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Virgin Coconut Oil (VCO)-Derived Fatty Acid Methyl Ester (FAME) as a Substitute Formulation and Solvent for Oil-Based Paint

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Abstract

The increasing application of petrochemical solvents in the oil paint sector has caused environmental problems owing to emissions of Volatile Organic Compounds (VOCs). Fatty Acid Methyl Esters (FAMEs) have attracted interest as environmentally friendly solvents, providing minimal toxicity and adaptability in uses from biofuels to chemical precursors. Consequently, this research intends to produce Fatty Acid Methyl Ester (FAME) from Virgin Coconut Oil (VCO) and assess its viability as a sustainable oil paint solvent. The FAME synthesis was conducted via a transesterification reaction employing methanol and an alkaline NaOH catalyst. The FAME product was utilized in an oil paint formulation to assess its drying duration and extent of swelling. At a temperature of 65°C, a catalyst weight of 1 wt%, and a 1:8 molar ratio, the maximum yield of 96.10% was achieved. The GC-MS analysis confirmed that methyl laurate was the primary component at a concentration of 40.44%. Its use in oil paints resulted in a maximum swelling percentage of 4.14% following a 30-minute immersion period and a drying time of 10 hours and 31 minutes. VCO-based FAME has proven to be highly promising as an eco-friendlier oil paint solvent alternative. This is supported by its ideal drying profile, low swelling rate, and compliance with physical standards, thereby reducing the use of conventional petrochemical-based solvents.

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1. Introduction

The use of solvents containing volatile organic compounds (VOCs) like benzene, toluene, xylene, and different kinds of hydrocarbons has historically been crucial to the solvent-based paint industry [1–3]. Even though they work well to dissolve resins and additives, using volatile organic compounds can occasionally cause a number of major issues. First, from an occupational health and safety perspective, exposure to volatile organic compounds can cause respiratory irritation, headaches, dizziness, and even long-term impacts on internal organs [2, 3]. Second, the environmental impacts are also very significant, as volatile organic compounds contribute to the formation of tropospheric ozone and smog, as well as the release of greenhouse gases [4, 5]. Government regulations in many nations are becoming increasingly strict, which pushes industry to look for safer and more ecologically friendly alternative solvents.

Future paint industry research and development will increasingly concentrate on finding environmentally friendly and sustainable substitute solvents. Various types of compounds have been explored and further researched, ranging from water (for water-based paints) to bio-based solvents [6–10]. However, there are problems when using solvents like water because they are incompatible with other solvent-based paint components. Some binders used in the solvent-based paint industry currently still use alkyd, acrylic, phenolic, and polyurethane binders that can only be dissolved in organic solvents. This can be an obstacle to the development of environmentally friendly solvent-based paints or low volatile organic compounds [11–14].

Developing conventional binders compatible with water-based and bio-based solvents is another option to accelerate the transition from conventional to environmentally friendly solvents. Modification of alkyd binders to Water-Reducible, or better known as alkyd emulsions, is one of the standard chemical modification methods carried out to improve the compatibility of alkyds in water solvents. Alkyd emulsion is done by inserting hydrophilic functional groups into the alkyd polymer chain with or without the aid of an emulsifying agent. This allows the alkyd to be dispersed or even dissolved in water with or without the aid of an emulsifying agent [15, 16].

Similar to alkyd emulsions, acrylic and polyurethane binders can also be modified by introducing neutralizable carboxylic or hydroxyl groups to form water-soluble salts, or by emulsifying them into a water-based polymer dispersion, Polyurethane Dispersion (PUD). This allows Polyurethane-based binders to be used in water-based solvents [17–19]. Modifying binders to be soluble or dispersed in water (or bio-based solvents) often requires complex processes, long development times, and higher production costs. This is one of the biggest challenges facing the industry in switching to more environmentally friendly paint formulations.

Therefore, the option to replace the type of solvent with a bio-based low-volatile organic compound solvent is the best choice at this time in terms of ease of application, compatibility with other paint components, and economic aspects. Several studies have developed bio-based solvents using renewable resources such as vegetable oils, fatty acids, and cellulose to reduce volatile organic compound (VOC) emissions and environmental impacts [20, 21]. Ethyl lactate, or lactate ester, produced from the esterification of lactic acid and ethanol derived from biomass, is a biodegradable and non-toxic solvent with excellent solubility properties. Ethyl lactate is currently used in various industries, including food and pharmaceuticals [22, 23]. However, the potential of ethyl lactate as an alternative solvent in the paint industry has not been discussed comprehensively.

Among these various solvent alternatives, Fatty Acid Methyl Esters (FAME), commonly known as biodiesel, have attracted attention for development as a renewable solvent for various industrial applications. FAME is produced from renewable resources such as vegetable oils (e.g., palm oil, castor oil, soybean oil) or animal fats through a transesterification process. The abundant availability of raw materials and their renewable nature make FAME an attractive solvent candidate [24, 25]. FAME has several characteristics that support its use as a solvent in the paint industry. In general, FAME has a higher boiling point than conventional solvents, which means a lower evaporation rate and the potential for fewer VOC emissions. In addition, FAME has lower toxicity and good biodegradability, making it a safer choice for workers and the environment [20, 24]. These properties are particularly relevant for the paint industry, where solvents not only function as solvents but also influence the viscosity, drying time, and flow properties of paints.

In oil-based paintings, the swelling of the paint film caused by solvent absorption presents a significant risk [20]. This swelling phenomenon results from the interaction between solvent molecules and the polymer structure of the paint binder. An unsaturated fatty acid triglyceride-based drying oil, like linseed oil, is usually used as the binder in oil paints. Linseed oil is predominantly composed of unsaturated fatty acid chains: 19.7% oleic acid, 18.03% linoleic acid, and 54.94% linolenic acid [26]. Many conjugated reactive sites that are vulnerable to oxygen attack are provided by the double bonds found in unsaturated fatty acid molecules. The rapid and highly exothermic autoxidation process causes the paint to dry quickly. A paint film with a high cross-link density can be incredibly stiff and hard, with outstanding resistance to solvents and abrasion [27].

Biribicchi et al. examined the swelling behaviour of oil paint fragments exposed to FAMEs with different carbon chain lengths to overcome these constraints. Their results show that the molecular structure of the FAME has a major impact on the swelling response. In particular, the high polarity of short-chain FAMEs (C6–C10) increases the likelihood of paint damage from swelling. On the other hand, medium-chain FAMEs (C12–C14), like methyl laurate or myristate, might be safer substitutes for solvents [20].

Virgin coconut oil (VCO) can be trans esterified to produce methyl laurate, which can be used as a substitute solvent and formulation ingredient in oil-based paints. Lauric

acid is the main component of the wide variety of fatty acids found in VCO [20]. The transesterification process, which employs a strong base catalyst (NaOH), is highly sensitive to FFA content.

According to research by Biribicchi et al. [20], the carbon chain length of FAMEs has a major impact on the swelling response of oil paint. FAMEs with shorter carbon chains (C6–C10) penetrate the paint layer more deeply and cause more noticeable swelling. On the other hand, FAMEs with medium carbon chains (C12–C14) typically have less penetrating power, which leads to more constrained swelling [20]. Additionally, Zaratti et al. reported that FAMEs are environmentally friendly solvents for oil paint, causing mild to moderate swelling comparable to white spirit [25]. However, the paint layer's response depends heavily on the specific type of FAME, particularly its carbon chain length and molecular structure. Short-chain FAMEs (C6–C10) pose a higher risk of swelling, whereas medium-chain FAMEs (C12–C14) tend to be more stable and controllable. Methyl laurate (C12) stands out in this research, offering several key advantages over other FAMEs: lower swelling levels compared to short-chain FAMEs; slow penetration that reduces the risk of excessive softening and mechanical damage to the paint layer; more balanced intermolecular interactions; and physicochemical properties similar to commonly used non-polar solvents, combined with the added benefits of biodegradability and lower toxicity.

Building upon previous research, this study involves the synthesis of FAME derived from VCO for use as an alternative oil paint formulation and solvent. The process incorporates variations in the VCO-to-methanol molar ratio (1:6, 1:8, and 1:10), NaOH catalyst concentration (1%, 1.5%, and 2% wt), and temperature (50°C, 60°C, and 65°C), with a fixed reaction time of one hour. Subsequently, the weight of the obtained FAME is measured to calculate the yield, allowing for the determination of optimal process conditions via Response Surface Methodology (RSM) using the Box-Behnken Design (BBD). The FAME product is then characterized in terms of density, viscosity, and constituent components using GC-MS. Finally, an oil paint based on the VCO-derived FAME is prepared and applied to a flat surface to assess drying time; additionally, the dried paint film is immersed in FAME to measure the degree of swelling.

2. Materials and Methods

2.1. Materials, Chemicals, and Equipment

The equipment used in this study included an analytical balance, Erlenmeyer flask, stand and clamp, spatula, beaker, magnetic stirrer, hotplate, three-necked boiling flask with a condenser setup, thermometer, graduated cylinder, dropper pipette, oven, separatory funnel, stopwatch, mechanical stirrer, Petri dish, oil paint container, paint test paper, paint test plate, four-sided bar applicator, and tissues. The analytical instruments used were a pycnometer, Ostwald viscometer, and GC-MS. The primary material used in this study is VCO from a local distributor. Other materials employed—serving as raw ingredients for oil-based paint—include methanol, NaOH, distilled water, alkyd resin, a drying agent, TiO_2 sourced from the KRONOS 2450 brand by Behrindotama Buana, a dispersing agent, anti-slip and levelling agents, an anti-foaming agent, and a thickener.

2.2. Synthesis of Fatty Acid Methyl Ester

The process of making Fatty Acid Methyl Ester (FAME) from raw materials in the form of commercial cooking oil is carried out simply through 3 stages, namely raw material preparation, transesterification reaction, and FAME purification. In the transesterification process, cooking oil with a free fatty acid (FFA) content of less than 2 wt% is converted using a 250 mL three-neck round-bottom flask equipped with a reflux condenser. Initially, 250 grams of cooking oil is preheated to 50, 60, and 65°C. Next, NaOH catalyst is added at concentrations of 1, 1.5, and 2% relative to the oil, along with methanol at molar ratios of 6:1, 8:1, and 10:1 (methanol to oil). The mixture is stirred at a speed of 400 rpm for 1 hour using a magnetic stirrer to accelerate the reaction. After completion, the catalyst is separated by vacuum filtration. A separating funnel is then used to isolate the FAME phase from glycerol, excess methanol, water, and other impurities. The FAME product is further purified through warm water washing to remove residual methanol, followed by vacuum evaporation to increase its purity.

2.3. Solvent-Based Paint Formulation Using FAME

The solvent-based paint formulation refers to the Indonesian National Standard (SNI) number 06-4827-1998 concerning the specifications for ready-to-use oil-based paint mixtures. In the production process of FAME-based paint, there are two stages, namely the preparation of binder materials and the preparation of pigment materials. The preparation of binder materials begins by mixing resin (alkyd medium oil resin, phenolic resin, petroleum resin, amino resin, acrylic resin) 72%, drier (cobalt naphthenate and manganese naphthenate) 5%, and FAME solvent 23% in a mixer according to the specified composition. The three materials are mixed ata stirring speed of 100-200 rpm, at a temperature of 35-40°C for 10 minutes.

Table 1. Preparation of binder and oil-based base coat.

Binder Preparation				
No	**Raw Material**	**Composition (%)**	**Composition (g)**	**Time (min)**
1	Alkyd resin	72	72	10
2	FAME	23	23	
3	Dryer	5	5	
Total		100	100	
Composition of Pigment Ingredients				
4	TiO_2	47	47	10
5	FAME	41	41	
6	Dispersing agent	3	3	
7	Anti-slip and levelling	3	3	
8	Anti-foam	3	3	
9	Thickener	3	3	
Total		100	100	
Mixing Oil-Based Paint Base and Binder				
10	Base oil	50	100	5
11	Binder	50	100	
Total		100	200	25

Table 2. Fatty acid composition of VCO (Virgin Coconut Oil) [28].

Fatty Acid	**Amount (%)**
Saturated Fatty Acids	
Caproic acid	0.37
Caprylic Acid	6.03
Capric acid	5.24
Lauric Acid	46.13
Myristic Acid	19.51
Palmitic Acid	9.81
Stearic Acid	4.73
Unsaturated Fatty Acids	
Oleic Acid	4.00
Linoleic Acid	8.97

Pigment material preparation involves mixing materials to form a film layer with opacity, including titanium dioxide (TiO_2), FAME solvent, dispersing agent, anti-slip agent, levelling agent, antifoam, and thickener. All these materials are mixed according to the composition shown in Table 1 with a stirring speed of 300 rpm for 10 minutes. Next, the binder material is mixed with the pigment material in a composition of 50 w/w, with a stirring speed of 300 rpm for 10 minutes.

2.4. Characterization of FAME Solvent-Based Paint

The FAME and acetone solvent-based paints that were produced were characterized, including the drying time (ASTM D 1640) and swelling.

3. Results and Discussion

This study optimized the transesterification process of VCO into FAME using the Response Surface Methodology (RSM) based on a Box-Behnken design. The independent variables examined included the VCO: methanol molar ratio (X1), reaction temperature (X2,°C), and NaOH catalyst concentration (X3, wt%). The final responses measured to evaluate the quality of the FAME product included yield (%), density (g/mL), and viscosity (cSt).

As a primary feedstock, VCO possesses physicochemical characteristics that make it ideal for direct transesterification using a basic catalyst. Pure VCO has a very low free fatty acid (FFA) content—generally below 0.2%—with a density ranging from 0.91 to 0.92 g/mL and a kinematic viscosity of approximately 25–30 cSt at 40°C [29]. This initial compositional profile and set of characteristics form the basis for determining reaction parameters and serve as a reference for evaluating the quality of the final product. The fatty acid composition of VCO is presented in Table 2.

A comprehensive summary of the treatment combination matrix and the experimental response parameter values is presented in Table 3.

3.1. Effect of Variable Factors on Fatty Acid Methyl Ester (FAME) Yield Response

The significance and adequacy of the generated mathematical model were evaluated using Analysis of Variance (ANOVA). According to Montgomery, ANOVA is an essential statistical procedure in Response Surface Methodology (RSM) that partitions the total response variability into variability attributable to the regression model and variability associated with residual error. The model's significance was determined via the F-value; a regression model is considered statistically valid if its probability value (p-value) is less than the significance level ($\alpha = 0.05$). Additionally, a lack-of-fit test was conducted to empirically verify the adequacy of the

Table 3. Results of fatty acid methyl ester (FAME) yield calculations.

Run	Mol Ratio VCO:Methanol	Temperature (°C)	Catalyst Concentraion (% wt)	Yield (%)	Density (g/ml)	Kinematic Viscosity (cSt)
1	1:6	50	1.5	79.58	0.8865	4.6
2	1:10	50	1.5	81.87	0.8831	4.5
3	1:6	65	1.5	82.74	0.8805	4.3
4	1:10	65	1.5	83.48	0.8788	4.2
5	1:6	60	1	79.07	0.8877	4.7
6	1:10	60	1	89.52	0.8756	3.5
7	**1:6**	**60**	**2**	**78.04**	0.8910	4.8
8	1:10	60	2	81.67	0.8834	4.5
9	1:8	50	1	93.61	0.8683	3.1
10	**1:8**	**65**	**1**	**96.10**	0.8727	2.9
11	1:8	50	2	86.24	0.8764	3.8
12	1:8	65	2	90.78	0.8710	3.3
13	1:8	60	1.5	81.46	0.8814	4.4
14	1:8	60	1.5	82.33	0.8807	4.4
15	1:8	60	1.5	80.78	0.8830	4.4

Table 4. Statistical model summary.

Source	Adjusted Sum of Square	DF	Adjusted Mean Square	F-Value	P-Value	
Model	408.584	9	45.398	12.07	0.007	Significant
X_1-VCO:Methanol	34.365	1	34.365	9.13	0.029	
X_2-Temperature	17.362	1	17.362	4.62	0.084	
X_3-Catalyst Concentration	59.634	1	59.634	15.85	0.011	
X_1^2	78.341	1	78.341	20.82	0.006	
X_2^2	105.960	1	105.960	28.17	0.003	
X_3^2	98.281	1	98.281	26.12	0.004	
$X_1.X_2$	0.022	1	0.022	0.01	0.942	
$X_1.X_3$	11.625	1	11.625	3.09	0.139	
$X_2.X_3$	1.710	1	1.710	0.45	0.530	
Error	18.810	5	3.762			
Lack-of-Fit	17.594	3	5.865	9.64	0.095	Not Significant
Pure Error	1.216	2	0.608			
Total	427.394	14				

model's order, and an analysis of residual normality was performed to ensure the validity of the ANOVA results [30]. The effects of the VCO: methanol molar ratio, temperature, and NaOH catalyst concentration on FAME yield were assessed based on the derived model equation. The ANOVA results for FAME yield are presented in Table 4.

ANOVA testing for the yield parameter indicates that the proposed model is significant, with a p-value of 0.007. In accordance with the model adequacy principles outlined by Montgomery, the fit of the quadratic model is corroborated by the lack-of-fit parameter, which yielded a p-value of 0.095, indicating a non-significant deviation. The model's predictive quality is supported by an R^2 value of 95.60% and an adjusted R^2 value of 87.68%. A model is considered robust when it exhibits a high R^2 value—approaching 100%—that aligns with the adjusted R^2 value. This confirms that optimal model data fitting is achieved when the R^2 value is high. Furthermore, a high R^2 value indicates that the majority of the total variation in the observed response can be explained by the designed model [31].

Individual partial assessment of the ANOVA coefficients reveals that the linear variables for molar ratio (X1) and NaOH catalyst concentration (X3) have p-values of 0.029 and 0.011, respectively, while temperature (X2) has a p-value of 0.084. Conversely, the quadratic components show highly significant effects, with p-values of 0.006 for $X1^2$, 0.003 for $X2^2$, and 0.004 for $X3^2$. The cross-interaction effects include X1·X2 (p-value = 0.942), X1·X3 (p-value = 0.139), and X2·X3 (p-value = 0.530). Response surface analysis of the FAME yield produced the following quadratic regression model in terms of coded variables (X_1, X_2, and X_3), as presented in Equation (1):

$$\begin{aligned} Yield = {} & 401.3 + 21.77X_1 - 12.73X_2 - 63.6X_3 \\ & - 1.152X_1^2 + 0.1099X_2^2 \\ & + 20.64X_3^2 + 0.0048X_1X_2 \\ & - 1.705X_1X_3 + 0.170X_2X_3 \end{aligned} \quad (1)$$

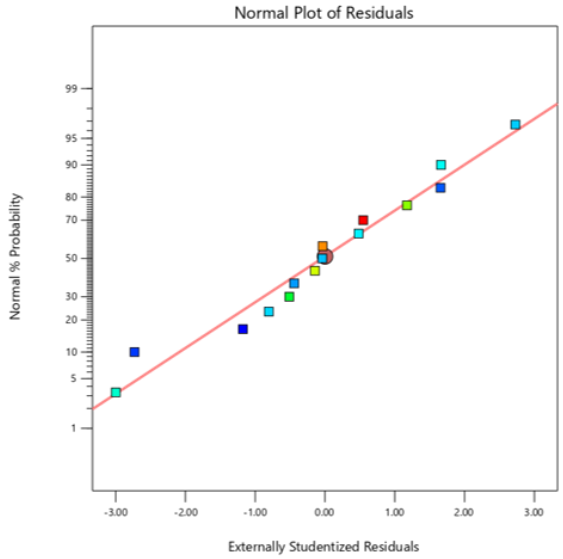


Figure 1. Relationship between actual and predicted FAME yield values.

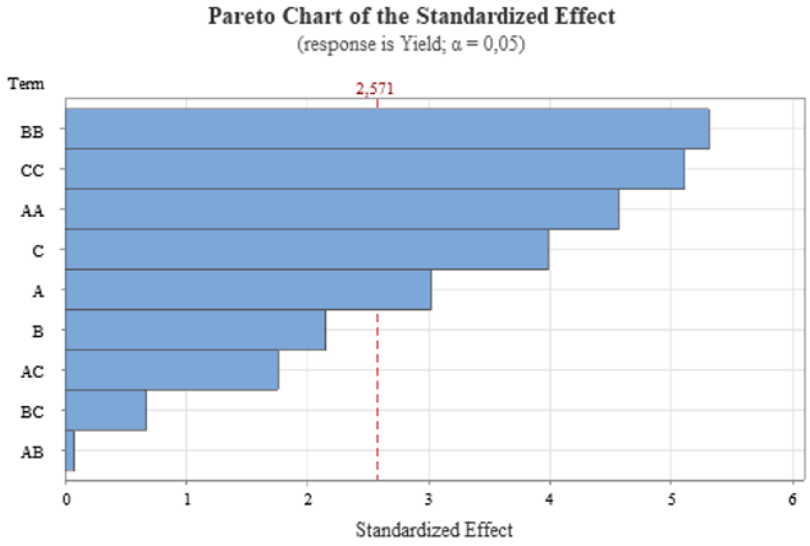


Figure 2. Pareto chart of the effects of process variables on FAME yield.

According to Zewide et al., a positive coefficient sign indicates that an increase in the variable's value contributes significantly to an increase in FAME yield, whereas a negative sign indicates that employing the variable at high levels or values can have the effect of reducing FAME yield [31]. To validate the suitability of the underlying ANOVA assumptions, an analysis of residual normality was conducted. Montgomery states that a sound, unbiased model must exhibit normally distributed errors [30].

Figure 1 shows that the residuals for the yield response are scattered closely along the red diagonal line, indicating an approximately normal distribution. This precise linear pattern indicates a good fit between the model and the response variable data; consequently, the statistical significance estimates and conclusions drawn from the ANOVA are considered fully valid.

The Pareto chart illustrates the individual and interaction effects of the variables on FAME yield. Effects exceeding the critical threshold (t = 2.571) are considered statistically significant (Figure 2). The negative effect observed in the quadratic t-value for the molar ratio indicates that increasing the methanol amount beyond the optimum level actually reduces the yield due to the partial dissolution of glycerol. This hinders the equilibrium shift, confirming that excess methanol complicates glycerol separation [32].

Figure 3 demonstrates that an increase in reaction temperature raises the kinetic energy of the molecules. However, a side reaction known as saponification is brought on by an overly high concentration of the basic catalyst [33]. The yield of pure FAME is directly decreased by this saponification step, which uses triglycerides to create soap.

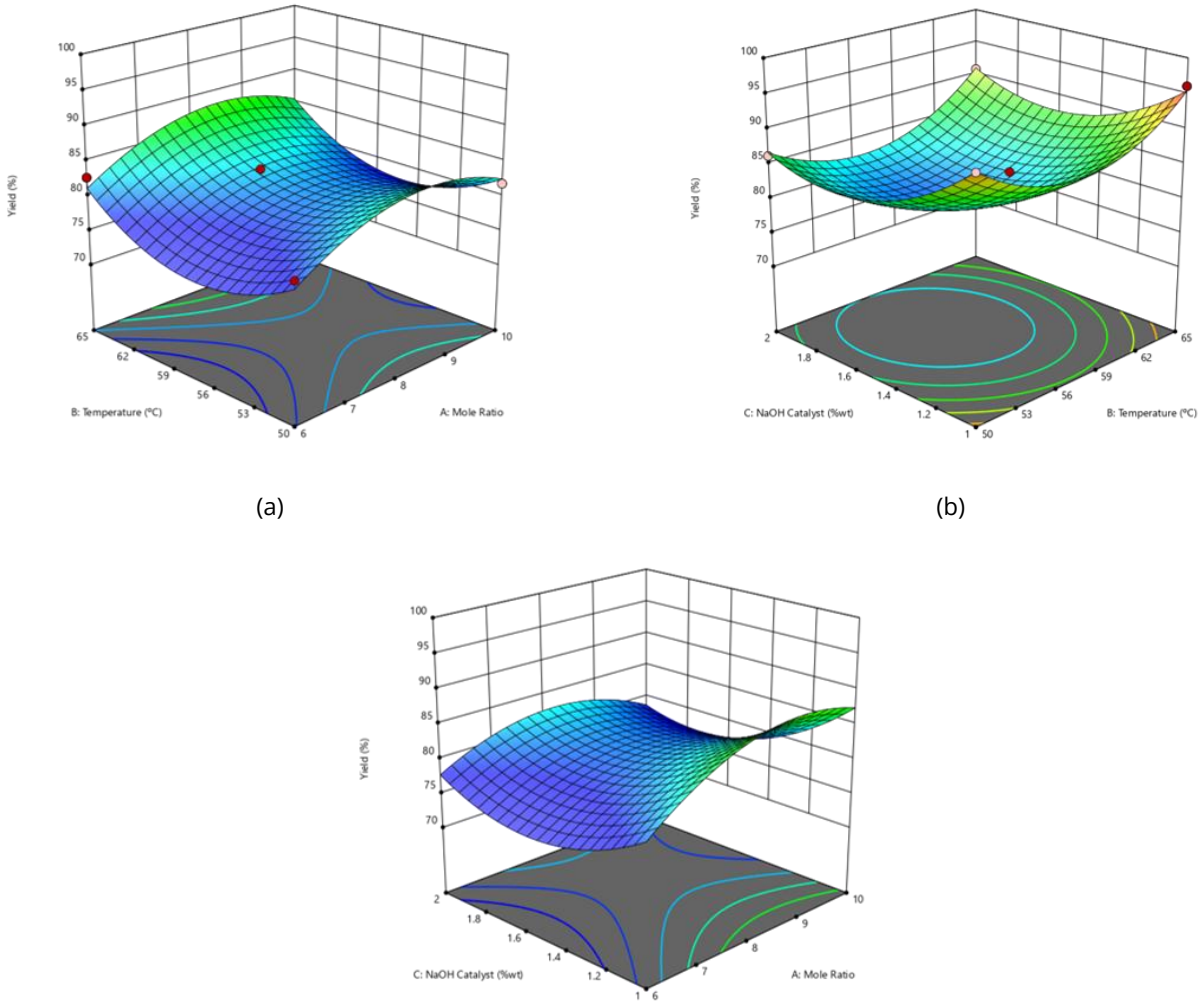


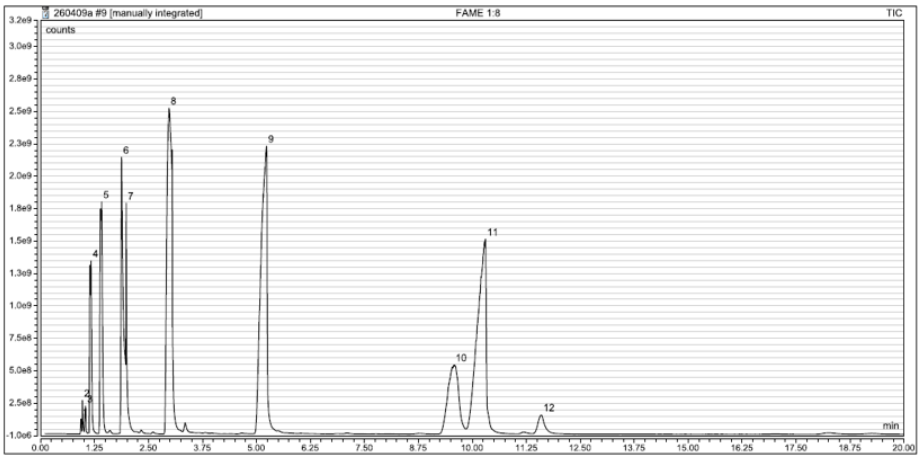
Figure 3. Three-dimensional response surface plots showing the interaction between VCO oil-to-methanol ratio and catalyst concentration on FAME yield at reaction temperatures of (a) 50 °C, (b) 60 °C, and (c) 65 °C.

3.2. Density and Viscosity Characteristics of Fatty Acid Methyl Ester (FAME)

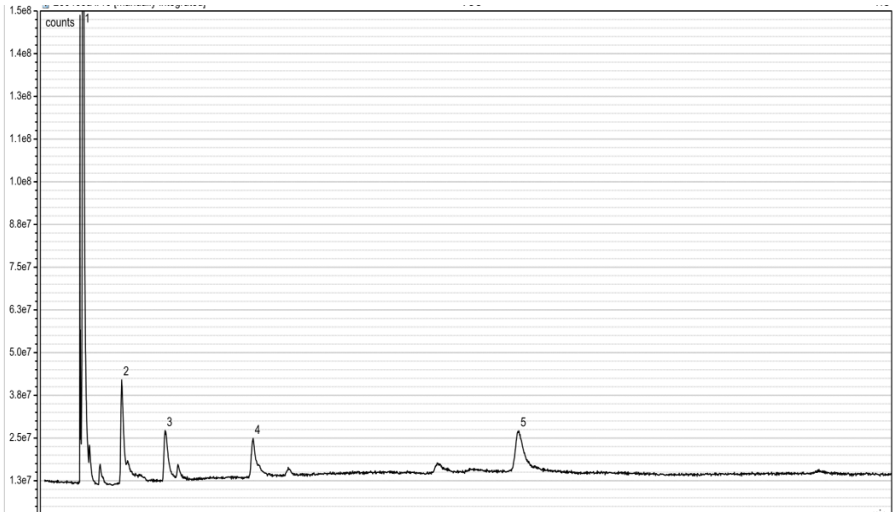
Physical characteristic testing is a crucial step in determining the suitability of FAME synthesized from VCO. The parameters evaluated included density and kinematic viscosity, measured at 40°C. These results were then compared against the Indonesian National Standard (SNI) 7182:2015 for Biodiesel to ensure the produced methyl ester compounds met the established quality criteria.

Based on the test results, the density of FAME derived from VCO fell within the range of 868.3–891.0 kg/m^3. The quality standard for biodiesel density is 850–890 kg/m^3 [34]; thus, the produced FAME met the established standards. Density is closely related to the carbon chain length of the constituent fatty acids. FAME derived from VCO is dominated by methyl laurate (C12:0), a medium-chain fatty acid. The conversion of triglycerides (vegetable oil) into methyl esters successfully reduced molecular weight significantly, as evidenced by the density values falling within the standard range. Furthermore, the structural characteristics of medium-chain FAME (particularly methyl laurate) provide specific solvency power regarding non-polar materials. In application, the FAME is capable of interacting with oil- and acrylic-based binder matrices through a diffusion mechanism [25].

Additionally, the kinematic viscosity results were between 2.9 and 4.8 cSt. The range of 2.3 to 6.0 cSt is the kinematic viscosity standard for biodiesel (National Standardization Agency, 2015). These findings show that FAME produced from VCO completely conforms to SNI requirements. The viscosity of VCO-derived FAME indicates that the liquid has a low enough viscosity to dissolve the organic polymer matrix of oil paint, but it does not have the



(a)



(b)

Figure 4. GC–MS chromatograms of FAME samples with (a) higher and (b) lower FAME yields.

extreme volatility of light hydrocarbon solvents [25]. Because FAME does not evaporate as quickly as traditional solvents, it permits a longer contact time during application, whether for pigment dilution or painting restoration and cleaning. Furthermore, the low viscosity makes it easier for solvents to penetrate the paint layer, causing a gradual, controlled swelling phenomenon that softens the paint or varnish layer without seriously harming the underlying material structure [35].

3.3. Analysis of Fatty Acid Methyl Ester (FAME) Composition

This research tracked the distribution of the main components' abundances and confirmed that fatty acids were successfully converted into FAME. The samples with the highest and lowest yields underwent GC-MS characterisation. The FAME compounds identified from the chromatograms of samples with higher and lower yields are presented in Figure 4.

Methyl laurate was identified as the most abundant chemical component based on the interpretation of the chromatographic data. The distribution of all methyl ester fractions resulting from the reaction is presented in Table 5.

The FAME product chromatogram reveals a distinct shift in the molecular profile, as reflected by the relative abundance of the identified compounds. High-molecular-weight peaks at retention times of 36–40 minutes disappeared completely. This phenomenon indicates that the transesterification reaction and the cleavage of triglyceride chains proceeded to completion [36]. The chromatographic peaks shifted to a much shorter retention time range (below 12 minutes), signifying the formation of lighter, short-chain FAMEs [37]. The composition of the optimized FAME product was functionally dominated by an organic ester—specifically methyl laurate—at 40.44%. This dominance was followed by methyl myristate at 23.55%. Although the initial lauric acid content in VCO typically reaches 46%, FAME analysis

Table 5. Composition profile of VCO-based FAME compounds.

Peak No	Retention Time (Min)	Compound	Molecular Formula	Area (%)	
				High Yield	Low Yield
1	0.93	5-(Hydroxymethyl)dihydrofuran-2(3H)-one	$C_5H_8O_3$	0.13	-
2	0.97	2-Propanone, methylhydrazone	$C_4H_{10}N_2$	0.25	4.05
3	1.04	2-Propanone, methylhydrazone	$C_4H_{10}N_2$	0.35	-
4	1.17	Hexanoic acid, methyl ester	$C_7H_{14}O_2$	2.79	-
5	1.41	Octanoic acid, methyl ester	$C_9H_{18}O_2$	6.35	-
6	1.88	Decanoic acid, methyl ester	$C_{11}H_{22}O_2$	10.86	-
7	1.98	Undecanoic acid, methyl ester	$C_{12}H_{24}O_2$	1.89	0.58
8	**2.97**	Dodecanoic acid, methyl ester	**$C_{13}H_{26}O_2$**	**40.44**	**0.51**
9	5.23	Methyl tetradecanoate	$C_{15}H_{30}O_2$	22.55	-
10	9.57	Pentadecanoic acid, methyl ester	$C_{16}H_{32}O_2$	3.37	0.44
11	10.30	Hexadecanoic acid, methyl ester	$C_{17}H_{34}O_2$	9.74	-
12	11.61	Methyl stearate	$C_{19}H_{38}O_2$	1.28	
13	36.80	(Dodecanoyloxy)-3-hydroxypropyl dodecanoate (1,2-dilaurin)	$C_{27}H_{52}O_5$		60.34
14	40.33	(Dodecanoyloxy)-3-hydroxypropyl dodecanoate (1,2-dilaurin)	$C_{27}H_{52}O_5$		33.65

Table 6. Data on drying times using FAME VCO as a binder.

Replication	Drying Time (sample A)	Drying Time (sample B)
Replication 1	10 h and 48 min	26 h and 46 min
Replication 2	10 h and 30 min	26 h and 12 min
Replication 3	10 h and 17 min	26 h and 56 min
Average	10 h and 31 min	26 h and 38 min

revealed a relative methyl laurate percentage of 40.44%. This reduction is attributed to the characteristics of medium-chain methyl esters, which are more polar and susceptible to saponification, resulting in partial product loss during the distilled water washing stage [38]. Methyl laurate continued to be the predominant component despite the drop in laurate content, which is a very advantageous result because this medium-chain molecule is totally saturated and lacks carbon-carbon double bonds [39].

In contrast, 1,2-dilaurin, which has lauric acid groups linked to the carbon atoms at positions 1 and 2 of the glycerol, is the biodiesel with the lowest yield. The amount of methyl laurate is merely 0.51%. FAME's capacity to function as a binder in oil-based paint will be impacted by this composition.

3.4. Effectiveness Test of Fatty Acid Methyl Ester (FAME)-Based Oil Paint

Effectiveness testing evaluated the performance of VCO-derived FAME in oil-based paint based on two key physicochemical properties: drying time and swelling behavior. Paint bases and binders were prepared using FAME samples obtained with high yields (molar ratio VCO: methanol 1:8; reaction temperature 65°C; 1 wt% NaOH catalyst) and low yields (molar ratio VCO: methanol 1:6; reaction temperature 60°C; 2 wt% NaOH catalyst), and each one was repeated three times.

3.5. Comparative Analysis of Drying Time

This testing evaluates whether the molecular composition of VCO-derived FAME, dominated by saturated medium-chain and some unsaturated fatty acid esters, can function as a bio-solvent for viscosity reduction and as a reactive binder to replace commercial hydrocarbon solvents. The drying time results are presented in Table 6, showing a stable and moderate drying profile with an average drying time of 10 hours and 31 minutes. Likewise, the drying time calculation using FAME VCO showed the lowest results, with an average drying time of 26 hours and 38 minutes (Figure 5). This drying profile is significantly faster than that observed with drying oils such as raw linseed oil. Coatings based on raw linseed oil require a very long drying time—ranging from 48 to 72 hours (2 to 3 days)—to reach the touch-dry phase, a result of the slow autoxidation polymerization process [40].

In contrast, coatings using commercial petrochemical solvents like thinners or mineral spirits dry much more rapidly, typically within 1 to 3 hours. This drying rate phenomenon is fundamentally influenced by the low vapor pressure and high boiling point of the medium-chain saturated ester fractions (Medium Chain Fatty



Figure 5. Drying time test of FAME-VCO-based oil paint.



Figure 6. Swelling test of oil-based paint in FAME-VCO solvent.

Acids Methyl Esters) that dominate the FAME VCO product—specifically methyl laurate (C12) and methyl myristate (C14) [25]. Based on these results, it is evident that FAME with a higher methyl laurate content exhibits superior drying performance.

Although the physical volatility of VCO-derived FAME tends to be lower than that of commercial petrochemical solvents, the final-stage drying mechanism of oil paint involves more than just liquid-phase evaporation; it is primarily governed by the chemical autoxidation and polymerization of the carbon chains. Petrochemical solvents function purely as non-reactive solvents that evaporate completely into the atmosphere, releasing harmful volatile organic compound (VOC) emissions [41]. The drying characteristics of VCO-derived FAME are supported by a study conducted by Johansson [42]; test results on paint formulations indicate that curing performance and the final properties of the paint film depend heavily on the fatty acid profile—specifically the number and position of double bonds (alkenes) within the FAME used. Johansson found that FAME with a low degree of unsaturation failed to fully penetrate the paint's polymer network. Consequently, these FAME molecules remained within the paint matrix, acting as plasticizers. The presence of these plasticizers was shown to significantly prolong the paint's drying time. This average drying time of 10.5 hours offers a technical advantage by providing an ideal "open time," allowing painters or applicators to manipulate the paint's texture and color gradations without the risk of premature hardening [43].

Drying time characteristics are also influenced by the concentration of FAME used in the paint formulation. If the FAME content is too high, the drying time increases due to steric hindrance, which reduces the interaction between oxygen and the resin [43]. Conversely, if the FAME content is too low, the drying time is shorter. However, an insufficient amount of FAME risks compromising the paint's flexibility, resulting in a brittle film prone to microcracking after application [27].

3.6. Analysis of Swelling Behavior Characteristics

The extent of swelling acts as a criterion for evaluating the reactivity of an organic solvent with the polymer matrix in oil paint. Based on test data obtained using the gravimetric method (mass weighing), paint samples with an initial weight of 1.53 grams were exposed to VCO-derived FAME for 30 minutes, as shown in Figure 6. Quantitative data from the laboratory tests are presented in Table 7.

There are two diffusion kinetic phases in the solvent absorption process, according to the data. The swelling percentage increases from 0% to 3.28% during the first phase (the first 0 to 4 minutes) due to a notable increase in solvent penetration. (with the paint weight reaching 1.5801 grams). As the second phase begins—that is, after six minutes—the rate of diffusion sharply slows down, and the paint weight increases very gradually, creating an equilibrium curve (plateau). The greatest swelling percentage was only 4.14% at the conclusion of the 30-minute observation period, and the final paint weight was 1.5934 grams. These results indicate the controlled and modest absorption of FAME into the cross-linked oil-based paint matrix (Figure 7).

The results of the gravimetric test on VCO-derived FAME align closely with the swelling behaviour of pure FAME compounds. VCO-derived FAME is predominantly composed of methyl laurate (C12:0). According to Biribicchi et al., swelling tests on methyl laurate using an optical microscopy method (measuring changes in 2D surface area) yielded a similarly gradual curve, with the swelling percentage stabilizing at approximately 5.3% after 15 minutes of observation [20]. A discrepancy exists

Table 7. FAME VCO swelling test data.

Contact time (minutes)	Initial Paint Weight (g)	Final Paint Weight (g)	Swelling (%)
0	1.53	1.53	0
2	1.53	1.5525	1.468
4	1.53	1.5801	3.275
6	1.53	1.5845	3.562
8	1.53	1.5853	3.613
10	1.53	1.5866	3.7009
12	1.53	1.5878	3.781
14	1.53	1.5890	3.855
16	1.53	1.5900	3.9214
18	1.53	1.5908	3.9756
20	1.53	1.5917	4.0357
22	1.53	1.5922	4.0678
24	1.53	1.5926	4.09345
26	1.53	1.5927	4.0982
28	1.53	1.5929	4.1125
30	1.53	1.5934	4.1427

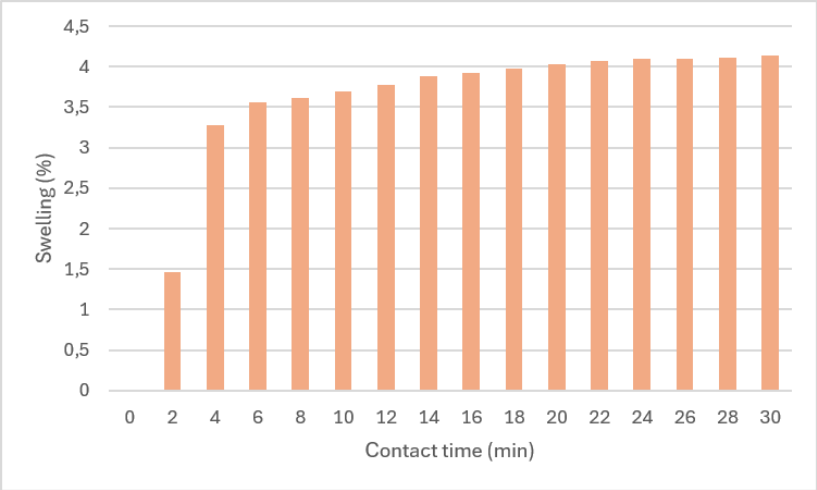


Figure 7. Swelling percentage of oil-based paint using biodiesel derived from VCO as a binder.

between the gravimetric test result (4.14%) and the optical method result (5.3%). This is attributable to density differences: FAME liquids have a significantly lower density (0.8683–0.8910 g/cm^3) compared to oil paint solids containing metallic pigments (2.0 g/cm^3). Consequently, a volume expansion that appears substantial optically does not result in a proportionally equivalent mass increase when measured on an analytical balance.

Furthermore, the phenomenon of solvent swelling is invariably accompanied by a leaching process—specifically, the dissolution of low-molecular-weight organic components from the paint binder. The mass of the FAME solvent entering the film (increasing weight) is partially offset by the mass of the binder leaching out (decreasing weight); consequently, gravimetric analysis registers a lower net mass increase than the visual expansion would suggest [44]. The remarkably low FAME-VCO swelling percentage (4.14%) offers a significant mechanical advantage for its application as an alternative "green solvent" in the restoration and conservation of oil paintings. In contrast, petroleum-based solvents (such as thinners or xylene) are highly aggressive, capable of inducing swelling of more than 30–50% in under two minutes—a rate that poses a critical risk of destroying the original paint matrix [44]. Because FAME-VCO reaches its swelling equilibrium at a very safe level and at a slow rate, it provides conservators with an ideal contact time.

These findings are supported by research conducted by Zaratti et al., which demonstrated that fatty acid methyl esters (FAME) can dissolve varnish or non-polar materials (such as microcrystalline wax and Regalrez 1094) on the canvas surface without damaging the underlying paint layer. Furthermore, to minimize further penetration and prevent direct interaction between the solvent and the paint substrate, Zaratti et al. recommend applying FAME

in a gel formulation. By combining specific solvency with a very low degree of swelling (4.14%), VCO-derived FAME proves to be highly promising, safe for the health of the person applying it, and ideal for use in the cleaning of paint surface layers [25].

The results regarding drying time and swelling percentage in this study demonstrate a consistent correlation. The paint drying time of 10 hours and 31 minutes indicates that cross-linking network formation proceeded relatively slowly due to steric hindrance from the saturated VCO FAME molecules [43]. This slow rate of oxidative polymerization resulted in a polymer matrix with lower cross-link density. The openness of this matrix network, combined with the plasticizing effect of the FAME, created greater free volume within the paint film [45]. This increased free volume provided space for external solvent penetration during the immersion process, resulting in a swelling percentage of 4.14%. Fundamentally, the reduction in cross-link density caused by the addition of a saturated fatty acid-based reactive diluent slows the drying process while simultaneously increasing solvent absorption in the paint film [27].

4. Conclusions

The obtained FAME yields ranged from 78.04% to 96.10%. The highest yield of 96.10% was obtained with a molar ratio of 1:8, a temperature of 65°C, and a 1 weight percent NaOH catalyst. Most of the resulting FAME was composed of medium-chain organic esters, with the largest fractions being methyl laurate (40.44%) and methyl myristate (22.55%). The paint's swelling value peaked at 4.14%, according to gravimetric measurements. Additionally, the paint formulation with FAME VCO substitution took an average of 10 hours and 31 minutes to dry. Continued assessment is essential concerning the performance of VCO-based FAME with a gel formulation matrix on test specimens, to mitigate penetration and harmful interaction with the substrate beneath the paint.

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