Waste plastic oil as an alternative fuel for diesel engine – A Review

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***Abstract*— With increase in energy expenditure, stringent emission norms, depletion of petroleum fuels and undulate cost of petroleum products in India, it has become vital to use alternative fuels for diesel engines. The energy conversion from waste plastics has been an intelligent way to tackle the environmental pollution problem of waste plastic management in the landfills. Plastics being derived from petrochemical source has higher amount of hydrocarbon which yield oil with high calorific value. In this review, performance combustion and emission characteristics of diesel engine using neat plastic oil, blends of waste plastic oil and additives used with plastic oil as fuels are addressed. It is concluded that it is possible to use plastic oil derived from plastic wastes as an alternative fuel for diesel engines.**

***Index Terms*— Combustion; Diesel engine; Emission; Pyrolysis; Performance; Waste plastic oil.**

I. INTRODUCTION

With the vast applications of plastics, the production of plastics is growing globally in leaps and bounds. Wood, metals and ceramics have been substituted by plastics as the quality of human improved with the invention of plastics. From the onset of invention of plastics, accumulation of plastic waste gives rise to environmental problems. It may take billions of years for plastic to degrade naturally. Recycling of plastics is found to be the optimal solution to manage the plastic waste. Chemical recycling conforms to the principles of sustainable development [1] and energy crisis, which has gained great attention by researchers. The challenges of waste management and increasing fuel energy crisis can be addressed simultaneously with the production of fuel from plastics. Some researchers showed that the fuel produced from plastics have properties similar to that of petroleum fuels [2-9].

This review is to analyze the diesel engine's performance and emission characteristics with waste plastic oil blends as fuel produced by pyrolysis.

1. Pyrolysis mechanism

Proximate analysis is usually adopted to measure the chemical properties of plastics. The important elements in plastics are moisture content, carbon, volatile matter and ash content as the liquid oil yield depends on the said elements [10]. Thermo chemical treatment and Catalytic conversion are the widely used methods for production of fuel from plastics [11]. In thermo chemical treatment, large polymers in plastics break into smaller hydrocarbons in an oxygen free environment at elevated temperatures. Whereas, in catalytic conversion, a catalyst is used to change the reaction mechanism which reduces the Pyrolysis temperature and selectivity [12,13].

2. Thermo chemical treatment

In pyrolysis process, the lighter molecular weight polymers need higher temperatures for degradation [14]. Parameters like temperature, degradation time, type of reactor, residence time governs the residue of plastic pyrolysis process. As such, the hydrocarbons having the boiling point between 350C and 1850C are used as gasoline and between 1850C and 2900C are used as diesel [15,16]. At the temperature range of 6500C – 7000C, the weight percentage of oil yield and wide distribution of hydrocarbon are obtained [17]. Viscosity of the plastic oil can be removed by adding solvents during cracking. Apparently, at the temperature between 3700C – 4200C, in the presence of oxygen, five liquid fractions having hydrocarbons between C_4H_8 and $C_{28}H_{58}$ were obtained [18]. Nitrogen when used for pyrolysis of mixed plastic wastes, resulted in higher concentrations of aromatics and alkanes [19]. The Pyrolysis of waste electrical and electronic equipment at an elevated temperature of 8000C has a yield of 30.4 – 45.5% of gas [20].

3. Catalytic conversion

Catalyst helps in increasing the reaction rate along with decrease in pyrolysis temperature in thermal cracking. This improves also the quality of fuel, increase selectivity and residence time [21]. Nano crystalline zeolites like HZSM-5, Hβ and HMOR are widely used catalysts [22]. On the onset, more amount of catalyst reduced the yield of plastic oil [23]. Hydrocarbon in the plastic oil yield was increased from 52% to 60% by using activated carbon bed containing Fe in the presence of hydrogen [24]. Catalysts HZSM-5 ans SiO_2-Al_2O_3 when used in combination resulted in the final product with improved octane rating [25].

II. ENGINE PERFORMANCE AND EMISSION ANALYSIS

In order to compensate the energy demand and replacement of fossil fuels at least to some extent, the development of alternative energy sources is evitable. And also, global warming and waste management policies have forced for the use of alternative fuels on engines.

Experiments were conducted by Ioannis et al [26] on a diesel engine fuelled with blends of waste plastic pyrolysis oil in proportions of 25%, 50%, 75%, 90% and 100% (v/v%). Brake thermal efficiency of WPO blends was found to be lower than diesel. It was observed that the ignition delay period was longer. The higher blending ratios of WPO resulted in higher in cylinder pressure, net heat release rate, NOx, HC, CO and CO2 emissions. Paul Daniel et al [27] used blends of 10%, 20%, 30% and 50% (v/v%) and exhaust gas recirculation of 5%, 10%, 15% and 20%. BSFC increased by 2.3%, 4.6%, 16.3% and 22.6% by EGR of 5%, 10%, 15% and 20% respectively. PPO helped in NOx reduction. However, HC, CO and CO2 emissions were increased with increase in PPO composition and EGR rate.

Plastic oil produced from crude landfills was tested as fuel on diesel engine by Adun et al [28]. The diesel equivalent fraction (LFPL3) was produced at a temperature range between 2500C and 3500C. They reported that BSFC reduced by 12.5%, EGT reduced by 11.6%, HC reduced by 12.5%, NOx reduced by 45.4% and CO reduced by 5.4% with LFPL3. Investigation was carried out by Ravi Shankar et al [29] on a CRDI engine with plastic Pyrolysis oil blends in proportions of 10%, 20% and 30% on mass basis. The calorific value of the blend decreased with the increase in quantity of plastic oil. The brake thermal efficiency significantly decreased by 12%, 31% and 48% for plastic oil-diesel fuel blends of 10%, 20% and 30% respectively. NOx emission was found to be 15%, 22% and 23% higher for 10%, 20% and 30% blends respectively compared to diesel under full load conditions. Sumit and Rohit [30] used semi batch type pyrolisis reactor to produce plastic oil from waste plastics and polyethylene. The Pyrolysis temperature was maintained between 5000C and 7000C. Plastic oil-diesel blends in proportions of 5%, 10%, 15% and 20% were used as fuels on diesel engine. They reported that the catalyst plays an important role in the thermal cracking. As such no catalyst was used in their process of production of plastic oil. Due to low oxidation stability, plastic oil been kept for some hours had gum out.

The addition of oxygenated additive, Di ethyl ether (DEE) reduced the emission levels with plastic oil-diesel blends [31]. Experimental investigations were carried out on VCR engine at compression ratios of 12, 16 and 20 with P2.5, P7.5, P12.5 and P100 blends. To this, 2.5% by volume of DEE was added to all blends. It was found that addition of DEE reduces the viscosity of fuel blends and increases the rate of reaction. Alcohols are highly volatile than DEE and when added to bio-diesels, reduce harmful emissions from diesel engine. Damodharan et al [32] synthesized oil from waste plastics in a laboratory scale batch reactor. Blends of diesel, waste plastic oil and n-Butanol like D50-WPO40-B10, D50-WPO30-B20 and D50-WPO20-B30 were used as fuel on a diesel engine. D50-WPO20-B30 delivered better performance than diesel. Smoke opacity of neat WPO was higher than neat diesel and blends of WPO. With addition of n-Butanol to blends, the smoke emission diminished. This may be due to the improved availability of oxygen and lower carbon content. On the onset, NOx, CO and HC emissions increased with increase in WPO composition.

Devraj et al [33] conducted experiments using diesel, WPPO(100% waste plastic oil), WD05(WPO blended with 5%DEE) and WD10(WPO blended with 10%DEE) on a diesel engine. BSFC for diesel was lower than WPPO by 12%. With addition of DEE to blends, HC and NOx emissions were higher than baseline fuel diesel. Under full load conditions, CO emission decreased by 10.5% when compared between WD05 and WD10. This may be due to availability of additional amount of oxygen in DEE. Ceyla Gungor et al [34] produced oil from waste polyethylene using sodium aluminum silicate catalyst in a thermal reactor. Experimental study was conducted on a 4 cylinder diesel engine with blends of WPE5, WPE10, WPE15 and WPE20 at varying speeds and the results were compared with diesel fuel. Power output increased by 1.6% and CO emission was decreased by 20.63% for WPE5 blend.

Hamzah et al [35] studied the performance of diesel engine using Waste Plastic Disposal Fuel (WPDF) and diesel as fuels at varying speeds and constant load on a single cylinder diesel engine. Reduction in brake power and torque was observed for WPDF at all speeds than diesel. This was attributed to lower cetane number for WPDF which is lower than diesel by 5.5%. The peak combustion pressure at lower speed (1200 rpm) and high speed (2400 rpm) for WPDF is inferior to diesel. Kaimal et al [36-39] synthesized plastic oil in a reactor at a temperature range of 3500C – 4000C with silica catalyst and obtained a yield of 80% by weight of plastic waste. Experiments were conducted with various blends of diesel-plastic oil such as PO, PO05, PO50, PO75 and diesel – plastic – Di ethyl ether like PD5, PD10 and PD15. They reported that the combustion of PO varies from 370CA to 460CA under full load conditions.

Emulsification of waste plastic oil with water was carried out by Senthil and Sankaranarayanan [40]. The emulsions like PW10 (Waste plastic oil 88% + Water 10% + Span 80-1% + Tween 1%), PW20 (Waste plastic oil 78% + Water 20% + Span 80-1% + Tween 1%) and PW30 (Waste plastic oil 68% + Water 30% + Span 80-1% + Tween 1%), PO (WPO 100%) and diesel were used as fuels. They reported that the NOx emissions for emulsions reduced greatly by 32%. Out of which PW30 recorded least NOx emissions under full load conditions. Rajan et al [41] used WPO diesel blends in proportions of 10%, 20% and 30% (v/v%) of WPO. The characterization of plastic oil revealed that the viscosity of WPO 100 is lower than diesel.

Plastic oil was produced by Kaoline catalyst from waste polypropylene at a temperature range of 680C to 3460C which is equivalent to diesel. Blends like, 10%B WPO, 20%B WPO, 30%B WPO, 40%B WPO and 50%B WPO were tested on a diesel engine. Brake thermal efficiency was higher than diesel for all blends up to 80% load. The exhaust gas temperature and NOx emissions were found to be higher for blends at all loads. This may be due to the improper penetration of WPO blends deeper into the combustion chamber. Also, the unsaturated hydrocarbons present in the fuel (WPO) might have lead to higher HC and CO emissions. It was also reported that the vibration of engine had occurred for 50B WPO at full load [42].

Mani et al [43-46] explored most of the avenues of utilizing WPO in neat and blend form. Tests were conducted at advance and retard injection timing using blends like WPO, WPO10, WPO30, WPO50, WPO70 and varying exhaust gas recirculation (EGR) rate as 10%EGR and 20%EGR. Characterization of WPO revealed that 75% of liquid hydrocarbon can be obtained on mass basis from plastic wastes. They observed that for WPO without EGR, heat release rate increased by 24.5% at full load. Marginal difference in BTE is found with 20% EGR. Also, the exhaust gas temperature, smoke, NOx and CO2 concentration decreased marginally. Table 1 lists the detailed summary of previous studies that demonstrated the use of waste plastic oil and its blends as fuels and Table 2 is the list of properties of waste plastic oil and its blends from previous studies.

Table 1: Summary of previous investigations

Ref No.	Blend	EM	BTE	BSFC	NOx	HC	CO	CO2	HRR	Smoke	EGT	Cylinder Pressure	Remarks
[26]	PPO		↓	↑	↑	↑	=	↑	↑		↑	↑	A blend of 60% - 70% PPO at 80-90% load is good
	PPO 25		↓	↑	↑	↑	=	↑	↑		↑	↑	
	PPO 50		↓	↑	↑	↑	↑	↑	↑		↑	↑	
	PPO 75		↓	↑	↑	↑	↑	↑	↑		↑	↑	
	PPO 90		↓	↑	↑	↑	↑	↑	↑		↑	↑	
	PPO 100		↓	↑	↑	↑	↑	↑	↑		↑	↑	
[27]	PPO 10			↑	↓								5% and 10% EGR can be selected as optimum value
	PPO 20			↑	↓								
	PPO 30			↑	↓								
	PPO 50			↑	↓								
		NO EGR		↑		↑	↑						
		5% EGR		↑		↑	↑						
		10% EGR		↑		↑	↑						
		15% EGR		↑		↑	↑						
		20% EGR		↑		↑	↑						
[28]	LFLP3		↑	↓	↓	↓	↓	↓			↓		LFLP3 is better than diesel
[29]	PO10		↓	↑	↑		↓	↑			↑		PO can be used in pure form with little modifications to the engine
	PO20		↓	↑	↑		↓	↑			↑		
	PO30		↓	↑	↑		↓	↑			↑		
[30]	WPPO 5		↑	↓	↑	↓	↑	↓					20% blend is best
	WPPO 10		↓	↑	↑	↓	↑	↓					
	WPPO 15		↓	↑	↑	↓	↑	↓					
	WPPO 20		↓	↑	↑	↓	=	↓					
[31]	P 2.5		=	↑	↑	=	↑	↓		↑			Waste plastic oil can be blended with diesel and DEE can be used as additive.
	P 7.5		↓	↑	↑	↑	↑	↓		↑			
	P 12.5		↓	↑	↑	↑	↑	↓		↑			
	P 100		↓	↑	↑	↑	↑	↓		↑			
		CR 12	=	↑	↑	↑	↑	↓					
		CR 16	↓	↑	↑	↑	↑	↓					
		CR 20	↓	↑	↑	↑	↑	↓					
[32]	D50WPO40B10		=	↑	↓	↑				↓			D50WPO20B30 is best and n-Butanol is favorable as additive
	D50WPO30B20		↓	↑	↓	↑				↓			
	D50WPO20B30		↓	↑	=	↑				↓			
	WPO		↓	↑	↓	↑				↑			
[33]	WPPO		↓	↑	↑	↑	↑	↑		↑		↑	Addition of DEE is favorable
	WD05		↓	↑	↓	↑	↑	↓		↓		↓	
	WD10		↑	↑	↓	↑	↑	↓		↓		↓	
[34]	WPE 5				↑		↑	↓					WPE 5 blend is the best blend
	CPE 5				↑		↑	↓					
[35]	WPDF										↑	↓	100% WPO can be used as fuel
[36]	PO		↓	↑					↑			↑	Engine can be run using 100% PO
	RME		↓	↑					↑			↑	
[37]	PO 25		↓						↑			↑	PO 25 shows better and compatible results
	PO 50		↓						↑			↑	
	PO 75		↓						↑			↑	
	PO 100		↓						↑			↑	
[38]	PO 25		↓	↑	↑	↑	=			↑			25 % blend is an effective replacement for diesel
	PO 50		↓	↑	↑	↑	↑			↑			
	PO 75		↓	↑	↑	↑	↑			↑			
	PO		↓	↑	↑	↑	↑			↑			
[39]	PD 5		↓		↑	↑	↑		↑				Addition of DEE is a viable solution without engine modifications
	PD 10		↓		↑	↑	↑		↑				
	PD 15		↓		↑	↑	↑		↑				
	PO		↓		↑	↑	↑		↑				
[40]	WPO		↓		↑	↑			↑	↑	↑		PW 30 has better performance.
	PW 10		↑		↓	↑			↑	↓	↓		
	PW 20		↑		↓	↑			↑	↓	↓		
	PW 30		↑		↓	↑			=	↓	↓		
[41]	WPF		↑	↓	↓	↑	↓	↓			↓		Performance of WPF10D90 is similar to
	WPF10D90		↑	↑	↓	↓	↓	=			↓		

	WPF20D80		↓	↑	↓	↓	↓	↑			↓		diesel
	WPF30D70		↓	↑	↑	↓	↓	↑			↓		
[42]	10%B WPO		↓	↓	↑	↑	↑			↑	=		Better performance up to 30% blend. Up to 80% load, BTE of blends is almost same as diesel
	20%B WPO		↓	↑	↑	↑	↑			↑	↑		
	30%B WPO		↓	↑	↑	↑	↑			↑	↑		
	40%B WPO		↓	↑	↑	↑	↑			↑	↑		
	50%B WPO		↓	↑	↑	↑	↑			↑	↑		
[43]	WPO		↓		↑	↑	↑	↑	↑	↓	↑	↓	WPO exhibits higher BTE up to 75% rated power
[44]	WPO	Retarded injection timing	↑	↓	↓	↓	↓	↓	↓	↓	↓	↓	Retardation reduced NOx emission by 30%
[45]	WPO	NO EGR	↑		↑	↓	↑	↓	↑	↓	↑	↑	EGR techniques reduces NOx emission
		10% EGR	↑		↑	↓	↑	↓	↓	↑	↑	↑	
		20% EGR	↑		↑	↓	↑	↓	↓	↑	↓	↑	
[46]	WPO 10		↓		↑	↑	↑	↓	↓	↑	↑	↑	Engine with WPO results in better performance than blend of WPO and diesel
	WPO 30		↓		↑	↑	↑	↓	↓	↑	↑	↑	
	WPO 50		↓		↑	↑	↑	↓	↓	↑	↑	↑	
	WPO 70		↓		↑	↑	↑	↓	↓	↑	↑	↑	
	WPO		↓		↑	↑	↑	↓	↑	↑	↑	↑	

↓ = Decreased; ↑ = Increased

Table 2: Properties of waste plastic oil and its blends.

Ref No	Blend	Density (kg/L)	Kinematic Viscosity (Cst)	Flash point (0C)	Calorific Value (Mj/kg)	Cetane No.
[26]	PPO	0.9813	1.918	13	38.3	-
	Diesel	0.8398	2.62	59.5	42.9	-
[27]	WPO	0.8423	-	28	40.05	
	Diesel	0.8377	-	66	44.8	-
[28]	LFLP3	0.802	2.085	50	46	65
	Diesel	0.834	3.162	75	45.5	60
[30]	WPPO	0.78	3.8	100	39.76	-
	Diesel	0.79	1-4.11	52-96	44.8	-
[31]	P 2.5	0.831	1.568	49	44.414	42.51
	P 7.5	0.824	1.79	48	44.091	43.03
	P 12.5	0.819	1.92	47	43.868	43.61
	P 100	0.790	2.52	42	43.34	51
	DEE	0.714	0.23	-40	33.85	126
	Diesel	0.84	2.0	50	44.8	42
[32]	Diesel	0.838	3.8	70	41.82	54
	WPO	0.813	2.16	38	40.35	51
	n-Butanol	0.810	2.2	36	34	-
	D50WPO40B10	0.825	3.0	36	40.45	48.6
	D50WPO30B20	0.8249	3.1	36	39.815	44.7
	D50WPO20B30	0.8246	3.2	36	39.18	40.8
[33]	Diesel	0.84	-	50	46.5	40-45
	WPPO	0.798	-	42	45.216	51
	DEE	0.713	-	45	33.9	126
	WD05	0.794	-	43	44.65	-
	WD10	0.754	-	43.5	44.084	-
[34]	Diesel	0.833	2.52	58.5	10790 (Kcal/kg)	54.58
	WPE 100	0.788	2.326	<100	10867 (Kcal/kg)	43.751
	WPE 5	0.831	2.49	58.5	10800 (Kcal/kg)	52.58
	WPE 10	0.828	2.48	59	10807 (Kcal/kg)	51.63
	WPE 15	0.826	2.43	59.5	10812 (Kcal/kg)	50.37
	WPE 20	0.824	2.4	61	10818 (Kcal/kg)	49.62
[35]	Diesel	0.8416	3.05	84	42.49	68.2
	WPDF	0.7710	2.149	72	34.72	64.4
[36]	Diesel	0.84	2.15	45	43.5	54
	PO	0.83	2.64	40	44.2	50
[39]	Diesel	0.84	2.15	45	43.5	54
	PO	0.83	2.64	40	44.2	50
	DEE	0.714	0.22	-45	33.87	125
	PD5	0.83	2.52	40	43.167	-
	PD10	0.827	2.4	40	42.834	-
	PD15	0.821	2.37	39	42.501	-
[41]	WPF10D90	0.804	0.616 (Poise)	65	44.87	46
	WPF20D80	0.832	0.052 (Poise)	66	44.39	46
	WPF30D70	0.815	0.064 (Poise)	69	45.58	47
	WPF100	0.78	0.0457 (Poise)	72	42.90	44
	Diesel	0.80	0.61 (Poise)	61	45.35	49

[43]	WPO	0.835	2.52	42	44.34	51
	Diesel	0.84	2.0	50	46.5	55

III. CONCLUSIONS

With faster depletion of petroleum fuels and environmental consequences, the use of alternative fuels has become invariantly important. It is concluded that, waste plastic oil indeed is found to be a potential alternative fuel wherein the waste management along with energy crisis could be addressed. This review is limited to analyze the performance combustion and emission characteristics of diesel – plastic oil blends on diesel engine. However, there are other issues such as kinetics of plastic oil, effects of combustion improvers and engine modifications that are to be considered for in depth analysis of combustion using plastic oil blends.

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