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An Effective Three Level Filtration System for Improved Contaminant Removal in High Ratio Biodiesel Blends

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Abstract: Implementation of high-ratio biodiesel blends up to 30% (B30) serves as a proactive measure in anticipating of the diminishing availability of the fossil energy availability, decarbonizing the heavy-duty vehicle sector and to improve environmental quality. However, the implementation of B30 still causes problems, particularly concerning fuel filters, which have prompted complaints from users in non-automotive industries such as mining or marine sectors. Several users have reported instances of temporary filter blockages or damage to engine components. In anticipation of this issue, the implementation of an appropriate filtration system design has been proposed, comprising a 30-µm pre-filter water separator, a middle filter, and a post-filter. The efficiency test was carried out by passing the test fuels through a filter paper with pore size proportional to those of the proposed filter. This test was performed using a standardized rig following the ASTM D2068-10 protocol, maintaining an ambient temperature of approximately 29°C. The differential pressure (differential pressure) across the filter tested was recorded before and after passing through the test filter paper, and a filtration efficiency was calculated, based on the captured contaminants on the filter paper. The findings show that the implementation of three-level filtration systems successfully improved the ISO-cleanliness levels of the tested B30 fuel from 19/17/12 to 16/14/10, aligning with the specification outlined in the worldwide fuel charter. Based on this study, it can be concluded that utilization of three-level filtration system has significant potential for increasing the filter lifespan and mileage of B30 fuel.

Keywords: biodiesel blend; multi-stage filtration; filter blocking; contaminants; cleanliness

1. Introduction

The utilization of high-ratio biodiesel blends has been implemented in Indonesia as part of an initiative to reduce reliance on petroleum-based energy sources and enhance environmental sustainability. The introduction of biodiesel blends with a composition of up to 30% (B30) was initiated in early 2020, and in February 2023, the government extended the policy to include the use of B35 in both passenger and heavy-duty vehicles. This policy aligns with the Indonesian government's targets of achieving a minimum utilization of new renewable fuels of 23% by 2025 and 31% by 2050[1)]. The implementation of high-ratio biodiesel blends aims to proactively address the anticipated rise in energy consumption as fossil fuel production continues to decline[2)]. With Indonesia being the largest producer of palm oil[3)], and having a thriving biodiesel industry supported by relevant programs[4)], continuous research and development efforts are underway to ensure the sustainable availability of environmentally friendly energy sources[5)].

However, challenges related to the use of high blend biodiesel have been reported. Biodiesel, which refers to ethyl or methyl esters of long-chain fatty acids derived from vegetable oils or animal fats, exhibits inherent instability due to the presence of double bonds in long-chain alkyls. Oxidized biodiesel can generate compounds such as aldehydes and small-chain esters. These degraded biodiesel components, along with other contaminants, can negatively impact the fuel supply system, resulting in deposits in the injector system[6)] and engine combustion chamber[7)]. Proper filtration through the fuel filter is crucial to address these issues.

Issues have arisen regarding the use of biodiesel blends, particularly in non-automotive sectors such as mining and maritime industries. In the mining sector, the use of B30 biodiesel in dump trucks has led to increased frequency of fuel filter replacements. Higher biodiesel contents in diesel fuel tend to contribute to filter clogging[8]. The marine sector is experiencing growth in biodiesel utilization, although challenges such as oxidation stability, economic considerations, feedstock availability, material compatibility, standards, and cold flow properties persist. Fuel filtration systems play a critical role in addressing biodiesel stability, compatibility, and cold flow properties[9].

Studies have shown that higher ratios of biodiesel increase the likelihood of filter blockages[10]. Changes in the properties of biodiesel blends correlate with an elevated risk of contaminants and subsequent filter blockage. Excessive sludge formation and fuel filter clogging have been observed when using biodiesel blends in marine engines. The sludge comprises metal components, water, organic material, and bacteria[11]. Laboratory tests have demonstrated that filter blockage acceleration occurs in filters made of high-efficiency materials with a mean flow pore size (MFP) of 5 µm. In contrast, filters with an 8 µm MFP exhibit similar filter blocking times between pure diesel (EN590) and B30 biodiesel blends[12]. An investigation of used locomotive filters and water separators revealed deposit components, including metal impurities and glycerides. The study concluded that after 125 hours of B20 biodiesel usage in the water separator and 3 months of B20 biodiesel usage in the locomotive fuel filter, satisfactory filtration performance was maintained[13]. Our previous research[14] using B30 and B0 (pure diesel) on test rigs with 30-micron filter paper indicated that using B30 biodiesel blend shortens the filter's service life by approximately 40%, with higher biodiesel compositions leading to shorter service lives. Filter blockages in the test paper are attributed to the accumulation of contaminants, including added dust contaminants and organic residues from biodiesel[15]. These test results align with the experiences reported by diesel engine users, where more frequent fuel filter replacements are necessary due to the sludge buildup associated with B30 biodiesel.

To address the challenges posed by B30 biodiesel, Tian, et al. proposed a two-stage filtration system for real-world applications, offering high efficiency and extended filter lifespan. The system comprises a pre-stage filter for larger contaminants and a main-stage filter for finer particles, particularly those below 2 microns in external combustion applications. A filtration system typically includes a pre-stage and main stage filter for capturing contaminants of different sizes[16]. Wilcox et al.[17] reported the use of a three-stage filter system in an external combustion application.

In our research, we developed a 3-stage filtration system to address fuel filter issues associated with a B30 biodiesel blend. The proposed system improves filtration efficiency and incorporates a 30-micron-rated fuel filter to accommodate large particle contaminants. The primary objective is to achieve a desired cleanliness level of ISO 18/16/13, which indicates the number and critical size of injection particles[18], and the separation of solid particles up to 6 µm[19]. This level meets the specifications in the sixth edition of the Worldwide Fuel Charter.

Fuel cleanliness is measured through the ISO 4406 code that defines the number of solid particles in a fluid (Table 1). ISO 4406 measures the number of particles larger than 4 µm, 6 µm, and 14 µm within the 100 ml fluid sample[20]. Particle count is not part of the fuel specification, but the Worldwide Fuel Charter 2019 (WWFC 2019) recommends a maximum value (ISO 4406 code) of 18/16/13 for modern low-emission engines.

Table 1. ISO 4406:1999 Code Chart

Range Code	Particles per milliliter	
	More than	Up to/including
24	80000	16000
23	40000	80000
22	20000	40000
21	10000	20000
20	5000	10000
19	2500	5000
18	1300	2500
17	640	1300
16	320	640
15	160	320
14	80	160
13	40	80
12	20	40
11	10	20
10	5	10
9	2.5	5
8	1.3	2.5
7	0.64	1.3
6	0.32	0.64

In order to evaluate the performance of the proposed filtration system for high ratio biodiesel blend, filter blocking and efficiency tests have been carried out on filter paper which has the pore size diameter proportional to the actual filter used. The test was carried out by passing the test fuels through the filter papers using the modified ASTM D2068-10 standard test rig at ambient temperatures (around 29°C). Contaminant was added to the test fuel (B30) to achieve the desired level of ISO cleanliness. This study is expected to support future development of filtration system that is applicable in the real field with highly effective and improved lifetime.

2. Methodology

2.1. Survey on Cleanliness of The Marine Fuels

Field surveys were conducted to obtain empirical data regarding actual cleanliness level of the stored fuel. Five samples of B30 were meticulously obtained from the tank of a supervisory vessel owned by the Directorate General of Surveillance for Marine and Fisheries Resources, Ministry of Oceans and Fisheries of the Republic of Indonesia as shown in Table 2. Afterwards, the samples were transported to laboratory for precise analysis to determine their ISO-cleanliness level.

Table 2. The identity of the B30 sample collected from the field

Sample No.	Source	Note
1	ship 10, after filter BP	2 weeks stored in the ship's tank, sample from additional fuel filter for biodiesel fuel
2	ship 10, daily tank	2 weeks stored in the ship's tank
3	ship 10, RC filter	2 weeks stored in the ship's tank
4	from land storage	10 months stored in fuel tank
5	from land storage	2 weeks stored in drum

2.2. Rig Test Experiment

Fuel specification, contaminants blended in the fuel and experimental methodology are described in this section.

2.2.1 Test fuel specifications

The biodiesel blend (B30) for the experiment was a mixture of CN51 Indonesian Diesel Fuel (base fuel) and palm-based biodiesel (B100). Specification of the base fuel met the quality standard regulated by the Indonesian government through the Decree of the Director General of Oil and Gas no. 3675 K/24/DJM/2006 and B100 specification met the biodiesel standard of SNI 7182:2015 as shown in Table 3.

Table 3. Specification of base fuel and B100

Parameter	Unit	Base Fuel[21]	B100[22]
Index Cetane	-	Min. 48	
Cetane Number	-	Min. 53	Min. 51
Kinematic Viscosity	mm2/s (cSt)	2.0-4.5	2.3-6.0
Density at 15 °C	kg/m3	820-860	850-890
Distillation			
90% vol	°C	Max. 340	Max. 360
95% vol	°C	Max. 360	Max. 341
Flash Point	°C	Min. 55	Min. 100
Pour Point	°C	Max. 18	
Cloud Point	°C		Max. 18
Sulphur Content	% m/m	Max. 0.05	Max. 0.005
Sediment	% m/m	Max. 0.01	
Water and sediment content	% vol.		Max. 0.05
	%-m	Max. 10	Max. 96.5
Free glycerin	%-m		Max. 0.02
Mono-glycerides	%-m		Max. 0.8
Total glycerin	%-m		Max. 0.24

2.2.2 Dust Contaminant, Its Characteristics and Test Fuel Cleanliness

For the assessment of contaminant dust and fuel cleanliness, a mixture of finely ground red bricks and sand was utilized. Approximately 0.5 kg of red bricks were finely ground and combined with 0.5 kg of sand, followed by the addition of 3 liters of water. The resulting mixture of brick powder and water was thoroughly stirred and allowed to settle for 1 minute. Afterwards, the turbid water was carefully separated from the sediment composed of brick particles. The sediment separated from turbid water was then dried under sunlight in an outdoor environment. A quantity of 0.3 g of the resulting dried dust was introduced into 15 liters of B30 for the purpose of conducting the filtration efficiency test[23].

Experiment on the filtration rig test used dust contaminant to simulate filtering capability of the proposed filter configuration to filter hard contaminant in the B30. The results of the particle analysis on dust contaminant used in the test is shown in Fig. 1.

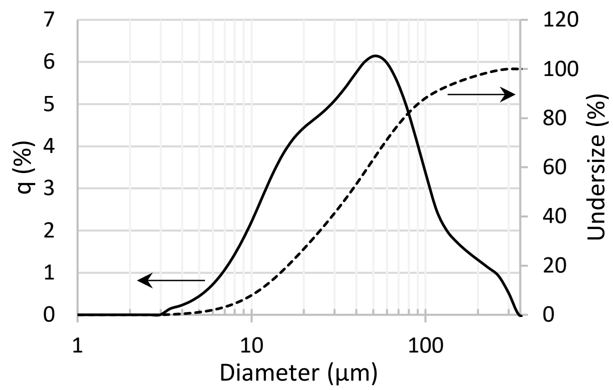


Fig. 1: Test Dust Particle Size Distribution by Mass %

The diameter of dust particles range from 3.4 µm to 300 µm with percentage of each particle size is illustrated in continuous line with left axis. The one illustrated by the dash line scaled with the right axis is the mass percentage of particles smaller (undersize) than certain particle diameter of horizontal axis. Fine dust consists of tiny particles with diameters of less than 10 µm and the coarse ones with diameters larger than 10 µm. This size distribution serves as a benchmark for assessing the contamination level of fuel samples in relation to the required cleanliness standards.

Size distribution of the dust contaminants aimed to match the standards for contaminant dust specified by JIS Z8901 Kanto Loam Test Dust Class 7. The distribution of particle sizes for the dust contaminants and the corresponding dust standard are provided in Table 4 for reference and comparison. The cleanliness of the fuel is determined from the distribution of particle sizes greater than 4 µm, 6 µm, and 14 µm according to ISO 4406 procedures. These sizes can be compared with the dust standard, JIS Z8901 Kanto Loam Test Dust Class 7 (fine dust), which has various representative dust sizes to be filtered by the filter, as the pore size of the 3-level filtration system to produce fuel according to the desired ISO cleanliness.

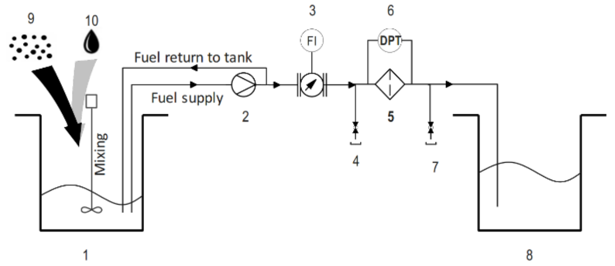
It is noteworthy that the majority of the utilized contaminant particles possess a diameter approximately 1% smaller than 4 microns. Moreover, over half of both the utilized contaminants and the JIS Z8901 Kanto Loam Test Dust Class 7 standard exhibit a diameter of 30 microns. Consequently, it is imperative to employ the filtration system to effectively remove all contaminants, thus safeguarding the injection system components against potential damage.

Table 4. Comparison of contaminant used to JIS Z8901 Class 7

Size (µm)	Particle size distribution by mass % greater than respective size	
	Contaminants used	JIS Z8901 Class 7
5	98.8	88.0 +/-5.0
10	91.9	76.0 +/- 3.0
20	73.3	62.0 +/- 3.0
30	58.7	50.0 +/- 3.0
40	47.7	39.0 +/-3.0
45	41.7	-
77	18.9	20 max.

2.2.3 Filtration Test Rig and Fuel Filter Paper

The experimental setup involved was utilizing a filter blocking test system in accordance with modified ASTM D2068-10 standard test rig. It was equipped with a differential pressure Transmitter 2 Wire brand VEGA type Pressure Transmitter + Indicator, capable of measuring pressures within the range of 0 to 50 kPa with a resolution of 0.1 kPa. This equipment configuration is depicted in **Fig. 2**. A filter holder, essential for affixing the filter paper, was integrated with a pressure sensor from the aforementioned delta pressure gauge, positioned at both the inlet (in) and outlet (out) locations of the filter paper. This method refers to the previous study conducted by Paryanto, et al.[24]



Remark:
1. Fuel tank A
2. Centrifugal pump
3. Flow transmitter
4. Valve sampling 1
5. Tested fuel filter
6. Differential pressure transmitter
7. Valve sampling 2
8. Fuel tank B
9. Fine dust contaminant
10. Fuel

Fig. 2: Schematic of the test rig (adapted from Ref.[24])

To store the test fuel, a stainless-steel tank or container with a volume capacity of 20 liters was employed. The selected filter paper was expected to possess a pore size diameter identical to that of the proposed filtration system. Information obtained from the filter housing indicated that the pre-filter paper had a rating of 30 microns, while the middle and post filters were designed for use in truck diesel engines featuring Euro-4 technology.

To examine the morphology of both the new and used filter paper, Scanning Electron Microscopy (SEM) using a Jeol JSM-IT200 instrument was employed. Additionally, a digital microscope, specifically the HIROX KH-8700 model, was utilized for further analysis.

2.2.4 Test run

The B30 test fuel was prepared by blending 10.5 liters of Indonesian Diesel Fuel CN 51 and 4.5 liters of B100 in a reservoir. The filter paper was cut into a circular shape with a diameter of 97 mm to fit the filter holder. Prior to conducting the test, the filter housing was opened, and a flushing process was performed using approximately 500 milliliters of pure diesel. Once the flushing was complete, it was replaced with the test fuel.

The initial test involved using a 30-micron filter paper for the B30 sample fuel contaminated with the dust particles. The experiment commenced by starting the pump and setting the flow rate to 0.8 mL/min. Once the flow rate was stabilized, data collection for differential pressure measurements between the inlet and outlet of the filter commenced. Differential pressure data were recorded at 30-second intervals. Fuel samples were taken before and after the filter paper after running the test for 6 minutes. The test continued for a duration of 10-15 minutes. The test equipment was configured to automatically shut off upon reaching a delta pressure of 45 kPa, ensuring overpressure control. Following the completion of one test, the procedure was repeated for the middle and post-filter papers, following the same protocol.

In later discussion, filter efficiency will be covered. Efficiency of the filter is calculated using the beta ratio value (β_x), the ratio of particles that pass through the filter to those that enter the filter as expressed in **Equation 1.**

β_x= Nu/Nd (1)

Where:

- β_x is the Beta Ratio for impurity larger than x mm
- Nu is the number of particles larger than x mm per unit of volume upstream/before the filter.
- Nd is the number of particles larger than x mm per unit of volume downstream/after the filter.

Efficiency of the filter was calculated directly from the beta ratio[25], where the percentage of capturing efficiency is expressed in **Equation 2.**

$$\text{Filter efficiency (\%)} = ((\beta_x - 1)/\ \beta_x) \times 100 \qquad (2)$$

3. Results and Discussion

3.1. Marine Fuel Characteristics

The engines manufacturer such as MTU, Caterpillar requires particle distribution in the fuel. In this study, the samples No 1,2,3 were taken from the ship 10 with the main engine Volvo Penta TAMD 165P. Its manual book mentions fuel specifications in accordance with (EN590, ASTMD975, JIS KK 2204 & Sulfur content according to regulations in each country). The specifications do not include particle distribution or cleanliness parameters but included solid contaminants as parameters of total contaminants (24 mg/kg maximum).

Analysis results of the B30 fuel samples from the ship tank and land storage in the field survey is presented in Fig. 3, with the limit for each filter size is shown in dash line. None of the fuel samples met the ISO-cleanliness requirement specified by various standards, such as Worldwide Fuel Charter (WWFC) and marine manufacturer standards. WWFC requires ISO Code 18/16/13 for particle sizes of 4/6/14 µm in diesel fuel category 2. These standards incorporate crucial particle distribution and cleanliness parameters, essential for ensuring optimal fuel quality.

Similarly, MTU mandates ISO cleanliness > 4 µm in class code 18 or less than 2,500 particles per milliliter (

Table 1). MTU require ISO Code 18/17/14 for engine series 2000Gx6 and 4000 and ISO code 21/20/17 for older engines.

In the analysis result, sample no. 1, representing the additional filter installed on Ship 10 for biodiesel fuel usage, exhibited a particle count of > 4 µm size particles of 2,891 particles/ml, approaching the class code 18 threshold with a particle count below 2,500. The additional filter demonstrated a reduction in the class code from the typical B30 value (class 22) to 19. Despite this improvement, it still fell short of meeting fuel specifications that encompass particle distribution values. Therefore, further design optimization of the filtration system is warranted to attain the desired targets.

Samples 2 and 3, derived from the daily tank and filter RC, displayed similar class codes. The filter RC exhibited a marginal reduction in particle sizes greater than 14 µm reaching 111 particles per milliliter. These findings emphasize the importance of carefully designing filtration systems to effectively address particle distribution, particularly in the context of biodiesel fuel usage.

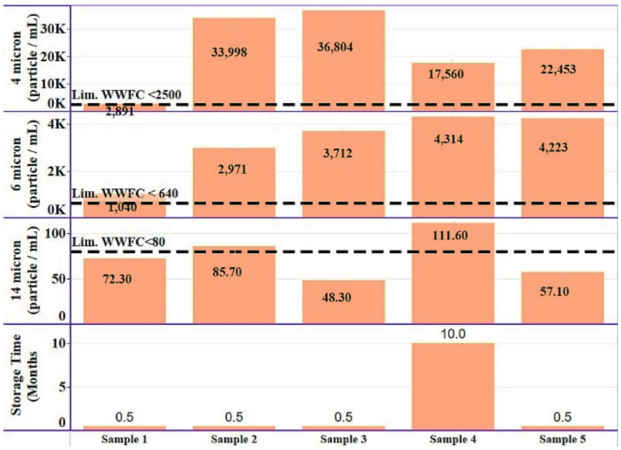


Fig. 3: Particle of sample and storage time from the field

Mass particle distribution is important parameter to design an appropriate filtration system. Other important properties effect on filtration are their size, shape, and their interaction with the surrounding fluid[26]. Especially with biodiesel fuel usage to prevent abrasive and harmful contaminated particles, the operating temperature needs to be considered because biodiesel contains monoglycerides which can form precipitation when exposed to cold temperatures[27]. ISO-cleanliness parameter also needs to be included in the national fuel specification to reduce the fuel cleaning load on the filtration system on ships to extend filter life and reduce maintenance costs.

3.2.Differential Pressure and Three -Stages Filtration Efficiency

The results of the differential pressure between the inlet and outlet of filter in the proposed 3-stage filtration system are shown in Fig. 4. During the differential pressure test, the filter paper did not get clogged and the value of differential pressure was relatively constant with time. The increasing differential pressure was only significant between the inlet and outlet of filter 3 (post filter) of about 5 kPa, suggesting its prone to clog which may be related to tighter porosity (as shown in Fig. 5(c)). This pressure is still low enough to reach the pressure that results in filter clogging. Filter blocking occurs when the differential pressure reaches a value of 45 kPa. This indicates that the contaminant particles did not cover the whole pores of the filter paper. Meanwhile, precipitates that may occur when using biodiesel were also not formed due to the relatively high operating temperature test of 29 °C. A study conducted by Suwannamit, et al.[28] showed that biodiesel precipitates were formed at 10 to 25 °C test operation. Differential pressure of 30 kPa can be achieved within 1 to 10 minutes if the biodiesel contains precipitates of 20 to 280 g/ml. For operating temperatures above 25 °C, the precipitates formed is close to zero.

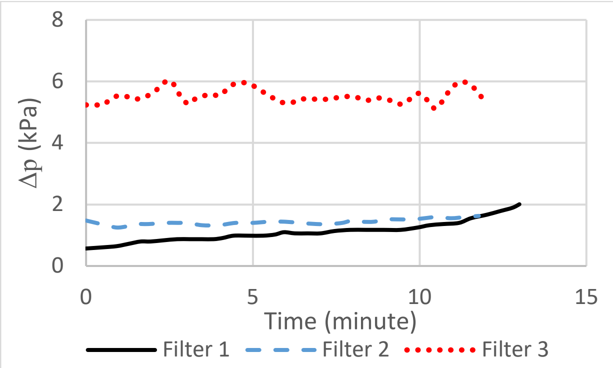


Fig. 4: Differential pressure of the 3-stage filters

A significant increase of differential pressure was noticeable in filter 1 since minute 12, indicating that it was clogging faster than filter 2 and 3. The pressure data can be used to determine the optimum filter size configuration by testing the filter to its clogging condition. Combination of filter data in clogging condition can be used to estimate the optimum filter area for the respective stage.

Comparison of fuel conditions before and after each filter stage are shown in

Table 5. Before passing through filtration process, the particle count was 19/17/12 of ISO-cleanliness and after filtration process, the particle count was 16/14/10 according to ISO-cleanliness range. The particle count after filtration indicated that 3-stages filtration process performed in this study was able to meet the target number of ISO-cleanliness. In other word, the efficiency of filtration process for each stage were 71.5% for particle >4 μm, 87 % for particle > 6 μm and 84% for particle > 14 μm.

Table 5. B30 filtration system test results

	Before Filtration (particles count)	**After Filtration (particles count)**	**Target of ISO-cleanliness**
ISO Code Rating	19/17/12	16/14/10	18/16/13
4 μm	3313	529	1300 ≤ 2500
6 μm	975	126	320 ≤ 640
14 μm	35	10	40 ≤ 80

As presented in table 5 and figure 2, contaminant particle >14 μm was counted 35 particles which constituted 85% of total mass. With 84% filtering efficiency, almost all of contaminant was estimated to be filtered in filter no. 1 and the remaining in filter 2. This suggests that filter no.1 was properly selected since filter no. 2 functioned as a buffer filter. With filter no. 2 worked as buffer, filtration system was expected to be uneasily clogged. Meanwhile, contaminant particles >4 μm was captured in filter no. 3, despite partially might be captured in filter no. 1 and no. 2.

Measuring pore diameter of the filter paper is difficult because it is formed from piles of fibers with irregular patterns and layered fiber positions. Thus, the holes formed between the fibers of the filter paper are of irregular shape and size. Therefore, more detailed analysis was performed via SEM photography on filter pores. Illustration of the aperture size of the three filters is shown in Fig. 5. The photography using SEM show that for filter-1 or pre-filter or water separator, the aperture diameter is around 10.81 - 17.30 μm. Meanwhile for the middle 7.678 – 22.13 μm and for the post filter 2.822 – 8.240 μm. It can be seen that in filter 1 and filter 2, the pores diameter are not much different. This filter is thought to be intended to filter particles larger than 14 μm, while the post filter is intended to filter contaminants larger than 6 μm and 4 μm. Therefore, relatively large particles are filtered out in filter 1, and more particles that pass-through filter 2 are filtered in the post filter.

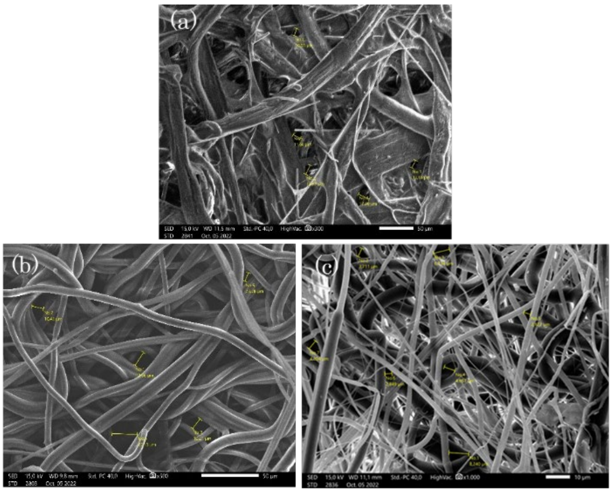


Fig. 5: Microphotography of the new filters; (a) Pre-filter, (b) middle filter, (c) post filter

The condition of the used filter papers are set out in Fig. 6. Visual appearance of the pre-filter (filter no. 1) indicates that contaminant particles were filtered by filter no. 1 in more dominant level than filter no. 2, while the finer particles that pass from filter no. 2 then fed to filter paper 3. The condition is in line with 84% filtering efficiency that is mentioned previously. This suggests that filter size optimization could result in balanced loading on each of the filtration stage.

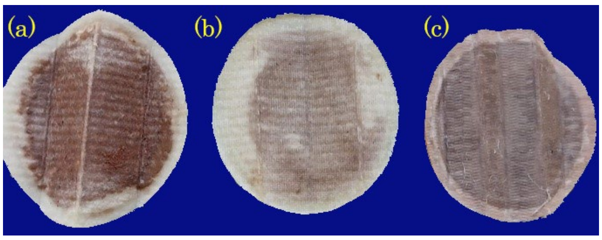


Fig. 6: Used paper at: (a) pre-filter, (b) middle filter, (c) post filter

The filter was analyzed further via microscopic photograph depicted in Fig. 7. Brown circles indicate dust contaminant particles. The figures suggest that the filter pores were not yet fully clogged. Filtered contaminant visually as shown in Figure 7 is affected by the pore diameter of the new filter paper. Filtering occurs on particles both larger and smaller than the pore diameter. For larger particles, they will be retained on the surface of the filter paper, while the small particles accumulate in the porous paper through the mechanism of retention of a depth filter. The retention of depth filters can be in form of sedimentation, impaction, or by electrostatic absorption[29)].

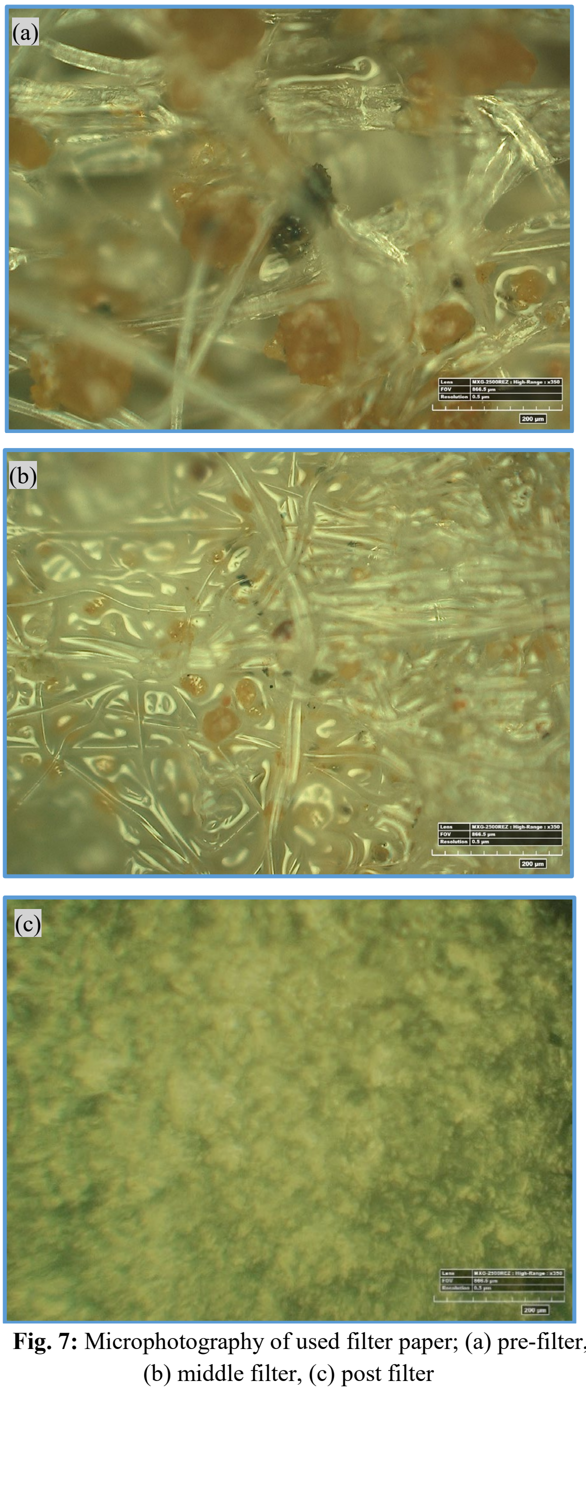


Fig. 7: Microphotography of used filter paper; (a) pre-filter, (b) middle filter, (c) post filter

The experimental results revealed that the proposed three-level filtration system could effectively capturing contaminants in fuel samples to fulfill WWF charter recommendation. Furthermore, diesel engine manufacturers (OEM's) specified that the minimum fuel cleanliness level is 14/13/11 and Fuel Injector OEM specify 12/9/6. The challenge to improve the level of filtering efficiency could be achieved by optimizing the second filter porosity.

Generally, application of three-stages filtration system can mitigate the reduction in filter lifetime due to B30 usage. In addition, it could avoid premature failure on critical fuel system components caused by dirt-induced abrasive wear, thereby extending the service life of filters, pump and diesel injection system.

4. Conclusion and Recommendation

Impact of storing biodiesel blend (B30) to its cleanliness level for diesel engine was surveyed in this study. Three stages filtration was investigated to filter hard contaminant in the B30, aiming to achieve the acceptable ISO-cleanliness level for the diesel engine as required by regulation or manufacturer. Several conclusions are made from the results of this study:

1. Typical cleanliness level of the incoming biodiesel blend (B30) from the surveyed storage were above the recommended level.
2. Mass distribution of contaminants in the fuel sample become key point to select pore size and volume of the filtration system.
3. Test rig methodology could support pore size selection for the filtration process to produce a required ISO-cleanliness and predictable filter size requirement to be used for certain period of use.
4. Sequential contaminant filtering from large pore size to small pore size results in required fuel quality according to ISO-cleanliness target of 18/16/13 or WWFC 18/16/12 while usage duration of each filter could be more easily adjusted
5. A 3-level filtration system which is quite simple in application was proposed to deliver fuel quality below the limit of cleanliness value in accordance with the recommendations of the worldwide fuel charter from the ISO cleanliness level 19/17/12 to 16/14/10
6. The efficiency of filtering from the 3-stage filtering for each contamination size is 71.5% for 4 μm, 87% for 6 μm and 84% for 14 μm particles

For future study, investigation could be continued by testing various filter papers with various efficiency and pore size for contaminant and water content. The optimum configuration of pore size and paper filter area could be obtained in order to achieve a similar duration of use.

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Nomenclature

ASTM	American Society for Testing & Materials
BRIN	*Badan Riset dan Inovasi Nasional* (National Research and Innovation Agency)
B30	Palm Biodiesel 30% (-)
B100	Palm Biodiesel 100% (-)
EN	European Norm
ISO	International Organization for Standardization
JIS	Japanese Industrial Standard
MFP	Mean Flow Pore-size (μm)
OEM's	Original Equipment Manufaturer's
PSDKP	*Pengawasan Sumber Daya Kelautan dan Perikanan* (Surveillance for Marine and Fisheries Resources)
SEM	Scanning Electron Micrograph
βx	Beta Ratio for impurity larger than x mm (-)
Nu	The number of particles larger than x mm per unit of volume upstream (-)
Nd	the number of particles larger than x mm per unit of volume downstream (-)
WWFC	World Wide Fuel Charter

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