OPTIMIZING PRODUCTIVITY IN SEPARATING BIOMASS AND ORGANIC MATERIALS FROM PALM OIL MILL EFFLUENT: EXPERIMENT TOWARDS REDUCING CARBON EMISSION FOR CLIMATE CHANGE EFFECT

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ABSTRACT: *This paper describes a problem that exists in palm mill effluent treatment; and also presents a technologically and environmentally sustainable solution achieved from experimental research. At the first stage, a two-stage batch anaerobic reactor (TBAR) with carbon to nitrogen ratio enriched inoculum has used for the digestion biomass and organic materials of POME. In the second stage, nanomembranes have used for separating biomass and organic materials from effluent discharged from TBAR. This research investigated the performance of the anaerobic reactor and the nanomembrane in reducing organic materials and biomass from POME for producing dischargeable effluent. The anaerobic reactor was operated at temperature 35^{0}C with various range of manipulating variables; the outcome of this research had demonstrated a 62.5 % digesting performance of biomass and organic materials. The nanomembrane system was operated at a feed pressure range of 60 psi to 120 psi, which had demonstrated over 95% performance in separating biomass and organic materials from the effluent discharged from the anaerobic reactor. The findings of this research would be useful in POME treatment for optimizing the environmentally friendly effluent production for recycling as process water for the crude palm oil process. However, the novelty of this research is to use a two-stage anaerobic reactor and nanomembranes system in series in optimizing the performance and operating cost in POME treatment.*

Keywords: Palm Oil Mill Effluent, Bio-Technology, Anaerobic Digestion, Bio-Effluent, Waste to Energy [WtE], Renewable Energy, Production and Productivity, Nano- Membrane; Environmental Sustainability, Climate Change

1.0 RESEARCH BACKGROUND

This paper presents research outcomes conducted on Palm Oil Mill Effluent (POME) to optimize treatment performance in producing dischargeable (environmentally friendly) effluent. The broad objective of this study was to reduce total organic materials (TOM) from POME for reducing carbon emission towards mitigating climate change effects in line with global sustainable Agenda 2030 [1]. This research conducted with Batch Anaerobic Reactor (BAR) to convert TOM to biogas. And, the Nano membrane (NM) was also used to separate TOM from effluent. However, this work is a continuation of previous studies that were published in various journals [2–5]. Published reports suggested that palm oil mills have been using anaerobic technologies for POME treatment [4]–[6]. It was also reported that biogas and quality effluent production performance of currently available BAR and other anaerobic technologies have appeared to be poor and not technically and financially feasible to use [3, 6, 7]. It has been also claimed that due to the poor performance of anaerobic digesters, the palm oil mills are not showing interest to install anaerobic technology [3, 6, 7]; thereby they continuing with the traditional POME treatment method [8]. However, this scenario suggests that a research gap exists in POME treatment in reducing TOM. Indeed, this research was undertaken to reduce the gap that exists in improving the performance of POME treatment for producing dischargeable effluent. The novelty of this research is to use a two-stage anaerobic reactor and nanomembranes in series in optimizing performance in POME treatment for *contributing to achieving SDG-6(clean water),SDG-7(clean energy) and SDG-13(climate actions) towards achieving the UN Agenda 2030.* [1, 9].

1.1 Problem Statement

Shahbandeh (2020) reported in the global production volume 2012/13-2019/20 that the global Crude Palm Oil (CPO) potential was about 74.0 million metric tons in the marketing year 2019/2020 [10]. Indeed, the CPO processing is an identified Greenhouse Gases (GHG) emission source and a primary driver of climate change. Malaysia is about 40% of the global CPO producer. The carbon (CO_2eq) emission potential of this country from the CPO process and POME is approximately 25m^3(ton POME)$^{-1}$ to 28m^3(ton POME)$^{-1}$. It was also reported that the carbon (CO_2eq) emits from POME contain Methane (CH_4 $\geq$65%) which is about 25 times higher global warming potentials compared to the carbon dioxide (CO_2). One the other hand, biogas is a source of POME based energy [11]. The estimated energy potential of POME in Malaysia is about 13,600 MWh (Year)$^{-1}$ [9, 12].

The estimated water potential of POME in Malaysia is about 25 million tons a year [13]. This information demonstrates that by deploying efficient technologies, the organic wastes materials of POME could be converted to clean energy and water could be produced. In addition to resources recovery, the problem relating to POME in carbon emission and pollution could be solved in line with SDG-6(clean water), SDG-7 (clean energy), and SD-13 (climate action) for achieving economic and environmental sustainability of this country by 2030 [9].

It is also reported that a few mills are discharging poor quality effluent from palm oil mills to the environment due to the lack of available required technology. However, it was found that palm mills are struggling to comply with environmental regulations and they need an affordable and efficient technology for POME treatment [12, 14]. A few types of research have reported that the performance in TOM conversion to biogas and other products is about 65% which has appeared an environmental sustainable problem to society and palm oil mills [2, 5, 15]. However, the reported problem in the palm oil mill domain demonstrated that in many cases, the process used for decomposing TOM is not fully able to meet the requirement of the Department of Environment (DOE) [2, 5, 15, 16]. Indeed, this research was designed to address the TOM reduction problem from POME and to find an environmentally acceptable solution.

2.0 LITERATURE REVIEW

This section describes a literature review published on research in POME treatment. The aim of this review was to update the knowledge of decomposing and separating TOM from POME. The main focus of this review was to update the current performance level of BAR based anaerobic reactor and NM in the POME digestion process. The second focus was to know the effect of pH, Hydraulic retention time (HRT), Sludge Retention Time (SRT), Carbon to Nitrogen ratio (C/N), and Organic Loading Rate (OLR) on the performance of TBAR based anaerobic reactor and Nano membrane.

POME is a bio-effluent generated during the extraction of crude palm oil (CPO) from the fresh fruit bunch (FFB). This effluent contains water and a large amount of organic materials [8, 13]. The organic materials of this effluent include carbohydrates, proteins, lipids, and other micronutrients [17]. The properties of TOM and water potential of POME are listed in Table 1.

Table 1: Properties of the POME [12]

Parameter	Range
Organic Material (mg/L)	15,000–100,000
Total Solids (TS-mg/L)	11,500–79,000
Volatile Suspended Solids (VSS-mg/L)	9,000–72,000
Water	92%–96%

2.1 Performance of TBAR in POME Treatment

During the biodegradation process of POME, methane (CH_4), carbon dioxide (CO_2) and hydrogen sulphate (H_2S) produce and emit to the air as greenhouse gas (GHG). In order to minimize GHG emission, several types of BAR have been used for digesting TOM [2, 3]. However, two-stage anaerobic reactors is a proven technology for digesting TOM. It has been reported that the C/N, pH, HRT, SRT, temperature, and OLR of the substrate inside the BAR reactor plays a vital role in decomposing TOM for producing biogas from POME [6, 7, 18]. Khemkhao (2015) and Irvan et al. (2012) revealed that two stages anaerobic reactor is effective in digesting TOM for reducing carbon emission from bio-fluid including POME [19, 20]**.**

2.1.1 Effect of Operating Variables on Performance of Anaerobic Reactor in POME treatment

Eugene et al. (2019) and Abdelgadir et al. (2014) have conducted studies to reveal the effect of pH on TOM reduction from POME. The research was conducted at a pH range from 6.9 to 7.5. The findings demonstrated that the performance of the anaerobic reactor has a positive effect on the anaerobic digestion process and on TOM conversion to biogas. The published reports have also demonstrated that while using an anerobic digestion process for POME, the environment in the anaerobic reactor becomes toxic at pH less than 6.6, which was negatively associated with the digestion process and biogas production [21, 22].

Siddique et al. (2016) and Poh and Chong (2009) revealed that at higher HRT ($4<HRT<8$) in anaerobic process, the contact time between microbial communities and organic substance increase which was contributed to the increasing of digestion performance of the substrate and result in the increasing of biogas production and effluent quality [2, 14, 23].

Eugene *et al.* (2019) and Abdelgadir et al. (2014) stated that SRT has a positive and significant (p-value<0.05) effect on TOM digestion, and it was effective between SRT 13 days to 20 days. It was also reported that beyond that time limit, the TOM utilization rate in the digestion process would reduce [12, 21, 24].

Krishnan et al.(2017), Mao at el. (2015) and Nayono(2010) revealed that in the POME process, the OLR is positively associated with the anaerobic digestion process and has a significant effect (p-value<0.05) on biogas production from TOM. It was also stated that at OLR higher than 5.0 $g.m^{-3}.d^{-1}$, biogas production tends to reduce. It was reported that the LOR lower than ($\leq$ 3.5 $g.m^{-3}.d^{-1}$), the digestion performance also tends to reduce [25–29].

It was reported that C/N between 26 and 32 was required to provide the optimum level of Carbon and Nitrogen for anaerobic bacteria growth in the digesting process [30]. At the lower C/N (C/N<26), the Nitrogen concentration in the digestion process gets higher and contributes to forming an acidic environment. At the higher C/N (C/N>35), the Nitrogen concentration in the digestion process suffers for lack of Nitrogen and tends to reduce activities of the bacteria. In both cases, the anaerobic process exhibits poor performance in TOM digestion [5, 30–32].

The literature review concludes that the performance of anaerobic digester depends on pH, HRT, SRT, C/N, and OLR. All these manipulating variables have a certain limit to use in the digestion process. In order to reduce the negative effect, process optimization is essential for achieving economic operating conditions (EOC). The EOC could be estimated by following methods used in estimating Economic Order Quality (EOQ). Through the EOC method, operating performance can also be optimized [33, 34].

2.2 Nano Membrane in TOM Separation from Effluent

Nano membrane (NM) is defined as having a pore size of of membrane at Nano-scale (nm) (1×10^{-9} m). This postulate, NM is used to remove small ions from fluid. The NM family has been sued in fluid possessing to separate dissolved solids of molecular weight cut-off (MWCO) ranging from 200 Da to 500 Da MWCO. Da scale is also widely used to estimate molecule rejection performance from fluid [35].

Membrane technology has attracted the attention of scientists and engineers as a tool for separating dissolved solids from fluid. Various membrane technologies such as reverse osmosis membrane (ROM), Nano membrane filtration (NMF), Ultrafiltration membrane (UFM), and microfiltration membrane (MFM) have been successfully used in fluid treatment applications including water, wastewater, bio-fluid, and POME [36, 37]. The NNF technology together with the anaerobic process has appeared to be an efficient process to handle higher OLR in reducing the COD and biomass from POME [4, 38]. However, Abdurahman et al. (2011) and Espinoza-Gómez (2003) revealed that membrane technologies specially NMF is a potential separation means for reducing dissolved solid from bio-fluid like POME [38, 39].

2.3 Theoretical Framework in Evaluating POME Treatment Performance

The anaerobic digestion process is used to convert waste biomass and organic materials of POME to biogas and to produce dischargeable effluent. Nanotechnology is used to separate Nanoscale fine biomass particles from effluent in increasing POME treatment performance.

2.3.1 Anaerobic Process to Produce Biogas from POME

At anaerobic conditions, the long-chain of fats, proteins, and carbohydrates break down to the short-chain polymers. This process contributes to an increase in digestion performance of POME. The digestion process of TOM is taken place in four basic steps [7, 30]:

Hydrolysis is the first step where long chains of TOM, basically complex organic molecules, breakdown to short chains at lower pH (between 4 to 5.5). In this stage, soluble organic molecule, sugar, amino acid, and fatty acid produced from POME.

Acidogenesis is the second stage of the process where volatile fatty acids produce at lower pH (between 4 to 5.5).

Acetogenesis is the third stage of the process where TOM of POME is converted to acetic acid, water, and carbon dioxide.

Methanogenesis is the last part of the digestion process where TOM is converted to biogas (CH_4 and CO_2) and sludge. The highest performance in methanogenesis was reported at pH (between 7 to 7.5). The required digestion time (HRT) ranged from 5 days to 10 days [6, 12].

2.3.2 Nanotechnology in POME Treatment

Figure 1 showed the inputs and outputs configuration of the nanomembrane for POME treatment [38].

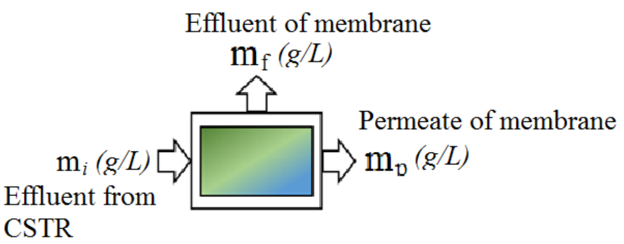

Figure 1: Nano Membrane

2.3.3 Mass balance in NMF for TOM:

$m_i = m_f + m_p$

Here m_i *is* effluent discharge from Anaerobic reactor and feed to membrane.

$m_i(g/L)=[COD(g/L)]_i+[VSS(g/L)]_i+[TSS(g/L)]_i.$ Eq (1)

m_f *is* the mass in effluent discharge from membrane

$m_f(g/L)=[COD(g/L)]_f+[VSS(g/L))]_f+[TSS(g/L)]_f.$ Eq (2)

m_p *is* the mass in permeate of membrane as quality effluent

$m_p(g/L)=[(COD(g/L)]_p+[VSS(g/L)]_p+[TSS (g/L)]_p.$ Eq (3)

The VSS is the biomass contents of POME. TSS is the total solid to be suspended from POME.

2.3.4 Membrane Efficiency in TOM Removal

$\eta_m = \frac{mp}{m_i}.100$ Eq (4)

Here, η_m is the TOM removal efficiency of the membrane [40].

2.3.5 Membrane Productivity in Separating TOM from POME

Productivity is a measure of the output rate of the production process.

$Pr(g/hr) = m_p / T$ Eq (5)

Here, Pr (g/hr) is the productivity of membrane in separating TOM. The m_p is the amount of TOM separate by membrane [41]. Then (T) is the time in hour used to separate m_p by a membrane.

2.4 Research Objective

The broad objective of this research is to model the performance of the anaerobic reactor and the Nano membrane in producing dischargeable effluent from POME. In order to achieve this goal, the works were divided into three specific objectives:

2.4.1 To evaluate the efficiency of the anaerobic reactor in digesting TOM.

2.4.2 To determine the optimum performance of Nano-membrane in separating TOM.

2.4.3 To determine the Economic Operating Conduction of nanomembrane in separating TOM.

The scope of works for this study encompasses the collection of inputs and outputs data from laboratory-scale research which involved the TBAR and nanomembrane for POME treatment. The inputs and outputs data were used to estimate the productivity and efficiency of the BAR and nanomembrane. The optimum performance level of NMF was evaluated (for productivity and efficiency) with respect to feed pressure for membrane operating conditions.

3.0 MATERIALS AND METHOD

The research activities were divided into two parts. In the first part, TBAR was used to carry on the digestion process of TOM for producing biogas and effluent. The second part, three sets of nanomembranes were used to separate biomass and organic materials from the effluent of TBAR.

The methodology includes the POME sample collection, experimental setup, conducting experiments as per outputs of Design of Expert (DOE) (version 2018) software, inputs-outputs data collection of experiments and data analysis for report writing. The DOE (version 2018) software was used to estimate the required experimental runs [7]. The DOE has also been used as a tool for data analysis of these experiments for achieving research goals.

3.1 POME Sample Collection

The total estimated experiment was 50 samples for this experiment. To meet the requirement, samples of POME were collected between September 2017 until February 2019 from Bau Palm Oil Mill and Felcra Jaya Palm Oil Mill. The samples were transported to the Operations Research laboratory of Universiti Malaysia Sarawak (UNIMAS) for conducting the required experiments.

3.2 Experiment Setup

To achieve the research goal, TBAR and three sets of nano membrane have been used. The feedstock was prepared with the required inoculum and the POME. The experiments were conducted with an inoculum prepared from the waste banana peel (C/N = 83) and was added into the digestion process [42]. The C/N in the substrate was adjusted by varying the inoculum dosing rate which ranged from 11.8 mg/L to 40.3mg/L. The pH in the substrate also was adjusted by adding sodium hydroxide (NaOH) [5, 42].

The first BAR was used for hydrolysis and acidogenesis purposes and it was operated at pH 5.0 and 35°C for 2 days [HRT 2 days] in order to break down long-chain organic materials into short chains [2]. Mamimin et al. (2015) and Kim et al. (2015) have also used this method [43, 44].

In the second BAR, the acetogenesis and the methanogenesis processes were performed at pH from 6.5-7.5 and 35°C. The HRT, SRT and OLR varied based on the values listed in Table 4 [24, 27, 28, 45].

3.3 Membrane for Waste Biomass Separation from POME

Three NMF has been used for conducting this research. These membranes have also been used by several researchers in the solid separations process from effluent [39, 46, 47]. The properties of membranes used in this research are listed in Table 2.

Table 2: Properties of Nano Membrane Used

Membrane Type	Surface Areas	Pore Diameter (nm)	Membrane CODE	Hydraulic Permeability (10^{-14} m)
NF270-4040	7.6 m^2	≈0.8	NMF1	0.899
NF90 4040	7.6 m^2	0.68	NMF2	0.929
GE NF4040	6.5 m^2	0.10	NMF3	0.699

The experiments were carried out at temperature 35 °C, feed pressure from 60 psi to 120 psi, and cross-flow velocity 0.9 m/s [48]. The outputs of NMF such as the volumes and dissolved solids of concentres and permeate were determined as per the method suggested by Van and Olieman (1991) [49].

3.4 Substrate Preparation

The substrate was prepared based on the estimate of DOE software which is listed in Table 3.

Table 3: The Properties of POME Substrate

Item	Value		
	POME	Inoculum	Substrate*
COD (g/L)	96	0.0	75
VSS (g/L)	30	80	35
pH**	4.5	5.5	7.5
TSS (g/L)	75	11	50
C/N	7	83	30

*The properties of the substrate listed are due to the mixing of POME and inoculum.

**pH of the substrate was adjusted to 7.5 by using of sodium hydroxide (NaOH).

3.4 Machinery Setup for Conducting Experiments

The machinery and experimental setup for this research is shown in Figure 2.

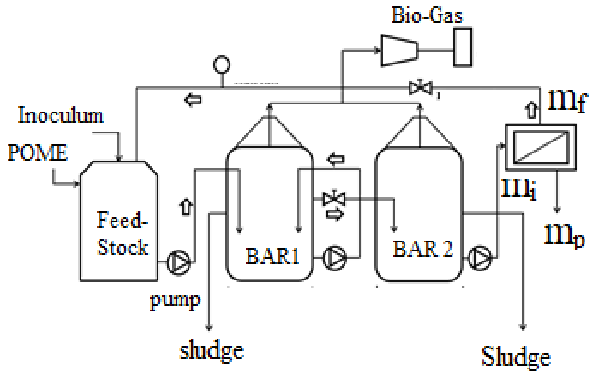

Figure 2: Machinery Setup

The POME and inoculum were mixed together at feedstock to maintain the required C/N and pH. The sludge was collected from both BAR1 and BAR2 and discharged to the pit for further process. The effluent (m_i) of TBAR was feed to the membrane system to separate TOM and water contained in the effluent. The concentrated effluent (m_f) enriched with TOM was recycled through BAR1 and BAR2. The data on permeate [m_p (water)] and m_f were collected from NMF. The collected data were analysed for achieving research objectives.

3.5 Estimate Independent Research Variables

The range of independent variables was estimated by using DOE software [7], which are listed in Table 4 and, Table 5(a) and 5(b).

Table 4: Independent Variables Estimated by DOE

Variables	Range				
	-α (2.378)	Low (-1)	Central (0)	High (1)	+α (2.378)
OLR	0.2431	3	5	7	9.7568
pH	5.1729	6	6.6	7.2	8.027
C/N	19.7971	26	30.5	35	41.2029
HRT	0.5539	4	6.5	9	12.446
SRT	5.1755	10	13.5	17	21.8244

The experiments were conducted with the inputs listed in Table 4. For total 50 experiments were conducted with the combination and range of independent variables listed in Table 4, Table 5(a), and 5(b).

Table 5(a): Experimental Runs Estimated by Using DOE

Std	Run	Factor 1 A:OLR VSSg/L.d	Factor 2 B:pH	Factor 3 C:C/N	Factor 4 D:HRT d	Factor 5 E:SRT d
2	1	7	6	26	4	10
44	2	5	6.6	30.5	6.5	13.5
7	3	3	7.2	35	4	10
18	4	7	6	26	4	17
36	5	5	8.02705	30.5	6.5	13.5
35	6	5	5.17295	30.5	6.5	13.5
15	7	3	7.2	35	9	10
46	8	5	6.6	30.5	6.5	13.5
41	9	5	6.6	30.5	6.5	5.17555
47	10	5	6.6	30.5	6.5	13.5
19	11	3	7.2	26	4	17
22	12	7	6	35	4	17
38	13	5	6.6	41.2029	6.5	13.5
32	14	7	7.2	35	9	17
1	15	3	6	26	4	10
25	16	3	6	26	9	17
39	17	5	6.6	30.5	0.553964	13.5
5	18	3	6	35	4	10
26	19	7	6	26	9	17
42	20	5	6.6	30.5	6.5	21.8244
17	21	3	6	26	4	17
3	22	3	7.2	26	4	10
23	23	3	7.2	35	4	17
31	24	3	7.2	35	9	17
43	25	5	6.6	30.5	6.5	13.5
4	26	7	7.2	26	4	10
37	27	5	6.6	19.7971	6.5	13.5
45	28	5	6.6	30.5	6.5	13.5

Table 5(b): Experimental Runs Estimated by Using DOE

Std	Run	Factor 1 A:OLR VSSg/L.d	Factor 2 B:pH	Factor 3 C:C/N	Factor 4 D:HRT d	Factor 5 E:SRT d
31	24	3	7.2	35	9	17
43	25	5	6.6	30.5	6.5	13.5
4	26	7	7.2	26	4	10
37	27	5	6.6	19.7971	6.5	13.5
45	28	5	6.6	30.5	6.5	13.5
33	29	0.243172	6.6	30.5	6.5	13.5
50	30	5	6.6	30.5	6.5	13.5
11	31	3	7.2	26	9	10
34	32	9.75683	6.6	30.5	6.5	13.5
24	33	7	7.2	35	4	17
30	34	7	6	35	9	17
21	35	3	6	35	4	17
49	36	5	6.6	30.5	6.5	13.5
27	37	3	7.2	26	9	17
29	38	3	6	35	9	17
13	39	3	6	35	9	10
16	40	7	7.2	35	9	10
40	41	5	6.6	30.5	12.446	13.5
28	42	7	7.2	26	9	17
20	43	7	7.2	26	4	17
12	44	7	7.2	26	9	10
48	45	5	6.6	30.5	6.5	13.5
14	46	7	6	35	9	10
9	47	3	6	26	9	10
10	48	7	6	26	9	10
8	49	7	7.2	35	4	10
6	50	7	6	35	4	10

The experimental data were analysed by using DOE software [7]. The ANOVA tests were also conducted for removing outlier's data, in estimating p-value, and to evaluate the effectiveness (R^2) of inputs. The findings were presented by 3D and 2D graphs.

4.0 RESULTS AND DISCUSSION

This section describes the research findings that provide an answer to the research questions. The first part of this section is established for presenting the ANOVA on the data generated from the experiments. The second part is developed to state the findings of the investigations made relating to the objectives of the research.

4.0(a) ANOVA of Research Data

The inputs and outputs of 50 samples runs of POME digestion have been analysed with DOE Software (version 2018) and results are listed in Table 6.

Table 6: The ANOVA Outputs

ANOVA for Quadratic model

Response 1: Biogas

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	6.73	20	0.3364	2.39	0.0158	Significant
A-OLR	0.8568	1	0.8568	6.09	0.0197	Significant
B-pH	0.5910	1	0.5910	4.20	0.0495	Significant
C-C/N	0.0209	1	0.0209	0.1486	0.7027	Insignificant
D-HRT	0.6075	1	0.6075	4.32	0.0466	Significant
E-SRT	0.6518	1	0.6518	4.64	0.0398	Significant

± Fit Statistics ± Model Comparison Statistics

Std. Dev.	0.3750	R^2	0.925
Mean	2.25	Adjusted R^2	0.3624
C.V. %	16.67	Predicted R^2	-0.5964

The R^2 (92.5%) value indicates the utilization of inputs to outputs. All inputs and outputs of this digestion process have appeared to be significant at 95% confidence level (p-value <0.05) except C/N (p-value >0.05).

4.0(b) Inputs–Outputs Data of Experiment

These experimental data of both TBAR and NMF system was listed in Tables 7(a) and 7(b).

Table 7(a): Inputs-Outputs data of TBAR and NMF

Organic materials and TSS* loading	TBAR		NM1 (average of 50 run)	
	Inputs	Outputs	Inputs	Outputs
COD (g/L)	90	33.2	33.2	5
VSS (g/L)	30	9	9	4
TSS (g/L)	75	5	5	1
Total loading (g/L)	201	47.2	47.2	10.5

Table 7(b): Inputs-Outputs data of NMF

Organic materials and TSS* loading	NMF2 (average of 50 run)		NMF3 (average of 50 run)	
	Inputs	Outputs	Inputs	Outputs
COD (g/L)	33.2	3	33.2	1.5
VSS (g/L)	9	2	9	1.0
TSS (g/L)	5	0.5	5	-
Total loading (g/L)	47.2	5.5	47.2	2.5

4.1 Data Analysis for Achieving Objective One

The Eq (4) was estimated to evaluate the digestion efficiency of TBAR by using inputs outputs data listed in Table 7(a). The findings are recorded in Table 8.

Table 8: Anaerobic Digestion Efficiency of TBAR

Organic materials and TSS* loading	Inputs to TBAR with influent	Outputs from TBAR with effluent	Digestion Efficiency (%)
COD (g/L)	90	33.2	63.1
VSS (g/L)	30	9	70.0
TSS (g/L)	75	5	93.3

Table 8 demonstrates that the TBAR discharged effluent with 37% COD (33.2 g/L) and 30% (9 g/L) VSS. The COD and VSS contents in the effluent are higher than the acceptable limit given by the department of the environment Malaysia [33]. The findings indicate, the effluent properties are not satisfying the required quality and it cannot discharge to the environment. From this finding, it could be stated that the anaerobic reactor used for this research is not able to produce dischargeable effluent. Thus, research objective one is achieved and the question is answered.

4.2 Determining the Performance of Nano-membrane in Separating TOM

Productivity and Efficiency have been used to evaluate the performance of NMF in separating TOM from POME. Productivity and Efficiency were estimated and presented in subsection 4.2(a), 4.2 (b), and 4.2 (c).

4.2(a) Productivity of NMF in Separating TOM from POME

The Eq (5) was estimated to evaluate the productivity of the membrane. The findings are plotted in Figure 3.

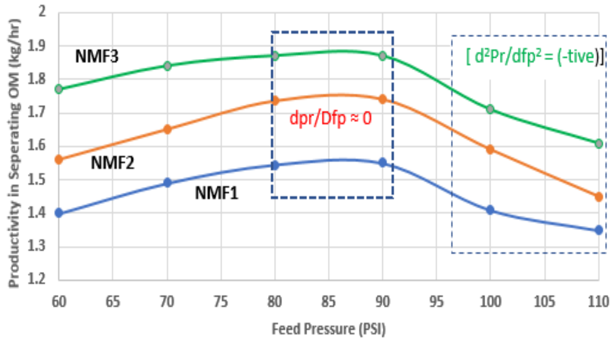

Figure 3: Productivity of NMF

Figure 3 shows that the productivity of NMF increased with feed pressure (≈ 80PSI) to the optimum level. But beyond feed pressure of 90 psi, the productivity tends to reduce. The maximum productivity of NMF3 was recorded as 1.87 $kg(hr)^{-1}$ $(m^2)^{-1}$ at feed pressure 80 psi.

$$Pr(P\approx 80\ psi) = Pr\ (P\approx=90\ psi) \approx 1.87\ kg(hr)^{-1}\ (m^2\ )^{-1},\ \text{and}$$

$$\frac{dpr}{dp} = 0$$

In the aspect of this experiment, results indicate the effect of pressure more than 80 psi on productivity is a non-valued added input. The characteristics and relationship between feed pressure and productive are presented by Equation (6).

$$Pr\ (kg/hr/m^2) = -0.0003P^2 + 0.0455P+0.74 \qquad \text{Eq (6)}$$

The Eq (6) demonstrates that at higher pressure, the productivity was further decreased which can be marked as negative [-ve].

4.2(b) Efficiency of NFM in Separating TOM from POME

The Eq (4) was estimated to determine the efficiency of NMF. The findings are plotted in Figure 4.

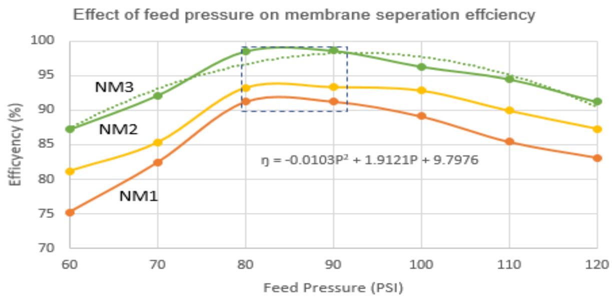

Figure 4: Efficiency of NMF

Figure 4 shows that separation efficiency depends on feed pressure and membrane pore size. The pressure 80 psi and 90 psi feed pressure, the pore size 0.1 nm (NMF3) exhibited the highest separation efficiency compared to the membrane of pore size 0.68 nm and 0.8 nm. The recorded maximum efficiency of NMF 3 is presented by Eq (7):

$$\text{For NMF3, } \eta(80psi) = \eta\ (90psi) \approx 98.5\%,\ \text{and}$$

$$\frac{dpr}{dp} = 0$$

The operating model is:

$$\eta(\%)=-0.010P^2+1.912P+9.97 \qquad \text{Eq (7)}$$

4.2(c) Model Validation

The experimental outcomes of NM3 (pore size 0.1nm) has been used to validate the models developed. The Eq (6) is developed to predict the productivity of NM3; and this equation was estimated to validate the optimum operating conditions for productivity. The value of the first derivative of Eq (6) is:

$$P= 82.5\ psi\ at:\ \frac{dpr}{dp} = 0,$$

While the experimental data revealed that the optimum productivity achieved between feed pressures 80-90 psi. The difference between the model estimate and experimental findings with respect to feed pressure 90 psi is about 8.33%. The error between the model developed and the experiment was less than 10% which is acceptable [50].

The Eq (7) is developed to predict the efficiency of NM3; and this equation was estimated to validate the optimum operating conditions for efficiency.

The value of the first derivative of Eq (7) is:

$$P= 95.6\ psi\ at:\ \frac{d\eta}{dp} = 0$$

While the experimental data revealed the optimum efficiency achieved between 80-90 psi feed pressure. The difference between the model estimate and experimental findings with respect to 90 psi is about 5.5%. The error between the model developed and the experiment is less than 10% ,which is acceptable [50].

4.3 Economic Operating Condition of NMF in Separating TOM

Economic Operating Condition (EOC) of NMF was evaluated based on feed pressure, productivity, cost of separation for TOM (Cu), and total membrane operations cost (Ct). The evaluation for EOC of NMF was conducted only for NM3. To evaluate the optimum level of Ct, data used were taken from Table 7, Figure 3, and Figure 4. The findings are plotted in Figure 5.

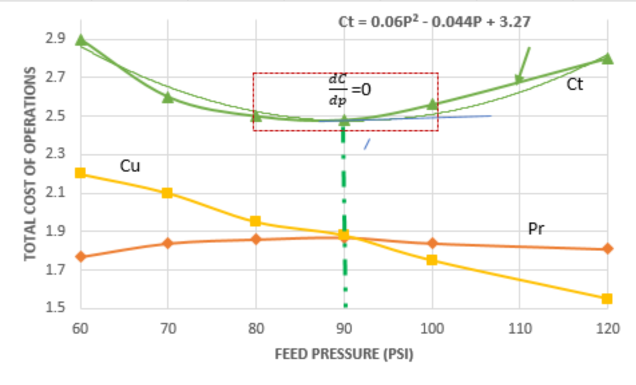

Figure 5: EOC of NMF in Separating TOM

Figure 5 demonstrates that at 90 psi feed pressure; the separation could be achieved at a minimum total operating cost. If the plant operates at higher pressure (>90 psi) or less (<90 psi), the Ct would increase. This behaviour of cost indicates that feed pressure 90 psi is the optimum level; and EOC could be achieved at 90 psi. This behaviour is satisfying optimum economic conditions for operation. Basically, the operating model EOQ (Economic Order quantity) and EOC are similar in nature[33]. The EOC model for NMF3 is presented by Eq (8).

$Ct_{(EOC)} = 0.06P^2 - 0.44P + 3.27$ Eq (8)

5.0 SCENARIO ANALYSIS OF FINDINGS

This paper discusses research outcomes conducted with anaerobic digestion process and nanomembrane for evaluating the TOM separation performance from POME, four research outcomes have recorded from this research.

5.1 The first research outcome, the overall TBAR's digestion efficiency was estimated and listed in Table 8 and plotted in Figure 4. The findings demonstrate that TBAR's digestion efficiency was 63.1%. It was also found that COD and VSS concentration in effluent produced from TBAR was 33.3 g/L and 9 g/L respectively; which were failed to satisfy the environmental requirement of Malaysia [33]. However, these findings concluded that the only TBAR operation is not able to produce dischargeable effluent from POME. The recorded optimum operating conditions for TBAR were pH ranged from 6.9 to 7.0, HRT from 6 to 8 days, SRT from 13 to 17 days, and C/N from 30.5 to 35. However, the similar findings were reported by other researchers [12, 28, 51, 52].

5.2 The second outcome, in reference to Table 7(b), nanomembranes produced dischargeable effluent as per the environmental requirement of Malaysia [33]. It was found that nanomembrane technology has contributed to increasing TOM separation efficiency from 63.1% to 98%. The finding concluded that combined operations of TBAR and NMF in series are the solution for producing environmentally friendly effluent from POME.

5.3 The third outcomes, in reference to Figure 3 and Figure 4, it can be stated that the optimum level of productivity and efficiency in separating TOM from POME has achieved between the feed pressure of 80 psi to 90 psi. The performances of all three NMF used in this research have listed in Table 9.

Table 9: Performance of NMF in Separating TOM from POME

NMF	Productivity Achieved $[kg(hr)^{-1}(m^2)^{-1}]$	Efficiency Achieved (%)
NMF1(0.8 nm)	1.25	98*
NMF2(0.68 nm)	1.73	95
NMF3(0.10 nm)	1.87	92

* NMF 01. nm exhibited the highest performance

5.4 Fourth outcome is the model validation**.** In reference to Figure 4 and Figure 4 for operations of NM3, the optimum performance was achieved at feed pressure 82.5 psi. The validations of optimum operating conditions are reported in Table 10.

Table 10: Validation for Optimization of NMF3

Validation and Outcomes	Productivity	Efficiency
Models for Membrane NMF3(0.1nm)	$Pr = -0.003P^2 + 0.0455P + 0.74$	$\eta = -0.011P^2 + 2.061P + 3.354$
Optimization Condition 1 Between 80- 90 psi	$\frac{dpr}{dp} = 0$	$\frac{d\eta}{dp} = 0$
Optimization Conduction 2	$\frac{d^2pr}{dp^2} = [-0.006]$	$\frac{d^2\eta}{d\eta^2} = [-0.022]$
Validation (Optimum operation)	Satisfied [33], [53]	Satisfied [33], [53]

Pr(kg/hr)-Productivity, ŋ(%)-Efficiency

5.5 Fifth Outcome is the economic operating condition of NMF. In reference to Figures 5 and Eq (8); for separating of TOM from POME, the nanomembrane with pore size 0.1nm and NMWCO about 200 Da would a be an economical solution for reducing TOM level in POME towards achieving SDG-6 and SDG-13 [9, 16]. The economic operating conditions recorded from this research were feed pressure 82.5 psi, pH 7.5, and temperature 35°C. Though, many other operating conditions have not tested in this research such as concentration and viscosity of TOM and membrane materials.

5.6 Implications of Research Outcomes

The research findings listed in this paper have a few implications in the domains of economy, health, and environment. The technologies and methods discussed in this paper would be a guideline in recovering waste biomass and organic material from POME, and contribute to reducing carbon emission (CO_2eq) as well. Additionally, the method described in this paper would be useful to increase the quality of dischargeable effluent which would contribute to reducing the pollution level in the air, water, and soil. These findings would be a reference for engineers and researchers working with palm oil mills to provide quality service in achieving higher efficiency in biogas production and quality effluent from the POME in line with the waste to resource [WtR] and waste to energy [WtE] models for contributing to achieving economic and environmental sustainability of industry.

CONCLUSION

This study concludes that experiments with anaerobic digestion combination of biotechnology and Nano-technology discussed in this paper for separating waste biomass, organic and inorganic materials from biofluid such as effluent of the tannery, dairy, fruit process, potato process, and meat process as a path to achieve SDG-6 (clean water), SDG-7 (clean energy) and SDG-13 (climate actions) towards Sustainability Agenda 2030 [5, 9, 54].

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