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Optimization of infrared radiated fast and energy-efficient biodiesel production from waste mustard oil catalyzed by Amberlyst 15: Engine performance and emission quality assessments

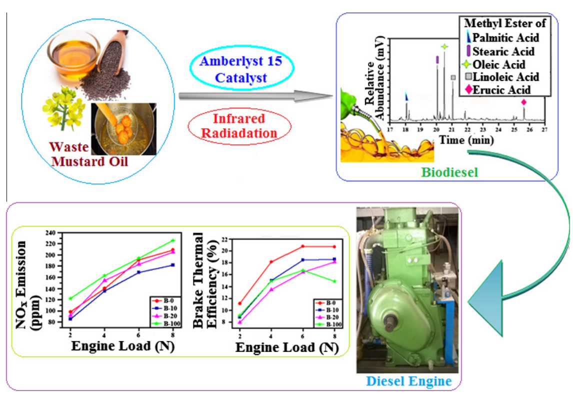
Piasy Pradhan, Sourojeet Chakraborty, Rajat Chakraborty *

Department of Chemical Engineering, Jadavpur University, Kolkata 700032, India

HIGHLIGHTS

- Infrared radiated reactor rendered fast biodiesel yield from waste mustard oil.
- Infrared radiation resulted higher FAME yield & superior energy-efficiency than conventional heating.
- Amberlyst 15 catalyzed process optimization through Taguchi Orthogonal Design.
- B100 and its blend with petro-diesel rendered promising engine performance.
- Euro-6 exhaust emission norms are satisfied.

GRAPHICAL ABSTRACT



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ABSTRACT

A novel protocol has been explored for fast and energy-efficient biodiesel production from waste mustard oil (WMO) using infrared radiated reactor in presence of heterogeneous Amberlyst 15 catalyst. High biodiesel yield (FAME content 97.13%) was obtained from WMO via simultaneous esterification–transesterification reactions in only 0.5 h using an energy-efficient, far infrared radiation (FIR) at the derived optimal conditions predicted through Taguchi Orthogonal Design (8:1 methanol to WMO molar ratio, 6 wt.% catalyst concentration, 800 rpm impeller speed). Experimental observations at the derived optimal conditions indicated much lower FAME yield (43.82%) with conventionally heated reactor even at the expense of 4 times energy input as that of FIR promoted protocol. Promising engine performance was observed at various blends of FIR produced optimal biodiesel with commercial petro-diesel. Notably, in comparison with petro-diesel, lower exhaust temperature was observed for all blends, indicating better engine durability and lower engine depreciation. The exhaust emissions measurements indicated that CO (0.05%) and hydrocarbon (HC) emissions (<0.00002) for B-100 were well below standard Euro-VI emission norms and were observed to decrease gradually with increase in biodiesel percentage in the blended fuel.

* Corresponding author. Tel.: +91 3324572689; fax: +91 3324146378.
E-mail addresses: rajat_chakraborty25@yahoo.com, rchakraborty@chemical.jdvu.ac.in (R. Chakraborty).

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1. Introduction

Increasing energy demands are a burning concern in today's era. The present century trends indicate that a global energy crisis is imminent [1]. In that scenario, it is the need of the hour to develop alternative, eco-friendly and energy-efficient fuels for the purpose of reducing the enormous demand load on coal and petroleum based fuels. Biodiesel is a renewable, alternative green fuel that is primarily derived from vegetable oils and animal fats [2–4]. Biodiesel has received considerable attention in recent years as a biodegradable, renewable, non-toxic, environment friendly substitute for commercial diesel [5]. However, with the advent of more stringent environmental emission norms, much work has been done to investigate the engine performance and emission characteristics of biodiesel blended diesel fuels [6–8]. Fernando et al. [9] reported reductions of harmful NO_X emission through biodiesel fuel. Various engine control parameters were used to control the particulate emissions to maintain the environmental emission norms as well as the effect on human health [10].

An et al. [11] studied the combustion and emission characteristics of diesel fuel blended with biodiesel at partially loaded conditions and reported improved thermal efficiency at higher engine loads compared to pure diesel. While the effort of An et al. [11] was commendable; however, the "optimal" reaction conditions necessary for industrial scale implementation were not evaluated. Notably, owing to higher oxygen content in biodiesel, fuel combustion is more complete, resulting in lower emissions of carbon monoxide, hydrocarbons and particulate matters [12].

Previously, our research group [13], presented an exhaustive literature review on the parametric sensitivity of waste cooking oil (WCO) for the synthesis of biodiesel; inferring that homogenous paths for biodiesel synthesis are difficult to capitalize on a large-scale basis, owing to complexity encountered in catalyst separation and product purification. Hence, heterogeneous catalytic routes are being increasingly preferred. Commercial acidic heterogeneous catalyst Amberlyst-15 was used in both esterification and transesterification reactions with regenerated and recycled characteristics [14]. Chavan et al. [15] had reported that Amberlyst-15 catalyst was used in transesterification reaction and although 95% biodiesel yield [16], was achieved from palm oil using Amberlyst-15; however, it required a lengthy 8 h reaction time.

Several works have been reported on heterogeneous catalysis, for instance, Sirisomboonchai et al. [17] employed calcined scallop shells, Farooq et al. [18] applied chicken bone derived catalyst, whereas Baskar et al. [19] used copper doped zinc oxide nanocomposite to synthesise biodiesel from waste cooking oil. Lam et al. [20] presented a comprehensive review on transesterification of WCO to biodiesel through homogeneous, heterogeneous and enzymatic catalysis. Besides, Tan et al. [21] reviewed the qualitative insights into the potential prospects of waste cooking oil for biodiesel production using heterogeneous catalyst developed from different calcined shells along with emission reduction and engine performance assessment. Fish scale-supported heterogeneous catalyst was used to derive biodiesel from waste frying soybean oil [22], while Jacobson et al. [23] and Park et al. [24] produced biodiesel from waste cooking oil using solid acid catalyst. Engine performance assessment of biodiesel derived from WCO [6,7,25] had revealed that utilization of WCO would not only help mitigate environmental pollution, but also would lead to economical production of eco-friendly, renewable engine-efficient, green fuel lessening the present demand of crude oil. Nevertheless, conventional conversion methods of WCO into biodiesel usually involve uneconomically long reaction time to render desired product quality [26]. Thus, reduction of reaction time and use of mild operating conditions are still a thought-provoking task for researchers and technologists. Notably, scanty reports are mentioned in literature on the application of waste mustard oil (WMO) as a potential feedstock for biodiesel production and its subsequent engine performance analyses [27].

Biodiesel blended fuels are typically recorded to have lower carbon monoxide (CO) and hydrocarbon (HC) exhaust emissions [28,29] but a very slight increase in the NO_X emissions [4,30–32]. Nonetheless, from the literature review, it is apparent that no biodiesel produced from waste mustard oil (WMO) has been tested for engine performance and emission quality assessments.

In the present article, fast biodiesel production from waste mustard oil (WMO) employing heterogeneous Amberlyst-15 acid catalyst in a far infrared radiation (FIR) promoted reactor has been reported. A three-parameter-three level L9 orthogonal Taguchi [33], experimental design was used to obtain the optimal process conditions for conversion of WMO to maximize biodiesel (FAME) yield. The superiority of the FIR in comparison with conventional conductive heat source with respect to FAME yield has been investigated. The optimal biodiesel was blended with petro-diesel in different ratio (B-10, B-20, B-100) and the blended fuel was tested in a standard Diesel Engine (DE) to assess engine performance and emission quality.

2. Experimental sections

2.1. Materials

WMO was collected from local restaurants; while Amberlyst 15 catalyst was procured from Sigma-Aldrich. Methanol (LR Grade; Merck India) and commercial petro-diesel were procured from Indian Oil Corporation.

2.2. Design of experiment

Taguchi Orthogonal Design (TOD) was used to assess and optimize the effects of three process factors viz. methanol to WMO molar ratio (λ_{MO}), catalyst concentration (λ_{CC}) and stirrer speed (λ_{SS}) (Table 1) on biodiesel (FAME) yield using MINITAB-16 software (Minitab Inc. USA for Windows 7).

Using TOD, different experimental runs (Table 2) were conducted to evaluate the optimal factorial values for maximum FAME Yield from WMO. Signal to noise ratio (S/N) for each run was calculated using Eq. (1); while, Eq. (2) was employed to compute the estimated value of S/N. In present study higher FAME yield (Y_{FAME}) was preferred i.e. "Larger is better" criteria was employed.

$$S/N = -10\log\left(1\Big/\left\{n\sum_{x=1}^{n}\frac{1}{K_x^2}\right\}\right) \quad (1)$$

$$S/N_{EST} = \overline{S/N} + \sum_{a=1}^{i}\left(S/N_a - \overline{S/N}\right) \quad (2)$$

where K_x: Y_{FAME} corresponding to run x; x: number of replication; n: number of experiments conducted using a particular combination of process factors as shown in Table 2. $\overline{S/N}$: mean of the SN ratio;

Table 1
Experimental process factors and levels for production of biodiesel from WMO under FIR radiation.

Process factors	λ_{MO}	λ_{CC} (wt.%)	λ_{SS} (rpm)
Lower Level (LL)	4:1	2	600
Middle Level (ML)	6:1	4	800
Upper Level (UL)	8:1	6	1000