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Bioethanol scheduling production with a combination of oil palm trunks and empty fruit bunches

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Abstract

Bioethanol production from lignocellulosic biomass is a combination of batch and continuous processes. Such processes mainly consist of pretreatment to recover the highest possible content of cellulose during fermentation using hydrolysis and yeast to convert cellulose into bioethanol with purification to produce the required level of biofuel concentrate. This study aims to develop a simulation model for producing bioethanol from oil palm trunks (OPTs) and empty fruit bunches (EFBs), involving the batch scheduling of pretreatment and fermentation to produce 99.0% wt. bioethanol at 10,000 L/day. Furthermore, OPTs and EFBs offer the flexibility to change feedstocks which also affects the schedule. In this study, Aspen Plus calculates the raw materials and utilities required using the Aspen Batch Process Developer (ABPD) and then schedules the batch operation. To produce bioethanol, the results indicate that OPTs and EFBs with a ratio of 1:1 should be fed 24,000 kg-OPTs/day and 24,000 kg-EFBs/day to produce the required amount of bioethanol. The pretreatment section should be operated in two cycles and fed into a fermenter every 240 min. Moreover, to schedule the fermentation process, ideally, 15 parallel fermenters should be used to ensure a continuous supply for purification. Extractive distillation and pervaporation technologies are proposed in this study, consuming 16.78 and 19.24 MJ/L, respectively, to produce bioethanol in the targeted amount.

Keywords: Bioethanol production, Oil palm trunks, Empty fruit bunches, Scheduling, Aspen batch process developer

Nomenclature

ABPD	Aspen Batch Process Developer	NRTL	non-random two-liquid
AHP	alkaline hydrogen peroxide unit	OPT	oil palm trunk
ACM	Aspen Custom Modeler	PVA	polyvinyl alcohol
EFB	empty fruit bunches	SE	steam explosion unit
FPU	filter paper unit	SHF	Separate Hydrolysis and Fermentation
HCW	hot compressed water unit	SSF	simultaneous saccharification and fermentation
HW	hot water unit	T-01	intermediate tank no.1
MJ/L	mega-joule per liter	T-02	intermediate tank no.2
MINLP	mixed-integer linear programming		

1. Introduction

Global warming and the energy crisis have been topics of interest for many decades. Lignocellulosic ethanol or bioethanol from biomass is regarded as an alternative energy source to reduce the impact of greenhouse gas emissions because it can be used in motor vehicles. The bioethanol can be produced through the fermentation of lignocellulosic biomass (the largest potential feedstock), such as sugar cane bagasse, rice straw, water hyacinth biomass, oil palm residue, etc. [1]. Due to the complexity of lignocellulosic biomass, pretreatment technology approaches (physical, chemical, and physio-chemical) are applied before fermentation to maximise the accessibility of enzymes and yeast by disrupting the biomass structure [2].

Agricultural waste products such as OPTs and EFBs are readily accessible and inexpensive for the production of bioethanol using fermentation since their major properties are cellulose, hemicellulose, lignin, etc. Afrasiab evaluated the conversion of OPTs into bioethanol through the fermentation of *Saccharomyces cerevisiae*. This research identified successful pretreatment methods for increasing the composition of cellulose using steam explosion (SE), hot water (HW), and alkaline hydrogen peroxide (AHP). Furthermore, Natchanok converted EFBs into bioethanol through the same fermentation approaches used by Afrasiab, but the pretreatment of EFBs involved hot-compressed water (HCW). High-yield ethanol has also been produced using Separate Hydrolysis and Fermentation (SHF) and Simultaneous Saccharification and Fermentation (SSF) under optimal laboratory conditions [3,4]. In pretreatment and fermentation, these processes are associated with batch manufacturing. A recipe or task is required for bioethanol production whereby each task is assigned using specific equipment but over a certain time interval. Such tasks are frequently integrated and performed in a single piece of equipment, which varies with batch size and usually limited by the size of equipment available. During the last few years, considerable research has been conducted on batch scheduling based on process simulation or mixed-integer linear programming (MINLP) to design a highly efficient batch process [5-7]. Since high-yield ethanol can be obtained using OPTs and EFBs involving step-by-step pretreatment and fermentation, the batch scheduling process is designed to support the two feedstocks with different pretreatment approaches.

In this research, the batch scheduling process is designed to accommodate commercial-scale bioethanol production of 99.0% wt. from OPTs and EFBs with a production rate of 10,000 L/day, thereby reducing the idle time and avoiding unit size overestimation. Moreover, Aspen Batch Process Developer (ABPD) is adopted as the simulation tool to enable the automatic generation of a Gantt chart and process scheduling with the minimum cycle time [7]. This scheduling allows continuous feeding into the extractive distillation or pervaporation process to produce the required capacity.

2. Material and methods

The experimental data produced by Afrasiab and Natchanok [3,4] in Table 1, shows the properties of OPTs and EFBs for use as feedstocks. This production is semi-continuous, comprising batch (pretreatment and fermentation) and continuous processes (purification). Nevertheless, the batch process must be designed to support the continuous process. Therefore, the continuous process is developed first using Aspen Plus for plant-wide generation and to determine daily feedstocks and utility requirements. SOLIDS and non-random two-liquid (NRTL) thermodynamic methods are selected to calculate the physical properties of the solid and liquid compounds [8,9]. Moreover, the mathematical model proposed by Opor [10] predicts the solid recovery and composition after treatment with SE, HW, HCW, and AHP. The 1:1 ratio of OPTs and EFBs is studied to support the scheduling of two feedstocks. The optimal conditions from the laboratory scale are also utilised for modelling [3,4]. During the purification process, extractive distillation by ethylene glycol is simulated to extract water from bioethanol [8]. On the other hand, a polyvinyl alcohol (PVA) membrane in pervaporation technology is modelled using the Aspen Custom Modeler (ACM) [11]. Following the estimation of each stream's feedstocks and mass flows, the ABPD develops batch scheduling. The recipes for scheduling pretreatment and fermentation are shown in Table 2.

Table 1 Composition of raw materials (% dry weight).

Raw materials	Source	Cellulose	Hemicellulose	Lignin	Ash	Others
OPTs	This study	38.67	23.30	23.76	1.62	12.65
	[12]	34.50	31.80	25.70	5.80	4.30
EFBs	This study	38.85	26.14	11.62	1.40	21.99
	[13]	45.06	28.51	12.39	14.04	

Table 2 Recipes for pretreatment and fermentation in ABPD.

Unit	Operation details	Time (min)	Unit	Operation details	Time (min)
SE	▪ Charge OPT ▪ Charge steam ▪ Age (optimal condition) ▪ Drain ▪ Transfer to HW	15 15 4 30 15	AHP	▪ Charge H_2O_2 and water ▪ Age (optimal condition) ▪ Neutralise by water ▪ Drain ▪ Transfer to autoclave	15 30 30 30 15
HW	▪ Charge water ▪ Heat up to 80°C ▪ Age (optimal condition) ▪ Drain ▪ Transfer to T-01	15 15 30 30 15	Autoclave	▪ Charge buffer ▪ Heat up to 120°C ▪ Cooldown to 40°C	15 20 15
HCW	▪ Charge EFB ▪ Charge water ▪ Heat up to 200°C ▪ Age (optimal condition) ▪ Drain ▪ Transfer to T-01	15 15 30 15 30 15	T-02	▪ Transfer to T-02 ▪ Transfer to SSF	15 15
T-01	▪ Transfer to AHP	15	SSF	▪ React (optimal condition) ▪ Transfer to purification	3600 15

2.1. Process description

Bioethanol production using yeast fermentation can be separated into three main sections: pretreatment, fermentation, and product recovery. Since *S. cerevisiae* can convert only glucose to ethanol, pretreatment is used to increase the composition of cellulose, a source of glucose. Firstly, the OPTs are fed into SE at 210°C, 18.6 bar for four min to destroy the rigid structure and increase enzyme accessibility. Next, the sludge is transferred to HW and treated at 80°C for 30 min to eliminate hemicellulose and then stored in the intermediate tank 1 (T-01). Simultaneously, the EFBs are treated using HCW to dissolve and eradicate hemicellulose at 200°C, 30 bar for 15 min, and transferred to T-01. The treated OPTs and EFBs are then delivered to AHP to extract lignin using 3% w/w of hydrogen peroxide at 70°C and pH 11 for 30 min. The OPTs and EFBs are then neutralised by water and transferred to the autoclave. The substrate is mixed with a buffer using a ratio of 1:10, pH 4.8, 0.05 M, and prepared with citric acid, sodium citrate, and distilled water. This mix is then sterilised at 120°C for 20 min. Since SSF requires less fermentation time than SHF and the equipment used is more cost-effective, SSF is selected for this study. Another advantage of SSF is that it can be subsequently used to simultaneously hydrolyse and ferment for 60 hours at 40°C. The 10 FPU/g-substrate of the Ctec2 enzyme converts cellulose to glucose, while a 10% v/v-buffer of *S. cerevisiae* converts glucose into ethanol. The ethanol, called broth, is obtained with 3.356% w/v [3,4,14]. Finally, the extractive distillation and pervaporation processes are used to purify ethanol to 99.0% wt.

3. Results and discussion

3.1 Results

3.1.1 Continuous process simulation in Aspen Plus

As illustrated in Figure 1, the Aspen Plus simulation model shows the production of bioethanol at a rate of 11,563 L/day. To achieve this, the raw materials must be fed with 24,000 kg-OPT/day and 24,000 kg- EFB/day. After treating OPTs with SE-HW, the cellulose composition increases from 38.67 to 56.98% (dry wt.). On the other hand, treating EFBs with HCW, the composition of cellulose is higher, ranging from 38.85 to 56.90% (dry wt.). Subsequently, the mixed OPTs and EFBs are chemically treated using AHP, raising the composition of cellulose to 71.58% (dry wt.) or 63.97% (wet wt.) in the sludge (AHP-S stream). The pretreatment process can increase the composition of cellulose from 38.00 to 71.58% (dry wt.) since hemicellulose, lignin, and others are removed. The solid recovery and composition of treated OPTs and EFBs are summarised in Table 3. Following fermentation in SSF, the broth is then purified to 99.0% wt. ethanol by extractive distillation with a solvent to a feed ratio of 0.46 and compared to the pervaporation technique. The energy demand of pervaporation is lower than extractive distillation at 16.58 and 19.24 MJ/L-ethanol, respectively. The broth flow rate to the purification process is determined at 182.39 L/min, which dictates the batch operation from Aspen Plus.

Table 3 Solid recovery and composition of treated OPTs and EFBs.

Details	SE-HW	HCW	AHP
	HW-S	HCW-S	AHP-S
Moisture	10.00	10.00	10.00
Solid content	90.00	90.00	90.00
Composition of solid content (% wet wt.)			
- Cellulose	51.28	51.21	63.97
- Hemicellulose	12.00	12.11	1.23
- Lignin	12.18	15.01	13.41
- Ash	1.38	1.16	0.24
- Other	13.16	10.51	11.15

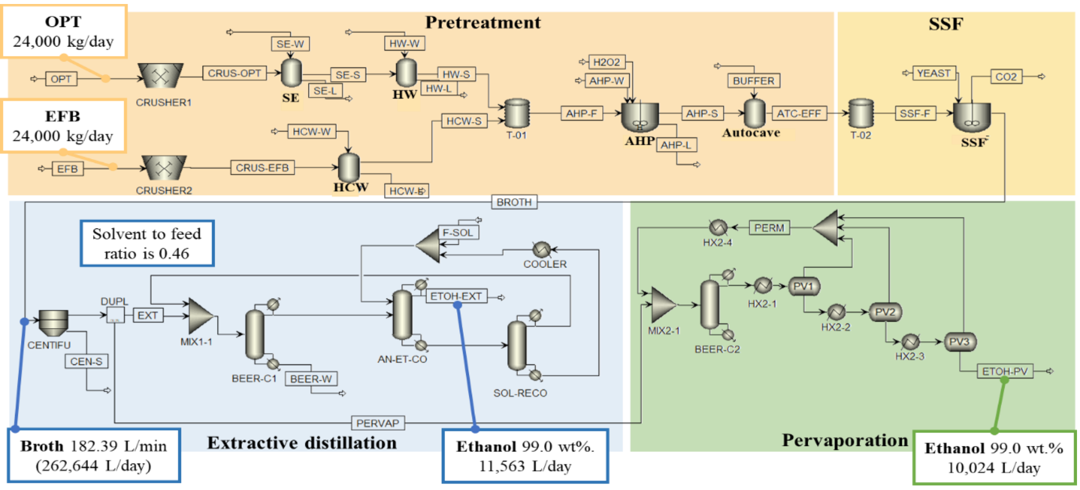

Figure 1 Process flowsheet in Aspen Plus. (Available source: https://drive.google.com/drive/folders/ 1lFgpfa E9AI82txoy96qhdHC8jOtlP7iS?usp=sharing).

3.1.2 Scheduling for pretreatment and fermentation in ABPD

The completed Gantt chart for feeding OPTs and EFBs is shown in Figure 2 and contains the batch operation for pretreatment and fermentation. The pretreatment is operated by feeding two cycles into one SSF in the fermentation section. To avoid unit size overestimation, the number of parallel SSF tanks holding 50,000 L each is determined as 15 units. The cycle time is minimised to 4,089 min/cycle with the SSF tanks producing broth at 182.39 L/min at a rate of six batches per day to complete the cycle.

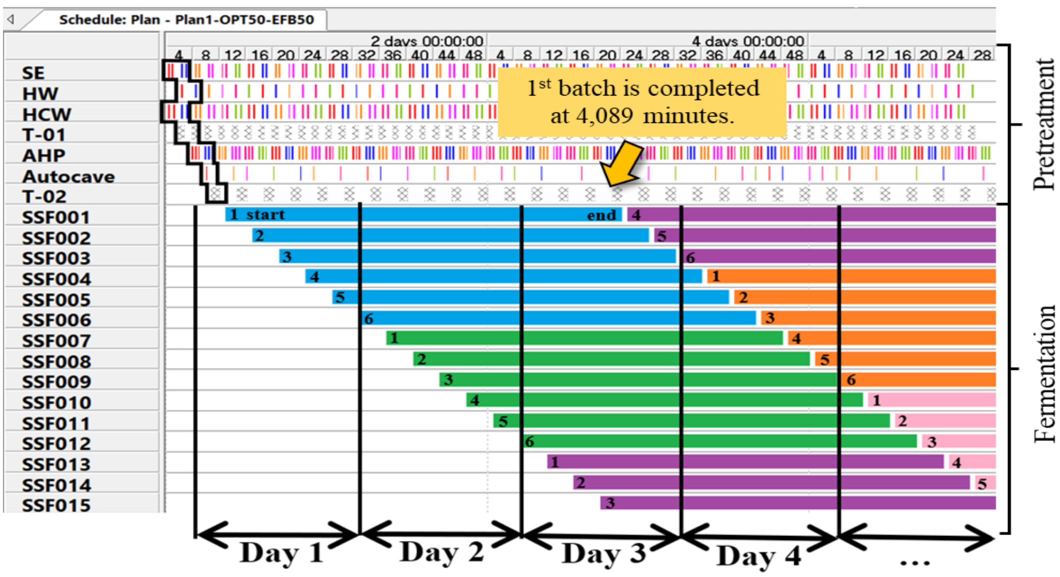

Figure 2 Completed Gantt chart for bioethanol production from OPTs and EFBs in ABPD.

3.2 Discussion

The Aspen Plus simulation model ferments sugar into ethanol at about 88% efficiency, which is lower than bioethanol production from OPTs using SHF in Daruwan's study [8]. However, hydrolysis and fermentation takes six days, which is longer than this current study, where the broth must be fed to produce 182.39 L/min (262,644 L/day) and used to develop the batch design. The Gantt chart without overlap time and parallel fermenter indicates that ethanol can be obtained in 3,600 min (2.5 days), as shown in Figure 3. Purification can be performed continuously; one batch must produce 656,610 L/batch (2.5 days/batch×262,644 L/day). Since high capacity is required for the fermenter, it also results in significant investment costs or unit size overestimation. Moreover, the efficiency of pretreatment equipment is low because idle time is extremely high.

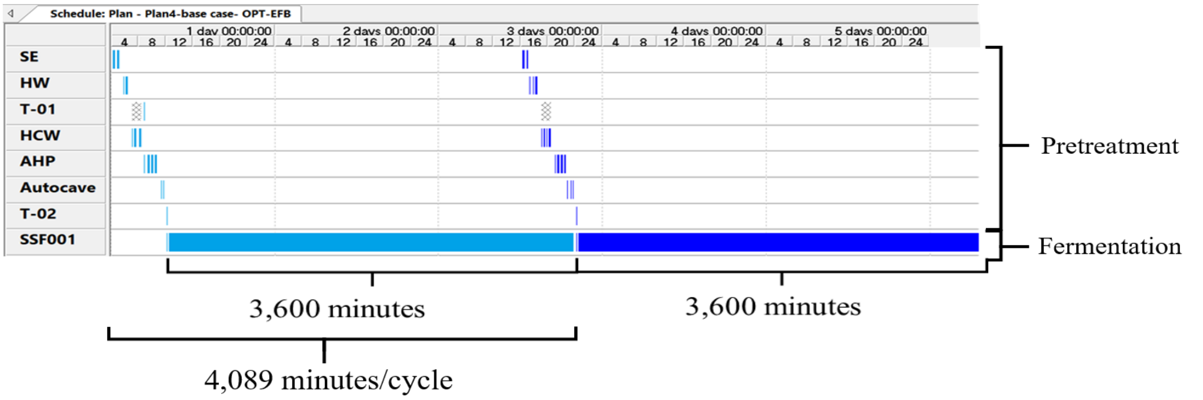

Figure 3 Gantt chart without overlap time.

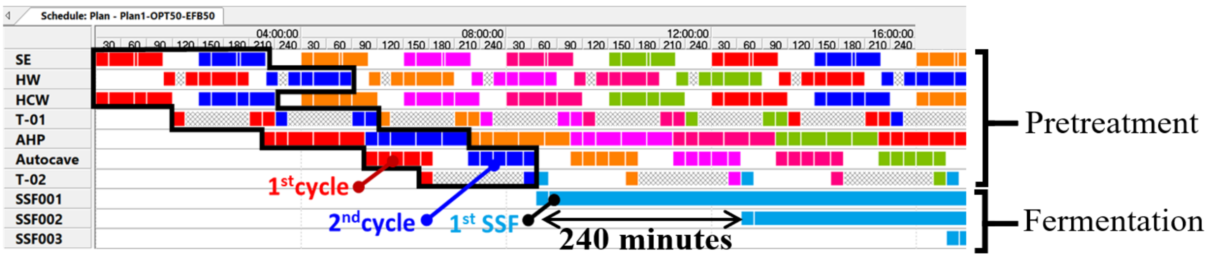

Figure 4 Gantt chart of pretreatment section with overlap time.

To improve production efficiency or reduce the idle time, the number of batch cycles during pretreatment is increased with overlap time, while SSF increases according to the number of batch fermenters, resulting in ethanol being obtained more frequently. The 50,000 L tank requires 6 tanks to handle broth of 262,644 L/day. In other words, one batch can be completed every 240 min (4 hours) to obtain ethanol. With a fermenting time of 3,600 min (2.5 days), the required number of parallel SSF should be 15 tanks (6 tanks/day×2.5 days), producing broth at a rate of 182.39 L/min, as shown in the fermentation section of Figure 2. Every 240 min, 43,774 L of treated OPTs and EFBs will be produced (262,644 L/day ÷ 6 tanks/day). However, one cycle of pretreatment requires extensive equipment, thereby affecting the investment cost. For this reason, the number of pretreatment batch cycles is increased to 2 with a batch overlap time to produce treated OPTs and EFBs at the rate of 21,887 L/batch (43,774 L/cycle÷2 cycles). Figure 4 indicates which colour in the pretreatment section represents a pretreatment cycle. As shown in Table 4, the increased batch cycle involves reduced idle time, leading to greater equipment utilisation in the pretreatment process based on 5 days operation, calculated by equation (1), when the equipment is used more frequently (equipment is being operated) and in use (equipment is waiting for the next operation).

$$Equipment\ utilisation\ (\%) = \frac{the\ time\ when\ the\ equipment\ is\ being\ operated}{total\ time\ for\ operation} \times 100 \quad (1)$$

Table 4 Equipment utilisation of pretreatment units.

Unit	Before improvement (%)			After improvement (%)		
	Running	Available	In use	Running	Available	In use
SE	3.26	96.74	0.00	66.21	33.79	0.00
HW	3.70	96.30	0.00	75.20	15.61	9.19
HCW	3.70	96.30	0.00	75.31	24.69	0.00
AHP	4.92	95.08	0.00	100.00	0.00	0.00
Autoclave	3.30	96.70	0.00	67.04	32.96	0.00

The fermenter size can be reduced 15 times (656,610 to 43,774 L), and ethanol obtained every 240 min, with 6 batches being completed each day. Furthermore, the scheduling of only EFBs as feedstock is also considered in this study. Switching to only the EFB mode does not alter the scheduling and is similar to the OPT/EFB mode whereby SE and HW units are stopped during operation. Conversely, switching from only the EFB mode to the OPT/EFB results in an interval time of 60 min (1 hour), making the time between batches 300 min instead of 240 min. The black block in Figure 5 indicates the EFB mode, while the red line indicates the OPT/EFB mode. The interval time represents the effect of SE and HW units being returned to operation, resulting in a longer operating time for SE and HW than HCW. In addition, the increased interval time is applied to the last batch using only EFB mode and the first batch of OPT/EFB mode but the remaining batch interval time is still 240 min. The variation in interval time means that the continuous process after fermentation cannot proceed at 182.39 L/min for broth feeding. Therefore, the broth obtained from the last batch using only EFB mode must be reduced from 182.39 to 145.91 L/min feeding time to maintain continuous operation. The configuration and layout of bioethanol production in ABPD are illustrated in Figure 6. Note that intermediate tank 3 represents the purification in ABPD.

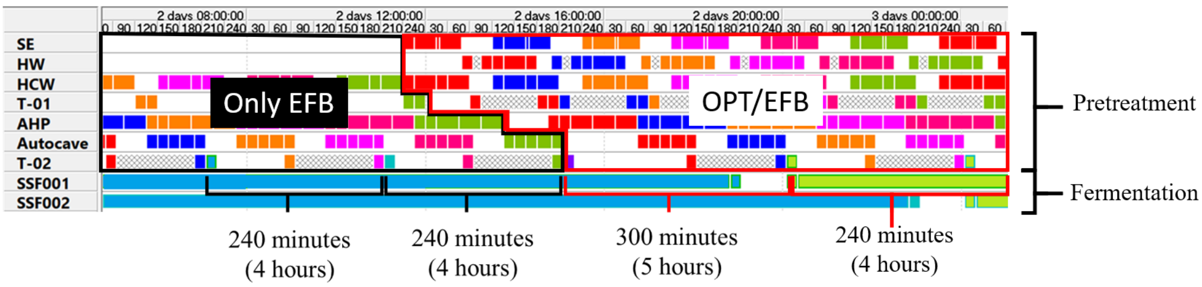

Figure 5 Gantt chart of the switching mode from only EFB to OPT/EFB.

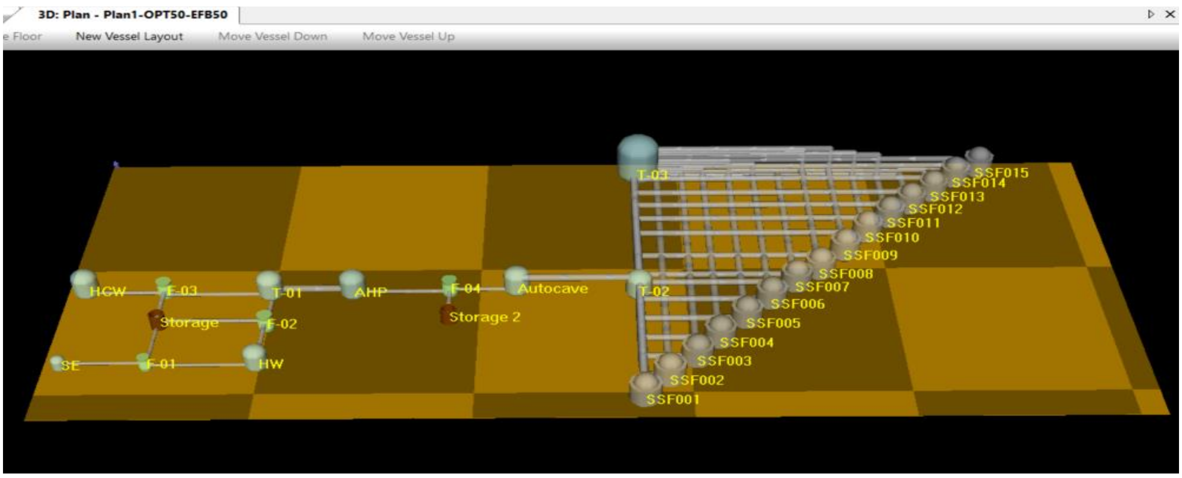

Figure 6 Layout of bioethanol production in ABPD.

4. Conclusion

The process simulation and scheduling of the bioethanol production from OPTs and EFBs have been successfully developed using Aspen Plus and ABPD. Bioethanol can be produced with 99.0% wt. at a production rate of 11,563 L/day using 24,000 kg-OPT/day and 24,000 kg-EFB as raw materials. Moreover, the pervaporation process should be utilised for ethanol dehydration due to its lower energy consumption. The use of 15 parallel 50,000 L fermenters is proposed. A cycle takes 4,089 min, and ethanol can be obtained from a batch every 240 min and continuously fed into a purification process in which 6 batches are completed every day. The pretreatment section can be operated in 2 cycles by being fed into an SSF tank every 240 min, resulting in greater production efficiency. Moreover, the ability to change the feedstock between OPT/EFB mode and only EFB mode can reduce the interval time and improve the ethanol production rate.

5. Acknowledgements

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