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Evaluation of Polar Lipid Waste from Vegetable Oil Extraction: Insights from Experimental and Simulation Results

Amani Salsabil Husodo[1], Nindia Noor Indah[1], Ratri Puspita Wardani[1], Setiyo Gunawan[2,*]

[1] Program Studi Teknik Kimia, Universitas Pembangunan Nasional "Veteran" Jawa Timur
[2] Department of Chemical Engineering, Faculty of Industrial Technology and Systems Engineering, Institut Teknologi Sepuluh Nopember

Correspondence Email (Author): gunawan@chem-eng.its.ac.id

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ABSTRACT
This paper examined the wastewater production attributed to the solvent-based cooking oil extraction assisted by Aspen Plus V.12. simulation. Distillate condensates that contained remaining solvents as well as free fatty acids (FFAs), were identified as waste streams. Three feedstocks were tested, Crude Nyamplung Oil (CNO), high-FFA Crude Palm Oil (CPO-acid), and regular Crude Palm Oil (CPO-regular). CNO generated 0.288 ton/h wastewater dominated of n-hexane and methanol, whereas CPO-acid (1.338 t/h) and CPO-regular (1.419 t/h) wastestreams were dominated by ethanol. The stoichiometric oxidation was used to estimate chemical oxygen demand (COD), whereas FFA content was used to determine oil and grease (O&G). The COD values of untreated streams were 293.236 mg/L (CNO), 2511.39 mg/L (CPO-acid), and 1662 mg/L (CPO-regular), which were higher than the Indonesian standard (350 mg/L). O&G values of the untreated waste streams were not met the standards. Solvent based processes founded to be more polluting, compared to refinery effluents (COD >15000 mg/L, O&G 4000mg/L), yet it was due to the nature of extraction and oil specifications. Solvent recovery and FFA valorization to biodiesel or PFAD are suggested to be enhanced to decrease the environmental burden.

1. INTRODUCTION

Vegetable oils refer to the oils that contain high triglycerides (TAGs) extracted from vegetables, and are one of the most commonly used commodities in the world, in the food, cosmetics, pharmaceutical, and renewable fuels (Gharby, 2022). CPO and coconut oil (CO) dominate the market in Indonesia and both are important feedstocks to downstream industries (Judijanto, 2025). Indonesia is a major producer of palm oil that contributes to more than half of the world vegetable oil trade (Freitas et al., 2024). Nevertheless, oil mining and refining also produce enormous waste fractions which bear financial losses as well as environmental hazards, and thus have to be handled.

Oil refinery wastes are FFAs, residual solvents, spent bleaching earth, polar fractions, and organic-rich wastewater (Awoh et al., 2023; Mohd Yusof et al., 2023). Lack of proper management not only wastes resources but also imposes a great burden on the environment (Awoh et al., 2023; Dashti et al., 2022). Among them, FFAs and residual solvents are quite abundant (Saputera et al., 2021). During hydrolysis and neutralization, FFAs: primarily palmitic, oleic, and linoleic acids are released (Hasanudin et al., 2015). High FFA concentrations decrease the quality of oil, decrease stability and augment effluent organic load (Low et al., 2021). When recovery is incomplete, residual solvents used in extraction units remain. These residues are toxic to health and pollute air and water when released in excess (Mohammad et al., 2021). Therefore, the industry stands in the challenge of quality of the products and reducing the environmental effect.

Indonesia controls the quality of the products as well as garbage release. SNI 7709:2019 restricts the FFA content of cooking oil, and SNI 06-3730-1995 places a limit on the amount of hexane left of 5mg/kg . On the environmental front, the wastewater discharge standards and the regulations proposed by the Ministry of Environment and Forestry (Aparamarta et al., 2025). Regulation (PERMENLHK) Regulation No. 5/2014 include the standards of COD, O&G, and hydrocarbon residues. Compliance thus involves monitoring as well as active treatment of waste.

The primary concern addresed in this study is the compliance of FFA-containing polar waste streams, with the threshold limits established in the Indonesian Ministry of

Environment and Forestry Regulation No. 5/ 2014 (Indonesian Ministry of Environment, 2014). Otherwise, it needs some extra processings such as adsorption, membranes, bioconversion (Kusnadi et al., 2025). In addition to the compliance, valorization provides a chance. FFAs can be used to produce oleochemicals, surfactants, or biodiesel, and recovered solvents can be recycled which reduces expenses and can be used to achieve a circular economy (Mohammad et al., 2021; Rahman et al., 2025). This means that waste management is not only possible in its disposal but also in its efficiency. But aside from valorization of the waste or by-product streams, different alternative technologies can be applied to make cooking oil.

One of the alternative methods applied to is counter-current extraction (CCE). CCE has become a promising technique of processing CPO and non-edible oils like Calophyllum inophyllum (nyamplung) (Gunawan et al., 2020). CCE increases the yield of TAGs by enhancing mass transfer in shorter time with smaller amount of solvent, compared to batchwise solvent extraction (BSE) method (Hirayama et al., **2021; Husodo et al., 2025). Nevertheless, FFAs and solvent** leftovers founded in the waste streams cannot be avoided. The studies of Gunawan (2020) and Mahardhika (2024) only focused on the TAGs content obtained from the CCE. (Gunawan et al., 2020; Mahardhika, 2024). The methodical analysis of waste composition has not been well introduced.

In this case, methodical analysis can be conducted after simulating the extraction process using process simulation tool. One of the widely used process simulator is Aspen Plus (Husodo et al., 2025). This software enables researchers and engineers to develop and simulate detailed process models (Mawarni et al., 2024). This software can also represent mass and energy balances, reaction kinetics, and separation processes under various operationg condition (Tan et al., 2021). Once the simulation model in Aspen Plus has been validated or the simulation , this can be used to optimize operating conditions and forecast the byproduct composition with a high level of accuracy (Husodo et al., 2024). A related processes simulation of CPO extraction using BSE, catalytic processes of fatty acid methyl esters (FAME), and FFAs removal; have been simulated using Aspen Plus (Mawarni et al., 2024; Saetiao et al., 2023; Tan et al., 2021). These simulation results give the industries an opportunity to predict compliance risks and plan treatment or valorization in advance.

The study proposed that Aspen Plus V.12-assisted simulation used to predict the wastewater characterization. This study evaluated further into the waste management prediction of the losses of FFA and solvent residues and their effects on wastewater quality parameters (COD and O&G), which are considered in this study. The analysis of the distillate wastes were applied for CCE as alternative extraction method for CNO, CPO-acid, and CPO-regular.

In addition, the findings are compared to Indonesian regulatory thresholds (PERMENLHK no 5 / 2014 standards) and real refinery effluents, to obtained apple-to-apple comparisons. This relationship between process engineering, regulatory compliance, and environmental management is a new contribution. This can give viable information towards the sustainable growth of vegetable oil industry in Indonesia. The strategy illustrates how process modeling in engineering can facilitate the implementation of the circular economy by finding the potential to reuse FFAs as a by-product (e.g., PFAD feedstock or biodiesel feedstock) and minimize the pollution load associated with solvents.

2. METHOD

2.1 Materials

According to Mahardhika (2024) study, that studied utilized regular grade CPO and palm-based acid oil, that were obtained from supplier on West Kalimantan (Mahardhika, 2024). For the CNO, the previous experiment conducted by Gunawan (2020) mentioned that they were sourced from local supplier on Pasuruan, East Java (Gunawan et al., 2020). Crude oil specifications can be seen on Table 1. Food grade ethanol (96 weight percentage (%w/w), PT. CIMS) was used to extract the CPO. Ethanol was used for its ability to extract the polar lipid compounds such as FFAs and MAGs, thus leaving the non-polar compounds aside.

For the CNO extraction, technical-grade n-hexane (99% w/w, PT. CIMS) and technical grade methanol (99% w/w, PT CIMS) were used, creating dual-solvent system. The n-hexane which was known for its affinity to non-polar solvent, was used to attach TAGs and other non-polar lipid fractions. Methanol then used to withdraw the polar lipid fractions like FFAs and MAGs.

Table 1. Raw Material Composition

Parameter	Content (%, w/w)		
	CNO***	CPO-acid**	CPO regular**
TAG	63.91	72.41	87.30
DAG	4.66	1.18	3.90
MAG	12.25	0.36	0.12
FFA	15.76	20.30	5.60
Other*	3.42	5.75	3.09

TAG: Triglycerides, DAG: Diglycerides, MAG: Monoglyceride, FFA: free fatty acid
*other : consisted of wax, gum, etc.
** obtained from Mahardhika (2024) study
*** obtained from Gunawan (2020) study

2.2 Experimental Extraction Method

Both CPO and CNO were extracted using CCE. Single solvent CCE using food grade ethanol was applied for CPO. For regular grade CPO, this CCE applied mass ratio of ethanol and CPO = 2.5 : 1 (w/w). For acid oil, this system applied exact mass ratio (Mahardhika, 2024).

For CNO, dual solvent CCE was applied using methanol as polar solvent and n-hexane for non polar solvent. This CCE performed volumetric ratio of methanol and feed (n-hexane+CNO) = 15 : 6. The mass ratio of n-hexane and CNO were also applied = 6 : 1 (Gunawan et al., 2020).

2.3 Process Simulation and Experimental Validation

Aspen Plus V.12 was used to simulate the process to model the experimental system according to Husodo (2025) study

(Husodo et al., 2025). It can be seen in Figure 1., that the CCE was modeled using an EXTRACT column with 8 equilibrium stages, operated at 30 °C and 1 atm with crude oil and solvent as feeds. The extraction process resulted in two outlet streams: extract that composed by polar lipid fractions (PLF) and raffinate stream (consisted of NPLF). The raffinate stream which dominantly consisted of solvents was recycled thus not considered as waste. The raffinate stream (NPLF) was fed into a distillation unit (DIST) that was running at 100 °C and 1 atm to remove remaining solvents. This unit has two outlet streams: "product" (cooking oil) and "residu". The "residu" stream was generated as vapor phase and contained residual solvents and PLF, underwent condensation process. In this study, the "residu" stream was considered as waste to be analyzed for its parameters.

The model used the Non-Random Two Liquid (NRTL) property package combined with binary interaction estimation parameter UNIQUAC Functional Groups Activity Coefficient (UNIFAC)-Lyngby thermodynamic model, which was proven by Husodo (2025) to be valid for CCE production of cooking oil, with $R^2 > 0.99$ and p-value ≈ 0.5 (> 0.05) (Husodo et al., 2025). The simulation performed in this study was purposed to construct process of making cooking oil with raw materials based on a) CNO with 0.288 ton/h capacity , b) acid oil with 1.388 ton/h capacity, and c) regular CPO based with 1.419 ton/h capacity; This detemination is in accordance to experimental results.

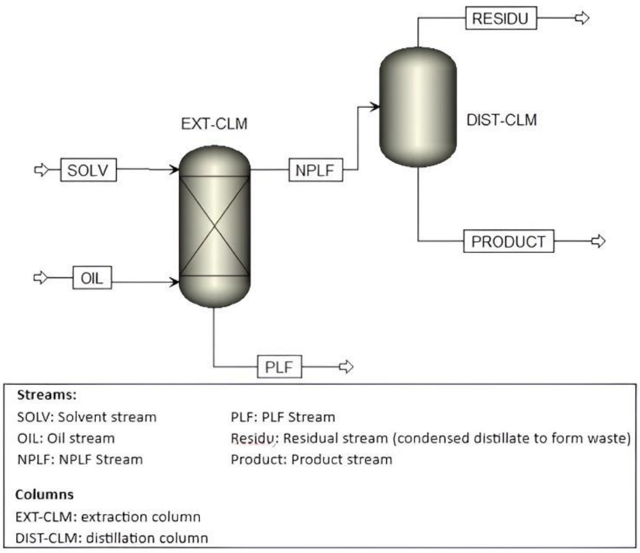

Figure 1. Simulation Scheme of Vegetable Oil CCE

2.4 Waste Stream Identification and Analysis

This work focused on the "residu" stream as the distillate of DIST column. This stream is the vapor stream which had been condensed following solvent recovery. As can be seen in Figure 1. and section 2.3, this "residu" stream was examined separately since it is directed to wastewater management along with other effluent streams. Hence, this stream was used to calculate COD and O&G loads.

The calculated loads were benchmarked against Indonesian regulations, specifically the PERMENLHK No. 5/2014 on palm oil industry effluents, which sets discharge limits for oil and grease, COD, and BOD (Indonesian Ministry of Environment, 2014). In addition, the simulated waste loads from extraction processes were compared with reported effluent characteristics from conventional CPO refinery operations, providing context on how novel extraction routes differ from or align with established industrial practices. A wastewater volumetric flow of 2.5 m^3/ton was applied for parameter calculation. The number was chosen as the maximum limit according to PERMENLHK no 5/2014 (Indonesian Ministry of Environment, 2014).

2.4.1 Oil and Grease Load Calculation

The FFA fraction was treated as the main contributor to oil and grease in the wastewater. The load was calculated directly from Aspen Plus simulation outputs as written in Equation (1):

$$O\&G = mass\%_{FFA} \times \frac{\dot{m}}{Q} \quad (1)$$

Where $O\&G$ is oil and grease content in the residual stream (mg/L). $\dot{m}$ is the residual stream rate (ton/h), $mass\%_{FFA}$ is mass percentage of FFA,and Q is the wastewater rate for cooking oil plant (ton/h) (Metcalf & Eddy et al., 2013). The Q itself can be written:

$$Q = plant\ capacity \times 2.5 \quad (2)$$

Where on Equation (2), the 2.5 value was selected due its regarded as a maximum value of wastewater rate on PERMENLHK no 5 year 2014 (Indonesian Ministry of Environment, 2014). The values calculated were in per ton of cooking oil produced to allow fair comparison between processes. This reflects predicted values obtained via simulation and subsequent calculation, consistent with the methodology applied.

2.4.2 Chemical Oxygen Demand (COD) Calculation

COD load was approximated from the FFA fraction, assuming complete oxidation of fatty acids as the worst-case scenario. COD represents the equivalent oxygen required to chemically oxidize organic matter in wastewater (Metcalf & Eddy et al., 2013). The load was calculated for each compound contributed in the wastewater stream: n-hexane, methanol, ethanol, and FFA itself. The calculation started by using the mass percentage of each compound to determine the compound mass rate as seen on Equation (3):

$$m_{comp} = \dot{m} \times mass\% \quad (3)$$

Where $\dot{m}$ is the residual stream mass rate (ton/h), m_{comp} is the compound mass rate (ton/h), and *mass%* is the mass percentage specific for each compound (Metcalf & Eddy et al., 2013). After all of the component mass rate determined, each component thus calculated the theoritical COD from these stoichiometric reactions, as written on Equation (4) to (7).

n-Hexane (C_6H_{14}):

$$C_6H_{14(aq)} + 9.5O_{2(g)} = 6CO_{2(g)} + 7H_2O_{(l)} \quad (4)$$

Methanol (CH_3OH):

$$CH_3OH_{(aq)} + 1.5O_{2(g)} = CO_{2(g)} + 2H_2O_{(l)} \quad (5)$$

Ethanol (C_2H_5OH):

$$C_2H_5OH_{(aq)} + 3O_{2(g)} = 2CO_{2(g)} + 3H_2O_{(l)} \quad (6)$$

FFA (as oleic acid):

$$C_{18}H_{34}O_{2(aq)} + 25.5O_{2(g)} = 18CO_{2(g)} + 17H_2O_{(l)} \quad (7)$$

and the COD determination itself, then calculated in unit of (kg O_2/h), followed the Equation (8).

$$COD_{comp} = m_{comp} \times COD_{fac} \quad (8)$$

COD_{comp} is calculated COD per compound (kg/h), COD_{fac} is COD factor that equals to O_2 coefficient on chemical reaction, and m_{comp} is the compound mass rate (kg/h) (Metcalf & Eddy et al., 2013).
After gathered the COD_{comp}, the COD per waste water rate is then calculated using Equation (9).

$$COD = \frac{COD_{comp} \times 10^6}{Q} \quad (9)$$

Where COD is chemical oxygen demand rate (mg/L), COD_{comp} is the COD calculated on mass rate for each compound (kg/h) and Q is the volumetric wastewater rate. This calculation provided a proxy for organic pollution potential and allowed comparison across feedstocks (Metcalf & Eddy et al., 2013).

3. RESULTS AND DISCUSSION

3.1 Waste Stream Parameters: Determination Results

The Aspen Plus V.12 simulation showed that there were three different condensated waste streams that correspond to solvents and PLF collected at the DIST unit. Each "residu" streams simulation results are: (i) CNO distillate (0.288 ton/h), which n-hexane was the predominant solvent (41.080% w/w), with a small amount of methanol (0.933% w/w) and FFA (0.770% w/w); (ii) CPO-acid distillate (1.338 ton/h), which was composed mainly of ethanol (51.445% w/w) and minor quantities of FFA (1.335% w/w); (iii) CPO-regular distillate (1.419 ton/h), with ethanol as major contributor (53.826% w/w) followed by FFA (1.648 % w/w). The detailed results can be seen on Table 2.

Table 2. Simulation Results of "Residu" Streams

Stream	CNO	CPO-acid	CPO-regular
Flow rate (ton/h)	0.288	1.338	1.419
Solvent composition (% w/w)	Hexane 41.05 Methanol 0.93	Ethanol 51.45	Ethanol 53.83
FFA (% w/w)	0.777	1.34	1.65

Table 3. COD Factor Used

	FFA	n-hexane	methanol	ethanol
COD factor	2.893	3.535	1.5	2.087

COD is quantity of oxygen needed to oxidize organic material (Metcalf and Eddy, 2014). The COD was estimated by multiplying the mass of the individual organic components by the stoichiometric COD factor of each (3.54 g O_2 /g hexane, 2.09 g O_2/g ethanol, 1.5 g O_2/g methanol and 2.9 g O_2/g FFA). O&G was calculated as the main non-polar constituent to this parameter based on the FFA fraction. Table 3 summarizes the detailed parameters adopted in the calculation.

Findings show that solvent residues dominate the COD, and the contribution of FFAs is considerably low. The estimation of O&G revealed that CPO-based streams have higher potential O&G loads (1723 mg/L) compared to CNO streams. These results highlight that the most important determinant of wastewater strength in this system is solvent recovery efficiency.

3.2 Waste Stream Parameters: Comparison and Analysis

The results of the analysis revealed that "residu" streams produced, mainly consisted of solvents and FFAs. The streams composition varied significantly based on feedstock and the use of solvents. Regarding for the O&G levels, CNO-based process had the lowest concentration (293.236 mg/L), CPO Acid and CPO Regular had much higher values of 2,511.395 mg/L and 2,851.841 mg/L, respectively. These outcomes were significantly higher than the discharge limit established by PERMENLHK No. 5/2014 (25 mg/L), showing the urgency of effective oil separation or flotation before discharge.

This evidence on O&G levels happened due to the facts founded on several studies, that single solvent CCE had lower efficiency compared to dual solvent CCE (Gunawan et al., 2020; Mahardhika, 2024; Vegas Mendoza et al., 2019). As mentioned previously, CNO was processed with dual-solvent CCE while CPO-Acid and CPO Regular were processed with single-solvent CCE. FFAs were included more in the "product" stream of CNO-based cooking oil than in the CPO-based cooking oil. Therefore, the FFA content of the CNO in the "residue" stream was lower than the single-solvent CCE system applied to the CPO-regular and CPO-acid systems.This happened due to the mass transfer limitations between the immiscible phases, as the introduction of two solvents (n-hexane and methanol) in the CCE process of CNO, enhanced the interfacial tension and diffusivity of solute molecules (Vegas Mendoza et al., 2019). This could also have reduced the driving force for solute transfer due to the partial saturation or solvent-solvent interaction, resulting in lower selectivity toward the lipids (Gharby, 2022). Increased viscosity and phase instability caused by dual solvent might hindered droplet dispersion and equilibrium attainment, thereby reducing the overall extraction efficiency, resulted on smaller ammount FFAs in the "residu" stream (Vegas Mendoza et al., 2019).

The similar phenomenon also occured for COD levels. The CNO-based process produced a total COD of 56,644 mg/L, which is majorly due to the n-hexane residues, with methanol playing a very insignificant role. On the other hand, the CPO Acid and CPO Regular-based processes produced much higher COD loads of 209,259 mg/L and 202,664 mg/L, respectively. These values were higher than the regulatory limit of 350 mg/L.

According to the results presented in Table 4, CCE-based processes delivered substantially higher COD values compared to conventional refineries. The O&G values were still within conventional refinery values. These findings can be discussed further by observing Figure 2. According to Figure 2., this difference value of COD and O&G arised from the fundamental design purposes of CCE. CCE composed by two processes : CCE and distillation, with solvent recovery as its target rather than impurity dilution. During the extraction process, part of organic phase such as TAG, DAG, FFA, and trace solvent remained unrecovered in the "residu" stream after separation process. CCE system worked without aqueous washing or neutralization steps, promoting organics accumulation in a concentrated form in the "residu" streams. This yielded on elevated COD and O&G levels. This behaviour discovered also in the other solvent-based oil recovery systems, where concentrate phase typically shows COD exceeding 40,000 mg/L due to residual organic solvents and extractable matter (Cravotto et al., 2023; Eladawy, 2025).

In conventional edible-oil refineries (physical and chemical refining), the major processes consisted of degumming, bleaching, and deodorization (Kusnadi et al., 2025). Each steps contributed differently to the organic load of the effluent (Rahman et al., 2025). Degumming released phospholipids and residual oil into aqueous sludge (Rahman et al., 2025). Bleaching produced clay waste laden with adsorbed organics (Mawarni et al., 2024). Deodorization condensated volatile content of degraded products (Mawarni et al., 2024). Specific for chemical refining, neutralization process resulted on flushed soapstock and created large volumes of oily waste water (Mawarni et al., 2024). Refinery effluents were also consisted of TAGs and FFAs, a fact that explained the high O&G results (Yong et al., 2023). This combination of TAGS and FFAS that added with deodorizer distillates, impacted on high ammount COD, as supported by several studies (Eladawy, 2025; Vegas Mendoza et al., 2019).

Feedstock characteristics also affected the COD and O&G levels, an evidence also founded in several studies (Cravotto et al., 2023; Rahman et al., 2025). As presented in Table 1., CNO and acid-CPO contained higher FFA content than regular CPO, which stand as the minimum standard used in the industry according to SNI 2901 : 2021 (BSN, 2021). This evidence resulted on higher amount of solvent to ensure effective solubilization into the solvent phase, thus increasing organic matter into the "residu" stream. Due to the absence of the dilution and neutralization in this CCE, even a slightest amount of unrecovered organics can yield significantly higher COD and O&G values when normalized to effluent volume (He et al., 2023).

Table 4. Waste Stream Parameter Calculation Results

Parameter		CNO	CPO Acid	CPO Reguler	FAME Refinery 1*	FAME Refinery 2**	PERMENLHK No 5 Year 2014
O&G (mg/L)		293.236	2,511.395	2,851.841	130-18,000	4,000-9,341	25
COD (mg/L)	FFA	293.236	2,511.395	2,851.841	N/A	N/A	N/A
	n-hexane	55,262.387	N/A	N/A	N/A	N/A	N/A
	methanol	354.168	N/A	N/A	N/A	N/A	N/A
	ethanol	N/A	206,747.605	199,812.159	N/A	N/A	N/A
	total	56,644.000	209,259.000	202,664.000	15,000-100,000	44,300-102,696	350

*These data collected from study conducted by Hasanuddin et. al (2015)

**These data collected from study conducted by Sinaga et. al (2018)

In general, CNO discovered to be relatively less polluting, whereas CPO-derived processes, in particular for those involving ethanol, produced much larger organic loads. Notably, the possible contaminants prevailed among feedstocks, with CNO effluents highly affected by remnant solvents like n-hexane, and CPO streams greatly affected by ethanol. Such differentiation could be inferred that wastewater treatment approaches should be identified as such: solvent recovery facility in Crude oil-related approaches and sophisticated biological or physicochemical remedies in alcohol-containing CPO effluents (Burmana et al., 2025; Medeiros et al., 2022).

With the very large values of O&G and COD levels, every stream inevitably has to be subjected to treatment in a wastewater treatment plant (WWTP) to meet the necessary environmental standards (Suprihatin et al., 2024). As an alternative, valorization methods, including recovery of residual oils, alcohols or other organics to generate energy and to use resources again; could be considered as a complementary measure in order to lower environmental impact and enhance process sustainability (Dewi et al., 2024; Hasanudin et al., 2015). Solvent recovery or integrated solvent reflux process scheme can also be considered, referring to the nature of CCE is for recovering solvents (Husodo et al., 2025). This nature differed from conventional refineries, which their main purposes were on minimizing waste content and oil loss, such as shown on the data obtained from Hasanuddin (2015) and Sinaga (2018) studies (Hasanudin et al., 2015; Sinaga et al., 2018).

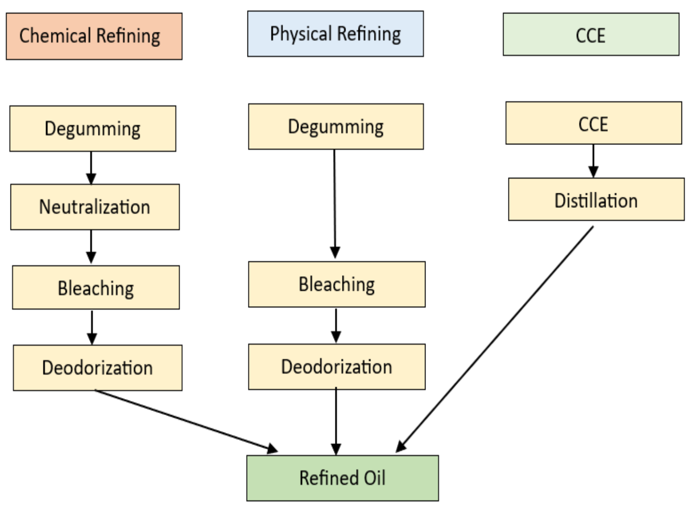

Figure 2. Comparison of CCE and Refining

3.3 Strategy for Waste Valorization and Treatment

The waste stream analysis has shown that the effluents of the CNO, CPO-acid, and CPO-regular processes were mainly influenced by the remaining solvents used and initial crude oil composition, aside from the CCE had different natures and steps compared to conventional refineries. The COD values obtained were higher than the regulatory threshold and typical conventional refinery, regardless of the fact that the amount of O&G values were still within the general range of conventional proceses. As discussed earlier in the previous section, the CCE was designed for solvent recovery with minimal processing steps, thus enhanced the process efficiency (Gunawan et al., 2020; Vegas Mendoza et al., 2019). Solvents management strategies should, therefore, considered solvent recovery, wastewater treatment, and possible valorization possibilities (Dashti et al., 2022; Rahman et al., 2025).

From a process-engineering perspective, mass transfer affected solvent recovery, thus influenced the COD load (Mohammad et al., 2021). COD is directly proportional to the fraction of the solvent and dissolvend organics, unrecovered in the condensed distillate. Therefore, improving mass transfer efficiency of this system, for instance by installing extra equilibrium stages in the column and employing solvent stripping or adsorption units, could reduce COD levels (Medeiros et al., 2022). These could enhance interphase contanct and higher driving forces for solvent-solute transfer, promote to more complete recovery. The recovery of over 95 percent of the solvents would be enough to make predicted COD compliant with the Indonesian standard (Mohammad et al., 2021). The refluxed solvent applied in the CCE process design, could be another alternative of the optimalizing solvent recovery and utilization (Husodo et al., 2025).

In addition to the process intensification, wastewater treatment is still required. Physico-chemical methods such as dissolved air flotation and coagulation have been used together with biological systems (anaerobic digestion or aerobic activated sludge) (Metcalf & Eddy et al., 2013; Vegas Mendoza et al., 2019). These have been shown to be effective in traditional palm oil refineries, and would also be applicable in solvent-based processes (Kusnadi et al., 2025; Yong et al., 2023). The aim of such integration were to remove both residuals O&G and COD, and to ensure a stronger effluent profile prior to discharge.

Furthermore, valorization of organic rich residuals could be among the alternatives along with solvent recovery and WWTP arrangement. The FFA fraction, although a minor constituent of mass balance to the solvents, contributed to the O&G levels with a heavy economic potential (Saputera et al., 2021). Recovery og FFA rich streams could yield PFAD or biodiesel feedstock (FAME), thereby transforming potential waste into marketable materials (Burmana et al., 2025; Rahman et al., 2025). This could minimize organic load within the wastewater, as well as facilitates the principles of the circular economy of turning a liability in the form of waste into a co-product.

Altogether, Aspen Plus V.12 simulations and predictions findings served the necessity of combining process evaluation through waste analysis to waste treatment and valorization. Process modifications by considering the raw materials specifications and process nature can minimze pollutant formation, while downstream recovery and treatment strategies ensure regulatory compliance and efficiency.

4. CONCLUSION

This paper has shown that simulated solvent-based cooking oil recovery produces wastewater streams that have different compositions based on the feedstock. The distillate condensates are made up of residual solvents which contain traces of FFAs, which directly contribute to COD and O&G loads. CPO-regular and CPO-acid caused higher COD values (2511.395-2851.841 mg/L) compared to CNO (293.236 mg/L), which were higher due to their higher solvent content and rate of waste release. However, CCE process resulted COD values that higher than conventional refineries (15000-102696 mg/L). For O&G, CCE produced O&G levels within the range of conventional refineries. The allowable limits of COD and O&G in wastewater streams are 350 mg/L and 25 mg/L, respectively. When contrasted with the Indonesian standards, the COD and O&G levels obtained were beyond PERMENLHK no 5 2014. Despite the purpose of CCE to enhance the mass transfer efficiency, these results promoted the necessity to apply solvent recovery and to convert FFA-rich fractions into PFAD or biodiesel feed. In general, the combination of innovative recovery and treatment plans were essential to reduce the environmental impact and establish the sustainable vegetable oil production.

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