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A Technical Review on Performance and Emission Characteristics of Diesel Engine Fueled with Straight Vegetable Oil

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Abstract

As energy reserves are depleting day by day and the environment is polluted, finding an alternative to fossil fuel has become an essential task for the world community. Green fuel (straight vegetable oil) has been found to be a capable alternative to fossil fuel in many applications. Using unprocessed unblended straight vegetable oils (UUSVOs) as a fuel for diesel engine is advantageous in minimizing the processing time, energy, and cost associated with biodiesel production. However, the higher viscosity of vegetable oils limits their long-run use in diesel engine. A planned methodology is, however, required to resolve the issues of poor engine performance and affected emission parameters. This article aimed to present a critical review of the impact of UUSVOs on the performance and emission level of diesel engine during short and long-run engine operations. The crucial aim of this article is to find an eco-friendly alternative to fossil fuel that may serve the world community. The recent literature review shows that straight vegetable oils (SVOs) may become an excellent alternative to diesel engines during short-run operations. However, long-run operation with SVOs as a fuel creates many problems related to damage and maintenance of the engine parts, deteriorated engine performance, significant variation in emission, chocking of injector and fuel line, degraded lubricating oil quality, etc. Engine performance can be improved through the optimization of operation parameters and fuel preheating prior to the injector.

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Introduction

Ecological concerns, exhaustion of fossil fuel reserves and escalating industrialization and transformation of the world have caused researchers worldwide to come across for substitute from renewable resources. From the present perspective,

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biofuels such as pure plant oil or straight vegetable oil (SVO) are a commercial alternative that can reduce load of dependency on petroleum fuels. The "SVO" is also called "raw vegetable oil or pure plant oil or neat vegetable oil or pure plant oil or straight plant oil or raw plant oil or crude vegetable oil and virgin vegetable oil.[1-14]

Indian farmers preferably use compression ignition (CI) engine or diesel engine (DE) for agricultural purposes. Because vegetable oil's unique characteristics, such as its properties are comparable to diesel, bio-degradable, locally and readily available in nature, make vegetables oils a good contender to substitute the existing fossil diesel (FD). However, instead of a unique feature to direct use of neat vegetable oil (VO) in the engine, there are certain limitations with vegetable oils as a alternative fuel for compression ignition engines. SVO causes carbon deposits in the combustion chamber, piston top, incomplete burning, and some other problems, like blockage fuel injectors and sticks piston rings.[5,15-18] To improve the properties and overcome the shortfalls of VOs, mainly chemical and heating techniques are employed to decrease their kinematic viscosity. Chemical techniques for lowering viscosity are pyrolysis transesterification, micro-emulsion and dilution. In the heating techniques fuel is preheated to decrease the viscosity.[11,18-22] Transesterification is the unique and proven technique for producing biodiesel.[5] Nevertheless, higher energy requirement and response time in *transesterification technique* are the major hurdles in making it popular. Also, crude glycerol is quite injurious to the environment and must be well disposed of.[23] Because of all these; preheating the unprocessed VO prior to injection is the most favorable method to reduce its viscosity. However, researchers reported more NOx emissions than FD.[24] Using unaltered SVOs in the engine creates various operational issues which affect the engine’s performance and emission.[25] These problems have significantly appeared during the engine's long-run operation rather than the engine's short-run operation. This paper aims to summarize the results and opinions of different investigators on engine performance and exhaust emissions level of compression ignition engines fueling with unprocessed unblended SVO during *Short and Long-run Operations.*

Properties of Vegetable SVOs

VOs are mainly produced from oilseed plants, oil-bearing fruits, kernels, and the seeds of textile fibers plants. VOs are divided into edible and non-edible oils.[15,26-28] The various Physical and Thermal Properties of SVOs are presented in Table 1. Most of the authors have broadly reviewed them. Different researchers have well-reported kinematic viscosity, which can be easily observed in Table 1. Thickness increases with the unsaturated structure and length of the carbon chain. At room temperature, the average thickness of SVOs is about 10–15 times more compared to that of FD.[6,15] Majorly, the calorific value of FD is around 10–15% higher than SVOs fuel. Cetane numbers are the measure of flammability. The lower the Cetane numbers, the higher the cold start-up problem of the engine.[6] VOs pose particular values of Flash points, Cloud points, and Pour points (Table 1). Rich-contained iodine VO has more double bonds and indicates a higher degree of unsaturation means lower oxidation stability.[6,13]

Table 1: Physical and Thermal Properties of SVOs.

Sr.No.	Properties of SVO	Values	References
1	Kinematic Viscosity (cSt at 38°C)	32.6-76.4	13, 15, 29, 30
2	Density (kg/m3)	870-970	13, 15
3	Flash Point(°C)	110-330	5, 6,13, 15, 30
4	Cloud Point (°C)	−11.6 to 23	15, 30
5	Pour Point (°C)	-40.0 to 31	6, 15
6	Carbon Residue (% w/w)	0.22-0.64	13,31, 32
7	Free Fatty Acid (%w/w)	1–5%	6, 32, 33
8	Calorific Value (MJ/kg)	34–42.15	13, 15, 29, 30, 32
9	Cetane number	32– 59.5	13, 32

VOs are triglycerides with a long atomic structure of carbon-containing glycerol and fatty acids with a carboxyl group. VOs consist of 95-97% triglycerides and the remaining 5-3% as monoglycerides, diglycerides, waxes, sterols, and a variety of impurities and free fatty acids.[6] Glycerol molecules with three fatty acid molecules respond in terms of triglyceride resulting in three water molecules and one triglyceride molecule.[27] Saturated and unsaturated fatty acids are with and without double bond chains[5] and VOs are lipid materials.[27] Geometrical differences exist in the different kind of saturated and unsaturated fatty acids of Vegetable oil such as carbon chain length, location and number of double bond.[34] Saturated fatty acids are generally available in solid form at room temperature, where as unsaturated fatty acids are in liquid form at room temperature.[34] These oils have Oleic acid, Caprylic acid, Capric acid, Palmitic acid and other fatty acids. It contains the straight chain of carbon and hydrogen atoms in aromatic configurations with better ignition quality, oxidation-resistant, reducing fuel oxidation problems.[27,35]

Literature Review on Performance and Emission Characteristics of DE fueling SVOs for Short-Run Duration

Literature shows the severity of the requirement for alternative fuel for DEs. Dedicated research work on "Direct use of UUSVOs in DE or CI engine" has been concentrated over the last two-three decades by investigators. A Summary of previously published review on SVOs is shown in Table 2. Most of the reviewers found that the SVOs as an alternative to FD (Table 2). Nettles-Anderson and Olsen,[4] Misra and Murthy,[5] Sidibe *et al.*[6] and Blin *et al.*[7] observed that the use of SVOs can be one of the way to reduce emissions load to environment and can be used in DE without any modification.[11,13,15,19,38-41]

Table 2: Summery of published review articles on SVOs

Reviewer	Area of Study	Type of SVO	Reviewer’s findings
Nettles-Anderson and Olsen[4] (2009) Misra and Murthy[5] (2010)	Scope and impact of SVOs on perfomance of DE	SVO	Need lipid acid profile test for SVO, proven green alternative to DE
Sidibe *et al.*[6] (2010) Blin et *et al.*[7] (2013) Russo *et al.*[11] (2012)	Behvieral anlysis, technological advancements, merits, demerits of VO as fuel in DE	Crude filtered oil/VOs Pure plant oil/SVO	Eco-friendly, rich oxygen content, less sulphur, locally available, suitable for non-transportation use
Hossain and Davies[13] (2010) Mat *et al.*[15] (2018)	Technical suitability of plant oils / SVO in DE		Advantageus over biodiesel and FD, no need modification in DE while using preheated SVOs
No[26] (2011)	Inedible VOs and their derivatives	Inedible VOs	Inedible VOs suited for DE
Asokan *et al.*[29] (2018) Sharma and Dwivedi[30] (2014)	Influence of SVOs on performance and emission of DE	VOs / SVO / WVO	SVOs can be used in DE, preheated SVO provide eco-friendly outcomes
Mondal *et al.*[32] (2008)	Detailed study of SVOs for DE		Suitable for small to medium use, required planed research on SVOs
D’Alessandro *et al.*[37] (2016)	Effect of SVO and WVO in DE		Comparable performance and emission, higher NOx emission for preheated VO
Ramkumar and	Technical feasibility of		

Kirubakaran[38] (2016)	preheated VO on DE		Degraded efficiency, higher CO,
Capuano *et al.*[39] (2017)	study of the effects of straight use of WVO in DE	H	C level than FD, more suitable as preheating VO
No[40] (2017)	Potential, production, Technical feasibility, application of SVO as fuel for DE		Great potential of inedible SVO, optimum preheat (60°C –85°C -edible and 80°C –120°C-non-edible SVOs)
Dabi and Saha[41] (2019)			suatable as fuel for the DE, more suited as preheated SVO
Seljak *et al.*[42] (2020)		Bio-liquids	Comparable physio- chemical properties of SVOs as DE fuel
Bari *et al.*[43] (2020)	Effect of airflow characteristics of combustion on DE	Higher viscous biofuels	Improved efficiency around 1.3 to 2.8% through vane geometry optimization
Saiteja and Ashok[44] (2021)	Comparative analysis of biofuels for DE	Biofuels/ Eucalyptus oil	Low HC, PM emissions, higher CO than FD, oxidation on HCCI engine
Ellappana and Rajendran[45] (2021)			Comparable performance and emissions leves with FD.

Researchers perform their tests for short duration (8 to 12 hour) and long duration (more than 200 cumulative hours). Findings of different investigators are tabulated in Table 3-6. Data are summarized based on loading conditions, fuel temperatures, injection pressures, operational hours, engine speeds, injection timings or injection angles. UUSVOs or SVOs have played a significant role in finding alternative fuel for CI engines. Direct use of SVOs is only the need of its reducing viscosity. Short-run operational conditions favor the SVO as fuel to the DE. Critical analysis of Tables 3-6 clearly indicate that SVO found a concrete foundation as a substitute for FD. Variety of engine with a combination of specifications like single, double, three, four, and six-cylinders (1C, 2C, 4C and 6C), four strokes (4S), air-cooled (AC), water-cooled (WC), constant speed (CS), naturally aspirated (NA), turbocharged (TC), direct injection (DI), indirect injection (IDI) engine for preheated (PH) or unheated (UH) SVOs were investigated.

Effect of SVOs on Engine Performance and Emission at Varying Loading and Speed Conditions

Investigators[36,46-47] reported that KO (UH) indicates inferior brake thermal efficiency (BTE) and higher brake specific fuel consumption (BSFC) than FD at all loads. They also reported that BTE and exhaust gas temperature (EGT) were found to be increased as load increases, however, it was always lower than FD. In the same UUSVO, Agarwal and Dhar[46] reported that applying straight KO (PH) on a DI, DE improves the BTE and reduces BSFC. A significant increment in BSFC for KO than FD at all loads was observed. However, the results of Acharya *et al.*[47] contradicted Agarwal and Dhar.[46] According to Acharya *et al.,*[47] applying straight KO at 120°C lowers the BTE and increases EGT more than FD. Higher CO, CO2, HC and lower NOx emissions at medium and high loads were observed compared to FD by Acharya *et al.* and similar results were also found for preheated Kusum oil. Mixed responses were noted by different researchers with the application of UH/PH straight Jatropha oil and UH/PH straight Mahua oil SVOs in a DE.[25, 27, 31, 48, 49] Kumar *et al.*[49] studied the behavioral changes of 1C, 4S, CS, WC, and DE fueling unheated neat Jatropha oil at different conditions. They found slightly less BTE, lower heat release rate, higher ignition delay and EGT due to poor combustion, high viscosity and low volatility of Jatropha oil. In addition, they observed higher smoke levels caused by the heavier molecular structure of VO. They also found lower NOx and higher CO and HC emissions of DE using Jatropha oil than FD. Singh[18] investigated the performance and exhaust emissions of direct ignition DE fueling de-waxed and degummed preheated straight

Jatropha oil at 80 to 90°C. During 100 hours of the short-run test, choking of the injector nozzle, soot deposition on the piston head, and deteriorated quality of lubrication oil within 25-30 hours of operation were noted. Some researchers reported that preheating of SVOs (up to 100°C temperature) is not significantly benefiting operational and engine performance. Instead, it is only helping to ease the flow of SVO inside the injection system and overcome filter choking, which could also be obtained at 60°C preheating.[50-53] Authors[50-53] concluded that preheated Palm oil increases peak pressure by 6% and lowers ignition delay by 2.6°. Corsini *et al.,*[54] Jazair *et al.,*[55] and Balafoutis *et al.*[56] reported higher BSFC, lower BTE and unchanged emissions levels at varying engine speeds (VES), loading conditions (VLC) and varying throttle positions (VTP) using SVOs in DI, DE. Diesel engines comfortably operate with preheated VOs during short-run operations.[57-62] Canakci *et al.,*[57] Yilmaz and Morton,[58] Garzon *et al.,*[59] Delalibera *et al.,*[60] Geo,[61] Acharya *et al.*[62] investigated combustion analysis of crude VOs (PH) in a DI/IDI, DE at VLC, VES and varying fuel temperatures (VFT). Performance and exhaust emission value of DI, DE fueling unprocessed unblended Poon oil, Orange oil, Pine oil, Lemongrass oil, Jojoba, Sunflower, KO, Mahua oil, Soya and other plant oil were investigated.[63-76]

Sonar *et al.*[73] worked on 1C, DI, DE (1500 rpm) using preheated (90°C) and unheated crude Mahua oil to investigate the engine performance and emissions at VIP (186, 196, 206, 216, 226 and 235 bar) and VLC (zero to 3.7kW kW rated load). They recorded higher BTE for preheated Mahua oil (29.1%) compared to oil and unheated Mahua oil (26.9%) at full load and designed injection pressure (196 bar). BTE was found to increase with load and fuel injection pressure, possibly caused by upgrading in atomization and improved mixing of air with fuel. Though, also, too high injection pressure decreases BTE. They found higher BSFC and EGT than FD for preheated Mahua oil and unheated Mahua oil. Value of NOX emissions were notably lower for Mahua oil (PH) and Mahua oil (UH) and higher for higher injection pressure at low loads. However, at the same time, CO and HC emissions were recorded to be significantly decreased. BTE for Mahua oil (UH) was found to be lower than all the test fuels just because of higher viscosity, and lower CV caused inferior combustion. Table 3 (a, b) shows the investigator's[44, 36, 46–48,71-74] outcomes on performance and emissions of 1C, 4S, WC, CS, DI, and DE compared to FD. In general, the higher BSFC increased EGT and lower BTE were observed for all loads at VLC, VFT and varying injection pressure (VIP) compared to FD using SVOs. Higher CO, CO2 and smoke were observed for KO and Mahua (UH).[36,46,48] However, lower HC and NOx were reported by some researchers. Sathiyamoorthi and Sankaranarayanan[75] investigated the performance behavior of DI, DE using Lemongrass (UH). They reported lower BSFC, increasing BTE and EGT with variable load and varying injection angle (VIA) at 1500rpm. In the same context, Sahu *et al.*[76] reviewed the engine's output adopting a variable compression ratio DI DE engine using SVO for short-run operations. However, some researchers[77-86] performed their investigation for short-run and long-run operation hours using SVOs. Acharya *et al.*[87] also found that KO (PH) produces higher CO, HC lower CO2 at low load, and lower NOx at all loading conditions. Similar results were found for DI, DE fueling Jatropha (UH)[88] and Rubber seed (UH)[89] compared to FD at VLC at 1500 rpm. Details results are tabulated in Tables 4 (a, b), 5 (a, b, c), 6 (a, b) and 7. More than 90% of researchers who worked on the direct use of UUSVOs agreed that VO (UH) degrades the engine's performance significantly more compared to SVOs (PH) and FD at all loads. However, heated SVOs at 90-100°C produce better performance and higher NOx levels at medium and high loads. Ranjit *et al.*[90] adopted 1C, IDI, DE for their investigation using preheated Schleichera Oleosa SVO at varying fuel temperatures of 40°C–120°C through an exhaust gas heat recovery system. BTE was found to be better (27.82%) than FD. Although, comparable NOx, higher CO and HC emissions were observed for SVO than FD at all loads. Sisi *et al.*[91] conducted experiments on 3C, 4S, WC, and DE using pure SVO fuels, and insignificant variations in BSFC for SVOs were found without engine knocking. They reported that the BTE of SVOs was established to be analogous with FD at 75% load. The CO2 emissions for the SVO were found to be lower than that of FD. However, higher CO emission was witnessed at all loads, probably due to a higher carbon and oxygen ratio in the SVOs, leading to incomplete combustion.

Table 3 (a): Engine performance using KO, Mahua and Kusum SVO at varying operating conditions

Operating Condition	Engine	SVO	Performance		EGT	Ref.
			BSFC	BTE		
VLC, 1500 rpm	1C, 4S, WC, CS, DI, DE	KO (UH)	↑AAL	↑WL, ↓AAL	↑WL, ↓AAL	36,46
VLC, VFT, 1500rpm	1C, 4S, WC, CS, DI, DE	KO (PH)	↓WL	↑WL	↓WL	46
			Δ AAL	↓WL	↑AAS	47
		Mahua (PH)	↑AFL	↓AFL	—	31
		KO (PH)	↑ AAL	↓WL	↑WL	71
		Mahua (PH, UH)	↑AAL	↓WL	↑WL	73
VIP,40,80, 100% load	1C, 4S, AC, DI, DE	Mahua (UH)	↑WL	↑WL	↑WL	48
VLC, VFT, 1500rpm	1C, IDI, DE	Kusum (PH)	↓AAL	↑AAL	↑WL	90
VLC,1500 rpm	3C, 4S,DI,DE	VO (UH)	Δ AAL	Δ 75% load	↑WL	91

(↑- increase, ↓- decrease, Δ- insignificant changes, AAL- at all loads, WL- with load, AAS- at all speeds, AFL- at full load, Ref.- Reference)

Table 3(b): Engine emissions using KO, Mahua and Kusum SVO at varying operating conditions

Operating Condition	Engine	SVO	Exhaust Gas Emissions					Ref.
			CO	HC	CO$_2$	NOx	Smoke	
VLC,	1C, 4S, WC,	KO(UH)	↑AAL	↓AAL	↑ AAL	↓ AAL	↑ ALL, ↓ AHL	36,46
VLC, VFT, 1500rpm	CS, DI, DE	KO(PH)	↓AAL	↓AAL	↓ AAL	↑ AAL	↓ ALL	46
			↑AAL	↑AAL	↑AML,AHL	↓ AAL	↑ AAL	47
			↑AAL	↑AAL	↓upto 40% load, ↑AHL	↓ AAL	↑ AAL	87
		Kusum (PH)	↑AAL	↑AAL	↓ uptp 30% load, ↑AHL	↓ AAL	↑ AAL	
		Mahua	↓AAL	↓AAL	—	↑ AAL	—	31
VLC, VIP, 1500rpm		(PH)	↓AAL	↓AAL	—	↓ALL, ↑ AML,AHL	—	74
		KO (UH)	↓AAL	↓AAL	—	↓ ALL, ↑ AML, AHL	—	
	1C, 4S, AC, DI DE	Mahua (UH)	—	↑ ALL	—	↓ AHL	—	48

(↑- Increase, ↓- Decrease, Δ- Insignificant changes, AHL-at high load, AML- at medium load, ALL-at low load)

Table 4(a): Engine performance using Jatropha SVO at varying operating conditions

Operating Condition	Engine	SVO	Performance		EGT	Ref.
			BSFC	BTE		
VLC, 1500 rpm	1C, 4S, WC,	Jatropha (UH)	↑WL	↓WL	↑ WL	49
	CS, DI DE		↑ WL	↓ WL	∆ WL	88
	2C, 4S, WC DE		↑AFL	∆ ALL, ↑ at 40% load	↑ AAL	25
		Jatropha (PH)	↑ AFL	∆ ALL, ↑ at 40% load	↑ AAL	
VLC, VFT, 1500 rpm	1C, 4S, AC, CS, DI DE		↑ WL	↓ WL	↑ WL	27
	1C, 4S, WC,		↑ AAL	↓ WL	—	31
VLC, VFT, VOH, 1500 rpm	CS, DI DE		↑ AAL	↓ WL	↑ WL	18
VLC,VOH, 2400 rpm			—	↑ after 100 hrs intervals	↑ WOH	80
VLC, VOH, 1500 rpm	4C, 4S, WC,		↑ WOH	—	—	81
VLC, 2400rpm	CS, DI DE		—	↓ AFL	—	82

(↑- Increase, ↓- Decrease, ∆- Insignificant change, WOH- with operational hours)

Table 4(b): Engine emissions using Jatropha SVO at varying operating conditions

Operating Condition	Engine	SVO	Exhaust Gas Emissions					Ref.
			CO	HC	CO_2	NO_x	Smoke	
VLC, 1500 rpm	2C, 4S, WC, DE	Jatropha (UH)	↑ AAL	↑ AAL	—	↓ AAL	↑ WL	49
			↑ AAL	↑AAL	↑ AAL	↓AAL	—	88
	2C, 4S, AC, CS, DI, DE		∆ up to 50% load, ↑AHL	—	—	∆ up to 40% load, ↓AHL	—	25
		Jatropha (PH)	∆ upto 50% load,↑AHL	—	—	∆ upto 80% load,↑ AHL	—	
VLC, VFT, 1500 rpm	1C, 4S, AC, CS, DI DE		↓ ALL, ↑AHL	↓ ALL, ↑AHL	↑ AAL	↓ALL	—	27
	1C, 4S, WC, CS, DI DE		↓ AAL	↓ AAL	—	↑ AAL	—	31
VLC, VFT, VOH, 1500 rpm			↑ AAL	↑ AAL	—	↑ AAL	—	18
VLC, VOH, 2400 rpm			↑WOH	↓ AAL	↑ AAL	∆ AAL	—	80
VLC, VOH, 1500 rpm			↑AAOH	↑ AAOH	—	↓ WOH	↑WOH	81
			—	—	↓ AAL, AAOH	↓ AAL, AAOH	—	83
VLC, 2400rpm			↑AAL	↑ AAL	—	↓ AAL	—	82

(↑- Increase, ↓- Decrease, ∆- Insignificant changes, AAOH -at all operational hours)

Hellier *et al.*[3] performed tests on DI, DE and investigated the influence of the fatty acid composition of preheated rapeseed, soybean, corn, groundnut, palm, and sunflower SVOs at 60°C considering low engine load. A shorter ignition delay was observed for groundnut and palm SVOs than FD. They found lesser NOx, HC, CO and PM emissions level for all test VOs, and also found to be lowest for Rapeseed oil SVO compared to FD (Table 5 & 6). D'Alessandro *et al.*[37] conducted the chain of investigation on an unmodified 4C, 4S, WC, TC, DI, DE using nine different preheated SVOs at 65°C (linseed, Palm, Corn, Soybean, Peanut, Sunflower, waste frying Sunflower, waste frying Palm oil) and FD. They noticed 10–30% higher BSFC of SVOs than FD. In addition, a decreasing tendency of CO and an increasing level of NOx emissions were also reported.

Hartmann *et al.*[9] worked on the 1C, 4S, NA, DI, CI engine and studied the performance and emission parameters running with SVOs (PH/UH). They adopted preheated (65°C- 95°C) neat sunflower, soybean, tong VOs for experiments at full load and VES (1300 to 2000 rpm with 100rpm steps) conditions. The BTEs for all SVOs were higher than FD, especially for soybean and sunflower oils, whereas lower EGT was recorded for all SVOs. In addition, investigators noticed an increment in NOx and CO emissions with a fall in engine speed due to incomplete combustion. Soltic *et al.*[50] conducted experiments on 6C, 4S, WC, CS, DI, DE fuelled with a different set of VO, i.e., preheated (45°C) straight rapeseed oil, soybean oil, and FD. Investigators observed considerably higher BTE, NOx emissions, lower HC and CO for preheated pure Soyabean and Rapeseed vegetable oil at almost full operational load compared to FD. The combustion behavior of preheated straight Coconut oil was studied by Hoang,[67] adopting the spray characterization, i.e., spray penetration and cone angle at VES. At the preheated temperature of 105°C, the higher spray penetration and smaller cone angle were added through the test for SVO. About 2.25% of BTE was lowered than FD at all engine speeds. It was concluded that UHC and CO emissions values were higher and CO_2, NOx and combustion products were lesser while using preheated Coconut oil at 105°C compared to FD. Hoang and Nguyen[68] evaluated the emission values of a DE fueling pure Coconut UUSVOs. At around 80°C of preheat temperature, the lowest NOx emissions were recorded for Coconut oil compared to preheated Coconut oil at 120°C and 100°C. The higher CO and HC emissions were recorded at similar conditions. Sunnu *et al.*69 investigated the performance of a TC, DE using palm kernel oil and Coconut oil (Tables 5a, 5b & 5c). It was experienced that BSFC shows dependency with engine speed and slightly higher value for SVOs than FD at all the speeds. The BTE was lower at a low speed and showed an incremental trend with speed up to 3300 rpm for all fuels. Beyond 3300rpm speed, BTE dropped down for all fuels, increasing load up to 100%. With the turbocharged condition, BTE for palm kernel oil was higher than crude Coconut oil but lower than FD. Using unheated sunflower oil, Shehata and Razek[70] investigated the performance and emissions parameters of DI diesel engine. BSFC was higher for sunflower oil irrespective of fuel type but marked insignificant compared to FD at low speed. The BSFC was noticed to be higher; however, BTE and NOX emissions were lower at a higher load for sunflower oil (UH) than FD. In addition, researchers recorded higher CO_2 and CO emissions.

Further, Geo *et al.*[61] attempted to improve the performance of similar engine specifications, using neat rubber seed SVO (PH/UH) and FD at VLC. BTE for preheated SVOs was higher than unheated SVO but found to be lower for all test fuels than FD. In contrast, BSFC was higher for unheated oil, followed by oil heated at 133°C than FD. EGT for unheated SVO was recorded as higher than preheated SVO and FD, whereas EGT for preheated SVO was higher than FD. NO_x emissions values were lesser for unheated UUSVOs than preheated SVO (133°C and 155°C) and FD. Further, HC, CO and smoke emissions level were recorded lesser for higher heated oil than oil at low temperatures, whereas these were higher than FD.

Table 5(a): Engine performance using Palm, Rapeseed, Soyabean, Rubber Seed, Corn, Coconut SVOs at varying operating conditions

Operating Condition	Engine	SVO	Performance		EGT	Ref.
			BSFC	BTE		
VLC, 1300rpm	6C, 4S, WC, CS, DI, DE	Rapeseed, Soybean (PH)	↓ WL	↑ WL	↑ WL	50
VLC, 1500rpm	1C, 4S, AC, DI, DE	Rubber (UH)	↑WL	↓ WL	↑ WL	89
VES, 1500-4500 rpm	4C, 4S, WC, CS, TC, DI, DE	Palm kernel, Coconut (PH)	↓ WS	↑WS	—	69
VES, 2200-1300 rpm	6C, TC, DE	Rapeseed (PH)	∆ AAS	↑WS	—	12
VLC, VFT, VIT	1C, 4S, WC, CS, DI, DE	Soybean (PH)	↑WL	↓WL	—	74
VLC, VFT, VES			↑ AAL	↓WL	↓ AAL	9
VLC,VES, 2000 rpm			↑ AAS	∆ AAS	↓ AAS	59
VLC, VFT, 1500 rpm	4C, 4S, WC,	Palm, Rubber, Coconut (PH,UH)	↑ AAL	∆ ALL, ↓AHL	—	52
	CS, DI, DE	Coconut (PH)	—	↓AFL	↓ AAL	67
	1C, 4S, AC,	Rubber (PH,UH)	↑AFL	↓ AFL	↑ AAL	61
VLC, VFT, 1800 rpm	CS, DI, DE	Palm (PH)	↑ AAL	↓ WL	↑ WL	51
VOH	4,6C, Tractor DE	Rapeseed (UH)	∆ AAOH	∆ AAOH	∆ AAOH	86

(↑- Increase, ↓- Decrease, ∆- Insignificant changes, WS- with speed)

Table 5(b): Engine emissions using Palm, Rapeseed, Soyabean Rubber Seed, Corn, Coconut SVOs at varying operating conditions

Operating Condition	Engine	SVO	Exhaust gas emissions					Ref.
			CO	HC	CO$_2$	NO$_x$	Smoke	
VLC, 1200 rpm	1C, DI, DE	Rapeseed (UH) Palm,Soybean,	↑ ALL	↑ ALL	—	↓ ALL	—	3
Corn, Groundnut (PH)								
VLC, 1300 rpm	6C, 4S, WC, CS, DI, DE	Rapeseed, Soybean (PH)	↓ AAL	↓ AAL	—	↑ AAL	—	50
VLC, 1500rpm		Palm, Rubber, Coconut (UH)	↑ ALL, ∆ AHL	↓ Rubber AAL, ↑ Palm AHL	↓ up to 80% load	∆ ALL, ↓ Palm, AHL, ↑AHL	—	52
	1C, 4S, AC,	Rubber (UH)	↑ AAL	↑ AAL	—	↓ AAL	↑ AAL	89
	CS, DI, DE			—	—	↓ AAL	↑ AAL	61
	1C, 4S, TC, DI, DE	Rapeseed , Camelina (UH)	↑ ALL, ∆ AML	↓AAL	—	↑ AAL	—	79

(↑- Increase, ↓- Decrease, ∆- Insignificant changes)

Table 5(c): Engine emissions using Palm, Rapeseed, Soyabean, Rubber Seed, Coconut SVOs at varying operating conditions

Operating Condition	Engine	SVO	Exhaust gas emissions					Ref.
			CO	HC	CO_2	NO_x	Smoke	
VLC, VFT, 1800 rpm	1C, 4S, AC, DI, DE	Palm (PH)	↑ AML, ↓ AHL	↓ AAL	—	↓ALL, AHL,↑ AML	—	51
VLC, VFT, 1500 rpm		Rubber (PH)	∆ AAL	∆AAL	—	↓ AAL	↑ AAL	61
	4C, 4S, WC, DI, DE	Coconut (PH)	↑ AAL	↑ AAL	↓ AAL	↓ AAL	↓ AAL	68
	1S, 4S, WC, CS, DI, DE	Palm, Rubber, Coconut (PH)	↑ALL, ↓AHL	↓ AAL	↑ AAL	∆ALL, ↓palm AHL, ↑AHL	—	52
VLC,VFT, VES		Soyabean (PH)	↑ALS	—	—	↓ ALS	—	9
VLC, VFT, VES, VIA	1C, DI, DE	Soyabean (PH)	—	—	—	—	↓ at 17° IA at 100°C	74
VLC, VES		Soyabean (PH)	↑ALS, AMS, ∆ AHS	—	↑ ALL	↓ AAS	—	59
		Rapeseed	↓ AAL	↑ AAL	↓ AAL	↑ AAL	↑ AAL	53
1500-4500 rpm	4C, 4S, TC, DI, DE	Palm kernel, Coconut (PH)	↓ AAS	—	—	↓ WS	—	69
VTP, VES	1C, 4S, WC, TC, DE	Rapeseed (PH)	—	↑ AAS	↓ AAS	↓ AAS	↓ AAS	54

(↑- Increase, ↓- Decrease, ∆- Insignificant changes, ALS- at low speeds, IA-injection angle)

Impact of SVOs on Engine Performance and Emission Parameters at VIP

The optimized fuel injection pressure plays a critical role in better combustion behavior and performance of UUSVOs. Modified nozzle opening pressure can increase the highest possible BTE, minimize BSFC, and engine emissions. The authors[71-73] presented the effect of fuel injection pressure at VLC using SVOs (UH/PH). It was also noted that the lowest smoke emissions (32%) and increased CO_2 emissions were at fuel injection pressure in the range of 196- 200 bar and 72% rated load[71, 72] Sonar *et al.*[73] reported a contradictory result compared to another researcher. Their findings showed higher BSFC and EGT than FD for both SVO. However, they also reported that NOx emissions were notably lower for preheated and unheated straight Mahua oil than FD at low loads. Tables 3(a, b) and 6 (a, b) can be referred to the detailed impression of SVOs on engine performance and emissions at VIP. VIP can be opted to overcome the engine's starting problem. Higher injection pressure increases EGT and usually enhances fuel atomization, resulting in combustion efficiency. Conversely, at lower injection pressure and loads, BTE decreases due to bigger size of droplets and lower calorific value of a fuel.

Impact of SVOs on Engine Performance and Emission Parameters at VIT

Performance, combustion behavior, and emission parameters of compression ignition engine are widely affected by VIT using SVOs as fuel.[72] Some researchers investigated the performance and exhaust emission values of DE running with UUSVOs at VIA/VIT (Tables 3a, 3b, 6a, and 6b). Different authors reported that the highest peak pressure for waste cooking oils was achieved at a 2.5° crank angle. Therefore, a simple modification kit was suggested by Basinger *et al.*[72] for a stationary IDI, DE running with UH/PH (100°C) waste cooking oil. Most consistent performance and emissions parameters were found at a tuned setting of 25° bTDC of injection timing at 3/4th load. A significant reduction in EGT, CO emissions and BSFC were noticed at 25°bTDC of advance injection timing (AIT) and 15 MPa of fuel injection pressure (FIP) compared to a reduction at 20°bTDC and 9 MPa FIP settings. However, a NOx emission increased nearly half a fold due to advancing the timing up to 25° bTDC.[72] Performance and emission of DE fueling UUSVOS such as Sunflower, Poon, Orange, WVO, Lemongrass, Rice brain and Pine SVOs at different operating conditions during short-run operation are shown in Table 6 (a, b).

Table 6(a): Engine performance using Sunflower, Poon, Orange, VWO, Lemongrass, Rice brain, Pine SVOs at varying operating conditions

Operating Condition	Engine	SVO	Performance		EGT	Ref.
			BSFC	BTE		
VES, full load	1C, 4S, WC, CS, IDI, DE	Sunflower (PH)	↑ WS	∆ WS	↑ WS	57
VLC, VES, 1500 rpm	1C, 4S, AC, CS, DI DE	Sunflower (UH)	↑ AAL	↓ WL	—	70
VLC, VIA, 1500rpm		Lemongrass (UH)	↓ AAL	↑WL	↑WL	75
VLC, VFT, VES, 2000rpm	1C, 4S, WC, CS, DI, DE	Sunflower, Tung (PH)	↑ AAL	↓WL	↓ AAL	9
VLC, 1500rpm		Lemongrass (UH)	∆ AAL	∆ AAL	∆ AAL	66
		Poon (UH)	↑ WL	↓WL	↑ WL	63
		Orange (UH)	↓WL	↑ WL	↑ WL	64
		Pine oil (UH)	↓AAL	↑WL	↓ AAL	65
VLC, VFT, 1500 rpm		Rice bran(PH)	↑WL	↓WL	↑WL	62
VIP, VIA,75% load, 650 rpm	4S, WC, slow speed, IDI, DE	WVO (PH)	↓ at 25° bTDC, 15 MPa	↑ at 25° bTDC, 15 MPa	↓with 25° bTDC, 15 MPa	72
VLC,650 rpm		WVO (UH)	↑WL	—	↑ WL	

(↑- Increase, ↓- Decrease, ∆- Insignificant changes)

Further, Canakci *et al.*[57] experimented to determine the full load characteristics at VESs (1000-3000 rpm) and VITs. In this study, an IDI, DE was adopted using straight sunflower oil (PH) at 75°C with VITs. Elevated consumption, turbulence and fuel atomization improve this oil's highest cylinder pressure of 9.94 MPa at 3000 rpm. Earlier injection timing of 1°, 1.5° and 0.75° crank angles were witnessed for preheated oil than FD at all speeds. Higher Cetane number and auto-ignition temperature of preheated oil increase the ignition delays. Higher ignition delays were found for preheated oil than FD at an engine speed of 1000-3000 rpm. The lower BSFC, an insignificant rise of BTE, brake torque and significant gain in UHC were witnessed at the entire speed range of experiments and full load condition. In their study, Wander *et al.*[74] presented the experimental results about the effects of different injection angles (17°, 15°and 19°) at different loads and fuel injection temperatures applied on a DI, DE. The engine was fueled with preheated straight soybean oil at 60°C. A slight reduction in BTE was recorded at intermediate load for preheated SVOs at 60°C, 19° injection angle compared to FD. The lowest value of smoke emission was identified at 17° crank angle for UUSVOs. In the similar context, Sathiyamoorthi and Sankaranarayanan[75] also investigated a DI DE's performance, emission parameters, and combustion behavior using unheated, straight lemongrass oil considering VIT of 21° (late injection), 23° (designed), and 27° (advanced) bTDC of fuel injection timings at 200 bar of designed injection pressure at 1500 rpm. Investigators found that a higher cylinder pressure, a notable fall in BSFC and a considerable rise of BTE were noticed with AIT for all test fuels used. The comparable CO_2, lower UHC, smoke, and NOx emissions were also higher for AIT.

Further results are shown in Table 6 (a, b). Few researchers have tried to optimize DE's performance, combustion, and emission behavior with VITs using UUSVOs. AIT reduces EGT due to earlier combustion, but EGT was recorded higher than FD at the same injection setting due to the late burning of constituents. AIT increases the ignition delay due to the lower pre-ignited initial air temperature and pressure. Retarded injection timing (later injection) leads to ignition delay.

Table 6(b): Engine emissions using Sunflower, Poon, Orange, WVO, Lemongrass, Rice brain, Pine SVOs at varying operating conditions

Operating Condition	**Engine**	**SVO**	**Exhaust Gas Emissions**					**Ref.**
			CO	**HC**	**CO_2**	**NO_x**	**Smoke**	
VLC,1200 rpm	1C, 4S, WC, CS, DI DE	Sunflower (PH) Corn(PH)	↑ALL ↑ ALL	↑ALL ↑ALL	— —	↓ALL ↓ ALL	— —	3
VLC, 1500 rpm		Poon (UH)	↑ AAL	↑ AAL	↓ AAL	↓ AAL	↑WL	63
		Orange (UH)	↓ AAL	↓ AAL	—	↑ AAL	↓WL	64
		Pine (UH)	↑ALL, ↓ AHL	↓ AAL	—	↓ALL, AML, ↑ AHL	↓ AAL	65
		Lemongrass (UH)	↓ AAL	—	↑ AAL	↑ AAL	↓ AAL	66
VLC, VFT 1500 rpm		Ricebran (PH)	↑ AAL	↑ ALL	↑ ALL	↓ ALL	—	62
VIA, VIP, 75% load, 650 rpm	4S, WC, slow speed, IDI DE	WVO (PH)	↓at 25° bTDC, 15 MPa	∆ at25° bTDC, 15 MPa	—	↑at 25° bTDC, 15 MPa	↑ ALL, ∆ AHL	72
VL, 650 rpm		WVO (UH)	↑ AAL	↑ AAL	—	↓ AAL		
VES, full load	1C, 4S, WC, CS, IDI DE	Sunflower (PH)	↑ALS, ↓ AHS	↓ AAS	↓ AAS	—	↓WL	57
VLC, VIA, 1500rpm	1C, 4S, AC, DI DE	Lemongrass (UH)	—	↓ AAL	∆ AAL	↑ AAL	↓ AAL	75
VLC, VES		Sunflower (UH)	↑ AAL	—	↑ AAL	↓ AAL	—	70

(↑- Increase, ↓- Decrease, ∆- Insignificant changes)

Impact of SVOs on Engine Performance and Emission Parameters at *Variable Compression Ratio (VCR)*

Experimental study on performance and exhaust emission parameters of DE considering VCR (mostly higher than 18:1) using UUSVOs is negligibly available for further investigation. Therefore, very few pieces of literature are available in this section. Researchers mostly adopted SVOs-based biodiesel fuel with VCR for their research. An increase in compression ratio affects to rise of BTE and reduces BSFC. A few researchers76 have attempted to study the same using pure waste cooking oil. Sahu *et al.*[76] reviewed the effect of VCR (18:1 to 20:1) on agricultural-based 1S, 4S, WC, and CI engine performance and emission parameters. They performed their experiments considering different loading conditions (zero to full load) at 1500 pm and found lower ignition delay by increasing compression ratio from 18 to 20 at a higher load. The NOx levels increased by the increased compression ratio, but CO_2, CO, UHC, and smoke were lower using SVO.

Impact of SVOs on Performance and Emission Parameters of Compression Ignition Engine during Long-Run Test.

Generally, CI engines are used for long-run operations.[77] But, a smooth run of the CI engine was witnessed during short-run operations. However, due to certain limitations with short-duration tests, investigators have suggested many ways to use SVO in the DE or CI engine. Tests above 200 cumulative hours have been considered long-run tests fueling SVOs. Critical findings from many investigators indicate no significant operational difficulties observed in using SVOs in DE while short-run tests. However, problems arise with the DE running for long-duration operations with unprocessed, unblended SVO.[77-86] Table 7 can be referred to for summarized results of investigators using SVOs during long operations.

The investigators[77-86] noticed elevated EGT with different loading conditions and operational hours. All investigator[77-86] analyzed the affecting variables and after-effects of SVOs on lubricating oil during the long-term test of 250 to 50000 cumulative hours (refer Table 7). Almutairi *et al.*[80] performed 300 hours of durability tests on a 1C, DE to study the effects of preheated crude Jatropha oil (90°C) as engine fuel. Through this study, investigators concluded that BTE fluctuates but suddenly increases at the interval of 100-200 hours. The lower HC, unchanged NOx emissions, increased CO and rise in CO_2 emissions were observed.[80] Poor combustion occurs due to inferior atomization. Investigators[12,77-86] found significant carbon deposition on the piston crown and higher wear on other engine parts. Therefore, anti-wear additives for lubrication oil were recommended by the researchers. Basinger *et al.*[78] suggested that the engine's break-in period should be between 200 and 300 operational hours and 110 hours of changing the frequency of lubrication oil. Emission values cut from 9% to 5% and 600 ppm to 400 ppm within the first 100 hours.[78] The replacement and inspection of piston rings are required within 1000 hours of an estimated time[78] and 500 hours of an operational interval is needed to minimize injectors' choking and clogging problems.[78-79] Improper combustion was observed, which led to a NOx level of SVOs than FD. With extended operational hours, Paulsen *et al.*[79] recorded significant changes in the tractor's field performance, equipped with a DE using pure Rapeseed and Camelina SVO for 1000 hours. Therefore, researchers concluded that 500 hours of an operational interval is needed to minimize injectors' choking and clogging problems. During the investigation, a severe effect on the engine was found due to the direct use of Rapeseed and Camelina SVO. Improper combustion was observed, which led to a NOx level of SVOs than FD. Through this study, the oxidation resistance of pure Rapeseed SVO increased for Camelina SVO and the mixture of SVO by adding fuel additives. From this field test, they concluded that unrefined Rapeseed, Camelina SVO and its mixture of SVO were found suitable as fuel for diesel engines.

Based on the analysis, these types of issues arise due to the higher viscosity and inferior instability of SVOs. However, the above problem can be overcome at a specific limit by preheating SVO up to 100°C before injection. The high stickiness of VOs leads to improper mixing of fuel with air and bigger droplet size of atomized fuel that causes incomplete combustion. An anti-wear agent can be tried to increase the operation hours. Metal deposition in lubrication oil is the factor that compels frequent inspection and frequent replacement of piston ring to be systematically in every 1000 hours run. There also, no significant damages to moving parts were reported by a few investigators. However, minor adverse effects were seen in engine performance, but no significant changes were witnessed in emission levels after the extended run test. Investigator's concluding remarks and results are shown in Table 7. By referring to Table 7, it seems that, to some extent, the researcher's findings are similar, whereas some of these findings contradict.

Table 7: Investigator's findings on long run operation of CI engine using SVOs

SVOs	Engine Type	Operational Hours (Cumulative)	Findings	Ref.
KO (PH)	1C, 4S, WC,CS, DI,DE	512	High carbon deposits and wear on engine parts, better engine performance, degraded lubrication oil (LO) quality within 400 hours	77
WVO (PH)	4S,WC, IDI,DE	500	Deposition of Cr in LO, mass loss and mentainance schedule frequency of 1000 hours for piston rings	78
Rapeseed, Camelina (UH)	1C, 4S, FA, DI, DE	1000	Insignificant changes and wear on engine parts, carbon deposits on injector tip, higher emission but lower NOx, reduced oxidation of SVOs by adding additive	79
Rapeseed (PH)	6C, TC, DE	1000	Upto 2–14% power drop, better BTE	12
Jatropha (PH)	1C, 4S, WC, CS, DI, DE	300	High carbon deposits, lower engine efficiency and higher emissions	80
	4C, 4S, WC, DI, DE	300	Significant metal concentration, degraded quality and reduced viscosity of LO High carbon deposits on injector tip, lower performance and higher emissions Higher metal concentration in the LO, high carbon deposits and wear on engine parts, lower NO_x and CO_2	81 82 83
Palm (PH)	8C, CS, DI, DE	300	high carbon deposits, degraded LO quality, higher wear in engine parts, reduced carbon deposits (27%) due to fuel preheat at 80°C rather than 60°C.	84
KO(PH)	1C, DE	250	Lower wear in designed system	85
Rapeseed (UH)	4- 6C, DE	50,000	Injection system clogging, identical emission, insignificant engine breakdown and performance variation, cold start problem	86

Discussion

Most of the research articles are meticulously reviewed here. It was observed that FD might be entirely replaced with unprocessed unblended SVO for DEs / CI engines. The studies on the utilization of UUSVO in DEs have been summarized as per varying operating conditions. Researchers have preferably adopted the non-edible SVOs/ UUSVOs for their investigation. SVOs are 10-15 times more viscous alternatives than that FD. SVO holds the long-chain, heavy molecular structure, and flow resistivity, resulting in higher viscosity which deteriorates combustion, engine performance atomization, smoke opacity and significant variation in emissions with other problems within the engine's internal parts. Investigated data of engine performance and emission fueling preheated / unheated SVOs have shortened. Direct use of UUSVOs (preheated/unheated) reasonably fits DE. The calorific value of FD is mostly around 10–15% higher than SVOs (34–42.15MJ/kg) fuel. By and large, all the researchers indicated that lower specific energy value of SVOs causes higher BSFC of SVO compared to FD. Engine consumes more SVO than FD to produce the same output and performance. Most investigators have agreed about the lower BTE of SVOs compared to FD due to the high viscosity, poor combustion efficiency and lower energy value of SVOs. Few researchers reported that sift of uncontrolled combustion to expansion stroke is the primary cause of lower BTE.

Nevertheless, contradicting results on BTE was found in a few articles. Some of them contradicted each other with their finding. Higher operation temperature increases EGT resulting in lower BTE due to the maximum portion of energy converted into heat. The review study includes the findings and comments on performance and emissions based on the short-run and long-run operation. Considering different operating parameters such as VLC, VIP, VIT, VOH, FIT, VES and VTP, investigators found significant variations in diesel engine performance and emission parameters fueling preheated and unheated UUSVOs in DE.

On the other hand, many researchers found insignificant variations in the performance and emission behavior of UUSVOs-based DE during short-run operations. Also, unheated UUSVOs degrade the engine's performance significantly more than preheated UUSVOs and FD at all loading conditions. However, preheated UUSVOs at 90-100°C produce better performance and higher NOx levels at medium and high loads due to lower cylinder temperature. As a result, some researchers suggested minor modifications like duel fueling, injection pressure variation, and injection timing adjustment during short-run operations.

Whereas, during engine endurance tests fueled with SVOs, few researchers reported variations in engine performance, an internal parts failure, carbon deposition on the crown and cylinder, quality of lubrication oil, injector nozzle coking, wear, and maintenance of piston rings. Most researchers found lower NOx levels for UUSVOs than FD, probably due to more oxygen content and low calorific value of SVO than FD. NOx emissions increase at higher operating temperatures and pressure. Further, this review study shows that incomplete combustion produces more CO emissions. CO emission is always higher for SVOs than FD, but varies according to engine loading conditions. Initially, it increases at low loading and slightly reduces as load increases. Researchers suggested many reasons for more elevated CO for SVO than FD. Some investigators presented higher CO Emissions than FD thought the test may be due to operating temperature. Researchers differ from each other. Some researchers opined that lower HC emission of SVO than FD by adopting a theory of rich oxygen content in the SVO. However, few of them categorically showed their results of higher HC for SVO than FD. Fuel accumulated at the end of compression stroke creates uncontrolled combustion (charge continued to burn with lesser oxygen in the power stroke and produces more CO Emission from SVO than FD). SVO produces higher smoke emissions than FD due to its large molecule structure and high viscosity.

Conclusion

Eco-friendly / Green fuel (SVO) is a capable substitute for FD in many applications. Using unprocessed unblended straight vegetable oils (UUSVOs) as a DE fuel reduces the processing time, energy, and cost of biodiesel production. However, the higher viscosity of VOs bound their long-run use in DE. This review study concluded that UUSVOs could be used in DE at short-run operations without affecting performance, emission, combustion, and ignition behavior. DE fueling with UUSVOs suffers from the rigorous carbon deposition to internal parts of the engine during long-run operation. The primary cause of poor atomization and inferior combustion of DE is the higher viscosity of UUSVOs. A fuel preheating system was recommended for lowering the viscosity of SVO. Also, the degraded lubrication oil quality, deteriorated overall engine performance, exhaust emissions value, and failure of engine parts were observed. Periodic maintenance could be implemented to overcome problems created during the long-run operations of engines. A Significant variation in emissions was observed. Many researchers found contradicting results of variation in NOx emissions of DE using UUSVOs.

Authors Contribution

All authors reviewed the manuscript. All authors have participated in revising it critically for important intellectual content; and approval of the final version. All authors have substantial contributions to the final manuscript and approved this submission.

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Nomenclature

MJ/kg: Mega Jule / Kilogram
cSt: Centi-stoke
kg/m3 : Kilogram/ Cubic Meter
w/w: Weight/ Weight
MPa: Mega Pascal
rpm: Revolution Per Minute
ppm: Part Per Million
bTDC: Before Top Dead Centre
°C : Degree Celsius

Abbreviations

UUSVOs: Unprocessed unblended straight vegetable oils
SVO: Straight vegetable oil
DE: Diesel engine
FD: Fossil diesel
VO: Vegetable oil
VLC: Varying loading conditions
VFT: Varying fuel temperature
VIP: Varying injection pressure
VOH: Varying operational hours
VES: Varying engine speeds
VIT: Varying injection timing
VIA: Varying injection angle
VTP: Varying throttle positions
1C, 2C, 4C and 6C: single, double, four and six cylinder
4S: Four strokes
AC: Air cooled
WC: Water cooled
CS: Constant speed
NA: Naturally aspirated
DI: Direct injection
IDI: Indirect injection
TC: Turbocharged
PH: Preheated
UH: Unheated
KO: Karanja oil
BTE: Brake thermal efficiency
BSFC: Brake-specific fuel consumption
EGT: Exhaust gas temperature
UHC: Unburnt hydrocarbon
WVO: Waste vegetable oil
AIT: Advanced injection timings
VIT: Varying injection timing
VCR: Variable compression ratio.
LO: Lubrication oil