic	2 024.6200	<0.0001
A-Pressure	5 544.2900	<0.0001
B-Steam mass flow	1.9500	0.2120
C-Sterilisation time	10 275.1200	<0.0001
AB	0.4506	0.5270
AC	2 383.8100	<0.0001
BC	0.8520	0.3916
A^2	11.0600	0.0159
B^2	0.0025	0.9617
C^2	8.6200	0.0261
R^2 = 0.9997, R^2 (adj) = 0.9992, R^2 (pred) = 0.9970		
Exergy destroyed		
Quadratic	1 891.2500	<0.0001
A-Pressure	179.2700	<0.0001
B-Steam mass flow	16 769.5200	<0.0001
C-Sterilisation time	0.0000	1.0000
AB	58.0200	0.0003
AC	0.0000	1.0000
BC	0.0000	1.0000
A^2	8.0400	0.0298
B^2	4.3900	0.0810
C^2	2.2400	0.1855
R^2 = 0.9996, R^2 (adj) = 0.9991, R^2 (pred) = 0.9974		



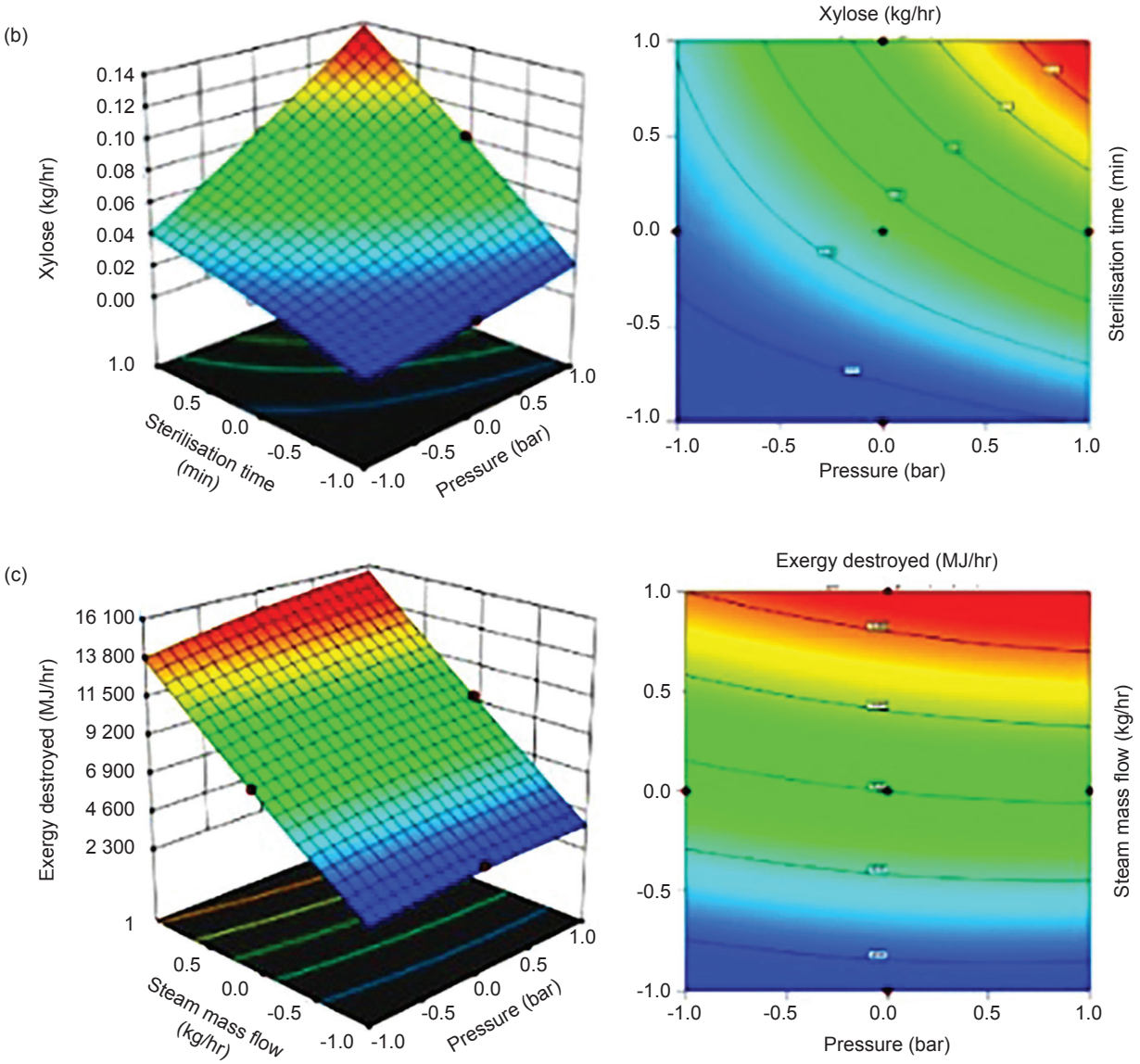


Figure 7. Interactions of (a) sterilisation time against pressure on glucose production, (b) sterilisation time against pressure on xylose production and (c) steam mass flow against pressure on exergy destroyed

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