

**ENGINE COMBUSTION, PERFORMANCE, AND
EMISSION CHARACTERISTICS OF HERMETIA
ILLUCENS LARVAE OIL IN A COMPRESSION
IGNITION ENGINE**

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Doctor of Philosophy

UNIVERSITI MALAYSIA PAHANG



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I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy.

A handwritten signature in black ink, appearing to read 'Rusdi' or a similar name, is placed over a horizontal line.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.



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In the Name of Allah, the Most Gracious, the Most Merciful

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ABSTRAK

Ekoran bahan api organik telah mendapat perhatian dunia sebagai salah satu bahan api alternatif berpotensi, ia juga telah menjurus ke arah perdebatan hangat yang disebabkan oleh kaedah semasa penghasilannya, seperti kesan jangka panjang terhadap harga makanan, kos yang tinggi, keperluan tanah pertanian, dan kebergantungan kepada bahan api berasaskan sayuran. Oleh yang demikian, sumber bahan mentah dengan kos rendah boleh digunakan untuk menghasilan bahan api organik telah dikaji. Kitaran hidup yang belum matang bagi sesetengah serangga berkebolehan untuk mengkonsumsi pelbagai jenis bahan buangan organik untuk pembentukan lemak. Jumlah lemak yang dihasilkan adalah berbeza antara kumpulan serangga dan spesis. Ia dijangkakan menghasilkan 1.5 ke 77.0% kandungan lemak daripada bahan keringnya. Ini menunjukkan setiap 100 g bahan kering serangga mengandungi kira-kira 1.5 ke 77.0 g lemak. Oleh yang demikian, serangga yang mempunyai kandungan lemak tinggi ini berpotensi sebagai bahan mentah kepada bahan api organik. Dalam kajian ini, bahan api berasaskan larva yang dihasilkan dari spesis *Hermetia illucens* ("black soldier fly") berpotensi untuk menghasilkan kandungan lemak dengan anggaran 15.5 ke 34.8% daripada bahan keringnya (anggaran 15.5 ke 34.8 g kandungan lemak daripada 100 g bahan keringnya) telah dikaji dengan melihat potensinya sebagai gantian minyak sayuran dan mengurangkan kebergantungan kepada sumber petroleum. Kajian ini diinspirasikan oleh keperluan kritikal untuk menyiasat kesan bahan api berasaskan larva *Hermetia illucens* yang dicampur dengan minyak diesel ke atas karakteristik pembakaran enjin, prestasi, dan pelepasan asap pada enjin penyalaan mampatan satu silinder suntikan langsung. Eksperimen telah dijalankan menggunakan enjin satu silinder tanpa modifikasi Yanmar TF120M penyalaan mampatan pada halaju malar 1500 rpm di bawah pelbagai bebanan enjin. Bahan api mentah berasaskan larva *Hermetia illucens* dan campurannya (B25, B50, B75, and B100) telah digunakan dalam enjin tersebut, bagi tujuan mengenalpasti karakteristiknya dalam pembakaran, prestasi, dan pelepasan asap. Model regresi telah dibina menggunakan metodologi permukaan tindak balas untuk meramalkan kepentingan parameter prestasi enjin dan pelepasan asap dengan perubahan trend sifat bahan api. Hasil kajian mendapati bahawa tekanan dalam silinder, kadar pelepasan haba, dan kelewatan pembakaran masing-masing telah berkurangan secara purata sebanyak 2.27%, 12.89%, dan 12.36%. Brek penggunaan bahan api tertentu dan suhu gas ekzos telah meningkat masing-masing 32.92% dan 4.70% berbanding dengan minyak diesel. Brek kecekapan haba telah didapati menurun sebanyak 30.0% berbanding minyak diesel. Kajian turut mendapati bahawa pelepasan karbon monoksida, karbon dioksida, dan hidrokarbon tidak terbakar telah meningkat pada 86.68%, 15.04%, and 950.00% tiap satu, dengan penambahan bahan api larva *Hermetia illucens*. Pencemaran nitrogen oksida menunjukkan trend yang baik dengan penurunan 14.67% berbanding dengan minyak diesel pada semua bebanan enjin. Analisis varians eksperimen menghasilkan tahap keyakinan pada 95% menunjukkan bahawa model yang dibina adalah signifikansi. Perbandingan hasil eksperimen dengan yang diramalkan oleh model yang dibina menunjukkan hubungan rapat yang mempunyai pekali kolerasi R^2 tinggi untuk pelbagai pemboleh-ubah tindak balas. Secara keseluruhan, kajian ini telah menyimpulkan bahawa bahan api larva *Hermetia illucens* mempunyai potensi yang tinggi untuk digunakan sebagai bahan api alternatif untuk kegunaan enjin pembakaran mampatan pada masa hadapan.

ABSTRACT

As biofuel grabbed the world's attention as one of the potential alternative fuels, it's also has promoted a drastic debate due to its present production status, such as the long-term impact on food prices, high cost, arable land requirement, and vegetable oil dependency. Therefore, lower cost feedstock can be used for biofuel production has been investigated. The immature life stage of certain insects is capable to consume numerous organic wastes for fat accumulation. The amount of fat produced is different among various insects order and species. It expected to produce about 1.5 to 77.0% fat content from its dry matter. This indicates that every 100 g dried matters of the insect comprise approximately fat about 1.5 to 77.0 g. Therefore, this high fat containing insect has the potential to serve as a biofuel feedstock. In this study, the insect larval grease extracted from *Hermetia illucens* (the black soldier fly) with the potential to produce fat content approximately 15.5 to 34.8% of its dry matters (about 15.5 to 34.8 g of fat content from 100 g of its dried matters) was investigated by looking at its potential as a substitute for vegetable oil and to reduce dependency on petroleum resources. The research is motivated by the need to critically examine the effect of *Hermetia illucens* larvae oil mixed with diesel fuel on engine combustion, performance, and emission characteristics of a single-cylinder direct injection compression ignition engine. The experiment was performed using a single cylinder unmodified Yanmar TF120M compression ignition engine at a constant speed of 1500 rpm under various engine loads. The neat of *Hermetia illucens* larvae oil and its blends (B25, B50, B75, and B100) were utilized in the engine in order to identify its combustion, performance, and emission characteristics. Regression models were developed using the response surface methodology to predict the significant of engine performance and emission parameters with fuel property's changing trend. The results revealed that in-cylinder pressure, heat release rate, and the ignition delay were reduced by an average of 2.27%, 12.89%, and 12.36%, respectively. The brake specific fuel consumption and exhaust gas temperature increased 32.92% and 4.70%, respectively than that of diesel fuel. The brake thermal efficiency was discovered to be lower by 30.0% compared to diesel fuel. The finding also shows that carbon monoxide, carbon dioxide, and unburned hydrocarbon emissions increased by 86.68%, 15.04%, and 950.00%, respectively with the addition of *Hermetia illucens* larvae oil. The nitrogen oxides emissions indicates good improvement trend by 14.67% reduction as compared to diesel fuel at all the engine loads. Analysis of variance (ANOVA) of the experimental results at 95% confidence level exposed that the developed models are significant. Comparison of experimental output with those predicted by the developed models indicated close proximity having high correlation coefficients R^2 for the various response variables. Overall, this study concluded that the *Hermetia illucens* larvae oil possesses a high potential to be utilized as a promising alternative fuel for compression ignition engines in the future.

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LIST OF SYMBOLS

α	Pressure sensitivity exponent
β	Temperature sensitivity exponent
β_0	The regression coefficient for the intercept
β_i	Regression coefficients of the linear parameters
β_{ii}	Regression coefficients of the quadratic parameter
β_{ij}	Regression coefficients of the interaction parameters
ε	Residual (error) associated with the experiments
f	Oscillation frequency
η_{Energy}	Energy efficiency
η_{Exergy}	Exergy efficiency
η_{mech}	Mechanical efficiency
ρ	Density
θ	Crank angle
ν	Kinematic viscosity
γ	Specific heat ratio
\uparrow	Increase / longer
\downarrow	Lower / decrease
\sim	Similar / no change
-	Not available

LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
A	Ash
A. pubescens	<i>Agonoscelis pubescens</i> (sorghum bug)
A. viduatus	<i>Aspongubus viduatus</i> (melon bug)
A, B	Cell constants measured from the oscillation frequencies
AFR	Air-fuel ratio
Al ₂ O ₃	Aluminium oxide
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
aTDC	After top dead centre
B. peregrine	<i>Boettcherisca peregrine</i> (flesh fly)
BBD	Box-Behnken design
Bd	Biodiesel
BDC	Bottom dead center
BEE	Brake exergy efficiency
BHA	Butylated hydroxyanisole
BHT	Butylated hydroxytoluene
BMEP	Brake mean effective pressure
Bp	Brake power
Bp _o	Observed brake power
Bp _c	Corrected power to the standard reference condition
BP	Boost pressure
BSFC	Brake specific fuel consumption
bTDC	Before top dead centre
BTE	Brake thermal efficiency
Bu	Butanol
C	Carbon content
c _p	Number of duplicates at the central point
C _v	Viscometer calibration constant
CA	Crank angle

CCD	Central composite design
CCFCD	Central composite face centred design
CCRD	Central composite rotatable design
CD	Combustion duration
CF	Fuel correction factor
CNG	Compressed natural gas
CO	Carbon monoxide
CO ₂	Carbon dioxide
CP	Cloud points
CR	Compression ratio
d	Dry air portion of the total inlet air supply pressure in kPa
df	Degree of freedom
DAQ	Data acquisition
DF	Diesel fuel
DGM	Diglyme
DEE	Diethyl ether
DMC	Dimethyl carbonate
DO	D-optimal
DOE	Design of experiments
Dwell	Time interval between two diesel injections
E	Ethanol portion for fuel blend
EGR	Exhaust gas recirculation
EGT	Exhaust gas temperature
EL	Engine load
ES	Engine speed
Eth	Ethanol
f	Number of distinctly different factor combinations
f(x)	Vector function of p elements
F-value	Difference between each sample (group)
F	Fuel rate in g/s
Fa	Atmospheric factor
FAEE	Fatty acid ethyl ester
FAME	Fatty acid methyl ester

FAWE	Fusel oil after water extraction
FB	Fuel blend/ratio
FC	Fixed carbon
FCE	Fuel conversion efficiency
FD	Factorial design
FEF	Fumigant energy fraction
FFD	Full factorial design
Fm	Engine factor
FR	Fuel / flow rate
FrFD	Fractional factorial design
FT	Fuel type
GC	Gas chromatography
GC-MS	Gas chromatography—mass spectrometry
GF	Gasoline fuel
GFD	General factorial design
H	Hydrogen content
H ₂	Hydrogen gas
H. illucens	Hermetia illucens (black soldier fly)
HHV	Higher heating value
HILO	Hermetia illucens larvae oil
HCCI	Homogeneous charge compression ignition
HDD	Historical data design
Hex	Hexane
h _{fg}	Standard heat of vaporization
High	Upper limit of the response
HRR	Heat release rate
ICP	In-cylinder pressure
ID	Ignition delay
II	Injection interval
IMEP	Indicated mean effective pressure
Inj1Fr	Fraction of first diesel injection
IP	Injection pressure
IR	Infrared radiation

IT	Injection timing
k	Number of input factors
LAC	Light absorption coefficient
LHV	Low heating value
Low	Lower limit of the response
M. domestica L.	<i>Musca domestica</i> Linnaeus (housefly)
MFB	Mass fraction burned
Mg	Magnesium
m_{H2O}	Amount of water vapour content
n	Number of experiments in the set
N	Nitrogen content
NDIR	Non-dispersive infrared
NIST	National Institute of Standards and Technology
NSGA	Non-dominated sorting genetic algorithm
NTP	Nozzle tip protrusion
NO_x	Nitrogen oxide
o	Observed at actual test conditions
O	Oxygen content
O_2	Oxygen gas
Oct	Octanol
p	Period
P_b	Brake power output
Pe	Pentanol
PG	Propyl gallate
P_{int}	Intake air pressure
PM	Particulate matter
P_{max}	Peak in-cylinder pressure
PP	Pour points
ppm	Parts per million
POAE	Percentage of absolute error
Pr	Weight of significance
Prop	Propanol
P_{rail}	Diesel fuel rail injection

PRESS	Prediction error sum squares
PY	Pyrogallol
Q	Fuel delivery in mg/L cycle
Q _f	Heating value of the test fuel (MJ/kg)
Q _{net}	Net heat release rate (J/deg)
r	Standard reference test conditions
R ²	Coefficient of determination
R ² _{adjusted}	Adjusted R ²
RCCI	Reactivity-controlled compression ignition
RH	Relative humidity
RoPR	Rate of pressure rise
RSM	Response surface methodology
S	Sulphur content
SOC	Start of combustion
SOCH	Single overhead camshaft
SOI	Start of injection
SOIC2	Start of injection command for the 2nd injection
SOP	Standard operating procedure
SS _{Res}	Sum square of residual (error)
SS _T	Total sum of squares
t	Measured flow time, s
T _b	Engine brake torque
TBHQ	Tert-butylhydroxyquinone
TCD	Thermal conductivity detector
TD	Taguchi design
TDC	Top dead center
T _{int}	Intake air temperature
UDD	User-defined design
UHC	Unburned hydrocarbon
V	Volume at any crank position
VCR	Variable compression ratio
VM	Volatile matter
W	Water content

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