

Hybrid Solar PV–CHP–Biomass Energy System Modeling and Optimization with Battery Storage Impact Employing Differential Evolution Algorithm.

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Abstract

The electric, thermal and cooling energy needs keep on increasing consistently due to the increasing consumption patterns. Diversification of energy sources, energy affordability and emissions reduction, as well as enhancing the performance and responsiveness of centralized energy networks have ensured hybrid energy systems are becoming crucial. This paper introduces a hybrid design based on photovoltaic (PV) energy generation with combined heat and power (CHP) systems, boilers, along with biomass-driven power generation. It is an optimization problem that is formulated based on the use of a differential evolution algorithm to reduce daily electricity expenses. It also has a battery energy storage system (BESS) to improve the high efficiency, reliable performance, and sustainable operation of the energy network. In order to manage the uncertainty of PV production, scenario-based stochastic optimization models are employed utilizing evident solar radiation information. Optimization also takes into consideration real-time time-of-use (ToU) real-time gas price data and electricity tariffs. The combination of a battery storage, when used in various operations, significantly lowers the cost of operation of the system by around -2838.585% instead of the cost of operation with a grid, PV, CHP, and a biomass fueled boiler. Sensitivity analyses also indicate that both Scenarios III and IV demonstrate an upward cost of operations as a result of an increase in the external gas prices.

Keywords: Multi-energy systems, Battery storage system (BSS), Differential evolution algorithm, Optimization, Smart grids (SGs).

I. Introduction

Urbanization, population growth and constant economic growth have seen the world of energy demand diverse categories of power like electricity, methane gas and thermal energy extensively in the past decades. The statistics published by the U.S. The Energy Information Agency shows that the combined power demand will grow by approximately forty-eight percent between 2012 and 2040 (International Energy Outlook U.S. Energy information administration, 2016). The rising fuel prices, the high demand rate, and the growing environmental issues, such as the greenhouse gasses emission, have heightened the emphasis on the distributed energy resources (DERs). DERs are good substitutes to traditional grid based systems since they can save on cost and enhance performance with regard to the environment (van Beuzekom *et al.*, 2015). CHP systems are among the prevalent useful technologies of distributed generation since they are able to produce electricity and thermal energy at the same time. CHP

technology is important in improving the overall system efficiency by consuming waste heat to address heating needs (Ohaegbuchi *et al.*, 2022).

Combined cooling, heat, and power (CCHP): CHP systems, and combined cooling, heat, and power units are becoming more popular due to their capability to satisfy electrical and thermal demands at a low cost. Heat pumps (HPs), refrigeration units, boilers, power-to-gas (P2G) along with thermal and electrical storage units converters are other important units of multi-energy systems (MES) (Javidi *et al.*, 2015), (Reynolds *et al.*, 2018). Nevertheless, it is rather difficult to model and manage such integrated systems. In order to overcome these issues, the model of energy hub has been presented as a powerful framework of MES modeling. It allows transformation, conditioning, and storage of various carriers of energy in one system (Mancarella *et al.*, 2016), (Huang *et al.*, 2017), (Rastegar & Fotuhi-Firuzabad, 2014).

Surveys of the academic literature reveal that many studies on MES technologies have been conducted, and they can be broadly divided into several groups: the comprehensive survey, the economic and environmental analysis, the model of power flow, the integration of the renewable resources and BESSs, and optimization techniques (both operational and stochastic). Indicatively, (Mancarella *et al.*, 2014) emphasized the importance of MES development, presented several modeling methods, exposed the challenges that exist, and suggested the research directions to be undertaken in the future. Equally, (Roustai *et al.*, 2018) have described and examined MES architectures, the modeling techniques, control concepts including power hub, virtual power plants and microgrids in detail, alongside a number of economic assessment techniques.

This paper also uses a differential evolution (DE) optimization algorithm to minimize the energy cost of a conventional hybrid power system that integrates a BESS (battery storage system). The optimization framework is formulated and implemented in Python by using the Pymoo. Four operation scenarios are examined to check the work of the hybrid power system and determine its cost-effectiveness under different working conditions. The DE technique is utilized to limit the power costs of the microgrid consumers, and the data of the natural gas pricing fueled by the Fuel Distribution System (FDS) is utilized to manage the energy at the best level. The major findings of the paper are highlighted below:

It gives an elaborate quantitative evaluation of the role of the battery storage systems in cost-effective energy management.

- (a) The following are the main differences between the traditional schemes of optimization as well as popular metaheuristic frameworks like particle swarm optimization (PSO) and genetic algorithm (GA).

This work proves as well as justifies the use of the differential evolution algorithm of optimal scheduling and performance of a multi-energy system.

II. Integrated Energy System Framework Development

Fig. 1 illustrates the combined power system that is planned to be efficient and powered with the help of the latest information technologies. It assists in reducing the operating expenses and the requirements of a hybrid energy network. These requirements are formed by modern smart grids which are influenced by such crucial parameters as the development of demand and reliability. Making renewable resources supplementary to the conventional electricity and gas infrastructure makes it very complicated. Such complexity demands new solutions and add-on technologies to maintain a smooth running of the system. The hybrid model enables numerous technologies to be integrated, which leads to a reduced total cost.

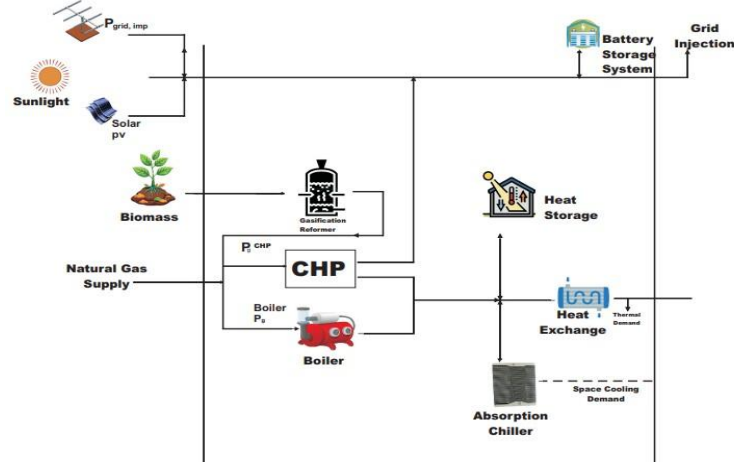


Fig. 1 Conceptual framework of the hybridized energy system

III. Problem Formulation

Scheduling the hybrid network aims at cutting down on both overall operating costs. The problem is developed as a differential evolution optimization difficulty is a planning horizon, which is split into discrete time. The time slots are one per hour thus 24 time slots per day.

A. Objective Function

The core objective function framework for this system is produced as highlighted below:

$$\min f(\text{cost}) = \sum_{t=1}^{24} \{ P_{\text{grid},im}(t) \tau(t) - P_{\text{grid},ex}(t) C_{\text{sell}} + P_e^{pv}(t) C_{pv} + P_g^{chp}(t) C_g + P_g^b(t) C_g + P_g^{bm}(t) NG + P_B^{Disch}(t) C_B^{Disch} \} \quad (1)$$

The objective function (1) is related to purchasing of gas $C_g(t)$ from network for the CHP (cogeneration) system $P_g^{chp}(t)$ and boiler $P_g^b(t)$ in period t with Natural gas price NG . Biomass gas is $P_g^{bm}(t)$ purchased with price $C_g^{bm}(t)$ in period t . C_{pv} and C_B^{Disch} designs PV cost of maintenance and battery storage structure, $\tau(t) \equiv TOU(t)$ refers to market time-of-use tariff at hour t (¥/KWh). $P_{\text{grid},im}(t)$ designates the purchased electric power from the main grid in period t , $P_{\text{grid},ex}(t)$ is sold electrical power to the principal grid in period t . C_{sell} represents the sold out electricity cost to the grid.

B. Constraints

The considered systems' constant and conditions are represented in these equations.

1) Grid Power Balance: The energy balance in the grid has to be such that the electricity produced should be equal to the consumption at any given moment in time ensuring the supply-demand balance:

$$P_{\text{grid},im}(t) + \eta_{pv} P_e^{pv}(t) + \eta_{ge}^{chp} P_g^{chp}(t) + \eta_{Disch} P_B^{Disch}(t) = P_D(t) + \eta_{Ch} P_B^{Ch}(t) + P_{\text{grid},ex}(t) \quad (2)$$

Where $P_D(t)$ represent power demand of the hybridized system in period t , $\eta_{pv} P_e^{pv}(t)$ designs PV power in period t through PV efficiency, η_{ge}^{chp} and $P_g^{chp}(t)$ are the CHP efficiency and its power in t supplied by natural gas and biomass. $\eta_{Ch} P_B^{Ch}(t)$ and $\eta_{Disch} P_B^{Disch}(t)$ are the energy charge and discharge by battery in t and their efficiencies; $P_{\text{grid},im}(t)$ and $P_{\text{grid},ex}(t)$ denotes the amount imported and the cost of electricity when it is traded to the grid in period t .

2) Equality Constraint of Heat: The principle of balance of heat is equivalent to the equilibrium constraint of the temperature. Heat balance equation (3) provides that heating by CHP and heat-only

units is equal to thermal demand in the system, and therefore it remains efficient in heat production. Heat demand $H_D(t)$ of hybridized energy system in period t is provided by

$$H_D(t) = \eta_{heat}^{HE} \times P_{heat}^{HE}(t) \quad (3a)$$

Where $P_{heat}^{HE}(t)$ designs heat exchanger power in period t , and η_{heat}^{HE} designates efficiency of heat exchanger.

$$P_{heat}^{HE}(t) + H_{ch}(t) = \eta_{gh}^{chp} \times P_g^{chp}(t) + \eta_{gh}^b \times P_g^b(t) - P_{heat}^{AC}(t) + H_{disch}(t) \quad (3b)$$

Where $P_g^{chp}(t)$ is CHP (cogeneration) power in period t through its efficiency η_{gh}^{chp} , $P_g^b(t)$ designs the boiler power in period t through its efficiency η_{gh}^b . $H_{disch}(t)$ denotes heat discharge from thermal energy storage system in period t , $H_{ch}(t)$ represent Injected heat to thermal energy storage in period t , $P_{heat}^{AC}(t)$ designs required power for absorption chillers. The Chiller must have the ability to absorb impurities in the water body and retain them within the device. Absorption Chiller Requirement $P_{heat}^{AC}(t)$ in period t is decreased from heat exchanger output which provides the required power by the chiller during its operation. This surplus heat is kept in the form of thermic energy and then used later as $H_{ch}(t)$ in period t .

3) Equality constraint for external gas network and biomass: Produced gas power $P_g^{bm}(t)$ from biomass in period t , and efficacy of their gas-conversion η_g^{bm} and gas network which are utilized for CHP (cogeneration) system along with boiler as depicted below (4)

$$P_g(t) + \eta_g^{bm} P_g^{bm}(t) = P_g^{chp}(t) + P_g^b(t) \quad (4)$$

4) Cooling Balance Equality Constraint: The cooling balance equality constraint guarantees that the cooling demand at every operating period is exactly met by the Absorption chillers driven by waste heat from CHP and boiler units fired by natural gas and biomass. It reflects the physical law of demand–supply balance and prevents infeasible solutions (such as unmet cooling demand) as shown in (5).

$$C_D(t) = \eta_c^{AC} \times P_{heat}^{AC}(t) \quad (5)$$

4) Upstream grid. Power purchased or sold to or by the upstream grid should not exceed the capacity limits based on regulations on the electricity market. The constraint is affected by their limit as shown below:

$$0 \leq P_{grid,im}(t) \leq P_{grid,im}^{max}(t), \quad 0 \leq P_{grid,ex}(t) \leq P_{grid,ex}^{max}(t) \quad (6)$$

Where $P_{grid,im}(t)$ and $P_{grid,ex}(t)$ represents the imported/exported electricity to/from the conventional network as in t ; $P_{grid,im}^{max}(t)$ and $P_{grid,ex}^{max}(t)$ symbolizes the maximum importation or exportation power within t . This implies that concurrent purchasing and selling is prohibited. The subsequent inequalities are the inequalities that provide the correct grid operation:

$$E_{im}(t) + E_{sell}(t) \leq 1 \quad (7)$$

5) The PV System: The highest amount of PV creation: $0 \leq P_{pv}(t) \leq P_{pv}^{max}(t)$ (8)

The generated output energy originating at PV system (Colson *et al.*, 2007),

$$P_{pv}(t) \leq A \times \rho \times SI(t) \quad (9)$$

When the highest power allowed is $P_{pv}^{max}(t)$ in period t , A thus represents the PV system cross-sectional zone, ρ represents the effectiveness, and $SI(t)$ is the sunlight in period t .

6) CHP unit

The proposed CHP model therefore includes a power generator, turbine, and heat recovery unit (HRU). The cogeneration arrangement is depicted in figure 2. The CHP uses methane gas to manufacture electricity and the HRU recycles the heat generated from waste to serve the heating requirements of the end users.

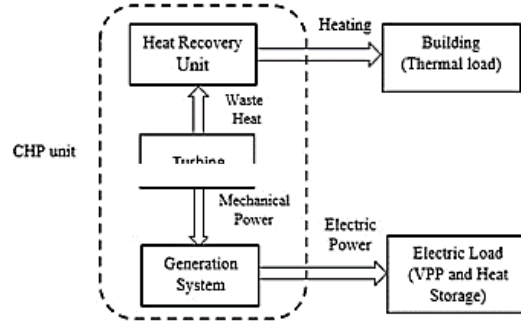


Fig. 2 Configuration of a (CHP) unit

The generated waste heat by the CHP is employed to warm the university; this increases the efficiency of the system. Its ramping potentiality renders it possible to use it in load-following and frequency control. The natural gas is supplied through the gas distribution network, which supplies the methane

gas to operate continuously. The power input $\sum_m P_{input}^{CHP}(t)$ of the (CHP) unit at period t is gas power $P^{gas}(t)$ and it is supplied by the gas network at period t expressed in Eq. (10).

$$P^{gas}(t) = \sum_m P_{input}^{CHP}(t) \quad (10)$$

$$P_{input}^{CHP}(t) = P_{elect}^{CHP}(t)/\eta_m^{elect} + P_{heat}^{CHP}(t)/\eta_m^{heat}, \quad P_{elect}^{CHP}(t) = P_{consumer}^{CHP,elect}(t) \quad (11)$$

Importantly, CHP generates electrical power $P_{consumer}^{CHP,elect}(t)$ for consumers at period t . The produced heat $P_{heat}^{CHP}(t)$ from CHP is recovered by the Heat recovery unit and utilized to serve the heating needs of the heat consumers in the micro-grid. Two conversion processes are occurring in the CHP unit of Fig.2, which are gas to energy and gas to heat. As well, CHP utilizes different efficacies for the change of gas to electricity and heating. The inequality limitation known with capability of equipment

which highlights that m^{th} CHP input power $P_{input}^{CHP}(t)$ strongly depends on highest electricity $P_{max}^{CHP,elect}(t)$ and heat $P_{max}^{CHP,heat}(t)$ products via its effectiveness as represented in Eq. (12).

$$P_{input}^{CHP}(t) \leq P_{max}^{CHP,elect}(t)/\eta_m^{elect} + P_{max}^{CHP,heat}(t)/\eta_m^{heat}, \quad (12)$$

The efficiencies are regarded as predefined parameters and are given as $\eta_m^{elect}, \eta_m^{heat}$. The fuel consumptions of CHP in m^3 is evaluated thus:

$$F_{CHP}(t) = \beta P_{CHP}(t)/\eta_e \quad (13)$$

Where $F_{CHP}(t)$ represents Natural gas consumption of CHP unit in period $t(m^3/h)$, β represent converting factor for natural gas m^3/KWh , $P_{CHP}(t)$ represent CHP generated electric power in $t(KW)$,

and η_e denotes electricity efficiency of CHP unit. The relationship between electric power generated by $P_{CHP}(t)$ unit and recovered heat from heat recovery unit $H_{CHP}(t)$ is modelled as follows:

$$H_{CHP}(t) = P_{CHP}(t) \times \eta_{heat} / \eta_e \quad (14)$$

Where η_e and η_{heat} are CHP electrical and thermal efficiencies, respectively. Other CHP operational constraints are represented as:

$$\mu_{chp}(t).P_{chp}^{\min} \leq P_{chp}(t) \leq \mu_{chp}(t).P_{chp}^{\max}, \quad \mu_{chp}(t).H_{chp}^{\min} \leq H_{chp}(t) \leq \mu_{chp}(t).H_{chp}^{\max} \quad (15)$$

The limitation of CHP generated power/heat is caused by an higher constraint as a result of its computed capacity which is tied to a smaller limit so as to stop decreasing its effectiveness

$$|P_{chp}(t) - P_{chp}(t-1)| \leq rr_e, \quad |H_{chp}(t) - H_{chp}(t-1)| \leq rr_e \cdot \eta_{th} / \eta_e \quad (16)$$

Where $\mu_{chp}(t)$ and rr_e are binary variables representing the operational status (on/off) of CHP at time t and its corresponding electrical ramp consecutively. .

Mathematical formulation of a constrained nonlinear optimization model for the integrated solar PV-CHP-Biomass-Boiler energy system in a micro-grid using the differential evolution (DE) algorithm.

Objective Function

$$\min f(\text{cost}) = \sum_{t=1}^{24} \{ P_{grid,im}(t)\tau(t) - P_{grid,ex}(t)C_{sell} + P_e^{pv}(t)C_{pv} + P_g^{chp}(t)C_g + P_g^b(t)C_g + P_g^{bm}(t)NG + P_B^{Disch}(t)C_B^{Disch} \} \quad (17)$$

Let us make the following identifications;

$$P_{grid,im}(t) = x_{1,t}, P_{grid,ex}(t) = x_{2,t}, P_e^{pv}(t) = x_{3,t}, P_g^{CHP}(t) = x_{4,t}, P_g^b(t) = x_{5,t}, P_g^{bm}(t) = x_{6,t}, P_B^{Disch}(t) = x_{7,t}$$

$$C_{sell}(t) = c_2 = 0.29, C_{PV}(t) = c_3 = 0.01, C_g(t) = c_4 = 4, NG = c_5 = 0.157, C_B^{Disch}(t) = c_6 = 0.01,$$

Hence the objective function becomes;

$$\min f(\text{cost}) = \sum_{t=1}^{24} \{ x_{1,t}\tau_t - 0.29x_{2,t} + 0.01x_{3,t} + 4x_{4,t} + 4x_{5,t} + 0.157x_{6,t} + 0.01x_{7,t} \} \quad (18)$$

Power balance equality constraint of Equation (2) can be transformed mathematically into

$$x_{1,t} + \eta_{pv}x_{3,t} + \eta_{ge}^{chp}x_{4,t} + \eta_{Disch}x_{7,t} = P_D(t) + x_{2,t} \quad (19)$$

$$\text{With } \eta_{pv} = 18.6, \eta_{ge}^{chp} = 35, \eta_{Disch} = 93, P_D(t) = 250KW \Rightarrow x_{1,t} + 18.6x_{3,t} + 35x_{4,t} + 93x_{7,t} = 250 + x_{2,t}$$

Hence the power balance equality;

$$x_{1,t} - x_{2,t} + 18.6x_{3,t} + 35x_{4,t} + 93x_{7,t} = 250 \quad (20)$$

By using the following given data, heat balance equality constraint of equation (3) can be recast thus:

$$\text{With } P_{heat}^{HE}(t) = 1000, H_{ch}(t) = 5, P_{heat}^{AC}(t) = 250, H_{disch}(t) = 5, \eta_{gh}^{chp} = 40, \eta_{gh}^b = 90, H_{ch}(t) = 5, \text{ the heat balance equality constraint becomes;}$$

$$\Rightarrow 40x_{4,t} + 90x_{5,t} = 1250 \quad (21)$$

Similarly, equality constraint for external gas network and biomass of equation of (4) is transformed

$$\text{using the data } P_g(t) = 0.157 \text{ and } \eta_g^{bm} = 80. \text{ Therefore, the constraint becomes; } P_g(t) + \eta_g^{bm}x_{6,t} = x_{4,t} + x_{5,t}$$

$$0.157 + 90x_{6,t} = x_{4,t} + x_{5,t} \Rightarrow x_{4,t} + x_{5,t} - 90x_{6,t} = 0.157 \quad (22)$$

Where $P_g(t)$ and $P_g^{bm}(t)$ are the gas prices from external gas network and biomass gas for the boiler and cogeneration units respectively.

Permissible Region of Operation

Figure 3 highlights the permissibility of the operating region permissibility in a simple-cycle cogeneration unit, where the heat and power generation are closely linked. Enclosed within within the boundary curve ABCDEF is the feasible heat–power operating range.

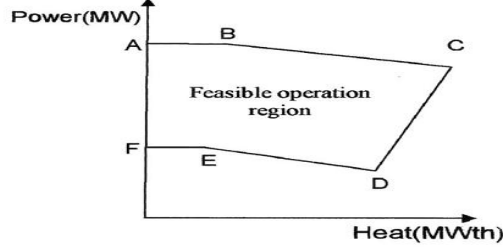


Fig.3. Heat power operational boundary of a CHP unit.

Limits of variables P and H

The modelling of the power operation limit by the cogeneration unit as inequality constraints is given by (23). The energy produced by PV unit should reside in the restrictions postulated by the lowest limit $P_i^{\min}$ and highest limit $P_i^{\max}$, as depicted in (24). Thus, the energy output of the i^{th} heat only unit should reside in the environment its restraint represented by the lowest limit $P_g^{b,\min}(t)$ and highest limit $P_g^{b,\max}(t)$ as depicted in (25). The inequality constraint of a biomass system given by (26) limit output capacity of fuel to ensure the system operates within safe and practical bound. The import capacity bound constraint of power import from the traditional grid given by (27) define limits on how much and how quickly power can be imported, ensuring safe, economic, and contract-compliant operation of a multi-energy system. The inequality constraint for power exported to the grid by the hybridized energy system given by (28) ensures that the amount of electricity sent to the centralized electricity network is within allowable operational or contractual limits. This model account for technical, regulatory, or economic considerations of the hybridized energy system. The inequality constraint of battery discharge given by (29) ensure the battery operates safely and efficiently within physical and operational limits. This ensures the discharge rate does not exceed the system's physical capacity. The limit of the amount of external gas supply imported from the external grid or supplier into the system within a given time period as shown in (30)

$$\eta_{gh}^{chp} \times P_g^{chp}(t) \leq P^{chp} \Rightarrow 0 \leq 40x_{4,t} \leq 700 \Rightarrow 0 \leq x_{4,t} \leq 17.5 \quad (23)$$

$$0 \leq P_{pv}(t) \leq P_{pv}^{\max} \Rightarrow 0 \leq x_{3,t} \leq 5 \quad (24)$$

$$\eta_{gh}^b \times P_g^b(t) \leq P^b \Rightarrow 0 \leq 90x_{5,t} \leq 1000 \Rightarrow 0 \leq x_{5,t} \leq 11.11 \quad (25)$$

$$0 \leq P_g^{bm}(t) \leq P_g^{bm,\max}(t) \Rightarrow 0 \leq x_{6,t} \leq 500 \quad (26)$$

$$0 \leq P_{grid,im}(t) \leq P_{grid,im}^{\max} \Rightarrow 0 \leq x_{1,t} \leq 5 \quad (27)$$

$$0 \leq P_{grid,ex}(t) \leq P_{grid,ex}^{\max} \Rightarrow 0 \leq x_{2,t} \leq 0.5 \quad (28)$$

$$P_B^{disch}(t) \leq P_B^{disch,\max} \times Z(t) \Rightarrow 0 \leq x_{7,t} \leq 1 \quad (29)$$

$$0 \leq P_g(t) \leq P_g^{\max}(t) \Rightarrow 0 \leq x_{5,t} \leq 1200 \quad (30)$$

The Optimization Model

The hybridized energy system is formulated to reduce the overall operational cost which is a sum of the expenditure used to purchase power vectors at input ports of hybridized energy systems. This study's objective function is presented in Eq.31. τ_t stands for the Time-of-Use (ToU), which is a tariff model or pricing scheme where the electricity cost fluctuate based on the time of day and $x_{n,t}$ denotes the

corresponding energy vector highlighted by x . The combined cost has been determined through the summation of the operating cost over the time horizon of 24 hours.

$$\min f(\text{cost}) = \sum_{t=1}^{24} \{x_{1,t}\tau_t - 0.29x_{2,t} + 0.01x_{3,t} + 4x_{4,t} + 4x_{5,t} + 0.157x_{6,t} + 0.01x_{7,t}\} \quad (31)$$

$$\begin{aligned} \tau_1 &= 0.033, \tau_2 = 0.027, \tau_3 = 0.02, \tau_4 = 0.017, \tau_5 = 0.017, \tau_6 = 0.029, \tau_7 = 0.033, \tau_8 = 0.054, \\ \tau_9 &= 0.215, \tau_{10} = 0.572, \tau_{11} = 0.572, \tau_{12} = 0.572, \tau_{13} = 0.215, \tau_{14} = 0.572, \tau_{15} = 0.286, \tau_{16} = 0.279, \\ \tau_{17} &= 0.086, \tau_{18} = 0.059, \tau_{19} = 0.050, \tau_{20} = 0.061, \tau_{21} = 0.181, \tau_{22} = 0.077, \tau_{23} = 0.043, \tau_{24} = 0.037. \end{aligned}$$

Subject to

$$\begin{aligned} x_{1,t} - x_{2,t} + 18.6x_{3,t} + 35x_{4,t} + 93x_{7,t} &= 250, \quad 40x_{4,t} + 90x_{5,t} = 1250, \quad x_{4,t} + x_{5,t} - 90x_{6,t} = 0.157 \\ 0 \leq x_{1,t} &\leq 5, \quad 0 \leq x_{2,t} \leq 0.5, \quad 0 \leq x_{3,t} \leq 5, \quad 0 \leq x_{4,t} \leq 17.5, \quad 0 \leq x_{5,t} \leq 11.11, \quad 0 \leq x_{6,t} \leq 500, \quad 0 \leq x_{7,t} \leq 1 \end{aligned}$$

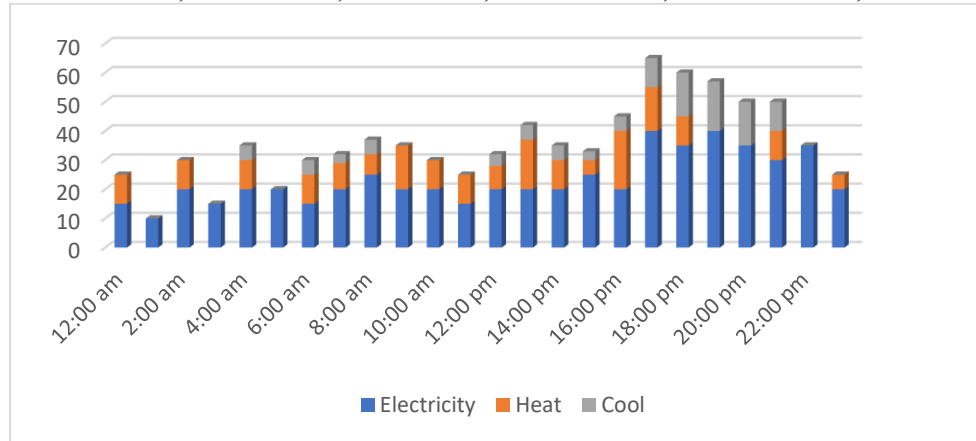


Fig.4. Power, heat, and cooling requirements

a). Input Data

In this research, the true input data of every unit is used to obtain the results of simulation that better represent the real working conditions. Energy cost parameters are characterized by a fixed real gas purchase price and actual electricity fees brought about by a time of use (ToU) tariff. The demand profile is shown by the electric energy and the heating and chilling consumption data obtained in the abattoir facility. Stochastic generation of solar energy is added to model the renewable energy input. In addition, the BESS can be defined in terms of its maximum, minimum and initial state-of-charge values, efficiencies of charging and charging powers. It can be noted that the efficiencies of the cogeneration system, biomass unit and boiler determine the maximum power capacities of these units.

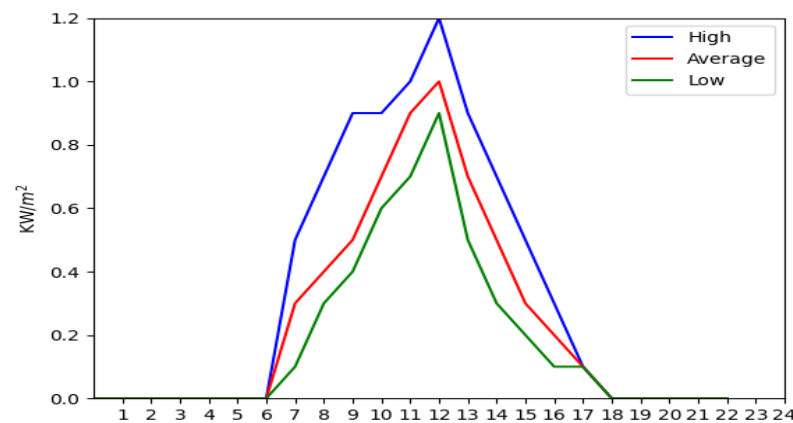


Fig.5. Daily solar irradiance.

Table II provides real data of electricity consumption, cooling, and heating of the hybrid energy system. At designated periods, the facility draws power either solely out of the electrical grid, or a mixture of the electrical and thermal loads, or all the three modalities, as in the case with Fig. 4.

Table I Hourly Electricity Price

t / ₦/KWh	1 / 0.033	2 / 0.027	3 / 0.020	4 / 0.017	5 / 0.017	6 / 0.029
t / ₦/KWh	7 / 0.033	8 / 0.054	9 / 0.215	10 / 0.572	11 / 0.572	12 / 0.572
t / ₦/KWh	13 / 0.215	14 / 0.572	15 / 0.286	16 / 0.279	17 / 0.086	18 / 0.059
t / ₦/KWh	19 / 0.050	20 / 0.061	21 / 0.181	22 / 0.077	23 / 0.043	24 / 0.037

b) Simulation results

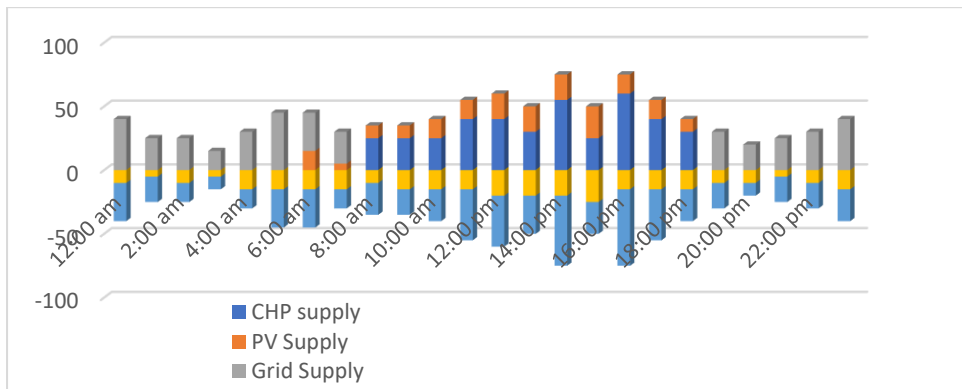
The simulations are run on a chosen day and the time resolution used is an hour and all the figures are given on the four scenarios being investigated. The micro-grid load remains fixed unless when it is charged by BESS where it varies. The integration multipliers between the CHP unit and the boiler are fixed to unity during the simulation in order to impose full integration of the system and to also allow an overall analysis. Such a design option is capable of influencing the development of unique working preferences. Fig. 6 represents the electrical balance of the hybridised energy system.

Table II: Characteristics of Grid, PV, CHP, Boiler, biomass, BESS, TES, and AC

Parameter	$\eta_{ge}^{chp}, \eta_{gh}^{chp}$	η_g^{bm}	η_{heat}^{HE}	$\eta_B^{Ch}, \eta_B^{Disch}$	$\eta_{heat}^{Ch}, \eta_{heat}^{Disch}$	$\alpha_B^{loss}, \alpha_{heat}^{loss}$	$P_B^{max}(t)$	C_{sell}	Biomass gas $C_g^{bm}(t)$	P^b	P^{AC}	η_{gh}^b
Value	35,40	80	95	93,93	90,90	3	500	0.29	4	1000	200	90
Unit	%	%	%	%	%	%	KWh	₦/KWh	₦/ m^3	KW	KW	%

Parameter	$P_g^{bm,max}(t)$	η_c^{AC}	$H_{heat}^{max}(t)$	$P_g^{max}(t)$	P^{chp}	P^{HE}	$P_{pv}(t), A, \eta_{pv}$	$P_{grid,im}^{max}(t), P_{grid,ex}^{max}(t)$	$P_D(t)$	$H_D(t)$	$C_D(t)$
Value	500	90	200	1200	700	1000	3.5,25,18.6	5,0.5	250	400	300
Unit	KW	%	KW	KW	KW	KW	KW, m^2 , %	KW	KW	KW	KW

Parameter	$P_g(t) = NG$	$H_{ch}(t)$	$H_{disch}(t)$	$P_{heat}^{AC}(t)$	P_{PV}^{Max}	$P_B^{Disch,max} Z(t)$	$C_B^{Disch}(t), C_{PV}(t)$
Value	0.157	5	5	250	5	1	0.01
Unit	₦/ m^3	KW	KW	KW	KW	KW	₦/KWh

**Fig.6.** Electricity supply–demand balance of the hybridized system (CHP, PV and Grid)

The net electrical demand of the system varies with time of the day. The CHP and the P_V system mainly meet the demand in the range of 08:00-18:00. Between 19:00 and 05:00, the hybridised system is

powered by the grid electricity, since electricity cost is minimal during this period. Moreover, during the period between 19.00 and 07.00 the electrical power is supplied by mixing the central electricity network with PV generation during the early morning of the day chosen.

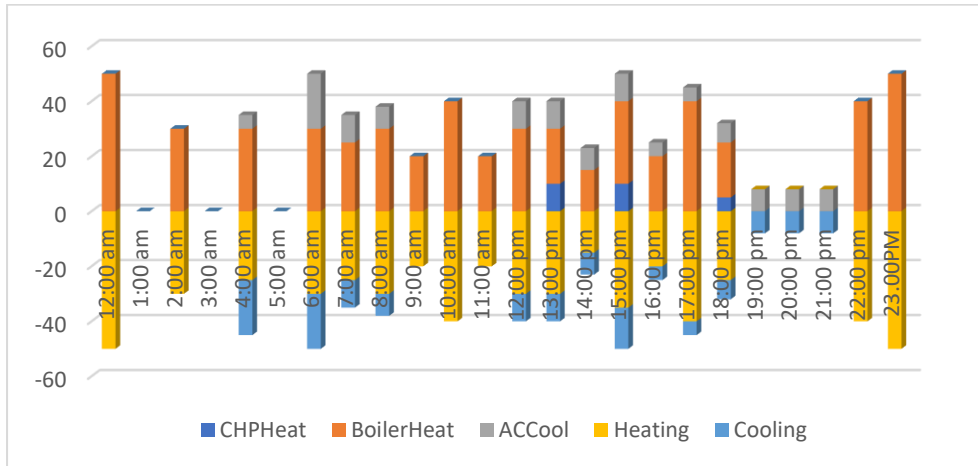


Fig.7. Thermal equilibrium of the hybridized system

The heating and cooling energy generated, and their utilisation is shown in figure 7. The CHP unit is turned on to respond to the heating and cooling demands at 13:00, 15: 00, and 18:00. During these periods, the boiler cannot meet the demand alone, hence the CHP unit is run since it lowers the cost during the peak hours of electricity prices, enhances the adaptability of this system through the simultaneous production of electricity, heating, and chilling, and addresses the high heating and cooling requirement during these hours. The CHP is also used as a reserve to the boiler and any surplus heat generated is kept in the thermic storage system. The CHP unit is used more often when there is high electrical demand hence minimizing the use of the boiler. The hybrid energy system is biased towards the provision of heat by the thermal storage unit at other times.

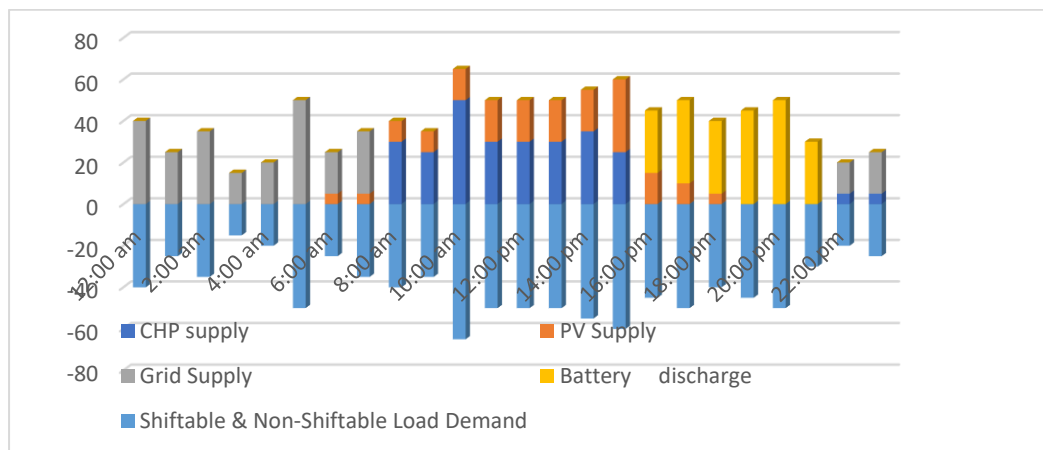


Fig.8 Energy equilibrium of the hybrid system for BESS discharge operation

Fig. 8 presents the best dispatch approach to the electrical resources; the photovoltaic (PV) array, CHP system, upstream grid, and BESS during the operation of the battery discharge processes. The CHP and PV system operate close to their rated capacities throughout most of the time in the simulation, which combined to provide approximately 90 percent of the summated energy demand. This is mostly attributed to the low prices of natural gas and high production of the PV system. The battery degradation will be minimized by limiting extended discharge cycles of BESS through the energy management system. The other important aspect is that the CHP unit is not operational between 16:00 and 07:00 and its function is replaced by the grid power. During these hours, the electricity price is significantly reduced but the PV output is still high and BESS discharging assists in satisfying demand. This is

coordinated dispatch, a combination of distributed generation and prosumer features, which enhances system balance. Base and off-peak demand is provided in the grid whereas PV, BESS discharge and CHP output are strategically employed to manage peak demand and short-term peaks. The multi-layered operation increases reliability, cost efficiency and flexibility. The demand of the load is satisfied, with no other resource needed in the event that the source of PV generation is renewable. When the generated power (P_{gen}) is more than the load, it is firstly kept in the BESS. The surplus energy is sold out to the main grid when storage becomes full. On the other hand, when PV output (P_{gen}) is insufficient the battery fills in. In case the deficit is more than BESS can handle, the CHP unit will be used to supplement. In case of the deficit remaining after CHP contribution, an upstream grid meets the extra load, resulting in stability of services and the system. Optimization output provides that, with the Scenario II, a 3.5 kW PV system can provide significant cost benefits. Nevertheless, the storage system is economical only at relatively low scales as per existing cost conditions. Four contexts are simulated to measure the efficacy and strength of the presented system.

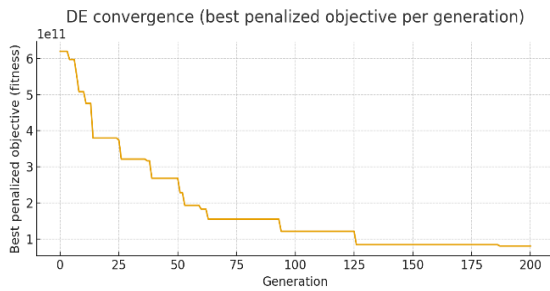


Fig.9. Convergence characteristic of differential evolution algorithm for scenario I

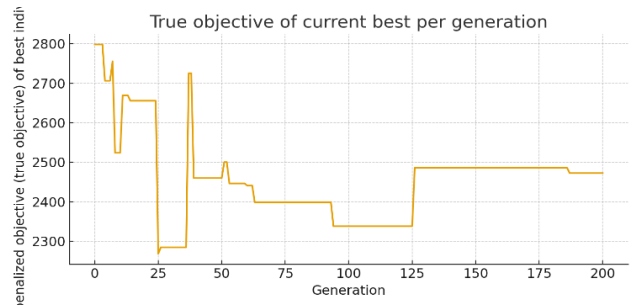


Fig.10. Penalized objective of current best per generation for scenario I

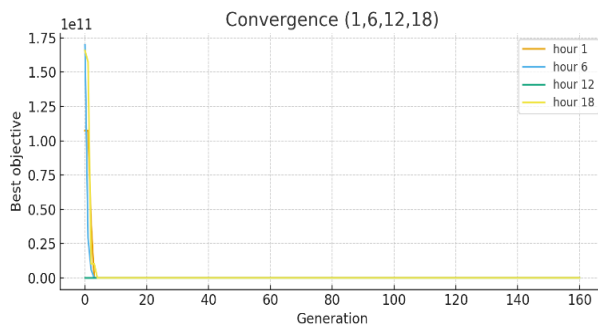


Fig.11. Minimum total objective (sum of feasible hour objectives) only for scenario II

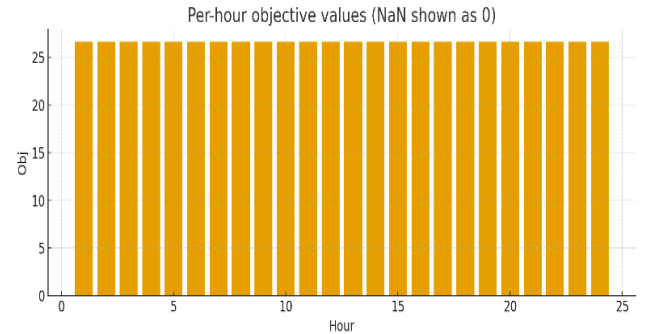


Fig.12. Per-hour objective (sum over 24 hours, summing feasible hours) using differential

Scenario I consists of the centralized electricity network, CHP unit, PV system, boiler, and biomass unit. The proposed configuration is adjusted with a BESS, which is the case of a scenario II. Scenarios III and IV are the same as Scenario II but with natural gas price rises of 50 per cent and 200 per cent, respectively. These are the situations that evaluate the impacts of changes in the fuel prices on the decision-making process of the system.

Table III. Comparative Analysis of the Estimated Scenarios

Scenario Specifications	Total Cost (₹)	Cost Change (%)
Scenario I (GRID, PV, CHP, BOILER & BIOMASS Generations)	2472.6919	-11276.544
Scenario II (GRID, PV, CHP, BOILER, BIOMASS & BESS generations)	638.7013804276503	-2838.585
Scenario III (Same as Scenario II; natural gas price increased by 50%)	3153.9532	-14,410.942
Scenario IV (Same as Scenario II; natural gas price increased by 200%)	271.59182605959893	-1149.561

All the elements of production and consumption are synchronized to work within the stipulated system limits. These limitations include grid balancing, CHP units, PV generation, battery storage, thermal storage, absorption chillers, boilers and biomass systems. Table III shows the total operating expenses in all the scenarios. As mentioned above, the Scenario I the baseline with no BESS has the largest cost of ₦2472.6919. By adding a battery storage unit the final cost is decreased to ₦638.7013804276503. These results are conclusive that the release of the BESS into the central grid is better economical as an effective energy management plan is established and all operation constraints are achieved. The analysis further shows that, in cases where, the BESS state of charge (SOC) is high at the time of charging, and the discharging cost is less than the price of purchasing energy at the grid, the stored energy is discharged co-ordinately to get the greatest savings. This means that the total demand of the micro-grid, comprising household requirements, BESS charging requirements and heating, cooling requirements can be easily optimized with the help of optimized coordination of the supply sources. This is carried out by use of a differential evolution (DE)-based optimization model which takes into account operating costs and various constraints. The figures of resulting costs justify the possibility and efficiency of an integrated energy system design.

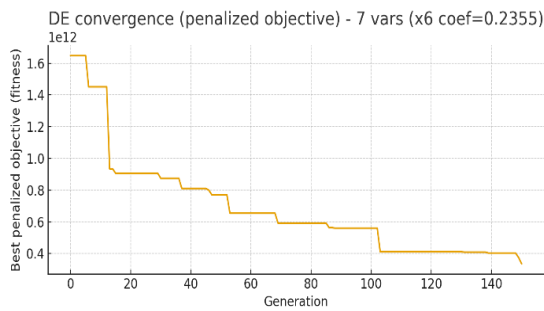


Fig.13. Best solution curve derived using the Differential Evolution algorithm for Scenario III (with a 50% rise in natural gas (NG) price).

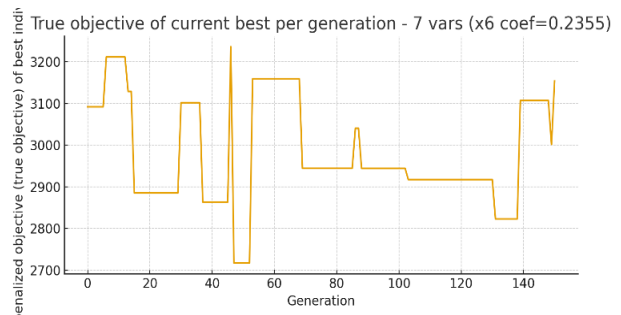


Fig.14. Penalized Objective of current best per generation for scenario III (with a 50% rise in natural gas (NG) price).

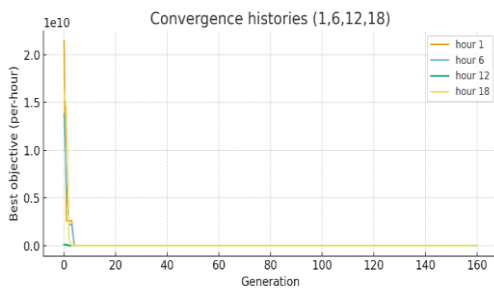


Fig.15. Minimum total objective (sum of feasible hour objectives) for scenario IV (with a 200% rise in natural gas (NG) price).

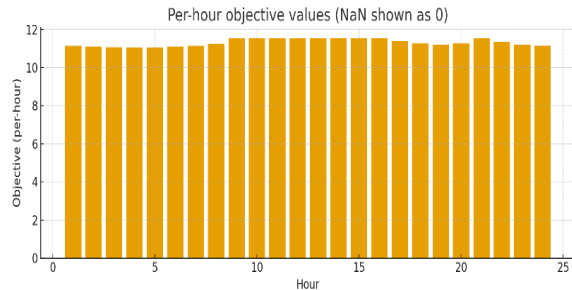


Fig.16. Per-hour objective (sum over 24 hours, summing only feasible hours) using differential evolution algorithm for scenario IV (with a 200% rise in natural gas (NG) price).

Figs.13-16 present the convergence properties of natural gas pricing of the integrated system in Scenarios III and IV, which was done as part of sensitivity analysis. This analysis shall attempt to measure and estimate the extent of responsiveness of changes in the main input parameters viz. fuel prices on the total electricity cost of this system as calculated through the DE model. Fuel cost was chosen as a sensitivity coefficient and the effects of this in cost minimization in the micro-grid were studied. In this analysis, the sensitivity of the external gas price has been set to 50 per cent and 200 per cent and the sensitivity curves have been drawn in Figs. 13-16. The plots suggest that there is a high dependency of the electricity cost on the external gas price change, particularly due to the CHP and boiler fuel usage. In addition, the findings indicate that the system will decrease gas use and switch to cheaper substitutes e.g. PV, grid electricity when the cost of gas increases. On the other hand, in cases where gas is cheap, gas-powered units such as the CHP unit and gas boilers are more important as in Scenarios I and II. The results strongly indicate that as gas prices are increased, so does the cost of operating which is indicated in Scenarios III and IV. Meanwhile, such outcomes validate the versatility and responsiveness of the combined energy system that can reallocate both the resources of the

generation dynamically in reaction to the market changes without compromising the cost and reliability optimization.

Conclusion

In this work, a hybridized system architecture of power systems is proposed and this will involve the combination of gas, electricity and heat networks to optimally work. We tested mathematical modeling and optimization of the process of management of micro-grids. The combined system is effective in addressing the cooling, heating, and electricity needs. The supply side of the system that was analyzed is a photovoltaic (PV) system, with a biomass boiler, CHP unit and centralized electricity network. A differential evolution algorithm was employed to design system components and its operational constraints to decrease the daily costs of electrical energy. Moreover, a BESS was incorporated on the consumer side to make operations more flexible. The uncertainty of PV generation was solved using a stochastic method based on a scenario. The PV output was estimated on a daily basis by use of solar irradiance. Real time-of-use tariffs and gas price were included in the analysis. Various configurations were tested by a number of scenario studies. The outcomes indicate that the operational costs are greatest in Scenario I (Grid, PV, CHP, Boiler, and Biomass) in the absence of BESS. The BESS addition saved on the cost by a huge margin of about 2838.585 as compared to the baseline. The DE-based optimization yields numerical results to verify that the model optimization method is used to optimize several sources of generation (solar PV), conversion devices (CHP, boiler), storage systems (electrical and thermal), and distribution networks (grid) to reduce the cost of electricity in micro-grids. Finally, it is concluded that the smart grid will be most effective when all consumer and producer equipment are pursuing the suggested strategy, as it will allow the owner to save a significant amount of money on operating the devices and even generate revenue trading the excess power to the network at the market price.

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Performance Evaluation of a Brake Fluid Tester for Testing the Suitability of Natural Oils as Brake Fluids

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Abstract

The abundant natural resources in African countries continue to receive attention with the advocacy for clean environments (SDG 7) and technological innovations (SDG 9). Many seed oils extracted have innumerable potentials, but few of these have been explored. Dynamometers are used to test engine and brake performances with different fuels or brake types. This work presents a brake dynamometer developed with a full brake system for testing seed oils for automotive power applications. A 750hp electric motor was used as the prime mover, coupled to the full brake system with a flexible jaw-type coupling to maximise power transfer. The mechanical properties of the fluid in terms of speed, torque, and fluid pressure were measured with a tachometer, strain gauges and a pressure sensor with jatropha oil and DOT 3 synthetic oil. The trend of the results showed that the brake tester was properly calibrated, and the results are repeatable and consistent. Hence, the device can be used for fluid power testing irrespective of the type of oil.

Keywords: brake dynamometer, seed oils, jatropha oil, brake oil

1. Introduction

The use of oil extracted from seeds has been applied in various fields, including automotive applications, as fuels and lubricants, in response to the Sustainable Development Goals (SDGs). It is expedient to consider the replacement of synthetic oils with natural oils, considering their abundance and environmental friendliness, which is in line with SDG 7. The automobile applications are based on the kind of tests conducted on these oils, which are mostly chemical tests. Mechanical properties of these oils have not been explored, even when the properties are close to those of synthetic oils used for power purposes. There is a proliferation of equipment for chemical analysis of oils Acharya et al. (2021), but for mechanical tests, it is scarce. It is therefore expedient to develop equipment that can perform the mechanical power tests for oils. Most tribological investigations of braking utilise the full brake system dynamometer, comprising all components of the braking system found in a vehicle (Grochowicz et al., 2010; Stephan & Georg-Peter, 2016). This work presents a full brake system to test the suitability of natural and synthetic oils as brake oils for automotive and power applications in line with SDG 7 and 9 on clean environments and responsible technological innovations.

Brake dynamometers are developed to test internal combustion engine performance, especially the effectiveness of different fuels and the performance of brake components (Vojtisek-Lom et al., 2021). Most of these oils were used as biodiesels when mixed with diesels in proportions. The production, optimisation and testing of these biodiesels have been widely reported (Singh et al., 2021).

Seed oils have been used as lubricants to replace petroleum products by automotive manufacturers. In 2005, Ford Research and Advanced Engineering Group published an article where soybean oil was investigated. Polyurethane foam was extracted from soybean oil by reacting a polyol blend of petrochemical and soy-based material with methane diisocyanate, aided by some chemical processes (Deborah F. Mielewski, 2005).

Kumar and Purushothaman (2012) (S.Senthil Kumar, 2012) explored the high acid content of rubber seed oil through esterification and transesterification to verify its viability through its emission characteristics. It was discovered that the emission characteristics fall within allowable limits for automobile applications (S.Senthil Kumar, 2012). Idris et al (2018) (Usman, 2018) experimented on neem seed, comparing its chemical properties with Society of Automotive Engineers' lubricant (SAE 40) lubricant. The results showed that it has close tribological properties to SAE 40 lubricant (Usman, 2018). Non-edible vegetable oil-based feedstocks have been used as bio-lubricants in automotive applications because they are more environmentally friendly (Singh et al., 2019).

The functionality of the braking is highly dependent on the quality of brake fluid. It was discovered that the boiling point of brake fluid offers better assessment than the moisture content (Caban et al., 2020). Vimallesh A et al (2024) developed a device for real-time monitoring of the fluid parameters in a braking system (Vimallesh A, 2024). This device comprises an electronic control unit which can be integrated into an automobile vehicle to detect moisture content, fluid level, and temperature of the brake fluid. Glišović et al (2012) described a dynamometer system for reproducing the brake noise to detect early noise, especially in newly changed brake pads (Jasna Glišović, 2012).

Magnetorheological braking systems have been tested with different fluids and braking scenarios (Singh & Sarkar, 2024). Acharya et al (2021) compared the torque output of synthetic and commercial fluids on the magnetorheological brake (Acharya et al., 2021). These commercial fluids have much lower viscosity compared to the synthetic fluid, but the torque generated was close to the synthetic fluid torque. An automated brake pad tester was developed to reduce the human effort during testing. The hydraulic system adapted was devoid of oil leakage and eliminated the risk of electric shock (Simatupang, 2021). To measure the residual brake torque during braking, a combined analytical method and a mechatronic device measurement approach was adopted to accurately give the value of the torque in the brake system (Kowalski et al., 2024).

2. Methodology

This section provides the design, materials selection, and experimental methods of a brake fluid testing apparatus with jatropha oil. Jatropha oil was selected because it has a similar coefficient of friction and service life as SAE 40. Jatropha oils have a 2.4% longer service life than SAE 40 (Omisanya, 2021).

2.1 The Dynamometer Design

The conceptual design presents the framework and operating principles for the apparatus. The key components and their assembly are also discussed. The following were considered for the design parameters selection;

- Ability to test a range of brake fluids under replicable conditions
- Variable speed control to evaluate speed-dependence
- Inclusion of sensors to measure torque, pressure, and stopping time
- Withstanding prolonged testing without deterioration
- Operational safety for the user
- Portability for flexible usage

A horizontal configuration was chosen for the motor and brake assembly for compactness. The braking system was arranged exactly as it operates in a car. Figure 1 shows preliminary sketches for the brake system assembly and the material selection in Table 1.

The components were selected, sized, and designed to simulate medium-duty automotive braking conditions up to 140 kph. The materials chosen balanced functionality, durability, and cost-effectiveness.

The open vertical layout enabled flexibility in testing different brake fluids. The final assembly is presented in Figure 2.

3.1 Design Calculations

The part designs are presented here. Table 2 presents the parameters considered in the design of the major components of the dynamometer, while Table 3 presents the properties of the electric motor selected.



Fig. 1: Sketch of the dynamometer

Table 1: Material selection

Material		Specifications	Purpose
Electric motor		750W (1hp), 220V This serves as AC single phase the prime electric motor mover in place 1400 RPM max of the internal speed, Inline- combustion mounted engine. configuration Coupled to the brake disc shaft via flexible jaw coupling	
Brake assembly		270 mm diameter cast iron brake disc 2-piston hydraulic brake calliper Automotive-grade brake pads Hand-operated hydraulic master	It comprises a full automobile brake set-up, where the oil pressure efficiency is tested.
		cylinder (10cc capacity)	
Frame		- Welded steel frame with dimensions $70.6\text{ cm} \times 41.7\text{ cm} \times 39.6\text{ cm}$ - Motor mounts and baseplate	It was designed to house and support the testing apparatus in a horizontal position.

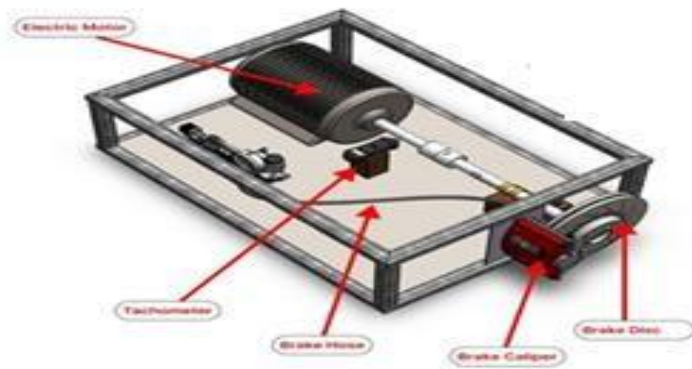


Fig. 2: 3D model of the brake fluid tester

Available car brakes all dissipate heat at a much higher rate, so for our application, heat dissipation is not a bottleneck for selection, but for compatibility, a small brake disc size of diameter 270 mm was selected.

1.2 Other Components Development

Frame and support: 2 mm L-shaped mild steel pipes were used for the frame, following the initial design. However, the final dimensions and shape were based on the calculation and the 3D Computer Aided drawings (CAD).

1.2.1 Electric Motor

A 750W AC single-phase induction motor was sourced from an automation equipment supplier to drive the brake disc during testing (Figure 3). This motor rating was selected to provide sufficient power to simulate medium-duty automotive braking conditions while allowing variable speed control across a wide rpm range.

The motor had an IP55 protective enclosure rating, meaning it was dust-proof and protected against low-pressure water jets from any direction.

To enable precise speed control for the experiments, the motor was coupled with a compatible variable 2000 W silicon-controlled regulator (SCR) Voltage Regulator/Motor Speed Controller Module (Figure 4). This electronic controller can vary the input voltage and frequency to the motor in order to adjust its rotational velocity as needed.

This was critical to systematically test the brake fluid performance across the planned speed range. The drive allowed the motor speed to be easily modulated via analogue inputs or directly from its digital interface. Speeds could be set accurately to within 1 rpm, and the acceleration/deceleration ramps could be customised for controlled starting and stopping. Multiple parameter pre-sets were configured into the drive for quick access during testing.

Table 3: Specifications for single-phase variable speed electric motor

Properties	Value
Power	0.75 kW
Horsepower	1 HP
Speed	1440 rpm
Voltage	220 V
Mounting Type	Foot
Frequency	50 Hz
Ambient Temperature	45°C
Material	Mild Steel

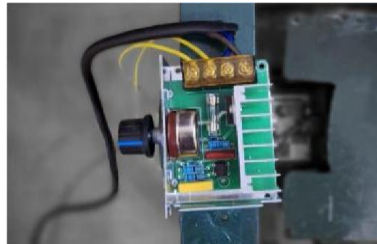
Table 2: Design calculations for the electric motor and brake disc selection

Part	Calculation	Results
Electric motor sizing	Moment of inertia (I) $I = 0.5 \times m \times r^2$ $= 0.5 \times 6.5 \times (0.135)^2$ $= 0.059 \text{ kg} \cdot \text{m}^2$	
	Angular velocity (ω) $\omega = 2\pi N/60$ $= 2 \times 3.14 \times 1400/60$	146 rad/s
	Kinetic energy (E) $E = 0.5 I \omega^2$ $= 0.5 \times 0.059 \times (146)^2$	628 J
	Power (P) $P = E/t$ $= 628 \text{ J} / 1 \text{ s}$	628W
Brake Disc Selection	Calculate maximum kinetic energy Kinetic energy (E) (previously calculated)	
	Calculate heat dissipation rate Given:	
	Energy to be dissipated per stop = 628 J Average stopping time = 2 seconds Heat dissipation rate = E/t	314 W
	$= 628 \text{ J} / 2 \text{ s}$	

Mass of disc (m) = 6.5 kg; Radius of disc (r) = 0.135 m; Max speed (N) = 1400 rpm Time to reach max speed = 1s; Disc mass (m) = 6.5 kg; Disc radius (r) = 0.135 m

1.1.1 Brake Assembly

A full brake assembly was purchased and set up, made with a 270 mm diameter automotive motor rotor made from premium grade cast iron for optimal wear resistance, friction, and heat dissipation. The brake calliper features parallel-mounted dual pistons to provide balanced clamping force. Silicone composite seals ensured fluid containment and pressure tolerances exceeding system requirements.

**Fig. 3:** Electric**Fig 4:** speed motor controller/voltage regulator

High-performance semi-metallic brake pads were chosen to provide optimal friction with the cast iron material while standing up to the heat and pressures involved. The pad compound was formulated for racing applications, with increased heat tolerance and low wear rates during aggressive braking.

The Toyota Corolla brake master cylinder was incorporated into the testing apparatus to provide hydraulic fluid delivery. The original equipment cylinder was adapted without modifications to leverage the stock bore size, sealing and fluid capacity suited for automotive braking. To actuate the master cylinder, a custom hand brake pedal was fabricated and integrated into a C-section steel mounting frame (Simatupang, 2021). The lever pushes the master cylinder input rod when braking is required. Flexible curved jaw-type couplings (Figures 4 and 5) were used to connect the shaft ends of the electric motor and the brake arrangement.

The jaws compensated for minor misalignments up to 0.5° and 0.15 mm offset, while dampening vibrations. High strength set screws and keys prevented slippage under torque loads.



Fig. 5: Flexible

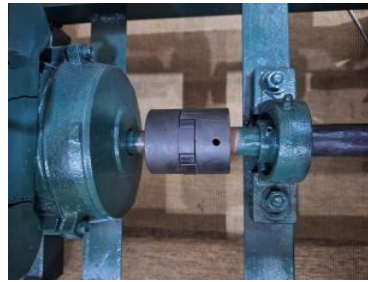


Fig. 6: Assembled coupling flexible coupling

1.1.2 Instrumentation

The torque measurement features a 4-arm strain gauge full bridge assembly (Figure 7) using 350 Ω resistance foil, which was glued to the shaft (Table 4). A pressure gauge of 0 – 70 bar was attached to the fluid pipe to measure the fluid pressure delivered to the brake system, while a digital tachometer was used for speed measurement. Data capturing was done with the aid of a data acquisition unit.

Table 4: Specification of the strain gauge

Specification	BF series
Nominal resistance(Q)	350, 650, 1000
Tolerance of resistance	< +/- 0.1%
Gauge factor	2.00-2.20
Gauge factor resistance	< +/- 1%
Strain limit	2.00%
Fatigue life	> 10 ⁷
Effective modulus compensation	not available
Metal foil	constantan alloy
Creep compensation	available
Working temperature range	-30-+800C



Fig. 7: Arrangement of the strain gauge

1.2 Testing

The testing of the dynamometer was conducted to compare the braking force of jatropha oil extracted from jatropha seed with synthetic brake oil. The following steps were taken to prepare the apparatus hydraulics with the fluid being evaluated:

- Draining of old brake fluid from previous tests
- Thorough flushing of the hydraulic lines and components with isopropyl alcohol to remove residue
- Bleeding the master cylinder and calliper lines by pumping the pedal to purge all air bubbles
- Refilling the system with the fresh brake fluid sample to be tested
- Additional bleeding to eliminate any remaining trapped air
- Pumping the pedal to build proper hydraulic pressure and confirm braking
- Inspecting for leaks and smooth fluid delivery at the calliper.
- Repeating drainage, flushing, bleeding, and filling between tests on different fluid samples

The time and pressure of the fluids in the brake pipes were recorded.

2. Results and Discussion

This section presents the outcome of the fluid tester development and its performance in providing the braking property of jatropha oil and synthetic fluid.

2.1 The Assembled Fluid Tester

The design calculations and considerations were utilised for the materials selection and assembly.

2.2 The Instrumentation Performance

A pressure gauge attached to the fluid transmission pipe gives the value of the pressure applied by the fluid for each braking activation. A tachometer was pointed at the input shaft of the brake system to measure the rotational speed, while the strain gauges attached to the shaft measured the change in voltage as a reflection of twisting stress. The resulting assembly is presented in Figure 8.



Fig. 8: Full assembly of the brake fluid tester dynamometer

2.3 Testing Results and Comparison of Oil Outputs

The following were carried out before each test batch.

- The frame, motor, brake assembly, and sensors were inspected for any damage or loosened connections
- The strain gauge bridge circuit was tested for continuity and calibration using precision loads
- The pressure gauge was calibrated up to its maximum range using a hydraulic pressure calibrator.
- The optical tachometer was pointed at the reflective tape on the target disc.
- Cameras were positioned optimally and configured to record in high definition
- The data acquisition system was programmed to sample sensors at appropriate rates
- Safety guards were checked, and warning signs were placed visibly
- Cables were secured to avoid entanglements during operation
- Lighting was adjusted to ensure good visibility of the apparatus and measurements.

- The area around the equipment was cleared of clutter to allow unobstructed testing

Table 5: Physical characteristics of the brake fluid tester

	Value	Unit
Equipment Dimensions		
Mass	49.4	kg
Length	70.6	cm
Width	41.7	cm
Height	39.6	cm
Brake Disc		
Mass	6.5	kg
Diameter	270	mm
Moment of Inertia, I	5.92×10^{-2}	kg.m ²
Modulus of elasticity, E	200	GPa
Shaft		
Diameter	25	mm
Polar moment of inertia, J	3.83×10^{-8}	m ⁴
Modulus of elasticity, E	200	GPa
Strain Gauge		
Resistance	350	ohms(Ω)
Gauge Factor (GF)	2	-
Excitation Voltage (V_{ex})	8.5	V
Unstrained Voltage (V_o)	0	V
Configuration	Full Bridge	-

Once configured, the motor was run through a range of speeds, and the brakes were tested to confirm smooth engagement across expected operating RPMs. Test runs confirmed proper functioning before commencing formal trials. The tests were repeated three times to ensure the integrity, repeatability, and reproducibility of the readings. The results of the raw data measured are presented in Table 6. The strain gauge readings were taken after the brake successfully halted the rotation of the electric motor.

Table 6: Test results for pressure, voltage and time

	DOT 3			Jatropha oil		
Speed (rpm)	1000	1100	1200	1000	1100	1200
Pressure (bar)	2.0	5.0	8.0	1.0	2.0	3.0
Voltage (mV)	5.1	7.5	12.6	2.6	3.9	5.9
Time (sec)	0.32	0.429	0.503	0.765	0.928	1.083

This means that the initial voltage was 0. The voltage was converted to torque by the developed data acquisition unit (Simatupang, 2021) and the calculated torque is presented in Table 7.

Table 7: Calculated torque values

	DOT 3			Jatropha oil		
Speed (rpm)	1000	1100	1200	1000	1100	1200
Torque (Nm)	178.82	262.97	441.79	91.16	136.7	206.87

The ratio of the torque exerted by jatropha oil is around half that of the synthetic oil. This indicates that twice the pressure needs to be applied to the brake disc to bring it to a halt at the same time as the synthetic oil, as evidenced by the time to halt rotation and the values in Table 8.

The brake system adapted for the system is that of a 2.0 L engine, hence the required braking effort is much. If smaller engine automobiles are used, there is the possibility of achieving the required braking power if the braking system is modified. The range of variation between the torque values for DOT 3 and jatropha oil is 53% and 35 % respectively.

From the standard deviation of the torque for jatropha and DOT 3, the increment follows a similar ratio, indicating that the expansivity of jatropha oil is similar to that of synthetic oils used for brake fluid (Acharya et al., 2021). In other words, the brake system can be modified to accommodate jatropha oil for use as brake fluid. However, more tests are necessary to determine the thermal properties of jatropha oil, as torque and braking power are more essential.

The range of values for the pressure exerted by the oil is relatively low compared to what is obtainable in real-life applications. These higher values are necessary because of the load to be overcome, such as the vehicle weight and the friction between the road and the tyres.

Conclusions and Recommendations

The brake fluid tester was designed and fabricated with the intention of testing the braking properties of synthetic and natural oils for automotive use. It was discovered that;

- The torque recorded for the jatropha oil was lower than that of DOT 3, which is a synthetic oil used in automobile braking systems.
- The deviation along the different speed braking application for the synthetic and jatropha oils is similar.
- Jatropha oil has the potential of being used as brake fluid if the braking system can be modified to accommodate the range of force and pressure it delivers.

Further studies into the thermal properties of jatropha oil are necessary in comparison to those of synthetic oil to further strengthen its adaptability for automotive applications. This property, in addition to the braking pressure recorded by the brake fluid tester, will provide the parameters of design for the modification of the braking system.

Table 8: Table of applicable descriptive statistics

	DOT 3		Jatropha oil	
	1100 (rpm)	1200 (rpm)	1000 (rpm)	1100 (rpm) 1200 (rpm)
Difference of torques		178.82		45.58 70.13
Ratio (max/min)		1.54		
Range (max- min)		115.71		

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Prediction of fuel-related properties of *papaya* seed oil and lard oil methyl esters from their fatty acid methyl ester compositions-based models

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Abstract

This work aims to establish a correlation between the compositions of fatty acid methyl ester (FAME) and the key fuel properties of methyl ester. The experimental data of the analysis was obtained from the methyl esters of calcined hybrid-banana-plantain-peel ash (CHBPPA)-catalyzed methanolysis of *papaya* seed oil (PSO) and lard oil (LO) produced at the optimal reaction conditions of temperature 60°C:57°C, catalyst amount 2.5 wt. %:2.5 wt. %, time 1 h:1.5 h, and methanol/oil molar ratio 9:1:10.5:1, respectively. PSO and LO methyl esters were characterized using American Society for Testing and Materials (ASTM) methods, as well as Fourier-Transform-Infrared-Spectroscopy (FTIR) and Gas Chromatography-Mass Spectrometry (GC-MS) to determine their physicochemical properties, functional groups, and FAME compositions. Methyl Oleate (C₁₉H₃₆O₂) was identified as the dominant ester in PSO (48.01%) and LO (31.63%) methyl esters. PSO methyl ester was found to possess 54% monounsaturated fatty acids, while LO methyl ester was predominantly composed of 58% saturated fatty acids. The predicted fuel properties included cetane number (CN), higher heating value (HHV), iodine value (IV), and saponification value (SV). These predicted values, derived from the FAME profiles, were compared with experimental values obtained through ASTM standard testing. The average absolute deviations (AAD) between predicted and experimental values for PSO and LO methyl esters were 3.64:4.85, 0.83:1.92, 11.66:10.46, and 2.16:3.29% for CN, HHV, IV, and SV, respectively, indicating a good correlation. Hence, a satisfactory prediction of the fuel-related properties based on the FAME composition can be given by the models, signaling the possibility of establishing a cost-effective and improved efficiency process.

Keywords: fatty acid methyl ester (FAME), fuel properties, lard oil, models, *papaya* seed oil, prediction

1. Introduction

In the pursuit of sustainable energy sources and the mitigation of environmental impacts associated with fossil fuels, methyl ester, commonly known as biodiesel, has emerged as a promising alternative for transportation and industrial fuels (Ezekannagha et al., 2025; Wang et al., 2025). Derived from renewable feedstocks such as vegetable oils, waste cooking oils, and animal fats, methyl ester offers the potential for reduced greenhouse gas emissions and decreased reliance on finite petroleum resources (Guimaraes, 2025). Amongst the available feedstocks for methyl ester synthesis, lard oil (LO) and *papaya* seed oil (PSO) stand out due to their abundance, oil content, low cost and potential as viable sources. Feedstock selection plays a vital role in determining the sustainability of methyl ester production (Ansari et al., 2025). In addition, understanding and predicting the fuel-related properties of

methyl ester derived from these feedstocks are crucial steps towards their sustainability and efficient utilization in the transportation sector. Lard oil is a by-product of the pork rendering process and is among the least expensive feedstocks available for methyl ester synthesis (Ezekannagha et al., 2024). On the other hand, papaya seeds are not consumed and have sufficient oil content ranging from 30% – 34%, which makes them useful as feedstock for biodiesel production.

Triglycerides, the main constituents of vegetable oils and animal fats, undergo transesterification reaction to yield fatty acid methyl esters (FAMES), the key components of biodiesel (Ezekannagha et al., 2023). The fatty acid composition of biodiesel is directly derived from its parent oil or fat, and this composition significantly impacts the fuel's properties, implying that the characteristics of biodiesel are largely dependent on the fatty acid structure of the source oil utilized (Ezekannagha et al., 2017, Knothe 2009). As the chemical composition of these FAMES, characterized by the types and proportions of fatty acids present, greatly influences the fuel properties of biodiesel, factors such as cetane number, higher heating value, viscosity, density, and oxidative stability play pivotal roles in determining biodiesel's performance in internal combustion engines (Bamgboye and Hansen 2008).

Prior research has elucidated correlations between the fatty acid composition of biodiesel feedstocks and their resulting fuel properties. For instance, saturated fatty acids tend to enhance oxidative stability, but they can also elevate viscosity, while unsaturated fatty acids often contribute to improved cold flow properties but may compromise oxidative stability. These complicated interaction patterns underscore the importance of understanding how the compositions of lard oil and papaya seed oil, specifically their FAME compositions influence the fuel-related properties of the resulting methyl esters (Esonye et al., 2018).

While predictive models exist for estimating biodiesel properties based on FAME compositions of common feedstocks like soybean oil and palm oil, there remains a gap in utilizing these comprehensive models tailored to predict the fuel-related properties of lard oil and papaya seed oil methyl esters. Employing accurate predictive models for these feedstocks (lard oil, papaya seed oil, etc.) and their methyl esters is essential for biodiesel producers, researchers, and policymakers to make informed decisions regarding feedstock selection and process optimization. Leveraging models to predict the key fuel properties of lard oil and papaya seed oil methyl esters will enhance understanding of the relationship between their chemical compositions and the fuel-related properties. Ultimately, there will be facilitation of the efficient utilization of these alternative feedstocks in methyl ester production, thereby promoting sustainability and reducing reliance on fossil fuels.

Notably, Tong et al., (2011) and Gopinath (2009) have demonstrated the feasibility of using FAME compositions to predict some key fuel properties of biodiesel derived from different feedstocks. However, to the best of our knowledge, there is limited research specifically on predicting the fuel-related properties of papaya seed oil methyl ester (PSOME) and waste lard oil methyl ester (WLOME) based on their FAME compositions.

Therefore, this study aims to address this gap in literature by employing models to predict some fuel-related properties (cetane number-CN, higher-heating-value-HHV, saponification value-SV and iodine value-IV) of PSO and WLO methyl esters based on their FAME compositions as determined by GC-MS. This will contribute to the advancement of utilizing models in biodiesel research and the sustainable development of the biodiesel industry. It will also facilitate the transition to a more environmentally friendly transportation sector. In addition, the influence of fatty acid composition on the fuel-related properties of PSOME and WLOME was ascertained.

2. Materials and Methods

2.1 Materials

Discarded *papaya* seeds and waste pork lard obtained from Ariaria market, Enugu, and home-based waste were utilized to extract *papaya* seed oil and lard oil, respectively. Calcined hybrid banana-plantain peel ash (CHBPPA) synthesized from a prior experiment by Ezekannagha et al., (2024) was utilized. Extractive solvent (n-hexane), methanol (CH_3OH , 99.8% purity) and other chemicals/reagents were purchased from Conraws Company Ltd, Enugu. All the chemicals and reagents employed were of superior purity.

2.2 Analytical Methods

The PSO, WLO, and the methyl esters of *papaya* seed oil and lard oil obtained at the optimum reaction conditions of temperature 60°C: 57°C, catalyst amount of 2.5 wt.%, 2.5 wt.%, time of 1 h: 1.5 h, and methanol/oil molar ratio of 9:1: 10.5:1 in prior experiments of Ezekannagha et al., (2024) and Ezekannagha et al., (2024a), respectively, were subjected to ASTM methods, FTIR, and GC-MS characterization techniques. The physico-chemical properties, FTIR-based functional groups and the GC-MS-based fatty acid compositions of the papaya seed oil (PSO), waste lard oil (WLO), *papaya* seed oil methyl ester (PSOME) and waste lard oil methyl ester (WLOME) were ascertained.

2.2.1 American Society for Testing and Materials (ASTM) Methods

The PSOME and WLOME fuel-related properties, saponification value (SV), and iodine value (IV) were determined using standard laboratory techniques as stipulated by the ASTM International standard (Equations (1-2)) while cetane number (CN) and higher heating value (HHV) were ascertained from Equations (3-4) suggested by Mohibbe et al., (2025) by substituting the experimental values of IV and SV in Equations (3) and (4), respectively.

$$\text{Iodine value-IV} = \frac{V_b - V_a \times 12.69 \times 0.1}{\text{Wt.}(g) \text{ of sample}} \quad (1)$$

$$\text{Saponification value-SV} = \frac{56.1 \times N \times (V_b - V_a)}{\text{Wt.}(g) \text{ of sample}} \quad (2)$$

w= weight of oil taken in grams, N= normality of HCl solution, V_a= volume of HCl solution used in the test in millilitres, V_b= volume of HCl solution used in the blank in millilitres.

$$\text{Cetane number-CN} = 46.3 + \left(\frac{5458}{SV}\right) - 0.225(IV) \quad (3)$$

$$\text{Higher heating number-HHV} = 49.43 - [0.041(SV) + 0.015(IV)] \quad (4)$$

2.2.2 Fourier Transform Infrared (FTIR) Spectroscopy Analysis

Papaya seed oil (PSO), papaya seed oil methyl ester (PSOME), waste lard oil (WLO) and waste lard oil methyl ester (WLOME) samples were subjected to FTIR spectroscopy analysis (Model: Agilent-Cary 630) for functional group identification in the wavelength region of 4000 - 650 cm⁻¹.

2.2.3 Gas Chromatography -Mass Spectrometry (GC-MS) analysis

The fatty acid compositions of PSOME and WLOME were examined using GC-MS (Model: Agilent 6890 gas chromatograph, CA, USA).

2.2.4 Prediction of PSO and WLO methyl ester fuel properties from their fatty acid methyl ester compositions-based models

Based on the compositions of the different compounds present in the PSOME and WLOME determined by GC-MS, the saponification value (SV), iodine value (IV), cetane number (CN), and higher heating value (HHV) of the biofuels were calculated.

The saponification and iodine values of the PSOME and WLOME were calculated, respectively, via the model expressions (Equations 5-6) adopted by Ezekannagha et al., (2017).

$$IV = \sum \frac{(254 \times D_i \times A_i)}{MW_i} \quad (5)$$

$$SV = \sum \frac{(560 \times A_i)}{MW_i} \quad (6)$$

where IV is the iodine value, SV is the saponification value, D is the number of double bonds; A_i and MW_i are the percentage composition and molecular mass of a particular ester, respectively.

The cetane number and higher heating values of PSOME and WLOME based on the GC-MS data were calculated by substituting the empirical values of Equations 5 and 6 in Equation 3 and Equation 4, respectively, as applied by Ezekannagha et al., 2017.

Degree of unsaturation (DU) was determined based on percentages of monounsaturated and polyunsaturated FAMES of the PSOME and WLOME, respectively, with Equation (7).

$$DU = (\text{monounsaturated Cn} : 1 \text{ wt}\%) + 2 (\text{polyunsaturated Cn} : 2, 3 \text{ wt}\%) \quad (7)$$

Saturated fatty acid methyl esters (FAMES) have single bonds between carbon atoms e.g. (Cn:0). Monounsaturated FAMES have one double bond between carbon atoms, e.g., (Cn:1); and Polyunsaturated FAMES have multiple double bonds between carbon atoms e.g., (Cn:2, 3).

2.3 Comparison of the ASTM experimental and model-predicted values

The error functions- absolute relative error (ARE), average absolute deviation (AAD), variance S^2 , and residual root mean square error (RMSE) were used to perform the error analysis and variability of the experimental and predicted datasets. The metrics are shown in Equations (8-11).

(i) The absolute relative error (ARE):

$$ARE = \left| \frac{(\text{predicted} - \text{experimental})}{\text{experimental}} \right| \quad (8)$$

(ii) The average absolute deviation (AAD):

$$AAD = \frac{100}{n} \sum_{i=1}^n \left| \frac{\phi_{cal} - \phi_{exp}}{\phi_{exp}} \right| \quad (9)$$

(iii) The variance (S^2):

$$S^2 = \sum \frac{(\phi_{cal} - \phi_{exp})^2}{n-1} \quad (10)$$

(iii) The residual root mean square error (RMSE):

$$RMSE = \sqrt{\frac{1}{n-2} \sum_{i=1}^n (\phi_{exp} - \phi_{cal})^2} \quad (11)$$

where n is the number of data points, ϕ_{exp} , ϕ_{cal} are the respective experimental and calculated/predicted property values

3. Results and Discussion

3.1 Physiochemical properties of PSO and PSO methyl ester

Table 1 comprises the results of the physicochemical characterization of the PSO and optimum PSO methyl ester. The PSOME results are compared with the ASTM D6751 and EN14214 international standards. The acid value, free fatty acid and kinematic viscosity reduced to a large extent, followed by specific gravity, saponification and iodine values, water content and flash point, which also reduced moderately after the transesterification reaction. This shows that the transesterification reaction has a great influence on the PSO conversion to PSO methyl ester. A great conformity was noted on comparing the PSO methyl ester with the international standards for fuel (ASTM D6751; EN14214), which indicates its aptness to be consumed in a diesel engine.

Table 1: PSO and PSOME fuel-related properties

Properties	Units	PSO	PSOME	ASTM D6751	EN14214
Acid-value	MgKOH/g oil	5.3	0.46	0.50 max.	0.50 max
Free-Fatty-Acid	%	2.7	0.23	-	-
Specific-gravity@30°C	-	0.902	0.855	0.86 – 0.90	0.85
Kinematic-viscosity@40°C	mm ² /s	44.860	3.56	1.9 – 6.0	3.5 – 5.0
Saponification-value	MgKOH/g oil	215.384	188.6	-	-
Iodine-value	gI ₂ /100g oil	46.192	40.30	-	3 min
Water-content	%	0.5	-	-	-
Peroxide-value	MEq/kg	43.91	-	-	-
Cetane-number	-	-	67	47 min	51 min
Higher-heating-value	MJ/kg	-	41.2	40 – 42	-
Flash-point	°C	228	126	130 min	120 min
Cloud-point	°C	-	+3	-3 to 12	-
Pour-point	°C	-	+2	-15 to 10	-

3.2 Physicochemical Properties of WLO and WLO Methyl Ester

Table 2 depicts the physicochemical properties of the WLO and WLO methyl ester. The acid value, free fatty acid, and kinematic viscosity decreased drastically when compared with the values obtained from the waste lard oil. This indicates the CHBPPA-catalyzed transesterification reaction has a great impact on the process with improved fuel quality. Though the physicochemical properties of the WLO methyl ester compared positively with other researchers' findings, they are contained in the ASTM D6751 and EN-14214 limits.

Table 2: WLO and WLOME fuel-related properties

Properties	Units	WLO	LOME	ASTM-D6751	EN-14214
Acid-value	mgKOH/g oil	2.2	0.28	0.50 max	0.50 max
Free-fatty-acid	%	1.1	0.14	-	-
Specific-gravity@30 °C	-	0.915	0.873	0.86 – 0.90	0.85
Kinematic-viscosity@40 °C	mm ² /s	80.994	4.63	1.9 – 6.0	3.5 – 5.0
Saponification-value	mgKOH/g oil	226.459	199.7	-	-
Iodine-value	gI ₂ /100g oil	34.491	32.42	-	3 min
Water-content	%	0.53	-	-	-
Peroxide-value	MEq/kg	81.40	-	-	-
Cetane-number	-	-	68	47 min	51 min
Higher-heating-value	MJ/kg	-	41.1	40 - 42	-
Flash-point	°C	240	135	130 min	120 min
Cloud-point	°C	-	+9	-3 to 12	-
Pour-point	°C	-	+6	-15 to 10	-

3.3 PSO and PSO methyl ester functional groups

The PSO and PSO methyl ester samples were analyzed via FTIR to determine the functional groups present in the samples, which exhibited a high level of similarities, as could be seen in Figs. 1-2. This could be as a result of the inherent high-level chemical similarities that exist between triglyceride and methyl ester emanating from the C=O and C-O ester functional groups present in the analyzed samples. However, functional group modification was observed in the FTIR spectrum of the PSO after the transesterification process whereby it was converted to biodiesel. The significant modifications were observed in the FTIR spectra region of 1500 – 1000cm⁻¹, which is due to the replacement of the CH₂ functional group in the triglyceride by the CH₃ functional group in the methyl ester. The peak at 1241.2cm⁻¹ in the PSOME spectrum suggests the asymmetric stretching of the group C-O-C. The nonexistence of a peak in the region of 1650 -1540cm⁻¹ implies the absence of soap formation, commonly referred to as saponification, in the synthesized biodiesel. Niju *et al.*, (2018) and Salaheldeen *et al.*, (2015) obtained similar results to the results recorded in this study.

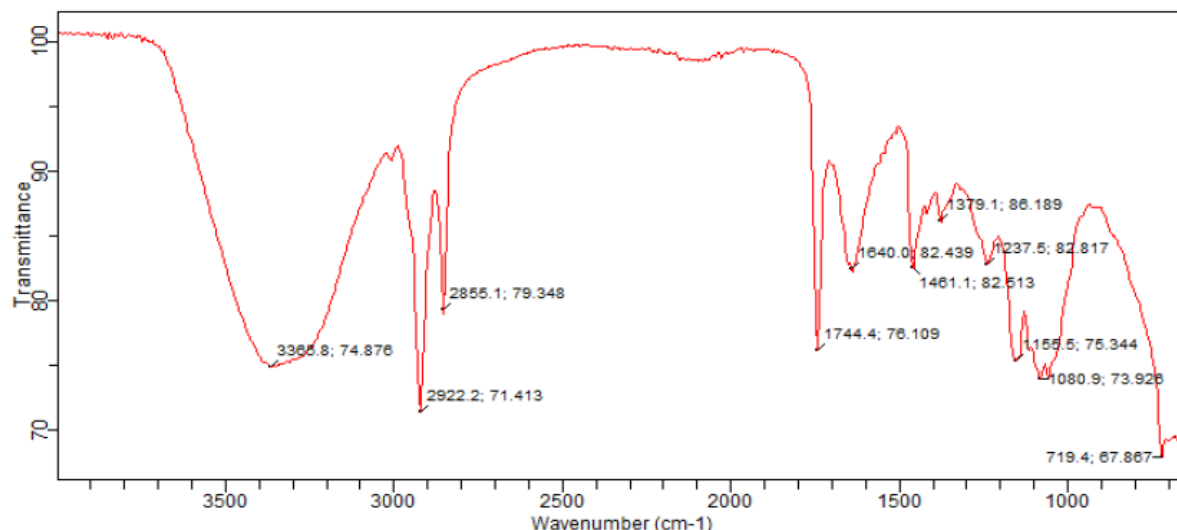


Fig. 1: FTIR spectrum of PSO.

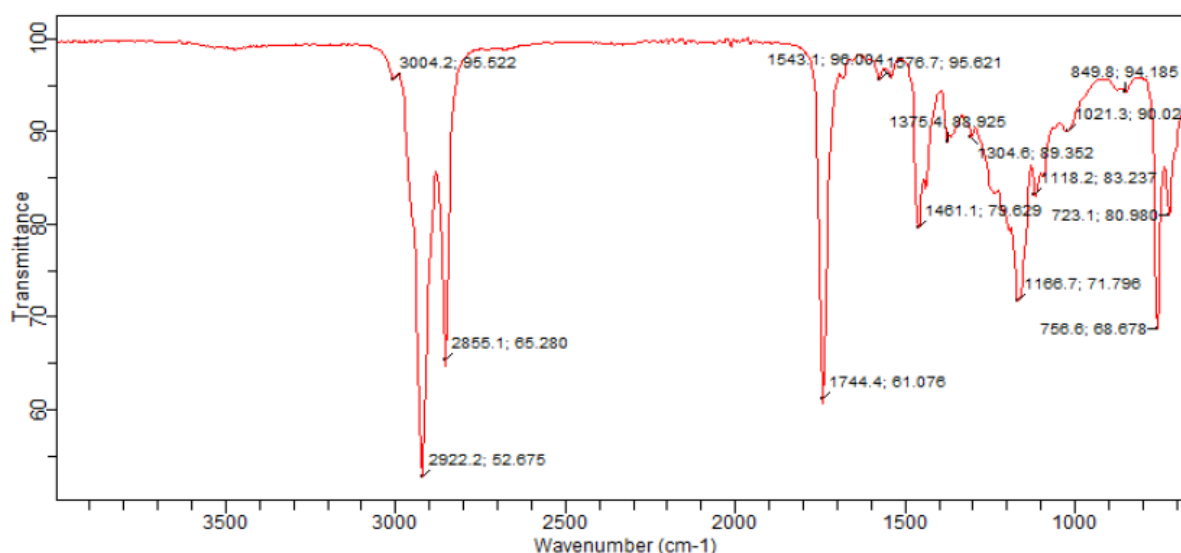


Fig. 2: FTIR spectrum of PSO methyl ester.

3.4 WLO and WLO methyl ester functional groups

WLO and WLO methyl ester samples were analyzed using FTIR to determine the functional groups present in the samples. The FTIR spectra of the WLO and transesterified lard oil-WLO methyl ester were carried out in the range of 4000 - 650 cm⁻¹ to study the effect of transesterification on the lard oil. The FTIR spectra results of WLO and WLO methyl ester are shown in Figs. 3 - 4, respectively. Changes were observed in the (%) transmission and the functional groups, which indicate the modifications that occurred during the transesterification process. The FTIR spectra of the WLO and WLO methyl ester are very similar because of high chemical similarities that exist between triglycerides and methyl ester. However, a small difference is observed in these three regions: C=O ester, CH₃ and C-O ester, as WLO methyl ester has a different compound/functional group bonded, methyl - CH₃, compared to the lard oil, which has CH₂ bonded to it. In Figs. 3 - 4, the strong ester peaks at 1744cm⁻¹ (C=O ester) and at 1170 - 1200 cm⁻¹ (C-O ester) are clearly present in the WLO and WLO methyl ester spectra, which is where the high similarities between the triglyceride and methyl ester emanate from. According to Meyer *et al.*, (2000), the wave frequencies (cm⁻¹); for C=O ester and C-O ester functional groups are 1750 - 1725cm⁻¹ and 1170 - 1200cm⁻¹ respectively. This compared favorably with the wavenumber ranges found in the WLO and WLO methyl ester spectra, in this study for the C=O and C-O ester groups. Outside these two regions, another characteristic peak which indicates the presence of CH₃ group in the

mixtures of methyl ester can be observed at 1445cm^{-1} . A similar finding was reported by Yun Hin *et al.*, (2011).

It should also be noted that triglycerides irrespective of the natural source they are derived from, like animal fats, vegetable oil, plant oil etc. contain the same functional groups. This could be seen in Fig. 1 and Fig. 3 for PSO and WLO, respectively. Similar functional groups in PSO and WLO were also recorded by several other researchers, such as Niju *et al.*, (2018) and Salaheldeen *et al.*, (2015), confirming the observation made.

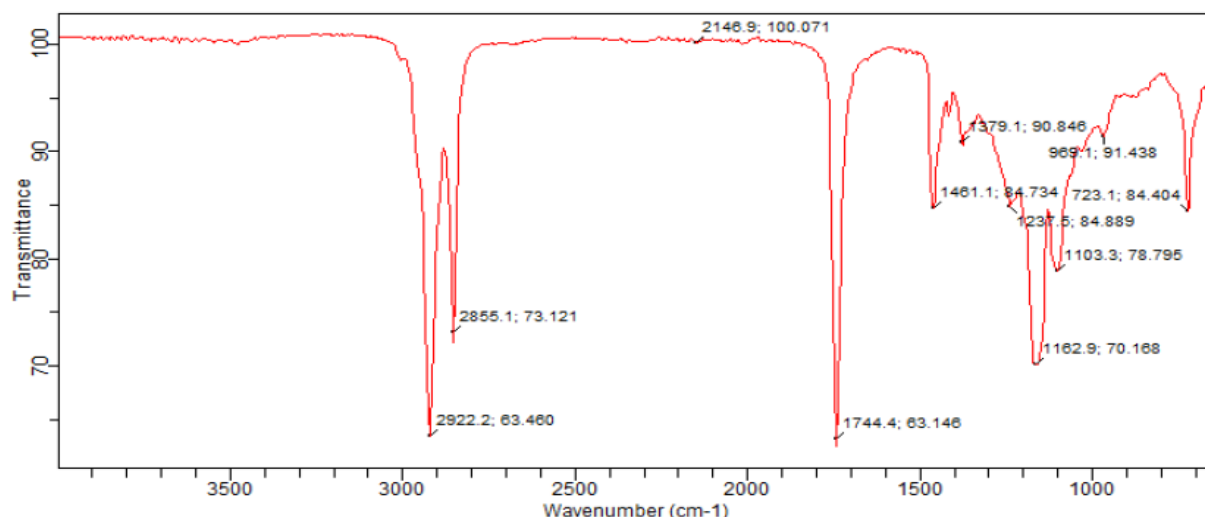


Fig. 3: FTIR spectrum of WLO.

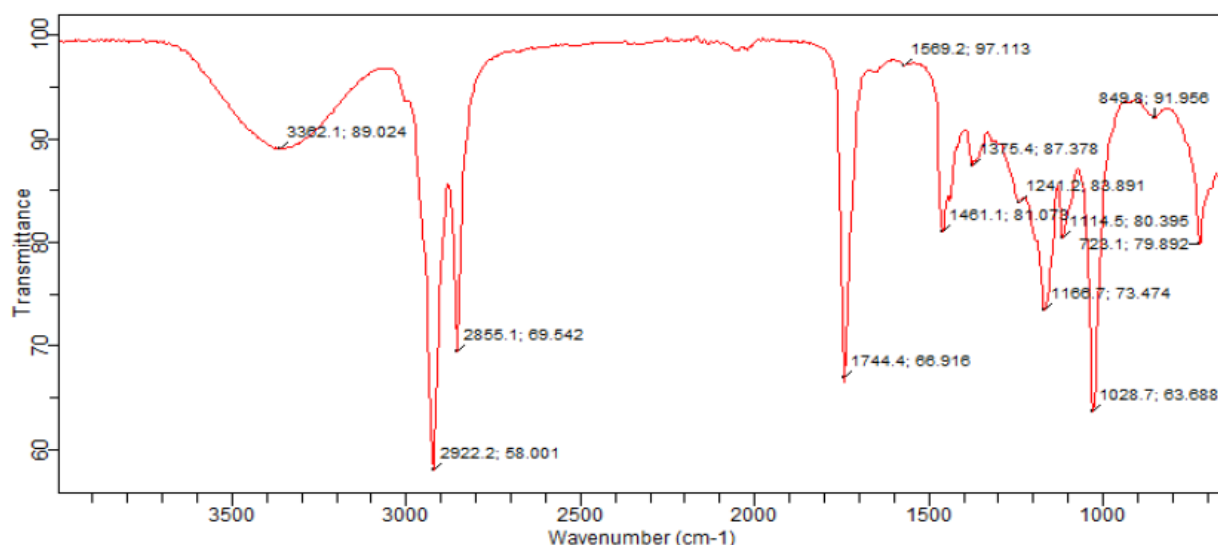


Fig. 4: FTIR spectrum of WLO methyl ester.

3.5 PSO Methyl Ester Fatty Acid Content

The fatty acid methyl ester (FAME) content of the analyzed PSO methyl ester was summarized in Table 3, while the chromatogram was depicted in Figure 5. The profile results of the analyzed sample shown in Table 3 revealed 9-octadecenoic acid, methyl ester (E)- (methyl oleate: $\text{C}_{18}\text{H}_{34}\text{O}_2$) as the predominant fatty acid compound with the highest percentage of 48.6%, followed by hexadecanoic acid, methyl ester (methyl palmitate: $\text{C}_{16}\text{H}_{32}\text{O}_2$) with 27.44%, and are monounsaturated fatty acid (MUFA) and saturated fatty acid (SFA), respectively. The result infers that the unsaturated compound is more than the saturated compound. This implies that the synthesized PSOME will not solidify easily when used in engines rather it will flow just like the conventional diesel fuel. The findings of Agunbiade *et al.*, (2014)

corroborate with the results of this study. The palmitic and oleic acids in the analyzed sample resulted in 75.45% of the fatty acid methyl ester composition which suggests good fuel properties. A similar order of FAME compounds was also observed in the LOME sample analyzed. Polyunsaturated fatty acids (PUFA's), also termed essential fatty acids, which are compounds with more than one carbon double bond, are not present in the analyzed sample. The methyl esters with area (%) less than 0.10 were unpublished in Table 3.

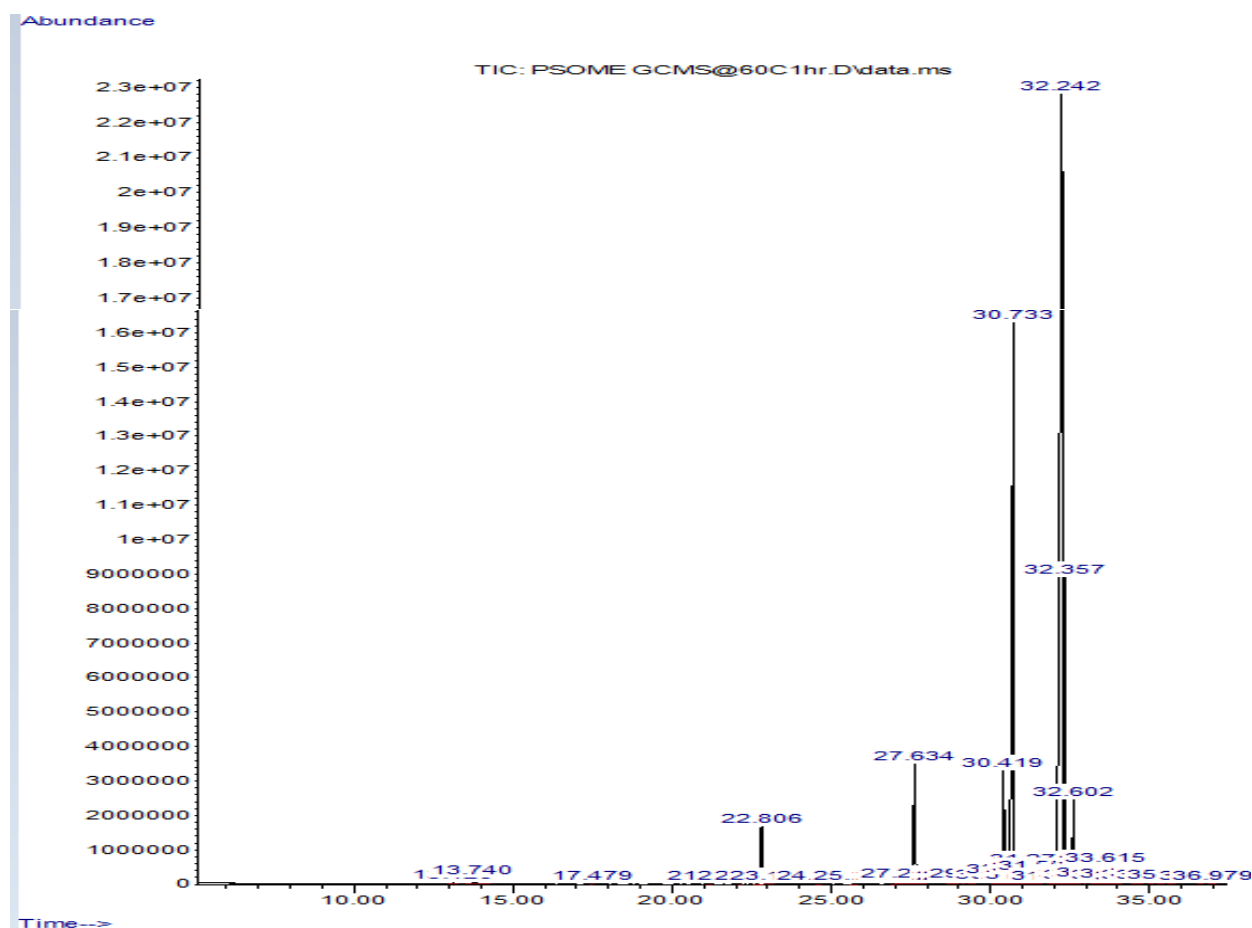


Fig. 5 GC-MS chromatogram of FAME of PSO methyl ester

Table 3: Fatty acid methyl ester content of PSO methyl ester

Retention Time (Mins)	wt. (%)	Compound	Structure	Formula
22.806	2.37	Dodecanoic acid, methyl ester (lauric acid)	C13:0	C ₁₃ H ₂₆ O ₂
27.257	0.14	Methyl myristoleate	C15:1	C ₁₅ H ₂₈ O ₂
27.634	6.13	Methyl tetradecanoate (myristic acid)	C15:0	C ₁₅ H ₃₀ O ₂
30.419	3.12	9-Hexadecenoic acid, methyl ester, (z)-(palmitoleic acid)	C17:1	C ₁₇ H ₃₂ O ₂
30.733	27.44	Hexadecanoic acid, methyl ester (palmitic acid)	C16:0	C ₁₆ H ₃₂ O ₂
32.242	48.01	9-Octadecenoic acid, methyl ester (E)- (oleic acid)	C19:1	C ₁₉ H ₃₆ O ₂
32.357	6.88	Methyl stearate (stearic acid)	C19:0	C ₁₈ H ₃₆ O ₂
33.458	0.52	cis-11-Eicosenoic acid, methyl ester (gondoic acid)	C21:1	C ₂₁ H ₄₀ O ₂
33.615	0.42	Eicosanoic acid, methyl ester (arachidonic acid)	C20:0	C ₂₀ H ₄₀ O ₂

3.6 WLO methyl ester fatty acid content

The values of the fatty acid methyl ester compositions and the chromatogram of the lard oil methyl ester (LOME) were presented in Table 4 and Figure 6, respectively. Only methyl ester peaks were seen on the chromatogram, with the nonexistence of other characteristic peaks, which ascribes that the synthesized methyl ester is of top quality. Table 4 shows that the lard oil methyl ester produced consists mainly of hexadecanoic acid, methyl ester, (palmitic acid: 27.84%) and 9-octadecenoic acid (z)-, methyl ester (oleic acid; 31.63%) which are saturated and monounsaturated compounds, respectively. The implication of this is that the biodiesel will have less affinity to oxygen, which leads to quick peroxidation. The synthesized LOME is also of high quality with respect to stability, as a higher degree of unsaturation in FAME limits the suitability for use as a fuel due to a high polymerization tendency resulting from peroxidation.

The methyl esters with area (%) less than 0.10 were not published.

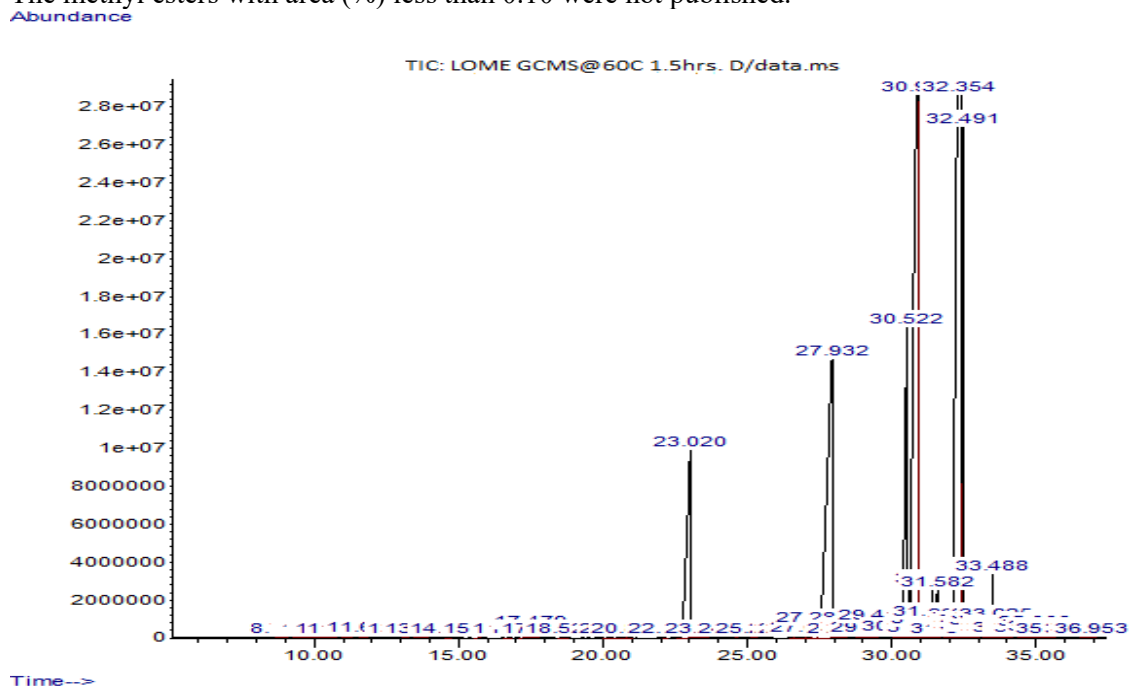


Fig. 6: GC-MS chromatogram of FAME of WLO methyl ester

Table 4: Fatty acid methyl ester content of LO methyl ester

Retention wt. Time (Mins) (%)	Compound	Structure	Formula
23.020 7.04	Dodecanoic acid, methyl ester (lauric acid)	C13:0	C ₁₃ H ₂₆ O ₂
27.286 0.36	Methyl myristoleate	C15:1	C ₁₅ H ₂₈ O ₂
27.932 14.95	Methyl tetradecanoate (myristic acid)	C15:0	C ₁₅ H ₃₀ O ₂
30.522 7.31	9-Hexadecenoic acid, methyl ester, (z)- (palmitoleic acid)	C17:1	C ₁₇ H ₃₂ O ₂
30.895 27.84	Hexadecanoic acid, methyl ester (palmitic acid)	C16:0	C ₁₆ H ₃₂ O ₂
31.405 0.45	cis-10-Heptadecenoic acid, methyl ester	C18:1	C ₁₈ H ₃₄ O ₂
31.582 0.39	Heptadecanoic acid, methyl ester (margaric acid)	C17:0	C ₁₇ H ₃₄ O ₂
32.354 31.63	9-Octadecenoic acid (z)-, methyl ester (oleic acid)	C19:1	C ₁₉ H ₃₆ O ₂
32.491 6.80	Methyl stearate (stearic acid)	C19:0	C ₁₉ H ₃₈ O ₂
32.674 0.20	9,12-Octadecadienoic acid, methyl ester (linoleic acid)	C18:2	C ₁₈ H ₃₂ O ₂

33.488	0.75	cis-11-Eicosenoic acid, methyl ester (gondoic acid)	C21:1	
$C_{21}H_{40}O_2$				
33.625	0.13	Eicosanoic acid, methyl ester (arachidonic acid)	C20:0	$C_{20}H_{40}O_2$

3.7 Prediction of Fuel Properties from the Models Based on the Fatty Acid Content

The compositions of PSO methyl ester and WLO methyl ester synthesized at optimum reaction conditions of temperature 60 °C:60 °C, catalyst content 2.5 wt%:2.5 wt%, time 1 h:1.5 h, and methanol/oil molar ratio of 9:1:10.5:1, respectively, were determined with GC-MS. Based on the compositions of the different compounds present in the PSO methyl ester (Table 3) and WLO methyl ester (Table 4), and the model expressions as given in Equations (3-6), the cetane number (CN), higher heating value (HHV), saponification value (SV), and iodine value (IV) of the fuel were calculated.

3.7.1 Prediction of PSO Methyl Ester Fuel Properties

The predicted values of the fuel properties, saponification value (SV), iodine value (IV), cetane number (CN) and the higher heating value (HHV) of the GC-MS-based fatty acid content of PSO methyl ester are summarized in Table 5. It could be visualized in Table 5 and Figure 7 that the percentage composition of the unsaturated fatty acid methyl ester of PSOME is more than the saturated percentage composition. This suggests that the synthesized PSOME will flow easily in a diesel engine.

The experimental values of the physicochemical properties of PSOME shown in Table 5 were found to be very close to the predicted values of these properties determined with the ASTM method, as confirmed by the low absolute relative error, thus in good agreement. This confirms the reliability of the listed fuel properties prediction from its fatty acid composition based on the model expressions, which looks very promising in mitigating laboratory cost and time spent.

Table 5: Predicted and experimental values of the PSO methyl ester fuel properties

Parameter	Experimental values	Predicted values	Absolute relative error
Saponification value (mgKOH)	188.6	192.68	0.0216
Iodine value (gI ₂ /100g)	40.30	45	0.1166
Cetane number (CN)	67	64.56	0.0364
Higher heating value (HHV) MJ/kg	41.2	40.86	0.0083
Saturated FAME (%)	-	43.24	-
Monounsaturated FAME (%)	-	51.79	-
Polyunsaturated FAME (%)	-	-	-
Degree of unsaturation	-	51.79	-

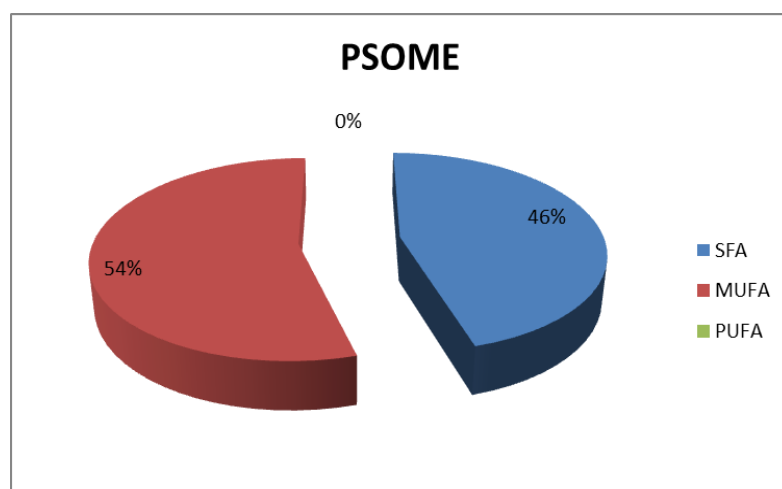


Fig. 7: Fatty acid distribution in PSO methyl ester

3.7.2 Prediction of WLO Methyl Ester Fuel Properties

Table 6 illustrates the predicted values of the fuel properties of WLO methyl ester. It could be seen from Table 6 and Figure 8 that the percentage composition of the saturated compound outweighs that of monounsaturated and polyunsaturated, hence the degree of unsaturation. This observation is typical of methyl ester synthesized from animal fats, which have a high content of saturated compounds. This implies that LOME may be more stable to deterioration than FAME compositions of samples with a higher degree of unsaturation and could also solidify at low temperature characteristics of cold and temperate regions of the globe. As could be visualized in Table 6, the predicted values of the fuel properties of WLO methyl ester determined via the models based on the GC-MS fatty acid compositions are in reasonable agreement with the experimental values of these properties determined with the ASTM method as confirmed by the low absolute relative error values. The results obtained in this study suggest that the fuel properties of the methyl esters could be satisfactorily estimated from their fatty acid composition, thus alleviating laboratory cost, time and energy.

Table 6: Predicted and experimental values of the WLO methyl ester fuel properties

Parameter	Experimental values	Predicted values	Absolute error	relative error
Saponification value (mgKOH)	199.7	206.28	0.0329	
Iodine value (gI ₂ /100g)	32.42	35.81	0.1046	
Cetane number (CN)	68	64.70	0.0485	
Higher heating value (HHV) MJ/kg	41.1	40.31	0.0192	
Saturated FAME (%)	-	57.15	-	
Monounsaturated FAME (%)	-	40.5	-	
Polyunsaturated FAME (%)	-	0.2	-	
Degree of unsaturation	-	40.7	-	

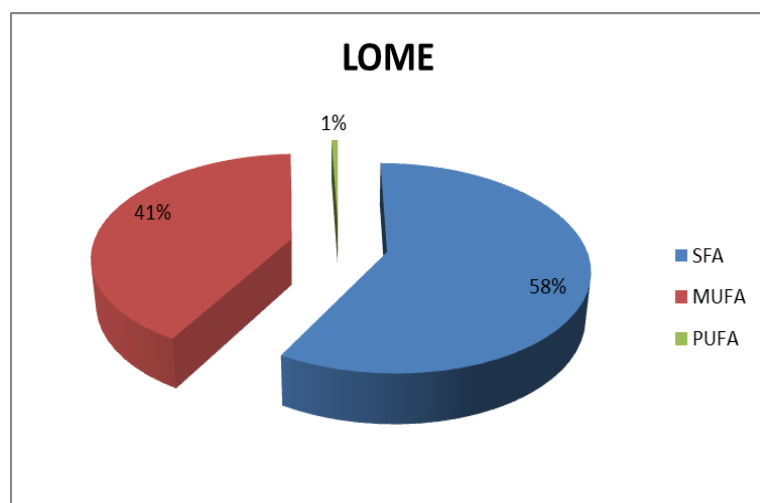


Fig. 8: Fatty acid distribution in PSO methyl ester

3.7.3 Comparison of PSO methyl ester and WLO methyl ester fuel-related properties

The degree of unsaturation of PSO methyl ester was observed to be higher than WLO methyl ester which suggests less stability than WLO methyl ester. This observation is supported by the iodine value of PSOME (45%), which was found to be greater than that of LOME (35.8%), corroborating its unsaturation property. The larger the iodine value, the larger the degree of unsaturation (UKessays, 2025). Cetane number measures how easily ignition occurs and the smoothness of combustion. PSOME and LOME showed relatively high cetane numbers of 64.56 and 64.70, respectively, indicating better ignition quality. According to Meher et al., (2006), the higher the cetane number, the better the ignition quality and efficiency of the fuel, and vice versa. Fuels with low cetane numbers show an increase in gaseous and particulate exhaust emissions due to incomplete combustion. Higher heating value (HHV)

or heat of combustion denotes the quantity of heat discharged by the complete combustion of a unit quantity of fuel and it is an important parameter for approximating fuel consumption. The greater the heat of combustion, the lower the fuel consumption. The ASTM D6751 standard for fuel specifies 40-42 as the limit for the HHV, while according to the EN14213, the minimum specification for the heating value is 35 MJ/kg. Both the PSOME and LOME HHV fall within this specification, indicating good fuel quality. Methyl Oleate ($C_{19}H_{36}O_2$) was found to be the dominant ester in PSO and LO methyl esters with percentage weights of 48.01% and 31.63%, respectively. However, PSO methyl ester consists of 54% monounsaturated fatty acids, while LO methyl ester is mainly composed of saturated fatty acids, totaling 58%. PSOME is likely to possess poor storage stability, enhanced cold flow properties (cloud and pour points) at low temperatures, and low thermal efficiency, deciphering to lower CO and HC emissions when compared with saturated LOME with better storage stability and poor low-temperature flow properties. This observation is also in accordance with the works of Agunbiade (2014). The fuel properties, cetane number (CN), higher heating value (HHV), iodine value (IV), and saponification value (SV) recorded an average absolute deviation (AAD) of 3.64:4.85, 0.83:1.92, 11.66:10.46, and 2.16:3.29% for PSO and LO methyl esters, respectively. The absolute relative error of the properties for each of the methyl esters was found to be very low, depicting a good correlation in existence between the predicted and experimental data. This was derived from the application of the error functions and subsequently comparing the fuel properties experimental data obtained from the ASTM method with the predicted data from the model based on the fatty acid composition of the PSO and WLO methyl esters, respectively.

4. Conclusion

The predicted values of the fuel-related properties, cetane number (CN), higher heating value (HHV), iodine value (IV), and saponification value (SV) of the PSO and WLO methyl esters via models based on their fatty acid methyl ester compositions indicated a good correlation with the experimental values derived from the ASTM methods. Hence, a satisfactory prediction of the fuel-related properties from the FAME compositions could be given by the models. Methyl Oleate ($C_{19}H_{36}O_2$) was found to be the dominant ester in PSO and LO methyl esters, with percentage compositions of 48.01% and 31.63%, respectively. PSO methyl ester possesses 54% monounsaturated fatty acids, while LO methyl ester has 58% saturated fatty acids. It is established from the results that the choice of feedstock can significantly impact the fatty acid content of the methyl esters and hence, the fuel properties. The methyl esters of PSO and WLO physicochemical properties established are within the EN14214 and ASTM D6751 allowable limits; hence, they are fitting for utilization in an internal combustion engine.

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Competing interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Data availability

The manuscript has no associated data.

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