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Formulation of fuel blends for diesel engines from cashew nut shell liquid, diesel fuel and acetone-butanol-ethanol (361): Performance and emissions characteristics in a stationary diesel engine

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Dedication

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Abstract

Most African countries import petroleum products to meet their population’s energy demands despite the large amount of biomass available, which can generate biofuels. The major concerns are a lack of knowledge and the cost of technologies, which limit the production of alternative fuels.

This study investigates using locally produced CNSL in fuel blends as alternative fuels for stationary diesel engines. It also aims to reduce commercial diesel consumption while ensuring optimal engine performance and emission characteristics. The first part of the study evaluated the feasibility of increasing the proportion of cashew nutshell liquid-based biofuels (CNSL) in diesel. Biofuel–diesel blends with different percentages of CNSL were prepared, and their physical properties, including the density, viscosity, and heating value, were determined. B10 (CNSL/diesel = 10:90 v/v) satisfied the diesel specifications without preheating, whereas B20 (CNSL/diesel = 20:80 v/v) and B30 (30:70 v/v) met the specifications only after preheating to 60 and 80 °C, respectively. To avoid preheating B20 and B30, an acetone/butanol/ethanol (ABE) mixture (30:60:10 v/v) was added to the fuel blends to improve their flow characteristics. The blends with CNSL/ABE (361)/diesel ratios of 20:10:70 and 30:30:40 (v/v) exhibited properties comparable to those of diesel and remained stable during prolonged storage.

The appropriate fuel blends were then tested in a stationary diesel engine (single-cylinder, four-stroke, 2.2 kW at 2,000 rpm) to evaluate their performance. The performance study of a diesel engine operating with various fuel blends revealed that the thermal efficiencies of B30ABE30 and B20ABE10 decreased by 3.75 % and 9.16 %, respectively, compared to diesel under high loads. However, the specific fuel consumption of B20ABE10 was very similar to that of B30ABE30, while it was 5 % higher for B30ABE30, compared to that of diesel. These fuel blends can serve as alternative fuels for low-speed diesel engines without any modifications.

The economic analysis indicated that fuel blends B20ABE10 and B30ABE30 are more expensive than B10, making the latter a more viable option for use in sub-Saharan African countries.

Keywords: cashew nut shell liquid (CNSL), diesel fuel, acetone–butanol–ethanol (ABE (361)), fuel blend, preheating, diesel engine, purification, performance.

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List of Abbreviations and Nomenclature

Abbreviations

ABE (361) : 30 % Acetone + 60 % Butanol + 10 % Ethanol
ASTM : American Society for Testing and Materials
B05 : 5 % CNSL +90 % diesel
B1 : 1 % CNSL +99 % diesel
B10 : 10 % CNSL+90 % diesel
B100 : 100 % CNSL
B10M10 : 10 % cardanol +80 % diesel +10 % methanol
B10T5 : 10 % CNSL+5% Toluene+85 % diesel
B15T5 : 15 % CNSL+5 % Toluene+80 % diesel
B2 : 2 % CNSL +98 % diesel
B20 : 20 % CNSL+ 80 % diesel
B20+DEE10 : 20 % CNSL+70 % diesel+ 10 % diethyl ether
B20+E10 : 20 % CNSL+70 % diesel+ 10 % ethanol
B20ABE10 : 20 % CNSL+70 % diesel +10 % ABE
B20M10 : 20 % cardanol+ 70 % diesel +10 %methanol
B30 : 30 % CNSL +70 % diesel
B30ABE30 : 30 % CNSL+40 % diesel +30 % ABE
B40 : 40 % CNSL +60 % diesel
B5 : 5 % CNSL +95 % diesel
B50 : 50 % CNSL +50 % diesel
B5T5 : 5 % CNSL+5 % Toluene+90 % diesel
B60 : 60 % CNSL +40 % diesel
B80 : 80 % CNSL +20 % diesel
B90 : 10 % CNSL +90 % diesel
BK20 : 20 % CNSL+80 % kerosene
BK30 : 30 % CNSL+80 % kerosene
BK40 : 40 % CNSL+80 % kerosene
C70ABE10 : 70 % CNSL+30 % ABE (361)
C80ABE20 : 80 % CNSL+20 % ABE (361)
C90ABE10 : 90 % CNSL+10 % ABE (361)
CC-CNSL : Catalytically cracked-CNSL

CMPRO30 : 70 % CNSL+30 % camphor oil
CNSL : Cashew nut shell liquid
CNSLP : CNSL obtained by mechanical pressing
CNSLT : Technical CNSL obtained from thermal treatment of CNSLP
CNSO : Cashew nut shell oil
CO : Carbon monoxide
cSt : Centistokes
DEE : Diethyl ether
DT-CNSL : Distilled technical cashew nut shell liquid
EGT : Exhaust gas temperature
Ha : hectare
HHV : Higher heating value
HPLC : High-performance liquid chromatography
ISO : International Standard Organisation
nCNSL : Natural cashew nut shell liquid
NO_X : Oxides of nitrogen
Ppm : Parts per million
Rpm : Revolution per minute
SSA : sub-Saharan Africa
SVO : Straight Vegetable Oils
TC-CNSL : Thermal cracked cashew nut shell liquid
tCNSL : Technical CNSL
T-CNSL : Technical cashew nut shell liquid
Toe : Tonne oil equivalent
VL : Variable loads
Wt: : Weight

Nomenclature

1C : Mono-cylinder
4S: : Four strokes
BSFC : Specific fuel consumption
BTDC : Before bottom dead center
BTE : Thermal efficiency

CI : Compression ignition

CN : Cetane number

CS : Constant speed

DI : Direct Injection

IP : Injection pressure

IT : Injection timing

Résumé long de la thèse

La consommation énergétique mondiale dépend en majorité des combustibles fossiles (pétrole, gaz naturel et charbon), qui sont utilisés dans les secteurs importants (industries, transport, agriculture, etc.) de l'économie mondiale. L'exploitation de plus en plus croissante de ces sources d'énergies conduit à des effets néfastes sur l'environnement tels que les changements climatiques qui en résultent, l'augmentation des couts des bruts et l'épuisement des réserves. Les secteurs du transport, de l'agriculture et de la production de l'électricité sont dominés de nos jours par l'utilisation des moteurs diesel, et ces derniers génèrent des niveaux élevés d'émissions polluantes.

Face à ces enjeux, il est important de rechercher et de développer des sources d'énergies alternatives, ayant un faible impact sur l'environnement, renouvelables et disponibles localement. Ainsi, l'utilisation des biocarburants issus de la biomasse non comestible offre une alternative appropriée au gazole pour une utilisation dans les moteurs diesel.

Dans beaucoup de pays africains, le potentiel de production de la biomasse est très important, mais reste encore sous-valorisé, soit par manque de connaissances ou de technologies efficientes. Concernant la filière anacarde, l'Afrique subsaharienne (Afrique de l'Ouest et de l'Est) est le deuxième producteur mondial des noix d'anacarde après l'Inde et la production mondiale ne cesse de croitre ces dernières années. Cependant, l'augmentation de la production mondiale accentue une importante pression sur la demande énergétique dans les unités de transformation. Par ailleurs, la production de noix d'anacarde génère de grandes quantités de coques, avec un potentiel énergétique élevé, mais souvent non valorisé en Afrique subsaharienne. Il se pose également le problème du stockage de ces coques, qui peuvent avoir des effets néfastes sur l'environnement. Lorsque ces coques sont utilisées comme des combustibles, elles émettent de grandes quantités de fumées irritantes et se traduisent par un faible rendement énergétique. Ces coques contiennent un liquide très visqueux (CNSL ou baume de cajou), dense, acide, moins volatil et possèdent un pouvoir calorifique élevé, ainsi qu'une forte acidité. Selon la méthode d'extraction, on distingue le CNSL naturel (riche en acides anacardiques) et le CNSL technique (cardanols).

L'analyse des propriétés physicochimiques des CNSLs et du gazole conventionnel révèle des différences significatives dans les caractéristiques clés du carburant, telles que la densité, la viscosité et l'indice d'acide. Le CNSL se caractérise par une viscosité élevée, une forte densité et une faible volatilité, ce qui n'est pas conforme aux spécifications du gazole. En outre, leur acidité élevée présente un risque de corrosion pour les réservoirs, les pompes et les systèmes d'injection. Compte tenu de ces résultats, l'utilisation directe de CNSL dans les moteurs diesel n'est pas réalisable dans les configurations actuelles des moteurs.

Le chapitre 1 explore le potentiel du CNSL en tant que biocarburant pour les moteurs diesel. Il a abordé les aspects suivants : l'utilisation du CNSL pur et en mélange avec du gazole, les méthodes d'extraction, les techniques d'amélioration des propriétés du CNSL, ainsi que l'analyse de performances et des caractéristiques des émissions des moteurs fonctionnant avec des mélanges CNSL-gazole. L'identification des limites des études existantes constituent également des points importants de ce chapitre.

Les études antérieures sur l'utilisation du CNSL comme carburant dans les moteurs diesel se sont principalement focalisées sur diverses techniques visant à améliorer les propriétés du carburant. Les techniques les plus rapportées dans les récentes études, telles que les procédés de craquage catalytique et thermique (180─380°C) produisent des biocarburants dont les propriétés se rapprochent de celles du gazole. Toutefois, ces techniques en sont encore en phase expérimentale et ne facilitent pas la production de grandes quantités de CNSL. Même lorsque le biocarburant CNSL est produit, il nécessite d'être mélangé jusqu'à 20 % au gazole ou à d'autres additifs (alcool, huile végétale, etc.) pour obtenir une performance proche de celle du gazole. Cependant, cela peut nécessiter des systèmes de préchauffage et des ajustements des paramètres d'injection. Avec une pression d'injection de 18,5 à 22 MPa, un temps d'injection de 19 ° BTDC (avant le point mort haut) et un préchauffage à 70 °C, les mélanges B20 peuvent alimenter avec succès les moteurs diesel avec des performances et des caractéristiques d'émission similaires à celles du diesel. Cependant, le préchauffage du carburant peut considérablement augmenter le coût d'exploitation du système.

Jusqu'à présent, les études sur le CNSL en tant que biocarburant sont limitées et font état de son utilisation dans de faibles proportions dans des mélanges avec du gazole et d'autres additifs, en raison de sa viscosité élevée, de son indice d'acidité élevé et de la présence de polymères. Les polymères entraînent une séparation des phases du carburant, ce qui est un facteur critique pour les mélanges de carburants et peut poser des problèmes de colmatage des injecteurs, de filtrage et de systèmes de pompage pour les moteurs. En outre, la teneur élevée en oxygène dans le CNSL peut entraîner une dégradation par oxydation au cours d'un stockage prolongé, ce qui peut affecter les propriétés telles que la densité, la viscosité et l'indice d'acidité. Ces propriétés sont essentielles pour les biocarburants, car elles affectent les caractéristiques de combustion et la durabilité des composants du moteur. En revanche, le CNSL technique a présenté des propriétés comparables à celles du fioul lourd, auquel il pourrait substituer dans diverses applications.

L'utilisation de biocarburants à faible proportion de CNSL dans les mélanges ne permet pas une exploitation adéquate du potentiel des unités de transformation de la noix de cajou. En fait, les techniques avancées de production de CNSL biocarburant ne sont pas facilement accessibles dans les unités de transformation des noix d'anacarde des pays en voie de développement, ce qui limite la valorisation énergétique de ces coques. Cette étude suggère l'utilisation du CNSL produit localement comme substitut au gazole commercial, ce qui pourrait réduire les coûts de production liés à son traitement.

La revue de la littérature a révélé les méthodes d'extraction des CNSLs, ses propriétés physicochimiques et des défis associés à son utilisation en tant que biocarburant. Elle donne un aperçu des avancées récentes dans l'amélioration des propriétés du CNSL en tant que biocarburant, ainsi que l'étude de performance et des caractéristiques d'émissions lorsqu'il est mélangé avec d'autres carburants dans les moteurs diesel.

Le chapitre 2 décrit la procédure d'extraction des matières végétales (CNSLs) pour la préparation des mélanges de carburants et décrit les équipements utilisés pour évaluer les propriétés physicochimiques des échantillons. Les matières végétales comprennent des échantillons de CNSL, obtenus auprès d'ANATRANS (Bobo-Dioulasso) et par extraction mécanique à l'aide d'une presse mécanique.

Du gazole (TotalEnergies, Burkina Faso) et un mélange ABE (361) ont été utilisés pour préparer différents mélanges de carburants : CNSL–gazole, CNSL–ABE et CNSL–gazole–ABE.

Le mélange ABE (361) a été préparé à partir d'acétone (qualité analytique), de 1-butanol (99,5 %) et d'éthanol (99,97 %) dans un rapport volumétrique de 30 % : 60 % : 10 %. Ces réactifs ont été mélangés à 800 tr/min par agitation magnétique pendant 15 minutes. Cette proportion correspond à la composition typique des produits de la fermentation acéto-butylique (ou fermentation ABE). L'ABE (361) a été utilisé comme additif renouvelable pour améliorer les propriétés des mélanges CNSL–gazole, notamment en réduisant sa viscosité et sa densité. L'objectif est d'identifier des mélanges de carburants alternatifs à base de CNSL, de gazole et d'ABE, capables de satisfaire aux spécifications du gazole conventionnel. Les propriétés des mélanges CNSL–gazole, CNSL–ABE et CNSL–gazole–ABE ont été analysées, et les mélanges les plus prometteurs ont été soumis à des tests de stabilité (au stockage et au vieillissement) et à l'évaluation de leurs principales propriétés. Enfin, les performances et les émissions d'un moteur diesel alimenté par ces mélanges ont été comparées à celles obtenues avec du gazole.

Afin de contribuer à la valorisation du CNSL en biocarburant, le chapitre 3 de cette thèse est consacré à l'étude de mélanges CNSL-gazole, dans le but de déterminer des formulations de carburants stables et adaptées aux moteurs diesels stationnaires.

Dans un premier temps, le CNSL a été extrait par pressage mécanique (l'extraction a été réalisée à 2iE). Ce processus d'extraction a permis d'obtenir un rendement d'environ 25 %, une valeur en accord avec les résultats rapportés dans la littérature scientifique. L'analyse élémentaire du CNSL par Vario macro cube CHN Analyseur rapporte les valeurs C :H :O de 76 % : 9,5 % : 14,2 %, qui sont comparables à celles de l'huile végétale carburant, rapportées dans la littérature. Le CNSL a ensuite été caractérisé par la détermination de ses propriétés physicochimiques, notamment la densité, la viscosité, le pouvoir calorifique supérieur, l'indice d'acide et la teneur en eau. Ces propriétés ont été comparées aux exigences spécifiées pour les moteurs diesel stationnaires. Ces exigences ont été établies dans cette étude sur la base des spécifications du gazole et des huiles végétales proposées par Blin et al. (2013). L'analyse des propriétés physicochimiques du CNSL révèle une acidité, une densité et une viscosité supérieures à celles du gazole, ce qui limite son usage dans les moteurs diesel existants. Sa viscosité élevée entraine une faible atomisation du carburant, réduisant ainsi l'efficacité de la combustion. Aussi, son indice d'acide élevé peut causer des problèmes de corrosion et de compatibilité avec les matériaux des moteurs.

Afin d'optimiser ses caractéristiques d'écoulement et d'assurer un fonctionnement optimal des moteurs diesel, l'effet du préchauffage du CNSL a été étudié en évaluant sa viscosité à différentes températures (40, 60, 80 et 100 °C). La viscosité du CNSL diminue considérablement avec l'augmentation de la température, avec une réduction de 91 % observée à 100 °C. Bien que sa viscosité à cette température (21 cSt) demeure légèrement supérieure à la limite maximale recommandée pour les pompes d'injection des moteurs diesel stationnaires, elle présente un avantage significatif par rapport au HFO (fioul lourd). En effet, alors que le fuel lourd nécessite un chauffage entre 90 et 100 °C pour atteindre une viscosité adéquate pour l'atomisation (entre 20 et 40 mm²/s), le CNSL atteint une viscosité similaire dès 80 °C. Cette caractéristique permettrait de réduire les besoins en chauffage et suggère que le CNSL pourrait constituer une alternative intéressante au fioul lourd. Le CNSL peut être considéré comme un biocarburant pour les moteurs diesel et les centrales électriques fonctionnant au fioul lourd.

Afin de permettre son utilisation comme alternative au gazole dans les moteurs diesel stationnaires conventionnels, et d'éviter le recours au chauffage, des mélanges de CNSL et de gazole ont été préparés avec des proportions de CNSL variant de 10 à 90 % pour améliorer ses propriétés d'écoulement. La préparation consistait à agiter magnétiquement (1500 tr/min) des échantillons de 100 mL pendant 7 à 8 heures, puis à les laisser reposer à température ambiante. Aucune séparation de phase n'a été observée dans les mélanges de carburants préparés. Pour sélectionner les mélanges qui répondent mieux aux spécifications du gazole, la densité, la viscosité et le pouvoir calorifique supérieur, ont été évaluées et comparées aux exigences des spécifications du diesel. Les mélanges B10 (10 % CNSL, 90 % du gazole) et B20 (20 % CNSL, 80 % gazole) ont été identifiés conformes aux spécifications des moteurs diesel stationnaires.

Les mélanges de carburants devant avoir présenter également des propriétés homogènes dans le temps, des tests de stabilité au stockage et de vieillissement accéléré ont été menés sur les mélanges de carburants, car un stockage prolongé peut entraîner une dégradation des propriétés des mélanges, notamment la densité, la viscosité et l’acidité. La stabilité au stockage a été examinée à l'aide de la méthode de Bora et al. (2016). Les mélanges ont été inspectés visuellement après avoir été stockés pendant 03 mois dans un dessiccateur à température ambiante. Les mélanges de carburants ont conservé une phase unique et ont été jugés physiquement stables et aptes à être utilisés dans des moteurs diesel. Cette étude a consisté également à suivre la variation de la densité, de la viscosité cinématique et de l'indice d'acide des mélanges (B10 et B20) au cours du stockage. La stabilité des mélanges a été confirmée par la faible variation des paramètres analysés (densité, viscosité et indice d'acide), qui sont restés conformes aux spécifications du gazole.

Afin d’étudier le comportement des mélanges sur le long terme, les tests de vieillissement accéléré ont été réalisés selon la méthode décrite par Lehto et al. (2013). Les mélanges de carburants ont été maintenus à une température de 80 ° C pendant 24 h, et leur stabilité a été évaluée en mesurant la viscosité à 40 °C. Ces mélanges peuvent être conservés pendant une année à température ambiante sans changement important de leur propriété. De faibles augmentations de la viscosité et de la densité des mélanges carburants après vieillissement accéléré ont été observées, et les valeurs de ces paramètres sont restées conformes aux limites spécifiées pour le gazole. Ces mélanges de carburants peuvent être conservés pendant une année à température ambiante sans changement significatif de leurs propriétés.

L'indice d'acide est un paramètre crucial à prendre en compte lors de la sélection de mélanges de carburants, en raison de son impact sur la durabilité des composants métalliques du moteur. Une forte acidité peut entraîner la corrosion des composants métalliques du moteur, tels que les injecteurs, les soupapes et les conduites de carburant, et peut causer des conséquences potentiellement graves. Le mélange B20 (20 % de CNSL et de 80 % de gazole) avait un indice d’acide plus élevé (26,24 mg KOH/g), comparé au gazole (0,5 mg KOH/g), ce qui constitue un inconvénient majeur. Par conséquent, l'utilisation du mélange B20 dans les moteurs diesel est déconseillée, en raison du risque de corrosion. Des recherches doivent être envisagées pour réduire l'acidité du mélange B20, soit en utilisant des additifs ou en modifiant le processus de production du CNSL. Cependant, le mélange B10 (10 % CNSL, 90 % gazole) avait un indice d'acide de 15,62 mg KOH/g, proche des valeurs rapportées pour l'huile végétal de *Jatropha curcas*, qui a déjà fait l'objet d'expérimentation dans les moteurs diesel. B10 apparaît donc comme une option plus sûre pour assurer la longévité et le bon fonctionnement du moteur diesel.

L'étude des paramètres de performances a été effectuée sur un moteur diesel à injection directe, monocylindrique, à quatre temps, de puissance nominale 2,2 kW à une vitesse nominal de 2000 tr/mn. Le banc à essai moteur est composé d'un moteur diesel, couplé par l'intermédiaire d'une courroie à un dynamomètre hydraulique, qui permet de régler la charge du moteur. L'étude des caractéristiques de performance a été effectuée pour le fonctionnement du moteur diesel avec le mélange B10. Les essais moteurs ont été effectués à différentes charges (20, 40, 60, 80 et 100 %) à une vitesse nominale de 2000 tr/min.

Les paramètres évalués montrent que le mélange B10 présente des performances satisfaisantes, et comparables à celles du gazole. Le moteur diesel a montré une performance acceptable avec un rendement global au freinage de 35,65 % et une consommation spécifique en carburant au freinage de 0,27 kg/kWh, proche du fonctionnement avec du gazole à forte charge du moteur. L'utilisation de la faible proportion du CNSL ne permet pas d'exploiter pleinement le potentiel de production dans les unités de transformations. Afin d'optimiser l'utilisation du CNSL, il est préférable d'envisager des mélanges carburants contenant une proportion plus élevée de CNSL, dans le but de maximiser la valorisation de cette ressource renouvelable, à condition que celle-ci soit disponible en quantité suffisante.

Vu le potentiel important de production du CNSL en Afrique subsaharienne ces dernières années, cette thèse se propose d'étudier la faisabilité de l'augmentation de la proportion du CNSL dans le gazole. Le chapitre 4 de cette thèse porte sur la formulation des mélanges carburants pour les moteurs diesel à partir de CNSL, du gazole et avec de l'additif ABE (361). Deux échantillons de CNSL ont été collectés auprès d'ANATRANS (Anacardium transformation), une compagnie locale située à Bobo-Dioulasso (Burkina Faso) : le CNSL naturel (CNSLP) et le CNSL technique (CNSLT).

Le CNSLT a été obtenu par traitement thermique du CNSLP (issu du pressage mécanique) à une température de 160 °C pendant 4 heures. Sur la base de la caractérisation physicochimique des échantillons de CNSL, particulièrement l'indice d'acide, la teneur en eau et le pouvoir calorifique, Le CNSLT a été sélectionné pour la formulation de mélanges carburants.

Les mélanges carburants ont été préparés dans des tubes coniques (50 mL) par agitation vortex pendant 10 minutes à température ambiante. Trois lots indépendants de chaque mélange ont été préparés :

- CNSLT-gazole contenant 10, 20, 30, 40 et 50 % de CNSLT (désignés respectivement par B10, B20, B30, B40 et B50) ;
- CNSLT-ABE (361) contenant 70, 80 et 90 % de CNSLT (désignés respectivement par C70ABE30, C80ABE20 et C90ABE10) ;
- CNSLT-diesel-ABE contenant x % de CNSLT et y % d'ABE (361) (désignés par BxABEy, où x = 20, 30, 40 et 50 % et y = 10, 20 et 30 %). Par exemple, le B20ABE10 contient 20 % de CNSLT, 10 % d'ABE et 70 % de gazole, et le B30ABE30 comprend 30 % de CNSLT, 30 % d'ABE et 40 % de gazole.

Les mélanges ont été centrifugés à 6000 rpm pendant 5 minutes pour être séparés des impuretés (résidus d'extraction). La densité, la viscosité et le pouvoir calorifique supérieur, ont été déterminées par des méthodes standards de caractérisation. B10 (CNSLT/gazole = 10 :90 v/v) répondait aux spécifications du gazole sans préchauffage, tandis que B20 (CNSLT/gazole = 20 :80 v/v) et B30 (30:70 v/v) ne répondaient aux spécifications qu'après un préchauffage à 60 et 80 °C, respectivement. Pour éviter de préchauffer les mélanges B20 et B30, un mélange acétone/butanol/éthanol (ABE) (30 :60 :10 v/v) a été ajouté aux mélanges de carburants pour améliorer leurs caractéristiques d'écoulement. Les mélanges CNSLT/ABE (361) /gazole à des proportions volumiques de 20:10:70 et 30:30:40 (v/v) ont présenté des propriétés comparables à celles du gazole. Le suivi des paramètres carburant (densité, viscosité et indice d'acide) pendant un mois de stockage à température ambiante ont montré une faible variation dans le temps et les valeurs des paramètres sont restées conformes à la spécification du gazole. L'étude du vieillissement accéléré (80 °C pendant 24 h) a montré que ces mélanges peuvent être conservés sans changement significatif de leurs propriétés importantes pendant un an à température ambiante (25-35 °C).

Concernant les mélanges binaires CNSL-ABE, L'ajout de 30 % de l'additif ABE (361) au CNSLT (C70ABE30) a réduit considérablement la viscosité, la rendant supérieure à environ 7 % à la spécification de l'huile végétale carburant (SVO), mais sa densité satisfait aux exigences de SVO. Le pouvoir calorifique de ce mélange est d'environ 6 % supérieur aux spécifications du SVO. La densité et la viscosité du mélange C80ABE20 satisfont aux exigences du fuel lourd (HFO) ; cependant, ce mélange indique un pouvoir calorifique d'environ 4 % inférieur à celui du HFO. Par ailleurs, la densité énergétique du C80ABE20 (40,79 MJ/L) est légèrement supérieure à celle du HFO (39,50 MJ/L). Par conséquent, l'ajout de 20 % à 30 % de l'additif ABE (361) au CNSLT permet d'obtenir des mélanges de carburants comparables au HFO et au SVO.

L'effet du préchauffage sur la viscosité des mélanges CNSL-ABE à 60 °C et 80 °C a été également évalué. Le mélange C70ABE30 préchauffé à 80 °C présentait une viscosité de 12,5 mm^2/s, inférieure à la valeur maximale de 17 mm^2/s recommandée pour les moteurs diesel stationnaires. En fait, la densité et le pouvoir calorifique de ce mélange répondaient aux exigences du SVO. Il peut donc être utilisé comme alternative au SVO dans les moteurs diesel. Lorsqu'ils sont préchauffés à 60 °C, les mélanges C70ABE30 et C80ABE20 présentent des viscosités comprises entre 20 et 40 mm^2/s, soit les valeurs requises pour obtenir une atomisation adéquate au niveau de la buse du brûleur d'une chaudière. Par conséquent, les mélanges C70ABE30 et C80ABE20 peuvent être utilisés comme combustibles pour les brûleurs à la place du HFO.

Cette étude montre que l'ajout de l'additif ABE (361) permet l'utilisation de concentrations de CNSL allant jusqu'à 30 % dans le gazole. Les mélanges ainsi obtenus sont considérés comme des carburants alternatifs au gazole pour les moteurs diesel. Une analyse des performances et des caractéristiques d'émissions des mélanges B20ABE10 et B30ABE30 a été menée sur un moteur diesel stationnaire.

Les tests de performance ont révélé que le rendement global augmentait avec la charge du moteur, mais qu'il restait inférieur pour le B20ABE10 (15,85 %) et le B30ABE30 (15,89 %) par rapport au gazole (22,03 %) à faible charge. À charge élevée, les rendements des mélanges se rapprochent de celui du gazole (24,78 %), atteignant 22,49 % pour le B20ABE10 et 23,79 % pour le B30ABE30. Cette diminution de l'efficacité du moteur est attribuée au faible pouvoir calorifique des mélanges, qui engendre une combustion moins efficace et laisse une part importante de carburant imbrûlé, impactant négativement le rendement. La diminution de l'efficacité du moteur est une conséquence directe des faibles pouvoirs calorifiques et des propriétés d'écoulement des mélanges (viscosité et densité élevée). Ces facteurs limitent l'énergie de combustion disponible pour produire de la puissance mécanique utile, ce qui se traduit par une réduction du rendement du moteur.

La consommation spécifique de carburant diminue avec l'augmentation de la charge du moteur. Les mélanges B20ABE10 et B30ABE30 présentent une consommation spécifique plus élevée que le gazole, ce qui se traduit par un volume de carburant plus important nécessaire pour produire la même quantité d'énergie (1 kWh). Cette surconsommation s'explique par le faible pouvoir calorifique des mélanges, qui requiert un volume de carburant plus important pour produire 1 kWh d'énergie. Cette surconsommation est attribuable à leur faible pouvoir calorifique.

À faible charge, le moteur fonctionnant au gazole présentait une température d'échappement inférieure (133 °C) à celle des mélanges B20ABE10 (159 °C) et B30ABE30 (170 °C). Cette température d'échappement plus élevée pour les mélanges contenant une forte proportion de CNSL est attribuée à leur viscosité et leur densité. La viscosité légèrement supérieure du mélange B20ABE10 par rapport au gazole peut entraîner une atomisation moins efficace et une combustion incomplète, en particulier à faible charge moteur où la température de combustion est relativement basse. Cette mauvaise atomisation peut alors provoquer une combustion retardée et prolongée, expliquant l'augmentation de la température des gaz d'échappement.

Les caractéristiques d'émissions sur le moteur diesel sont évaluées par la mesure des émissions de CO, CO_2, O_2 en utilisant un analyseur à gaz (Testo 340) pour le fonctionnement du moteur diesel à 75 % de charge. Le gazole avait une faible émission de CO (321 ppm) par rapport aux mélanges carburants. Le mélange B30ABE30 présentait des émissions de CO de 411 ppm, qui étaient plus faible que le mélange B20ABE10. Ce qui signifie qu'une proportion élevée d'ABE (361) dans le mélange de carburants permet de réduire de manière significative les émissions de CO. Le gazole émet moins de CO que les autres mélanges carburants, en partie parce que leur indice de cétane est faible par rapport à celui du gazole, ce qui peut donner lieu à une mauvaise combustion. Le B30ABE30 émettait 13 % de CO_2 de plus que gazole, car ce dernier nécessite moins de carburant pour produire la même quantité d'énergie.

Une analyse économique des mélanges de carburants appropriés a été menée afin de déterminer leur viabilité économique par rapport au gazole. Pour ce faire, une approche méthodologique, inspirée des travaux de Bangjang et al. (2016), a été adoptée. Cette approche consiste à évaluer le coût de chaque composant du mélange, puis à utiliser les proportions de chaque composant dans le mélange final (B10, B20ABE10 et B30ABE30) pour estimer le coût total du mélange. L'analyse économique révèle que les mélanges B20ABE10 et B30ABE30 sont plus coûteux que le gazole. À l'inverse, le mélange B10 présente un coût de production inférieur. L'utilisation de ce dernier pourrait générer des économies sur les importations de produits pétroliers à l'échelle nationale ou réduire la demande en gazole dans une unité de transformation de noix de cajou. Au Burkina Faso, le potentiel de production de CNSL permettrait d'incorporer jusqu'à 3 % de CNSL dans le gazole, ce qui réduirait les importations de gazole et créerait de la valeur ajoutée dans les industries de transformation des noix de cajou. Ce potentiel encourage l'exploration des mélanges CNSL-diesel comme alternative viable au gazole. L'utilisation de ces mélanges pourrait diminuer le volume de pétrole importé dans les pays sans ressources fossiles ou réduire la demande énergétique des industries de transformation. Cette perspective prometteuse ouvre la voie à un avenir énergétique plus durable pour les pays producteurs de noix de cajou.

Cette thèse avait pour objectif principal d'optimiser les propriétés du CNSL et de ses mélanges afin de les rendre compatibles avec les moteurs diesel stationnaires. L'incorporation d'un mélange ABE (361) aux mélanges B20 et B30 a permis de formuler des carburants stables (B20ABE10 et B30ABE30) qui respectent les spécifications du gazole en termes de densité, de viscosité, de pouvoir calorifique et d'indice de cétane. Toutefois, ces mélanges présentaient un indice d'acide supérieur à la spécification du gazole. La purification préalable du CNSL avec l'ABE (361) s'est avérée efficace pour réduire l'indice d'acidité à un niveau comparable à celui du gazole. Bien que l'indice de cétane des mélanges B10, B20ABE10 et B30ABE30 soit inférieur à celui du gazole, ils satisfont aux exigences des moteurs diesel stationnaires et leurs performances sont comparables à celles du gazole. Les mélanges B10, B20ABE10 et B30ABE30 pourraient donc être utilisés comme carburants alternatifs pour les moteurs diesel stationnaires. Au Burkina Faso, le potentiel de production de CNSL permettrait d'incorporer jusqu'à 3 % de CNSL dans le gazole, ce qui aurait pour effet de réduire les importations de gazole et de valoriser les déchets de transformation des noix d'anacarde.

Le coût des réactifs (acétone, butanol, éthanol) peut limiter l'utilisation de ces mélanges carburants. L'utilisation de pommes de cajou pour la production d'ABE (361) pourrait accroître la valeur des sous-produits des noix d’anacarde. Des recherches supplémentaires sont nécessaires pour confirmer cette stratégie. Nos résultats ont révélé que les mélanges CNSL-ABE peuvent être utilisés comme carburants alternatifs au fuel lourd et à l’huile végétal carburant. Une étude approfondie de leurs propriétés physico-chimiques et des essais de performance dans un moteur diesel ou un brûleur doivent être réalisés pour confirmer leur adéquation.

General introduction

The world heavily depends on petroleum-based fuels, such as diesel, kerosene, petrol, and heavy fuel oil, to satisfy the energy demands of agriculture, transportation, and industry. Diesel engines are preferred in many applications, such as standby and emergency applications in hospitals, airports, hotels, and industries, because diesel exhibits a high energy density at a low price[1]. However, the use of diesel contributes to environmental pollution via the emission of higher levels of nitrogen oxides and particulate matter than that of petrol [2]. The increase in energy consumption has intensified the volatility of crude oil prices, resulting in concerns regarding the depletion of oil reserves and growing climate change [3]. The age of industrialisation has not yet ended, and the release of fumes is responsible for all its harmful consequences for the environment and human health. Hence, researchers have begun investigating alternative fuels derived from sustainable renewable resources with low environmental impacts.

Biofuels are emerging as a sustainable alternative to fossil fuels, as their development can impact three levels: strategic (security of energy supply), economic (lower oil bills), and environmental (reduced greenhouse gas emissions). Furthermore, biofuels are easily accessible to rural populations and enhance energy independence in countries lacking fossil fuel resources [4].

Many countries in sub-Saharan Africa (SSA) rely primarily on imported petroleum products. For instance, the electrification rate in SSA is significantly lower compared to other regions, with only 32 % of the population having access to electricity, in contrast to the higher rates observed in North America, Europe, and Asia [5]. In West Africa, fossil fuels, including diesel, distillate diesel, and fuel oil, contributed to 73.3 % of electricity production. For instance, Burkina Faso has an overall electrification rate of approximately 24.5 %, with 72.53 % in urban areas and 5.90 % in rural regions (data from the Ministry of Energy, Mines and Quarries, 2020). A staggering 70 % of the total power generation relies heavily on thermal fossil fuels [6]. Fuel oil is used in thermal power stations, particularly for low-speed diesel engines, to generate approximately 36 % of electricity, highlighting the environmental impact of this significant dependence on fossil fuels in 2008. In 2018, the total volume of fuel received by SONABEL (National Electricity Company of Burkina) for electricity generation was 183,330,718 litres, consisting of 20,777,533 litres of distillate diesel oil (DDO) and 163,559,185 litres of heavy fuel oil (HFO).

Diesel generators are primarily used in the country to satisfy energy demands. As a result, there is a constant need for fuels such as diesel or heavy fuel oil to operate large diesel generators, with three generators powered by HFO for electricity generation. Nevertheless, the challenge arises because these generators depend on fossil fuels, which raises a concern for Burkina Faso as it is not an oil-producing country. In 2008, Burkina Faso imported approximately 522 kilotons of oil equivalent (ktoe) of fuel, which comprised 34.5 % diesel, 1.4 % distillate diesel oil, and 13.7% heavy fuel oil (HFO) [7]. Electricity generation through diesel engines generates a major source of pollutants, such as particulates, sulphur oxides, and nitrogen oxides, which contribute to climate change. Owing to ongoing crises in fossil fuel supplies caused by economic and geopolitical concerns, as well as price fluctuations in the global market, there is an urgent need to identify viable alternative fuels to replace fossil fuels.

Agri-food production units in Burkina Faso are flourishing, particularly in the shea, mango, rice, and cashew nut sectors, with production rising each year. However, processing units have limited access to energy, which particularly affects the cost of local production. Interestingly, the processing units of cashew nuts in SSA generate significant waste in the form of cashew nut shells. These countries can utilise their biomass resources to produce biofuels in Africa.

Africa is the second largest producer of cashew nuts after India, with a production level of approximately 432,026 tonnes in 2017–2018 [8]. Further, from 2000–2019, cashew nuts (with shells) were grown and harvested from 1,157,001–4,704,272 ha of land in SSA [9]. After removing kernels, large quantities of cashew nutshells were produced (approximately 30,104,678 tonnes). Cashew nutshells contain a dark viscous brown liquid known as cashew nutshell liquid (CNSL). The nutshells contain 25–35 % CNSL, which could have potentially generated approximately 6,020,935 tonnes of CNSL from 2000 to 2019 in SSA. However, the potential of CNSL has not been acknowledged, owing to inadequate knowledge and inefficient technologies. CNSL is a prospective alternative fuel with the potential to benefit both cashew nut processing and energy industries [10].

The chemical structure of CNSL is similar to that of diesel (C11–C20 range) owing to its cardanol composition. CNSL is a potential alternative fuel for diesel engines, with a calorific value close to that of diesel [11]. However, its viscosity and density are higher than those of diesel [12]. The main issues posed by high viscosity include pumping, atomisation, combustion inefficiency, and accumulation of gum deposits [13]. Moreover, a higher viscosity implies a lower fuel flow rate and engine output [14].

Over the past five years, researchers have extensively investigated methods for reducing the viscosity of CNSL for use as a biofuel. Among the various strategies studied, such as transesterification to produce CNSL biodiesel and the use of green-diesel-based CNSL from distilled and thermally cracked CNSL, the blending of the CNSL biofuel with diesel is effective [13]. This process does not require chemical treatment, and its cost is limited to the CNSL class.

Previous studies on using CNSL as a biofuel have primarily focused on various techniques for improving fuel properties. These techniques include distillation, thermal cracking, catalytic cracking, and the transesterification of neat CNSL. However, these techniques are still in the experimental phase and do not facilitate the production of large quantities of CNSL. Even when CNSL biofuel is produced, it must be blended at up to 20 % with diesel or other additives to achieve a performance close to that of diesel.

Many researchers have used additives, such as butanol, acetone, and ethanol, to improve the properties of the CNSL biofuel to improve its performance in diesel engines. Kasiraman et al. [15] explored the use of the high-density and high-viscosity CNSL fuel blended with butanol at various volumes and analysed its combustion, performance, and emission behaviour. This investigation showed that 30 % butanol blended with CNSL afforded the optimum engine performance. Moreover, butanol can be obtained from carbohydrates via an acetone–butanol–ethanol (ABE) fermentation process with a typical ratio of 30 % acetone, 60 % butanol, and 30 % ethanol (361) [16]. Shantharaman et al. [17] added acetone (4 %, 8 %, and 12 %) as an additive to CNSL–diesel blends (B20) to increase the content of CNSL and analysed their performance as a fuel in diesel engines. The results revealed that 12 % acetone with a B20 blend serves as a better alternative fuel for diesel engines. Thanigaivelan et al. [18] tested a diesel engine with TC–CNSL blended with diesel. Ethanol and hydrogen were added to a B20 blend (20 % TC–CNSL, 80 % diesel) at various flow rates. They concluded that a 10 %-ethanol-blended B20 blend with a hydrogen flow rate of 8 L/min exhibited the highest brake thermal efficiency and reduced CO and HC emissions. To the best of our knowledge, no previous studies have used a blend of acetone, butanol, and ethanol as an additive to improve the properties of pristine CNSL and its blends. Using low-content CNSL biofuels in blends does not allow for the full exploitation of the potential production of cashew nut units.

General objective

This study investigates the application of locally produced CNSL in fuel blends as an alternative fuel for stationary diesel engines, aiming to reduce diesel consumption while ensuring optimal engine performance and emission characteristics.

Specific objectives

Specifically, the following questions will be addressed:

(i) To examine the optimisation of formulated fuel blends consisting of CNSL, diesel fuel, and the additive ABE (361) for use in stationary diesel engines.

(ii) To investigate the storage stability and ageing tests of suitable fuel blends for stationary diesel engines.

(iii) To assess the performance and emission characteristics of a diesel engine operated with appropriate fuel blends and diesel fuel.

This thesis is divided into six sections: an introduction, four chapters, a conclusion, and outlooks. The details of the various chapters are presented below.

Chapter 1: A literature review of CNSL and its blends as alternative fuels for diesel engines.
This chapter discusses the potential use of CNSL in diesel engines as a biofuel, either as a pure fuel or mixed with diesel. It also discusses the CNSL extraction methods and techniques to improve fuel properties. Experimental studies on diesel engines operated by CNSL biofuels blended with diesel are reviewed, focusing on diesel engine performance and emission characteristics to identify the limitations of these studies.

Chapter 2. Materials and Methods
This chapter reviews equipment and raw materials used for experimental tests. The raw materials consisted of CNSL, ethanol, acetone, butanol, diesel, and conventional analytical equipment. The experimental protocols are meticulously defined. This work is punctuated by experiments on a test bench.

Chapter 3: Optimisation study of cashew nut shell liquid blended with diesel as alternative fuels in stationary diesel engines.
This chapter analyses the physicochemical properties of CNSL and its blends with diesel fuel to determine appropriate fuel blends that comply with the specifications for the conventional fuels most used in stationary diesel engines.

Chapter 4: Formulation and storage stability study of cashew nut shell liquid, diesel fuel, and ABE (361) blend as an alternative fuel for stationary diesel engines
This section examines the feasibility of increasing the proportion of CNSL biofuels blended with diesel to satisfy diesel specifications. This includes formulating fuel blends using CNSL biofuel, diesel fuel, and a mixture of ABE (361) and assessing fuel blend stability.

The general diagram of this thesis is presented in Figure 0.1.

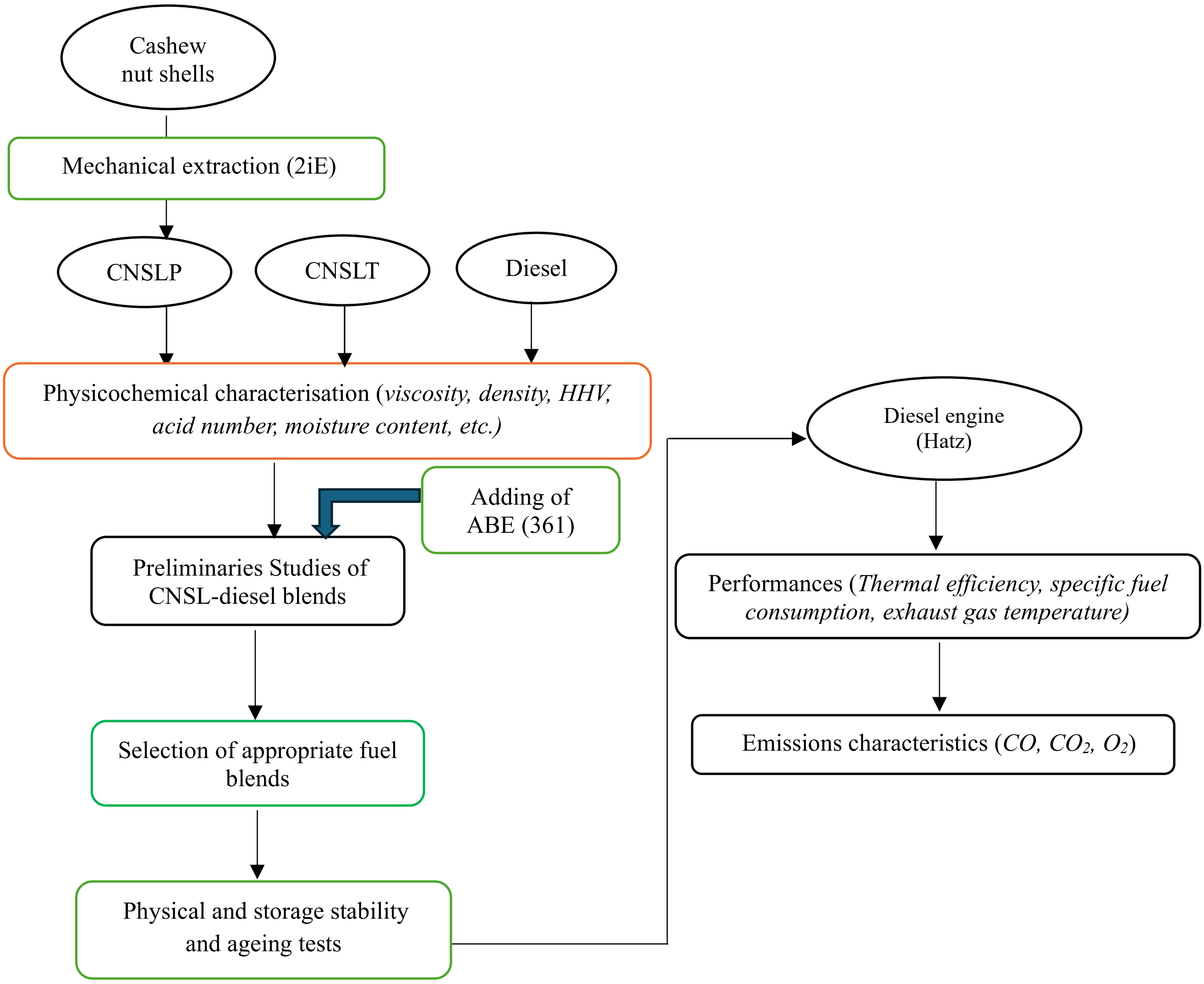


Figure 0.1. General methodology of thesis (CNSL: cashew nut shell liquid, HHV: Higher heating value, CO: carbon monoxide, CO_2: carbon dioxide, O_2: dioxygen).

Chapter 1. Literature review of cashew nut shell liquid and its blends as alternative fuels for diesel engines

1.1. Introduction

This chapter presents an overview of the extraction processes, chemical compositions, and physicochemical properties of cashew nutshell liquid (CNSL). In addition, we discuss the potential of CNSL as a biofuel for diesel engines. The primary concerns associated with the fuel properties are also discussed. CNSL biofuel can be used in diesel engines, either as a pure or blended fuel, with or without modifications to diesel engines. The second part of the analysis examined the performance and emissions of diesel engines using CNSL biofuels and their blends in diesel engines.

1.2. General information on the cashew tree

The cashew tree (known as Anarcardium Occidentale) is a tropical, evergreen tree that generally reaches a height of about 10–12 m and 25 m in width [19]. The tree is native to South America (Brazil) and Amazonia [19,20], and it was first introduced to Africa by the Portuguese. The cashew tree has a very high economic value [20], whose primary producers are India, Mozambique, Kenya, Madagascar, Thailand, Malaysia, Indonesia, Nigeria, Senegal, Malawi, Angola, Ghana, Philippines, Sri Lanka, Tanzania, Benin, Brazil, Cote d'Ivoire, Guinea Bissau and Vietnam. The cashew nut is a valuable cash crop in South America, India, Madagascar, and Malaysia [8].

The cashew tree produces an "apple" and the cashew seed (also called walnut), which grows at the base of the apple [21]. Cashew apples are edible and are used to prepare many sweet foods and beverages [22]. Cashew nuts, the "real" fruit of the tree, are used as an ingredient in cooked dishes and as a source of oil. It is, therefore, the main commercial product with the high added value of the cashew tree [21]. Cashews comprise about 55 to 65 % shells and 35 to 45 % kernels (almonds) [8]. CNS contains a dark reddish-brown caustic liquid (25-35 %), rich in non-isoprenoid phenolic lipids [8,23]. Figure 1.1 shows images of a cashew tree, apples and seeds, and nuts and shells.

The nut of the cashew nut is found on the outside of the fruit compared to other fruits containing the nuts (internal). The shell of the cashew nut has a low commercial value but is of relatively high importance due to its phenolic composition and, therefore, can be used as an alternative to phenol in several industrial applications [20].

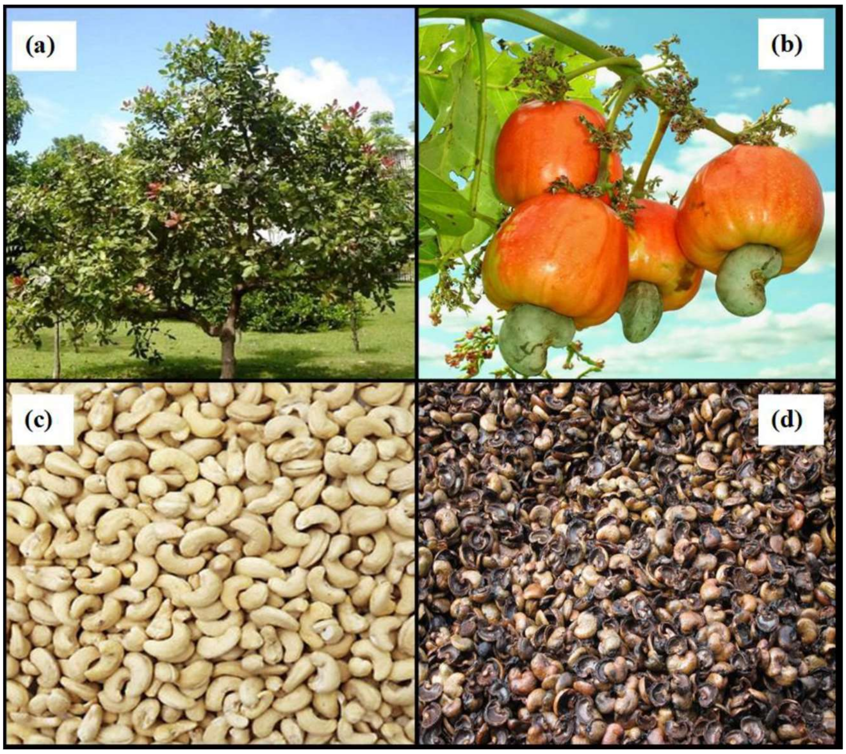


Figure 1.1. Cashew tree and products (a. cashew tree, b. apple and cashew nuts, c. almond, d. shells) [8].

1.3. Global cashew nut production

In the last decade, most commercial cashew nut production has been concentrated in four major regions: West and East Africa, India, and Vietnam. According to [8], global cashew production for the 2017/2018 season reached 789,050 metric tons. West Africa, comprising countries such as Côte d'Ivoire, Burkina Faso, Benin, Ghana, Nigeria, Mali, Guinea, Senegal, Gambia, and Guinea-Bissau, is the world's foremost cashew producer, accounting for 43 % of global production. India contributes 25 % of production, while Vietnam accounts for 9 %. East Africa (Kenya, Mozambique, Tanzania) accounts for 12 %, while Brazil, Indonesia, Cambodia, and other smaller producing countries make up the remaining 8 % [8].

Agriculture plays a critical role in the economies of most African countries, and cashew nuts have emerged as a significant export product. With its rich agricultural heritage, the SSA region produced a substantial 1,795,000 metric tons of raw cashew nuts in 2018, accounting for about half (49 %) of the world's production [24]. According to the N'kalo report [25], cashew nut production reached approximately 3,037,250 metric tons, representing 78.9 % of the world's production (3,850,000 metric tons). This significant increase in cashew nut production in the region from 2018 to 2023 is a direct result of the support provided by public authorities. Through various initiatives, such as research and development programs aimed at enhancing nut quality, as well as financial assistance in most countries, these authorities have played a crucial role in the growth of the cashew nut industry. Moreover, the diverse agro-climatic conditions in the region favour cashew nut cultivation, further contributing to its success.

Burkina Faso, along with other countries in SSA, such as Cote d'Ivoire, Guinea Bissau, Benin, Ghana, and Nigeria, is a significant producer of cashew nuts. In 2021, Burkina Faso produced approximately 100,000 metric tons of cashew nuts from a planted area of 389,000 ha [26]. The processing of cashew nuts leads to a substantial amount of waste, estimated at around 70 % of the weight of the cashew nuts. This waste is in the form of hard shells, which are challenging to recycle.

1.4. Potential of cashew nutshell liquid biofuel in sub-Saharan Africa

A metric ton of cashew nuts can generate approximately 700 kg of CNSs, so the total production of cashew nuts could lead to approximately 2,126,075 tons of CNSs. Although the shells have a high calorific value, burning them is problematic because of the corrosive nature of CNSL, which makes up approximately 25 % of the weight of the shells. In the past, shells are often discarded in processing plant dumps, contaminating water and soil. Shells are now being sold for the extraction of valuable products, which has potential applications in the chemical industry and energy production. CNSL, a bio-oil contained in CNSs, is a valuable product that attracts cashew nut processing units in West Africa. These units generate a large quantity of cashew nut shells as waste from processing. Extracting CNSL from this waste could also open up new revenue streams for farmers or units processing. The remaining CNS cake from the extraction process can be repurposed to make fuel briquettes. However, small cashew processing units face profitability challenges due to the cost of CNSL extraction and processing processes.

The significant production of cashew nuts in the SSA region can generate approximately 425,215 metric tons of CNSL. With its high energy content, CNSL holds excellent promise as a biofuel. It can serve as a renewable energy source for power generation and transportation and replace fossil fuels in various industrial uses. The use of CNSL as a biofuel not only helps lower greenhouse gas emissions but also offers a sustainable solution to our energy needs, lessening our reliance on fossil fuels. This potential inspires us to explore and invest in this innovative energy source.

1.5. Extraction and chemical composition of CNSLs

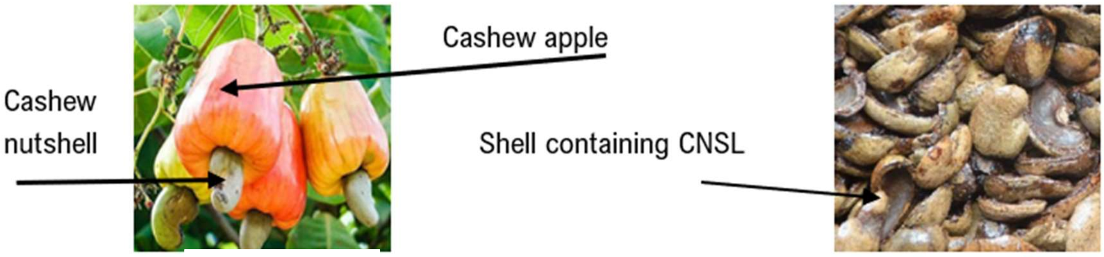
1.5.1. Extraction of CNSLs

CNSL is a viscous, dark brown bio-oil contained within the honeycomb structure of cashew nut shells [11,20]. The cashew nut is composed of 35–45 % kernels and 55–65 % shells [8].

The shells contain 25–30 % neat CNSL. The first method for CNSL extraction was developed by a Portuguese company in 1961 [27]. Since then, various extraction techniques, classified as mechanical, thermal, and chemical, have been developed for extracting bio-oil from the CNSs. Figure 1.2 presents cashew fruits and their components: the cashew apples, the cashew nut, and the shell containing CNSL.

1.5.1.1. Mechanical extraction

Mechanical extraction is the most commonly used method for extracting edible oils used in the world. In this process, the CNSL is extracted mechanically using an expeller or screw press, which applies pressure to the nut shells, which then release the oil. For instance, Srinivasan et al. [28] extracted CNSL employing a mechanical extraction method using a customised mechanical screw press. The compression screw was operated at a spindle speed of 7-13 rpm, while the maximum feeding and extraction rates were determined to be 54-95 kg/hr and 11.93-14.90 kg/hr, respectively.



(a) **(b)**

Figure 1.2. Cashew apple (a) and nutshell (b)

1.5.1.2. Thermal extraction process

Thermal extraction involves applying heat for facilitating the extraction of CNSL from cashew nut shells. This process requires heating CNSs in a reactor at temperatures up to 180 °C for extracting the bio-oil [29]. The liquid obtained from this process is referred to as technical CNSL. Thus far, numerous thermal extraction processes have been developed, including hot oil baths, roasting, solar cooking, and pyrolysis [30–33]. Pyrolysis is the thermal decomposition of materials at elevated temperatures in inert atmospheres. This process is used to extract valuable compounds from organic materials such as bio-oils. Das and Ganesh [31] used vacuum pyrolysis to extract CNSL at temperatures between 400 and 550 °C. Patel et al. [34] extracted CNSL from cashew nut shells using a packed bed reactor (pyrolysis reactor) operated at 500 °C and 720 mm Hg.

1.5.1.3. Solvent extraction

Solvent extraction results in a higher CNSL yield than that using other methods. Methanol, acetone, and methyl isobutyl ketone are among the most commonly used solvents for obtaining the highest CNSL extraction yield (38–40 %) [19,35–37]To extrude CNSL from the cashew nut shells, the solvent must be heated above its boiling point (65–100 °C).

Bangjang et al. [38] extracted CNSL using a solvent extraction method. Before extraction, the CNSs were washed with water and dried at 80 °C. A mass of 150 g of crushed CNSs was mixed with 1 L of ethanol and stirred continuously at room temperature for 1 hour. The mixture was then subjected to vacuum filtration to separate the liquid extract from the residue.

Chatterjee et al. [29] extracted CNSL using methanol and subsequently decarboxylated the resulting bio-oil with a silver-based catalyst. The CNSs were dried, crushed into smaller fragments, and placed in a Soxhlet flask containing methanol. The solvent was heated to 75 °C, maintained at a flow rate of 1 L/min. Each extraction cycle lasted 6–7 hours. The CNSL extract was then concentrated by removing the methanol under reduced pressure using a rotary evaporator.

1.5.1.4. Thermomechanical process

As illustrated in Figure 1.3, this process employs steam treatment followed by crushing using a mechanical expeller to produce CNSL from cashew nut shells [39].

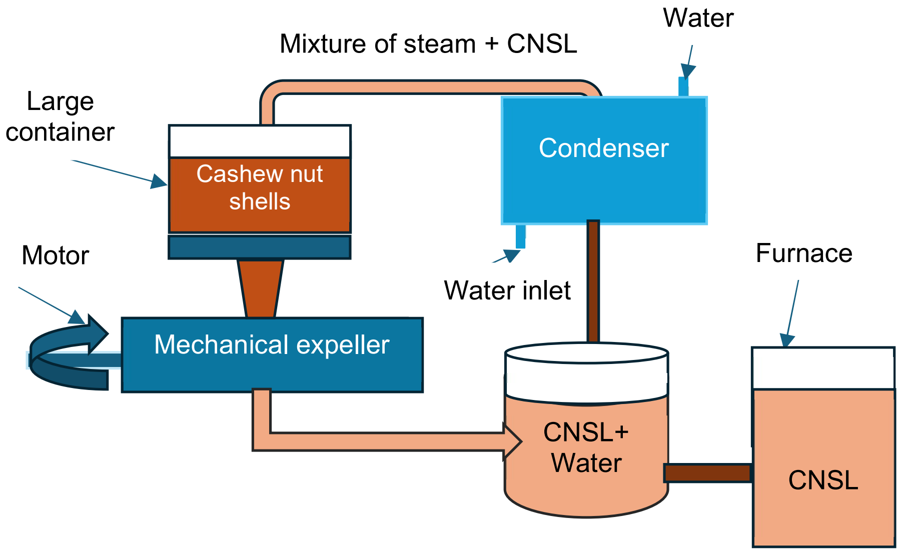


Figure 1.3. Thermomechanical process for extracting CNSL [39]

The cashew nut shells are placed in a large steel container, and hot steam, which can recover oil from soaked shells, is injected from the bottom to begin the steam treatment process. Subsequently, a mechanical press crushes the hot shells and extracts the CNSL. This process produces 20 % CNSL from any given quantity of cashew nut shells. However, compared to other extraction processes, the extracted CNSL has a lower viscosity. Therefore, this method improves not only CNSL recovery from cashew nut shells but also its fuel properties (viscosity, density, heating value, etc) when compared to the one extracted by another process, as reported in [40]. In contrast to roasting and hot baths, thermomechanical extraction allows for mass oil extraction in a single run, reducing production costs. This process involves high temperatures of up to 100 °C for evaporating water from a mixture of CNSL and steam. The thermo-mechanical process can be costly due to the equipment and energy required. It involves operating a mechanical press and equipment to generate steam, significantly increasing process costs. The integration of solar thermal collectors can help mitigate the effect on the overall feasibility and sustainability of CNSL production [41].

1.5.2. Chemical composition of CNSL

CNSL primarily consists of anacardic acids, cardanols, cardols, and other components (such as 2-methyl cardols and polymeric materials). The chemical composition of CNSL may vary depending on the extraction method used.

1.5.2.1. Pressed CNSL

The mechanical extraction is quick and easy [8]. This method produces lower CNSL yields, with high impurity levels and viscosities [29]. Srinivasan et al. [28] extracted CNSL by using a mechanical pressing and reported a high-purity, low CNSL yield of 17.7 % containing ~52 % anacardic acid, 34 % cardol, 8 % cardanol, 0.04 % methyl cardol, and 6 % other compounds. They also indicated that the extraction residue contained up to 5.7 % CNSL. The CNSL obtained using this method exhibited high viscosity and low thermal oxidation stability [42]. Neat CNSL in the shell comprised up to 10 % cardanols. Thus, the chemical composition of the pressed CNSL indicated that heating occurred during extraction, increasing the cardanol content. Depending on the intended use of the final product, temperature elevation during the extraction process can be controlled to prevent alterations in the CNSL.

The main drawback of this method is that the residue from the extraction still contains residual CNSL up to 15%. This technique also requires electricity, approximately 50 kWh per tonne of CNSs. If this energy is derived from fossil fuels, it can increase environmental pollution. This can be significantly solved by employing renewable energy sources to power mechanical presses. The mechanical extraction methods can produce vast amounts of CNSL with minimal low-skilled labour.

1.5.2.2. Pyrolytic CNSL

Das and Ganesh [31] extracted CNSL by vacuum pyrolysis and obtained bio-oil had a heating value of 40 MJ.kg^{-1}, which was very close to that of diesel fuel. This bio-oil exhibited excellent miscibility with diesel, methanol, acetone, and hexane, with ash and water contents of 0.01 and 3–3.5 % wt., respectively. Patel et al. [34] extracted CNSL from CNSs and achieved a yield of 28 % containing high concentrations of polymeric materials and impurities. Further, a supercritical fluid extraction method (CO_2) was used for enhancing the bio-oil composition, which results in products containing high concentrations of cardanols (86 %) and phenols (~ 5 %).

The thermal extraction process yields bio-oil with a higher cardanol content than natural extraction methods. Owing to its high cardanol content, it can be used for many industrial applications and has potential interests in industries, such as epoxy and acrylic and monomers, plasticisers, and surfactants [43]. Moreover, this CNSL's high heating value and lower moisture could make it advantageous as an additive in the fuel mixture.

1.5.2.3. Solvent-extracted CNSL

The chemical composition of CNSL obtained via solvents can depend on the type of solvent. Solvent extraction yields a liquid product referred to as natural CNSL. The obtained CNSL contains 10–45 % cardols, 26–50 % cardanols, 26–30 % anacardic acids, and other compounds. Yuliana et al. [37] evaluated the composition of CNSL extracted using supercritical water, carbon dioxide (CO_2), and solvents (hexane and methanol). Supercritical CO_2 extraction yielded 52.24 % anacardic acids and 29.58 % cardols. A considerable amount of cardanols (68.93 %) was obtained via supercritical water extraction, followed by two-stage extraction with methanol (49.22 %) and hexane (48.84 %).

Using a solvent to extract CNSL involves an additional step in the process like solvent recovery. This method requires energy for vacuum filtration and solvent recovery. Moreover, it consumes a significant amount of solvent, which is costly [44]A higher solvent recovery rate is necessary to improve the economic viability and feasibility of large-scale extraction.

1.5.3. Classification and Composition of CNSL

The structures of the three main components of CNSL (anacardic acids, cardanols, and cardols) are shown in Figure 1.4 [29].

Depending on the extraction process, CNSLs can be classified into two types natural CNSL (nCNSL) and technical CNSL (tCNSL). Natural CNSL (also referred to as immature CNSL) are extracted using cold extraction processes, such as using solvents or mechanical pressing, and they contain 51–70 % anacardic acids, 10–20 % cardols, 3–10 % cardanols, 2–3 % of 2-methylcardols, and other minor constituents (Table 1.1).

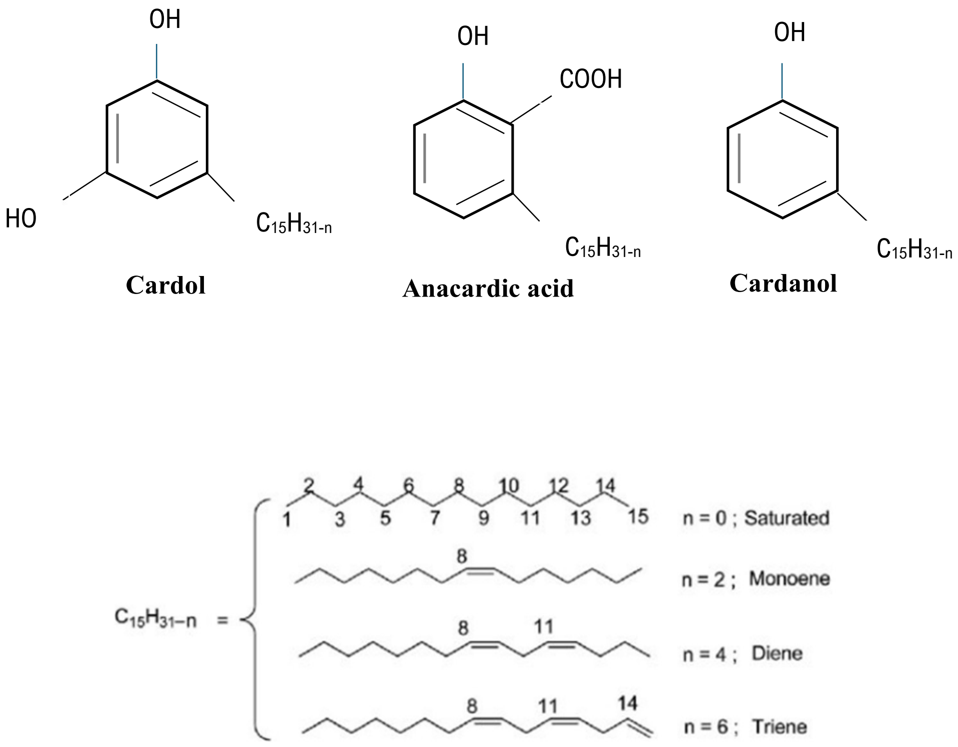


Figure 1.4. Structures of the major liquid constituents of CNSL [29].

Anarcardic acids are thermodynamically unstable and easily converted into cardanols at temperatures above 100 °C. The heat treatment decarboxylates anacardic acids into cardanols, resulting in an increase in cardanol content and a drastic reduction in anacardic acid content. This yields a product known as technical CNSL, which can be obtained using high-temperature processes, including vacuum pyrolysis, supercritical water extraction, and thermomechanical processes. Technical CNSL is chemically different from natural CNSL and contains 60–70 % cardanol, 10–20 % cardol, anacardic acid (< 5 %), 2–3 % 2-methylcardol, and 7–10 % polymeric materials (Table 1.1). Technical CNSL is rich in cardanols and contains highly polymeric materials that lead to phase separation when used in fuel blends.

CNSL has emerged as a promising candidate to replace phenol in the chemical industry. For example, Cardolite company produces high-purity cardanol from CNSL, which is valuable in the chemical industry, and the residue is used to create durable friction materials for automotive brake linings. Scaldaferri and Pasa [45] have identified CNSL as a cost-effective, natural phenolic compound for producing phenol/formaldehyde polymers. These polymers, derived from CNSL, present a renewable and economical alternative to petroleum-based materials. According to Sharma et al. [46], CNSL has diverse applications across multiple industries, including pharmaceuticals, coatings, laminates, adhesives, biofuel derivatives, and insecticides. Cardanol serves as an alternative raw material for synthesising coatings, adhesives, and plasticisers [47] [48].

Further treatment is necessary to remove or eliminate polymeric materials that are not interesting for diesel engine applications. CNSL can exhibit different chemical compositions based on the extraction and treatment methods. nCNSL contains a higher oxygen content than tCNSL because of heat treatment, which improves the hydrogen and carbon content (Table 1.2). CNSL contains 4–13 % oxygen, which reduces its heating value compared to that of diesel. However, the elemental composition of TC–CNSL is similar to that of diesel fuel, which implies that TC–CNSL may have a higher heating value than that of straight vegetable oil (SVO).

Table 1.1. Composition of nCNSL, tCNSL, and DT–CNSL (distilled technical CNSL) [48]

Type of CNSL	Cardanols	Anacardic acids	Cardols	2-methyl cardol	Polymeric Materials
nCNSL	3–10 %	51–70 %	10–20 %	2–3 %	–
tCNSL	60–70 %	<5 %	10–20 %	2–3 %	7–10 %
DT–CNSL	> 90 %	Not detected	< 5 %	Not detected	–

Table 1.2. Elemental analysis of CNSL, SVO, and diesel fuel (nCNSL: natural CNSL, tCNSL: technical CNSL, SVO: Straight vegetable oil, TC-CNSL: Thermal cracked-CNSL)

Components	**nCNSL** [28]	**TC–CNSL** [28]	**tCNSL** [11,31]	**SVO** [11]	Diesel
Carbon (%)	81.02	84.16	76–80	78	86.5
Hydrogen (%)	8.50	11.45	10–12	12	13.2
Oxygen (%)	8.62	4.01	8–13	10	0
Nitrogen (%)	0.30	0.33	<0.2	-	0.18
Sulphur (%)	0.09	0.05	-	-	-

1.5.6. Post-processing of CNSLs

1.5.6.1. Vacuum distillation of the CNSL

As shown in Figure 1.5, the CNSL is further processed by vacuum distillation in a distillation reactor (0.2 mm Hg at 230 °C).

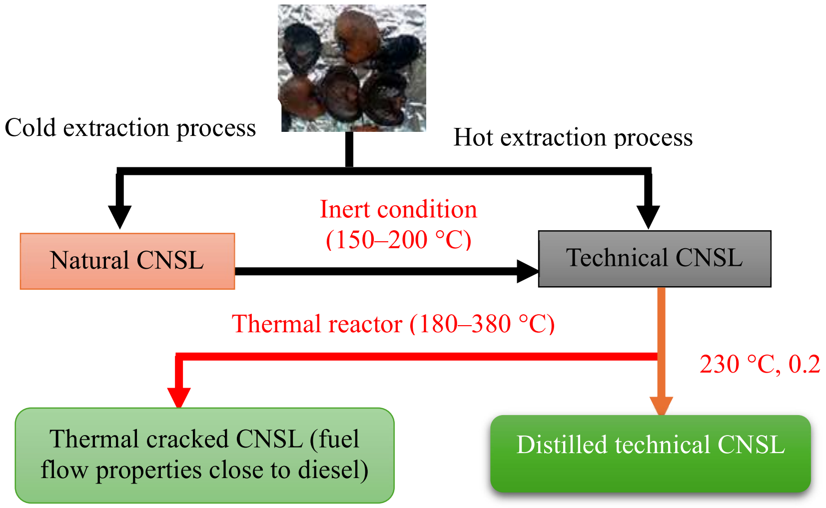


Figure 1.5. Process of obtaining CNSL biofuels.

The bio-liquid product obtained contains higher amounts of cardanols (> 90 %) and cardols (<5 %), and it is referred to as DT–CNSL or cardanol (Table 1.1). DT–CNSL has been used as a non-transesterified biofuel and as an additive to convert triglycerides to biofuel without methyl ester formation [49,50]. Further, it has been used to stabilise blends of SVO and tallow oil in diesel, exhibiting uniform solution behaviour and stability [49].

1.5.6.2. Thermal cracking of CNSL

Thermal cracking has been investigated in recent studies that aim to improve the properties of CNSL [18,51–54]. In this process, the cracking reactor is filled with DT–CNSL and heated until a temperature range of 180–380 °C (Figure 1.6).

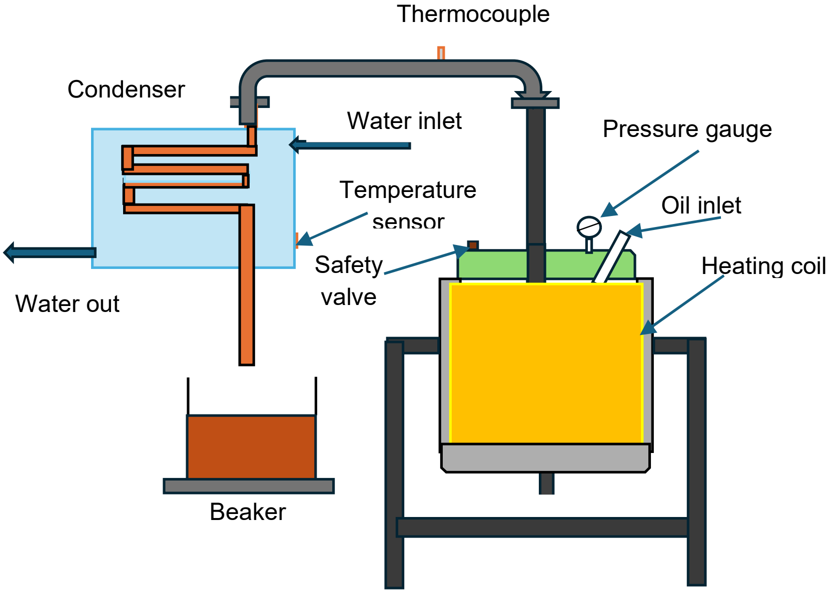


Figure 1.6. Thermal cracking reactor [18]

Under this heat, vapour forms and condenses in the condenser, and subsequently, the condensate is collected in the collector. The obtained organic fraction is referred to as TC–CNSL, which is produced by subjecting CNSL to a thermal cracking process at high temperatures to produce biofuel. This process alters the chemical composition of CNSL, which makes it a direct biofuel or a blend with diesel for diesel engines [53]. The physical properties of the obtained TC–CNSL, including density, viscosity, and calorific value, are closer to those of diesel.

Both DT–CNSL and TC–CNSL are derived from CNSL; however, they are processed differently. Interestingly, DT–CNSL has been highlighted for its ability to stabilise fuel blends and improve the income of farmers [49], and TC–CNSL has been studied for its potential as a biofuel, focusing on its performance, emissions, and combustion characteristics in diesel engines [53].

1.5.6.3. Decarboxylation of natural CNSL

The reaction for decarboxylation consists of converting anacardic acids to cardanols. Chatterjee et al. [29]achieved the decarboxylation of CNSL extracted by solvent extraction using a vertical autoclave. CNSL was mixed with silver carbonate (10 mol%) and acetic acid (5 mol%) in 0.5 M DMSO (dimethyl sulfoxide). The autoclave was heated to 140–150 °C at 35 psi pressure. As a result of the application of pressure, the silver catalyst has settled at the bottom of the autoclavable container. After decantation, the dark brown liquid was separated from the silver carbonate. A significant conversion of anacardic acid to cardanol was observed (nearly 88%) at 100 °C, and a higher cardanol yield was observed at 140 °C. Decarboxylated CNSL showed improved fuel properties due to a diminution in acidity and viscosity.

1.6. Fuel characteristics of CNSL biofuel

Several fuel characteristics determine fuel quality. Table 1.3 lists the most investigated characteristics of CNSLs as biofuels: density, viscosity, heating value, acid and cetane number, and flash point. These fuel characteristics are important when selecting biofuels for diesel engines to achieve the best performance, emission characteristics, and safety.

1.6.1. Density of CNSLs

Density indicates the relationship between the mass and volume. For liquid fuel, a high density indicates more energy per cycle; however, excess fuel–air equivalence in the combustion chamber can result in higher unburnt hydrocarbon and particle emissions [7]. Therefore, the density of a fuel can affect the performance and emission characteristics of diesel engines.

The density of DT–CNSL is between 930 and 957 kg.m^{-3}, which is lower than that of tCNSL (973 kg.m^{-3}). Both DT–CNSL and tCNSL have a higher density than that of the diesel standard (Table 3). In contrast, TC–CNSL displays densities between 821 and 890 kg.m^{-3}, which is similar to that of diesel fuel. The high density of tCNSL can be attributed to the high proportion of polymeric materials that have considerably higher molecular weights than cardanol, which is the principal constituent of DT–CNSL [42]. CNSL's density can be reduced by blending it with secondary fuels of lower molecular mass, such as diesel, ethanol, methanol, and butanol. Although transesterification or preheating can also reduce the density of biofuels, both processes require complex equipment and techniques.

1.6.2. Viscosity of CNSLs

The viscosity of a fluid determines its resistance to the flow. This is an important fuel characteristic because it affects atomisation and injection. Further, viscosity affects the performance of the fuel-injection equipment, which leads to insufficient fuel atomisation, affecting the performance and emission characteristics of diesel engines [7,55].

The viscosities of TC– and CC–CNSL (4.1 and 4.4 cSt, respectively) are in accordance with the ASTM D975 standard (5.9 cSt). In contrast, DT–CNSL has an average viscosity of 24.6 cSt, which is higher than that of diesel fuel specifications. This value is slightly higher than the maximum recommended value for stationary diesel engines (17 cSt). Although the viscosity of tCNSL is ~66 times higher than that of diesel, it satisfies the specifications for heavy fuel oil. Therefore, tCNSL can be used as an alternative to heavy fuel oil in stationary diesel engines and industrial boilers.

Significant differences were observed between the viscosities of DT–CNSL and tCNSL. Cardanol is the main component of DT–CNSL and has a considerably lower viscosity than that of polymeric materials. Reducing the viscosity of CNSL biofuels before injection into diesel engines is critical because high-viscosity fuels can lead to poor atomization during injection, resulting in incomplete combustion and the formation of deposits in the fuel injectors and on engine components [39]. The viscosity of CNSL can be reduced by blending it with diesel or other low-viscosity organic liquid fuels, as shown in Figure 1.7. Adding methanol (with B30) reduces the viscosity of fuel blends due to its low viscosity. However, methanol can also introduce potential drawbacks, such as increased corrosiveness, which can damage engine components over time. Additionally, methanol has a lower energy content than traditional fuels, which may reduce fuel efficiency. Finally, the increased volatility of methanol can pose safety risks, particularly in terms of storage and handling.

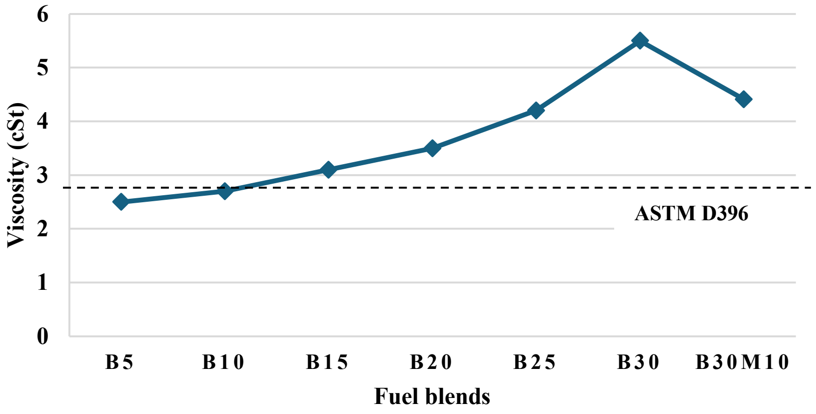


Figure 1.7. Evolution of viscosity according to the percentage of CNSL in the blend (B5: 5 % CNSL, 95 % diesel, B10:10 % CNSL, 90 % diesel, B15:15 % CNSL, 85 % diesel, B20:20 % CNSL, 80 % diesel, B25:25 % CNSL, 75 % diesel, B30:30 % CNSL, 70 % diesel, B30M10:30 % CNSL, 60 % diesel, 10 % methanol).

Fuel blends containing up to 20 % (v/v) CNSL have viscosity values close to that of diesel fuel at 40 °C (ASTM D396). The viscosity of CNSL exceeded the required range, requiring preheating to reduce it. Preheating the CNSL before injection improves its flow properties because the viscosity (and density) decreases with an increase in temperature, as shown in Figure 1.8. The CNSL viscosity does not meet the requirements of the diesel fuel standard, which sets a limit value of 5.9 cSt at 40 °C.

For low-speed stationary engines, manufacturers recommend an optimum viscosity between 13 and 17 cSt for the fuel before entering the pump [7]; the CNSL viscosity measured at 80 °C meets this specification. The preheating temperature for CNSL must be limited to less than 100 °C to avoid decarboxylation, which is accompanied by the production of polymeric materials that are undesirable for fuel applications.

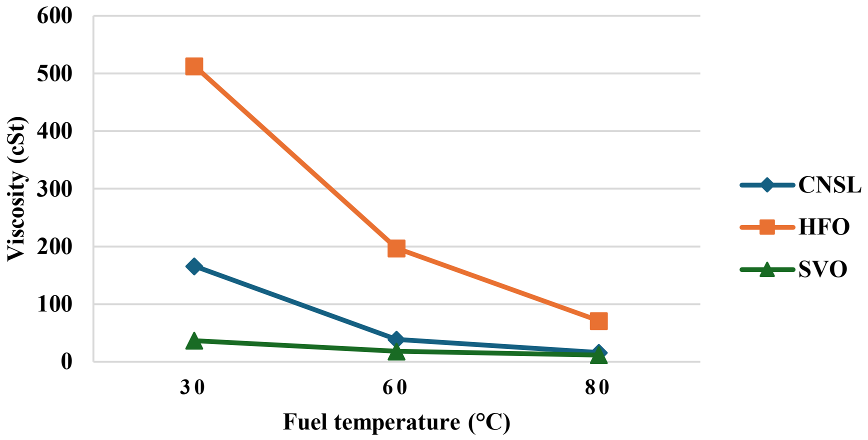


Figure 1.8. Effect of the temperature of viscosity of the CNSL, heavy fuel oil (HFO), and straight vegetable oil (SVO) [7,56,57].

1.6.3. Higher heating value of CNSLs

The higher heating value (HHV) represents the amount of energy released by fuel combustion and is an important parameter for selecting the biofuel, which depends on the combustion application [55]. Further, this parameter can provide information on the fuel consumption, heat release rate, and engine efficiency. Table 1.3 shows that the heating values of CNSLs differ slightly from each other in the range of 39–42 MJ.kg^{-1}; however, they are slightly lower than that of diesel (45 MJ.kg^{-1}). The lower HHV of the CNSLs was attributed to the presence of oxygen in their compositions. However, other authors reported an HHV for CNSL compared to that for diesel fuel [11], which can be attributed to the extraction techniques employed that affect CNSL composition.

1.6.4. Cetane number

The cetane number indicates the ignition quality of the fuel, which affects engine performance and combustion [58]. A higher cetane value indicates a shorter time between the start of injection and fuel ignition, as well as better combustion and engine efficiency. Low cetane numbers in fuels can cause knocking and increase exhaust and particulate emissions caused by incomplete combustion [7,55].

DT–CNSL exhibited a cetane number ranging from 25−41, which is lower than that of TC–CNSL (Table 1.3). The cetane number of TC–CNSL (45–48) matches that of diesel fuel (> 45). In contrast, DT–CNSL exhibits cetane numbers less than that of diesel but close to those of most vegetable oils (29−43) [7]. The lower cetane number is attributed to the higher concentration of aromatic compounds in DT–CNSL [59].

1.6.5. Flash point of CNSLs

The flash point is the temperature at which the fuel ignites in the presence of a flame or a spark without affecting the performance of the engine [7]. The flash point is specified by ASTM D-93 and is a crucial property of any fuel. A minimum acceptable flash point value is required to reduce fire risks. A high flash point ensures safe transportation, storage, and use of the combustion units. Fuel is considered non-hazardous for storage and fire safety if its flash point is ~90 °C or higher [60]. DT–CNSL has a high flash point (>185 °C), whereas CC– and TC–CNSL have flash points less than 94 °C (Table 1.3). Therefore, DT–CNSL has a low fire hazard. Owing to their low flash points, CC– and TC–CNSL pose greater risks of accidents, fires, and explosions, particularly in confined spaces where ignition sources are present.

1.6.6. Acid number of CNSLs

The acid number indicates the number of carboxylic acid groups in the fuel. For biofuels derived from vegetable oil, this parameter provides information on the degree of lubricating oil degradation [55]. The acid numbers of CNSL biofuels range from 5−36.2 mg KOH/g (Table 1.3), which are higher than that of the standard diesel. Anacardic acids are not completely decarboxylated into cardanol, as evidenced by the high acidity of CNSL. Fuels with high acidity can damage engine feed circuits (e.g. hoses and gaskets), cause tank corrosion, fuel pumping, and fuel injection problems during prolonged engine use [7]. Therefore, the acidity of CNSLs should be reduced before introducing them into an engine because engine components can be significantly damaged by prolonged exposure. The high acid number of CNSLs limits their direct use and proportion in fuel blends. However, the CNSL acid numbers match the specification values of bioliquid oils (0.39–35.43 mg KOH/g) [56]. Hence, CNSL can be used as a heavy-fuel oil replacement without causing major damage to boilers or low-speed stationary diesel engine components.

1.6.7. Ash content of CNSLs

The ash content indicates the content of abrasive minerals and oxides in the engine [7]. Petroleum products typically contain extremely small amounts of ash. The maximum value of diesel ash content is 0.001 % (ASTM D975), which is similar to that reported in [28] for TC–CNSL. In contrast, tCNSL has a high ash content (Table 1.3), and therefore, its use can generate large deposits in engine combustion chambers, resulting in incomplete combustion, reduced fuel efficiency, and increased emissions. This not only decreases the overall performance of the engine but also contributes to environmental pollution. Further, these deposits can cause engine knocking, reduced power output, and increased wear and tear of the engine components. Thus, regular maintenance, such as cleaning the combustion chamber, is necessary for preventing these issues and ensuring optimal efficiency when using CNSL biofuels.

Table 1.3. Other properties of cashew nutshell liquid (CNSL).

CNSLs	Density $[kg/m^3]$	Viscosity [cSt]	HHV $[MJkg^{-1}]$	Cetane number	Acid number [mg KOH/g]	Ash [%]	Carbon residue [%]	Flash point [°C]	References
DT–CNSL	914–956	8–43	39.2	25–41	5–15	-	-	185–226	[18,38,39,51,53,58,58,59,61–64]
TC–CNSL	821–890	4.1–4.4	42.0	45–48	-	0.001	-	28-94	[18,51,54,61,63]
tCNSL	973	388	41.6	-	10.7–36.2	0.06	6.74	283	[14,28,38,42,65]
nCNSL	961.1	77.05	37.9	-	-	1.3	6.45	206	[28]
Diesel fuel	820–889	1.6–5.9	>45	>50	0.5	-	<0.15	>61	[7]

1.6.8. Storage stability of CNSLs and its use as a fuel blend surfactant

Fuel stability is an important property of biofuels, ensuring uniform fuel properties during prolonged storage. CNSL has an elevated oxygen content, and therefore, it exhibits lower chemical and thermal stabilities than those of conventional fuels. Sanjeeva et al. [49] studied the stability of DT–CNSL using a colorimetric method (ASTM 1500). They observed that DT–CNSL was stable for 60 d when stored in galvanised iron cans, and in the presence of an anti-polymerising agent, it took 120 d for the colour change to be significant. The authors argued that a small amount of DT–CNSL blended with tallow oil and mixed with diesel contributed to the absence of phase separation, thereby making the mixture more homogeneous. Bangjang et al. [58] suggested the use of DT–CNSL as an emulsifying agent to stabilise an ethanol and diesel blend, whereas Mallikappa et al. [66] proposed using ethanol as a solvent that solubilised ethanol in diesel.

1.6.9. Limitations of using CNSLs as biofuels for diesel engines

The analysis of the physicochemical properties revealed differences between nCNSL, tCNSL, and diesel fuel. These differences are related to fuel properties such as density, viscosity, and acid value. CNSLs are characterised by high viscosity, high density, and low volatility, and they do not meet the diesel specifications. Further, they have high acidity, which can cause the corrosion of tanks, pumping, and fuel injection systems. Based on these observations, the direct use of CNSLs is not of interest or conceivable for the current configuration of diesel engines. Researchers focused on DT– or TC–CNSL because of their miscibility with diesel and other solvents (methanol and acetone) and superior key fuel properties to overcome the challenges limiting the use of CNSLs as biofuels.

Most studies on CNSL as a biofuel used it in mixtures such as blends with diesel and/or alcohol (ethanol, methanol, and butanol), acetone, diethyl ether, toluene, and vegetable oils[15,17,62,67–71]. Some researchers [72,73] preheated CNSL or its mixtures before injecting them into diesel engines to improve performance. However, other studies [74,75] focused on adjusting the fuel injection parameters in the engine, including the injection pressure and timing.

1.7. Applications of CNSL and its blends with other additives as fuel in diesel engines

1.7.1. CNSL as a biofuel in diesel engines

Although the use of CNSL in blends with diesel has been studied extensively, few studies have investigated the performance of diesel engines powered solely by CNSL biofuels. Velmurugan et al. [53] performed a comparative study to evaluate the performance of a diesel engine fuelled by CNSL (20, 40, 60, 80, and 100 %) blended with dies. The test results for diesel engines indicated that pure CNSL consumes more fuel and is less efficient than diesel engines. Kasiraman et al. [15] compared the performance characteristics of diesel engines operated with pure CNSL and diesel fuel. The study found that the thermal efficiency of pure CNSL (23.1%) was lower than that of diesel fuel (30.14 %).

1.7.2. CNSL-diesel blends

CNSL is blended with diesel or other secondary fuels and is used to reduce its high viscosity, which improves the spray and atomisation characteristics of CNSL in diesel engines. The diesel engines fuelled by CNSL can achieve acceptable engine performance and emissions for short-term operations because of carbon deposits on injectors, valves, and pistons. CNSL is typically blended with diesel to overcome the problems associated with CNSL-fuelled diesel engines.

Senthilkumar et al. [12] reported that blending CNSL with diesel in different proportions resulted in products with diverse characteristics. To achieve an optimal combustion performance, biofuels must exhibit viscosity comparable to that of diesel [76].

Srinivasan et al. [28] investigated the performance and combustion characteristics of a diesel engine using a thermally cracked CNSL (TC–CNSL) blended with diesel [28]. CNSL was thermally cracked at 350–400 °C using a liquefied petroleum gas burner as the heating source. The properties of TC–CNSL were improved, with a significant decrease in viscosity and density and a slight increase in the calorific value, which were similar to those of diesel. However, the combustion of TC–CNSL in internal combustion engines resulted in low performance and high emissions. The authors stated that a blend of 20 % TC–CNSL is a globally accepted high-performance biofuel for compression ignition engines. Thermal cracking and distillation require high temperatures, which constrain the efficiency of these processes.

A comprehensive review conducted by Adekanbi and Olugasa [77] concluded that fuel blend B20 (80 % diesel and 20 % CNSL biodiesel) is a promising alternative fuel for diesel engines. Coulibaly et al. [78] explored the feasibility of using high-content CNSL in stationary diesel engines. To obtain purified CNSL, they mixed CNSL with ethanol, followed by evaporation. Despite the improvements in viscosity and calorific value, purified CNSL did not exhibit the potential for application as a biofuel. Next, they blended purified CNSL with diesel at different ratios and found that fuel blends with up to 60 % CNSL worked efficiently in a stationary diesel engine. However, this method required considerable amounts of ethanol, and the authors stated that the purification technique requires further improvements.

Krishna [13] investigated the performance characteristics of a diesel engine fuelled by CNSL biodiesel–diesel blends. They prepared the CNSL biodiesel from CNSL via a transesterification reaction using methanol as the reagent in the presence of an acid (catalyst). The CNSL biodiesel was mixed with various proportions of CNSL (5–30 %) and diesel. Then, they investigated the performance of a single-cylinder diesel engine at a constant speed of 1,500 rpm and various loads (0 %, 20 %, 40 %, 60 %, 80 %, and 100 %). A 25 % CNSL biodiesel blend achieved optimal performance at 60–80% load. While transesterification is an effective method for converting CNSL into biodiesel, it necessitates chemical reagents (e.g., methanol or ethanol) along with catalysts, which can restrict this process due to the significant quantity of glycerol that needs to be evaporated.

Chatterjee and Rokhum [29] studied the properties of a mixture of diesel and CNSL extracted with methanol and decarboxylated using a silver-based catalyst. They observed that B05 (5% CNSL+95 % diesel) and B10 (10 % CNSL+90 % diesel) exhibited fuel properties comparable to those of conventional diesel.

Thanigaivelan et al. [52] investigated the performance and emission characteristics of diesel engines using diesel blended with 20, 40, 60, and 80 % CNSL. The test engine was investigated on a single-cylinder, four-stroke, direct injection, compression ignition diesel engine at 1,500 rpm at various engine loads. They reported that B20 (20 % CNSL and 80 % diesel) exhibited the best performance compared with that of the other blends.

Santhanakrishnan and Ramani [79] conducted a similar study and found that B20 exhibited the best performance and could be used in diesel engines without modification. Pushparaj et al. [80] blended 10, 20, and 30 % CNSL with diesel and assessed the diesel engine performance. The diesel engine used was a single-cylinder, four-stroke, direct injection, and the experimental test was conducted at 1,500 rpm at various loads. They found that blends with up to 20 % CNSL showed comparable fuel characteristics to those of diesel. Further, they suggested that blends containing up to 20 % CNSL could be used as alternative fuels for diesel engines. Mallikappa et al. [81] experimentally investigated diesel engines fuelled by a blend of 10 %, 15 %, 20 %, 25 %, and 30 % CNSL with diesel. Pyrolysis was used to obtain CNSL, which was decarboxylated at 170–175 °C under a reduced pressure of 4,000–5,333 Pa. They found that the density, viscosity, calorific value, and flash point of blends up to 20 % were comparable to those of diesel fuel, and the emissions were acceptable.

Existing studies have shown that blends of diesel and up to 20 % CNSL exhibit fuel characteristics similar to those of diesel fuel; however, when tested in diesel engines, other studies [18,28] demonstrated a slight decrease in performance and higher emissions, including those of NO [64,80], compared with those of diesel fuel. Several studies modified the fuel-injection parameters of diesel engines, including the injection pressure and timing, to improve these characteristics.

Vedharaj et al. [39] assessed the performance characteristics of a diesel engine running on 20 % CC–CNSL blended with diesel (B20) at different injection pressures (20, 23.5, 27, and 30 Mpa). B20 showed superior engine performance compared to that of diesel; however, it had higher composite carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxide (NOx), and smoke emissions than that of diesel, and it did not comply with the legislative norms for gensets.

Vasantha and Kumar [75] conducted a similar study and found that B20 exhibited a performance similar to that of diesel fuel at injection pressures ranging from 18−19.5 MPa. Velmurugan and Loganathan investigated the effects of injection pressure (18, 20, and 22 MPa) and timing (18 °, 19 °, 21 °, 23 °, 26 °, and 28 ° before top dead centre (BTDC)) in a diesel engine running on blends of 20, 40, 60, 80, and 100 % CNSL with diesel fuel [74]. They found that the B20 blend showed better efficiency at 22 MPa and 19° BTDC than that of diesel.

Some authors proposed preheating fuel mixtures before injection into diesel engines to enhance the fuel flow parameters of CNSL and its blends without changing the default injection parameters of diesel engines. For example, Krishnamoorthi et al. [64] investigated the effect of preheating (50, 70, and 90 °C) 20 % CNSL in diesel (B20) fuelling a diesel engine. The viscosity of the blend is reduced with increasing fuel temperature, which increases diesel engine efficiency, especially at 90 °C (full load). Further, fuel preheating resulted in decreased CO and smoke emissions and increased NO emissions (full load). They also found that B20 preheated to 70 °C can be considered an alternative fuel to diesel without major modifications to the diesel engine. Govindan et al. [73] investigated the performance and emission characteristics of diesel engines powered by preheated CNSL–diesel blends at various temperatures (60, 70, and 80 °C) with ethanol fumigation. The results indicated that B20 preheated to 80 °C improved engine efficiency and emission levels. However, a preheating system is required to maintain fuel blend properties similar to those of diesel to maintain engine performance.

Radhakrishnan et al. [82] presented similar observations and found that the HC emissions of B20+E were similar to those of diesel; however, the CO and NO emissions were lower than those of the other blends and higher than those of diesel. The emission levels of the CNSL-diesel blends were higher than those of diesel; however, these high emissions can be reduced using oxygenated additives.

1.7.3. CNSL in diesel blended with other additives

Alcohols such as ethanol and butanol are attractive biofuels for blending with CNSL because they are renewable energy sources. The addition of alcohol to the CNSL-diesel mixtures enhances the fuel flow characteristics. Furthermore, methanol is a good additive for blends because it is completely miscible with CNSL, which has been used as an antioxidant to improve the miscibility between ethanol and diesel. Therefore, surfactants are not required to stabilise CNSL-diesel blends containing alcohols, such as methanol and ethanol. Additives such as toluene, acetone, camphor oil, and kerosene have also been used to improve the fuel characteristics of CNSL (blends) and are presented in this section.

Venkatesan [69] prepared ternary blends of CNSL, toluene, and diesel (CNSL: toluene: diesel= 5:5:90, 10:5:85, 15:5: 80 %, respectively) and investigated their performance and emissions in diesel engines. Experiments were conducted on a naturally aspirated, single-cylinder, four-stroke diesel engine, developing 4.4 kW output power at 1,500 rpm. The fuel blends (CNSL: toluene: diesel= 5 %:5 %:90 %) exhibited properties similar to those of diesel and the best combustion characteristics and performance relative to diesel, as well as reduced HC, CO, and NOx emissions.

Shantharaman et al. [17] investigated the effects of acetone in 4 %, 8 %, and 12 % (v/v) blended with B20 on the performance and emissions of a single-cylinder, four-stroke direct-injection diesel engine. They found that 12 % (v/v) acetone added to B20 showed the best BTE compared to that of other blends and diesel. Further, they found a reduction of 34, 49, and 16 % of the HC, NOx, and smoke emissions compared to those in an engine running on diesel.

Kasiraman et al. [15] tested a diesel engine running on CNSL blended with diesel and other secondary fuels in various proportions. The test engine was conducted in a Kirloskar TV1, single-cylinder, four-stroke, water-cooled, direct-injection engine at 1,500 rpm at various loads and showed only the results at full load (100 %). The authors found that the BTE of neat CNSL (23.1%) was lower than that of diesel (30.14 %), and the BSFC for neat CNSL was higher (450 $g\cdot KWh^{-1}$) than that of diesel (290 $g\cdot KWh^{-1}$). The diesel engines fuelled by CNSL biofuels can achieve acceptable engine performance and emissions for short-term usage because of carbon deposits on injectors, valves, and pistons. Among the fuel blends, CNSL blended separately with 30 % diethyl ether, 30 % butanol, and 30 % camphor oil exhibited the best performance, which was close to that of diesel fuel.

Aruna and Vardhan [83] investigated the variation in compression ratios (16:1, 17:1, and 18:1) in diesel engines running on CNSL-kerosene blends (CNSL: kerosene = 20:80 %, 30:70 %, and 40:60 %). The experimental test was conducted in a single-cylinder, four-stroke, water-cooled, nominal power of 3.5 kW, with 20 MPa fuel injection pressure and 23 °BTDC injection timing, and at various loads. The brake thermal efficiencies of the fuel blends increased with an increase in the compression ratio from 16:1 to 18:1. The highest thermal efficiency of 29.87 %, with a reduction in CO, HC, and smoke emissions and an increase of 1.8 % in NO emissions, was observed for fuel blends with 30 % CNSL.

Dinesha and Mohanan [67] investigated a diesel engine fuelled by CNSL-diesel blended with methanol (CNSL: diesel: methanol=10:80:10, 20:70:10, and 30:60:10 %). The test conditions of the engine are 20MPa injection pressure and 27.5 ° BTDC injection timing. They reported that the properties of all fuel blends satisfied the diesel standard, with the thermal efficiencies of B10M10 (10:80:10 %) and B20M10 (20:70:10 %) matching those of diesel. Further, the low CO, HC, and smoke emissions of the B20M10 blend (20 MPa and 27.5° BTDC) are acceptable for its use as an alternative fuel to diesel.

Nallusamy [62] investigated the emission characteristics of a single-cylinder diesel engine at a constant speed (1,500rpm) using B20-ethanol and B20-butanol blend. This study revealed that 20 % CNSL blended with 10 % ethanol reduced emissions and can be used in diesel engines without any modification. Another study investigated the effects of engine intake air oxygen enrichment (3, 5, and 7 %) in a diesel engine running on a B20M10 blend [84]. The results of this study revealed that enriching the intake air with 7 % oxygen reduced CO, HC, and smoke while achieving a high thermal efficiency (~33.98 %). Thus, intake air enrichment with 7 % oxygen improves the performance and emission characteristics of diesel engines.

Pushparaj and Ramabalan [71] investigated the performance and emission characteristics of a diesel engine fuelled by CNSL–diesel blend (B20), B20 blended with 10% ethanol, and B20 blended with 10% diethyl ether. The test engine was conducted in a single-cylinder, naturally aspirated, four-stroke, water-cooled, 16.5:1 compression ratio, direct injection diesel engine, and the maximum engine power is 3.7 kW at 1,500 rpm. The results showed that NO emissions were reduced by ~51% when using 10% diethyl ether with B20 to run diesel engines. In addition, the fuel blend (B20+10 % diethyl ether) exhibited better engine performance and lower emissions than those of the B20 blended with 10% ethanol and B20 blend.

Many researchers have used additives, such as butanol, acetone, and ethanol, to improve the properties of the CNSL biofuel to improve its performance in diesel engines. Kasiraman et al. [85] explored the use of the high-density and high-viscosity CNSL fuel blended with butanol at various volumes and analysed its combustion, performance, and emission behaviour. This investigation showed that 30 % butanol in a blend with CNSL afforded the optimum engine performance. Moreover, butanol can be obtained from carbohydrates via an acetone–butanol–

ethanol (ABE) fermentation process with a typical ratio of 30 % acetone, 60 % butanol, and 30 % ethanol (361) [16]. Shantharaman et al. [17] added acetone (4 %, 8 %, and 12 %) as an additive to CNSL–diesel blends (B20) to increase the content of CNSL and analysed their performance as a fuel in diesel engines. The results revealed that 12 % acetone with a B20 blend serves as a better alternative fuel for diesel engines. Thanigaivelan et al. [18] tested a diesel engine with TC–CNSL blended with diesel. Ethanol and hydrogen were added to a B20 blend (20 % TC–CNSL, 80 % diesel) at various flow rates. They concluded that a 10 %-ethanol-blended B20 blend with a hydrogen flow rate of 8 L/min exhibited the highest brake thermal efficiency and reduced CO and HC emissions. To the best of our knowledge, no previous studies have used a blend of acetone, butanol, and ethanol as an additive to improve the properties of pristine CNSL and its blends.

1.8. Performance analysis of diesel engines fuelled by CNSL biofuels (and its blends)

Studies on the performance characteristics of diesel engines fuelled by CNSL biofuels have focused on using DT– and TC–CNSL and their blends with other fuels (Figure 1.9, Table 1.4).

1.8.1. Brake thermal efficiency

Brake thermal efficiency (BTE) represents the combustion efficiency, that is, the conversion of fuel chemical energy into mechanical energy. Several researchers examined the thermal efficiency of diesel engines fuelled by CNSL (and their blends) under different engine loads. Most studies found that thermal efficiency increases with engine load [69,86]. This can be explained by the reduction in heat loss and increase in power developed at high loads. However, the thermal efficiency decreased with increasing proportion of CNSL in the fuel blends because the high proportion of CNSL results in high viscosity, high density, low volatility, and low calorific value, which leads to poor engine performance. In contrast, Vedharaj et al. [39] reported that the thermal efficiency of a blend of 20 % CC–CNSL with diesel fuel was slightly higher than that of diesel. In addition, Velmurugan et al. [53] found that TC–CNSL performed similarly to diesel, with an efficiency of 34.52 %. This good performance can be attributed to the TC– and CC–CNSL, which have fuel properties identical to those of diesel.

Other studies reported the enhancement of thermal efficiency by preheating fuel before injection in a diesel engine. For example, Vedharaj et al. [87] observed a 20 % increase in thermal efficiency when the CNSL biofuel was preheated to 80 °C, which can be attributed to an improvement in fuel flow properties caused by preheating. One study [15] found an improvement in the thermal efficiency of 22 % for a CNSL blended with 30 % camphor oil, when compared to that of neat CNSL. This can be attributed to camphor oil not containing oxygen, which reduced the heating value of the fuel and the viscosity of the fuel blend. Figure1.9 illustrates the comparison of BTE of different fuels at full load and diesel fuel.

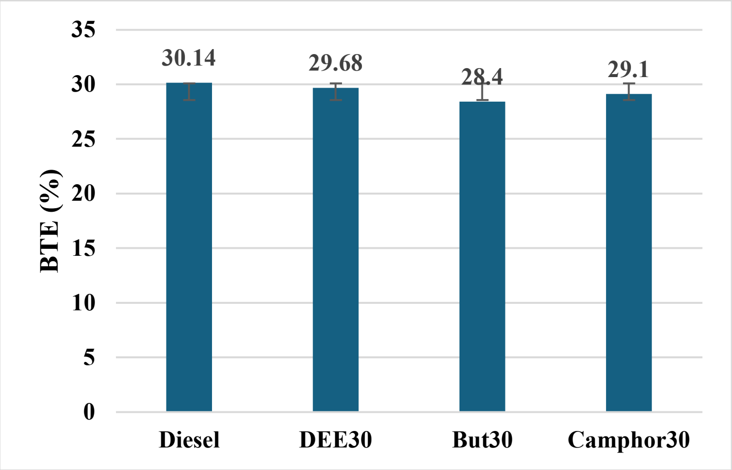


Figure 1.9. Comparison of the brake thermal efficiencies (BTE) of different fuels at full load (DEE30: 70 % CNSL and 30 % DEE, But30: 70 % CNSL and 30 % butanol, Camphor 30: 70 % CNSL and 30 % camphor oil)

1.8.2. Brake Specific fuel consumption

Brake specific fuel consumption (BSFC) refers to the amount of fuel that produces 1 kW of output power from an engine crankshaft within 1 h. Several researchers have evaluated the BSFC of diesel engines fuelled with CNSL biofuels and their blends under different engine loads. The BSFC of CNSL (and its blends with diesel) is higher than that of diesel [79,80], which is attributable to the low calorific value of CNSL and its blends. Further, the BSFC decreases with increasing engine load [69,73,79] because of the significant amount of fuel required to produce the same amount of power. However, other researchers found that blends with up to 20 % CNSL exhibit fuel consumption similar to that of diesel [50,64,88].

1.8.3. Exhaust gas temperature

Exhaust gas temperature provides information on energy loss and use. Many researchers investigated the variation in exhaust gas temperature with engine load in engines fuelled by CNSL biofuels and their blends with other additives. Most studies reported an increase in the exhaust gas temperature with engine load [28,72,75], which can be attributed to more fuel being injected to produce more power, increasing the exhaust gas temperature. Moreover, neat CNSL and CNSL in blends reportedly exhibit higher exhaust gas temperatures than diesel [28,72] because the combustion process is enhanced by the oxygen in the fuel, which increases the combustion temperature [53]. Further, this can be attributed to the presence of higher-boiling-point CNSL components that did not evaporate sufficiently during the main combustion phase and continue to burn in the later combustion phase. In contrast, Vedharaj et al. [39] found that the exhaust gas temperature of CC–CNSL was lower than that of diesel. Vedharaj et al. [87] observed that preheating CNSL biodiesel to 80 °C resulted in a reduced exhaust gas temperature until it was close to that of diesel. In addition, Kasiraman et al. [15] observed a greater decrease in the exhaust gas temperature for CNSL blended with 30 % butanol and 30 % diethyl ether separately.

1.9. Emission analysis of diesel engines fuelled by CNSL and its blends

Compared to vegetable oils, CNSLs have very different chemical structures that can affect the combustion and exhaust emissions of diesel engines fuelled by CNSL biofuels (and their blends). The chemical composition of CNSL can significantly influence the combustion process and, therefore, the exhaust emissions of diesel engines. This section presents an overview of the exhaust gas emissions from diesel engines fuelled by CNSL biofuels and their blends.

1.9.1. Emission of carbon monoxide

CO emissions are an intermediate result of the incomplete combustion of fuel and depend on the air–fuel ratio. Analyses of the CO emissions of diesel engines fuelled by CNSL (and its blends) have shown inconsistent trends [64,66,80,89]. Some studies demonstrated a reduction in CO emissions with an increase in engine load [53], whereas others reported an increase [87,90]. Many studies showed that the CO emissions of CNSL-diesel blends tend to increase with the proportion of CNSL in the blend, producing more CO than diesel. Owing to their high viscosities, fuel blends result in incomplete combustion, causing high CO emissions. The decrease in CO emissions with increasing engine load can be attributed to the increased temperature in the cylinder engines, which improves the spray air–fuel ratio. For example, Kasiraman et al. [40] enhanced the combustion characteristics of CNSL by blending it with 30 % camphor oil and observed a lower amount of CO emissions (0.30 %) compared with those of pure CNSL (0.38 %). The addition of oxygenated components improves combustion, reducing the CO levels. Vedharaj et al. [87] argued that preheating CNSL at 80 °C reduced CO emissions by ~66 % compared with that of the unheated CNSL blends at full load. In addition, Masimalai and Nandagopal [65] observed decreased CO emissions because of the intake of oxygen-enriched air compared to those under normal conditions.

1.9.2. Emission of unburnt hydrocarbons

Various factors contribute to unburnt HC emissions from diesel engines, including wall quenching, excessive mixing with air, and oxygen deficiencies. Several studies showed that HC emissions increase with an increase in the engine load and CNSL proportion [69,75]. The HC emissions are higher for CNSLs (and their blends) than that for diesel. CNSLs (and their blends) have higher densities and viscosities, which result in poor atomisation and combustion, and consequently, higher HC emissions. Velmurugan et al. [53] reported that TC–CNSL resulted in a 20 % reduction in HC emissions compared with unmodified CNSL. Meanwhile, other authors reported similar HC concentrations for fuel blends with up to 20 % CNSL [39,72]. The HC emissions can be reduced by adding oxygenated additives to CNSLs (and their blends). For example, Kasiraman et al. [40] demonstrated an 8.3 % reduction in HC emissions by adding 30 % camphor oil to CNSL (full load). Dinesha and Mohanan added 10 % methanol to a B20 blend and observed a 14 % reduction in HC emissions compared with that of pure CNSL. Moreover, Pushparaj and Ramabalan [71] observed a large decrease of ~ 35 % in HC emissions for B20 blended with 10 % diethyl ether compared to those of B20 alone. In addition, an increased oxygen intake decreased the engine HC emissions [84].

1.9.3. Emission of nitrogen oxides

Diesel engines emit dangerous and toxic gases such as NOx, which are produced by high-temperature combustion via the oxidation of N_2. The gas temperature, oxygen concentration, and reaction time affect NOx formation. Several studies concluded that NOx emissions increase with engine load and the proportion of CNSL in fuel blends [50,75,79,82,88]. This trend can be attributed to the high flame temperatures and prevalence of excess oxygen within the combustion chamber at higher loads [87].

In contrast, Sanjeeva et al. [50] found that NOx emissions were significantly lower for DT–CNSL blends than that for diesel. Krishnamoorthi et al. [91] observed lower NOx emissions from unheated CNSL compared to that from diesel fuels, which can be attributed to the poor atomisation of CNSL oil leading to poor combustion and lower NOx emissions. However, other studies reported that NOx emissions from 20 % CNSL-diesel blends are very low compared to those from diesel [39,75]. For example, Dinesha and Mohanan [67] observed reduced NOx emissions from the B30M10 and B20M10 blends compared to those from diesel. After adding 10 % diethyl ether to B20, Pushparaj et al. [71] observed a significant reduction in NOx emissions of ~51 % compared to those of diesel. Shantharaman et al. [17] observed an ~49.4 % reduction in NOx emissions for B20 blended with 12 % acetone (high loads). Fuel modification strategies, such as preheating, increasing the injection pressure, and intake of air oxygen enrichment, can improve fuel blend combustion and consequently lead to high combustion temperatures and the production of significant NOx emissions.

1.10. Overall conclusions and outlook

The use of CNSL biofuels in diesel engines (e.g. particularly DT–, CC–, and TC–CNSL, has been widely discussed in recent years because of their appealing fuel characteristics. However, CNSL biofuels perform poorly in diesel engines, generating higher NOx, CO, and HC emissions. This can be improved by blending CNSL biofuels with diesel or other additives (ethanol, butanol, camphor oil, and diethyl ether). Blends containing 20 % CNSL with diesel (B20) and other additives (e.g., ethanol, butanol, camphor oil, diethyl ether) achieved physicochemical properties similar to diesel. However, these blends may require additional preheating systems or injection parameter adjustments to ensure optimal engine performance and emission characteristics. However, this necessitates additional preheating systems and adjustments to injection parameters. At injection pressures of 18.5–22 MPa, injection timing of 19° BTDC, and preheating to 70 °C, B20 blends can successfully fuel diesel engines with performance and emission characteristics similar to those of diesel. However, preheating the fuel can considerably increase the operational cost of the system.

This review describes the various techniques for improving the properties of neat CNSL; however, these techniques are still in the experimental phase, and they do not facilitate the production of large quantities of CNSL. Even when CNSL biofuel is produced, it must be blended (up to 20 %) with diesel and/or other fuel additives to achieve a performance similar to that of diesel. This small proportion of biofuels used in the blends does not facilitate the appropriate exploitation of the potential of cashew nut processing units.

Thus far, studies on tCNSL as a biofuel remain limited, and the existing studies report on its use in small proportions in blends with diesel and ethanol. The limitations of tCNSL blending include its high viscosity, high acid number, and use of polymeric materials. Polymers lead to fuel-phase separation, a critical factor for fuel blends and can lead to challenges in engine injector clogging, filtering, and pump systems. Moreover, the high oxygen content in tCNSL can lead to oxidative degradation during prolonged storage, affecting their properties, such as density, viscosity, and acid number. These properties are critical for biofuels because they affect the combustion characteristics and engine compatibility. In contrast, tCNSL exhibited fuel properties comparable to heavy fuel oil, an alternative for various other applications, such as low-speed stationary diesel engines or boilers for furnaces. Further research is necessary to evaluate their application in the diesel engine without a preheating fuel system. This would include optimising their properties by blending them with diesel and other additives. This review also stated acetone, butanol, and ethanol as suitable additives, improving diesel engines' performance and emissions characteristics fuelled with the CNSL and its blends. The combination of these additives shows strong potential for optimising energy efficiency and reducing harmful emissions, making it a promising area for further research.

Table 1.4. Performance characteristics of CNSL-diesel blended with additives

CNSL and its blends (%)	**Engine Specification**	**Modifications or operating conditions**	**Mains results**	**Ref.**
Cardanol: kerosene (20:80, 30:70, 40:60)	VCR diesel engine Mono-cylinder (1C), Four strokes (4S), Water cooled (WC), 3.5 KW @ 1,500 rpm. 20 Mpa IT-23° BTDC	Variable load (VL), Constant speed (CS)-1,500 rpm Variable compression ratios (VCR)-16:1 to 18:1	BTE ↑with load↑ for all the tested fuels. CR↑, BTE ↑ for all blends. Maximum BTE for BK30 (29.87 %) and diesel (30.36 %) at CR-18:1. CO↓, smoke↓ , and uHC↓, as the CR↑,whereas NOx↑. CO, HC, and smoke emissions of the biofuel blends were lower than those of diesel.	[83]
Cardanol: diesel: methanol (20:70:10)	Kirloskar TV1, 1C, 4S, WC, CI Engine, 5.2 kW @ 1500 rpm 17.5:1, IP: 22 Mpa IT-29.5° BTDC	VL, CS-1,500 The intake air is enriched with 7 % oxygen and the exhaust gas recirculation (EGR) by 10, 15 and 20 %.	BTE↓ as the percentage of EGR to the intake air ↑. Lower BTE for higher EGR percentages. As the EGR↑ from 0 to 20 %, NOx levels↓ . Higher CO, uHC, and smoke and lower brake thermal efficiency were obtained for higher EGR percentages. 15 % EGR showed a better reduction in NOx emissions with minimal loss of performance.	[92]
CC-CNSL: diesel (20 :80)	Kirloskar, CS, WC, 1C, 4S, (CR)=17.5:1. SOI= 23 ° BTDC	VL, CS-1,500 rpm, Variable injection pressures (20, 23.5, 27, 30 Mpa)	Improvement in BTE with increasing injection pressure. Specific fuel consumption (BSFC) improved as the injection pressure increased. CO, UHC, NOx, and smoke performed better than diesel under the same operating conditions.	[39]
CNSL: diesel: methanol (20:70:10, 10:80:10, 30:60:10)	Kirloskar TV1, 1C, 4S, WC, CI, DE 5.2 kW @ 1500 rpm 17.5:1; 200 bars IT-27.5° BTDC	VL, CS-1,500 SOI-27.5 °CA bTDC IP- 20 Mpa	Higher BTE of B10M10 and B20M10 are like that of diesel. Lower CO, HC and smoke emissions for B20M10, except NOx increased marginally.	[67]
CNSL: diesel: methanol (20:70:10)	Kirloskar TV1, 1C, 4S, WC, CI, DE 5.2 kW @ 1500 rpm 17.5:1 IP: 200 bars IT-27.5° BTDC	VL; CS-1,500 IP-200bar, SOI- 27.5 °CA bTDC	Maximum BTE observed for 7 % intake air oxygen enrichment. For the same conditions HC, CO and smoke were lowest. B20M10 achieved the highest BTE of 33.98 % with 7 % oxygen intake air. CO and HC levels decreased as the oxygen intake of air increased. NOx increased significantly.	[84]
TC-CNSL: diesel (20:80, 40:60, 60:40, 80:20, 100:0)	KirloskarAV-1, WC, DE, 1C, 4S, CR=17.5:1 IT=23CAbTDC, IP=20 MPa CS=1,500rpm	VL, CS-1,500 IP-20MPa ; SOI-23° CA bTDC	Compared to diesel, the CO and HC emissions were lower and further reduced as the proportion of the blends increased. NO increased with increasing CNSL in blends. Compared to diesel, the SFC was higher for B100. BTE was higher for diesel than for B100.	[53]

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CNSL-diesel-methanol (20:70:10)	Kirloskar TV1, 1C, 4S, WC, CI, DE 5.2 kW @ 1500 rpm 17.5:1, IP: 200 bars IT-27.5° BTDC	VL, CS-1,500 SOI-27.5 °CA bTDC; IP-180 bar	With increased air intake of 3, 5, and 7 % by weight, there HC, CO, and smoke reduced, NOx increased to 28 % (full load). As B20M10 was enriched by 3 %, 5 %, and 7 % by weight by air intake, BTE increased.	[93]
CNSL: diesel (20 :80)	1C, 4S, WC, CI, DE 4.4 kW @ 1500 rpm	VL, CS-1,500 Preheating (70 °C, 90 °C)	BTE at 50 °C, 70 °C and 90 °C was increased by 0.9 %, 2.2 % and 2.8 % respectively. For the preheated blend, CO and smoke emissions were drastically reduced. Unheated CNSL blend at full load had slightly higher NO emissions.	[64]
CNSL: diesel (20:80, 40:60, 60:40, 80:20, 100:0)	Kirloskar, 1C, 4S, WC, CI, DE, 3.7 kW @ 1500 rpm	VL, CS-1,500	BTE of CNSO (20.4 %) was lower compared to diesel (30.8 %). B20 showed better performance compared to all the other blends.	[79]
CNSL: diesel (10 :90, 20 :80, 30 :70)	Kirloskar, 1C, 4S, WC, CI, DE, 3.7 kW @ 1500 rpm	VL, CS-1,500	B20 exhibits a heating value of about 42.25 MJ/kg that is slightly lower than that of diesel. BTE of B20 and B30 come very close to that of diesel. The trends of NO and HC emission for CNSL are slightly higher at full loads. Maximum BTE obtained for 30 % CNSL biodiesel. Increase smoke, CO and NOx emission with an increase in blend percentage.	[80]
CNSL: diesel (20 :80)	Kirloskar 1C, 4S, WC, 5HP @ 1500 rpm	CS-1500 IP- 180, 195 and 210 bar	BTE for B20 (210 bar) were better compared to diesel (60 % load). BSFC decreases with load; for B20 it is lower than that of diesel (40 and 60 % loads) at 210 bar compared to other injection pressures. EGT increases with load; and slightly lower for B20 than diesel. Slightly increases for B20 and diesel (180 to 210 bar).	[75]
CNSL: diesel (20 :80, 40 :60, 60 :40)	Kirloskar, 1C, 4S, AC, DI, 4.4 KW@ 1500rpm	VL, CS-1,500	BTE increases with load, BTE of diesel slightly higher, comparable to those of mixtures EGT of biodiesel blends higher than diesel. EGT increases with load	[86]
CNSL: camphor oil (90:10, 80:20, 70:30)	Kirloskar TV1, 4S, 1C, AC, 5.2 KW@ 1500rpm, CR-17.5:1 IP-200 bar, IT-23 °bTDC	VL, CS-1,500rpm	Higher BTE for CNSL with 30 % camphor oil (29.1 %) peak load compared to diesel (30.14 %), whereas it is 23.1 % for neat CNSO. CO, HC and smoke were reduced whereas NOx emission increased.	[40]
CNSL: butanol (90:10, 80:20, 70:30). CNSL: camphor oil (90:10, 80:20, 70:30). CNSL: DEE (90:10, 80:20, 70:30).	Kirloskar TV1, 4S, AC, DI, 1C, 5.2 KW @ 1500rpm, CR-17.5:1, IP-200 bar, IT-23 °Btdc	VL, CS-1,500	Better performance for CNSO with 30 % butanol and 30 % camphor oil BTE increases to the maximum with DEE30 (29.68 %) followed by CMPRO30 (29.1 %) and BUTANOL30 (28.4 %). Smoke emission:4.01 BSU for DEE30, 3.91 BSU for both CMPRO30 and BUTANOL30 which is lower than neat CNSO and CNSOME.	[15]
CNSL: diesel: ethanol (20:70:10). CNSL: diesel: DEE (20:70:10).	Kirloskar, 4S, AC, DI, CR-16.5:1, 1C, 3.7 KW@ 1,500rpm	VL, CS-1,500	B20 with 10 % diethyl ether resulted in higher BTE and reduced CO, HC, NOx, and smoke emissions compared to B20 CNSL with 10 % ethanol.	[70]

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CNSL: diesel (40:60)	Kirloskar AV1, 1C, 4S, AC, DI, IP-200 bar, CR-16:1, IT-27° BTDC, 3.7 KW @ 1,500rpm	VL, CS-1,500 Oxygen at various concentrations (21, 22, 23, 24, and 25 %)	BTE was 30.5 %, 32.6 %, 33.2 % and 33.1 %, respectively, for 22 %, 23 %, 24 % and 25 % of oxygen enrichment at 100% power output. Higher BTE for 24 % intake air oxygen enrichment. CO and smoke reduced, whereas NOx increased.	[65]

1.11. Limitations of CNSL biofuel research

While some studies have been conducted on technical CNSL as a biofuel, it is evident that more comprehensive research is needed. The existing work has primarily focused on its use in small proportions in blends with diesel and ethanol, leaving many aspects unexplored. The limitations of CNSL blending, including its high viscosity and acid number, have been identified, but more research is needed to overcome these challenges. This review also found that preheating and blending CNSL biofuel with diesel fuel, as well as adding oxygenated fuel (acetone, butanol, ethanol, etc.), can be effective strategies. However, their full potential and implications need further investigation, highlighting the importance of ongoing research in this area.

1.12. Research questions

Based on the literature analysis, it seems appropriate to address the following questions:

(i) Is it possible to formulate an appropriate fuel blend for diesel engines using locally produced CNSL and diesel fuel, with (or without) additives?

(ii) Are the critical characteristics of the appropriate fuel blends stable over time?

(iii) Do these appropriate fuel blends operate with similar performance and emission characteristics to diesel fuel in a diesel engine?

Chapter 2. Materials and Methods

2.1. Introduction

This chapter outlines the procedure for obtaining vegetable materials (CNSLs) for fuel blend preparation and describes the equipment used to assess the physicochemical properties of the resulting samples.

2.2. Extraction process of CNSLs

First, pressed CNSL was obtained by pressing cashew nuts shells (CNSs) with a mechanical press (Oleane, France), as illustrated in Figure 2.1. Shells were obtained from Anacardium Transformation (ANATRANS) in May 2021, a local cashew nut processing company in Bobo Dioulasso (Burkina Faso). These shells served as the raw materials for the extraction of CNSL. The yield from mechanical extraction was approximately 25 %, which is lower than the CNSL content of the shells (39 %) [94]. This indicates that about 14 % of the remaining CNSL was present in the extraction cake, as also noted by Srinivasan et al. [28].

Figure 2.1. Mechanical press used for CNSL extraction

CNSL samples were also obtained from Anacardium Transformation (ANATRANS), a company specialising in cashew nut processing in the Bobo–Dioulasso region of Burkina Faso.

As shown in Figure 2.2, pressing the cashew nut shells (CNSs) produces natural cashew nut shell liquid (CNSLP), which is subsequently heated to approximately 160 °C in a batch reactor for around 4 hours and then stored in barrels for 2 weeks to yield technical cashew nut shell liquid (CNSLT).

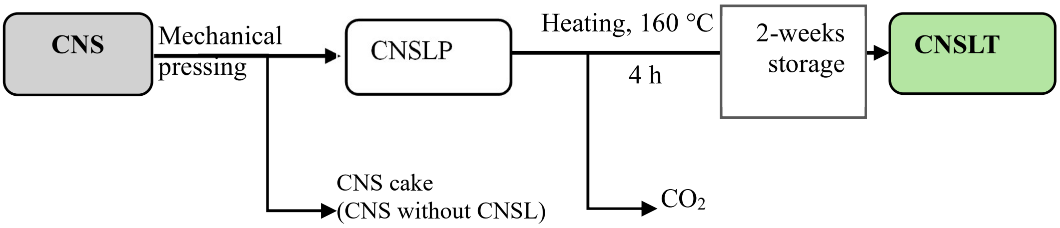

Figure 2.2. Extraction process of pressed cashew nut shell liquid (CNSLP) and technical cashew nut shell liquid (CNSLT) from cashew nut shells (CNSs)

Commercial diesel was obtained from Total Petroleum Service (Burkina Faso, Ouagadougou). Acetone (analytical grade), 1-butanol (99.5 %), and ethanol (99.97 %) were acquired from Mining and Chemicals (MAC) Services (Bobo-Dioulasso, Burkina Faso).

Preparation of ABE (361)

The ABE mixture was prepared using acetone (A), 1-butanol (B), and ethanol (E) in a volumetric proportion of 30:60:10 %. The three reagents were mixed for 15 minutes at 800 rpm using a magnetic stirrer [16]. The resulting blend is referred to as ABE (361).

The fuel blends were prepared using CNSL, commercial diesel, and ABE (361), and these components are shown in Figure 2.3.

Figure 2.3. Samples of CNSL, diesel, and ABE (361) mixture.

ABE mixture can be produced from renewable resources, such as cellulose found in various waste materials [95]. This is achieved through the acetone-butanol-ethanol (ABE) fermentation process, which typically produces ABE in a 3:6:1 ratio. Cashew apples, which are rich in sugars, have previously been used for ethanol production [96]. Due to their sugar content, cashew apples can be employed to produce ABE through the aceto-butyl fermentation process. ABE (361) has been demonstrated to be a potential additive in diesel engines, successfully applied in blends with diesel and SVO [95]. Research indicates that ABE (3:6:1) can be blended with diesel fuel at higher percentages of up to 42 % [16], whereas other additives (ethanol or acetone) can only be blended up to 12 % [17,18]. This increased blending of ABE makes it a potentially more versatile option for diesel engines. This presents a valuable opportunity to valorize cashew apples as sustainable sources of biofuels and other chemicals.

2.3. Evaluation of the chemical composition of CNSL

2.3.1. High-performance liquid chromatography (HPLC)

High-performance liquid chromatography (HPLC) is a form of column chromatography used frequently in biochemistry and analytical chemistry to separate, identify, and quantify compounds [19]. Figure 2.4 shows the image of Dionex Ultimate 3000 HPLC system used to evaluate the composition of CNSL samples.

Figure 2.4. Dionex Ultimate 3000 HPLC system

HPLC uses a column that holds chromatographic packing material (stationary phase), a pump that moves the mobile phase(s) through the column, and a detector that shows the molecules' retention times. The retention time varies depending on the interactions between the stationary phase, the analysed molecules, and the solvent(s) used.

The contents of cardanols, cardols, and anacardic acids in the CNSL samples were determined using the HPLC technique with a Dionex Ultimate 3000 HPLC system equipped with a diode detector. A SUPELCOSIL LC-18 HPLC column (20 × 4.6 mm, 5 μm particle size) was employed to separate the components, while an acetonitrile/water/acetic acid solution (80:20:1 v/v) was injected at an elution rate of 1.80 mL/min. The eluent was monitored at λ = 280 nm. All samples (25 mg in 5 mL acetonitrile) were injected in 20 μL aliquots [42].

2.3.2. Elemental analysis

Elemental analysis of the CNSL and commercial diesel samples was performed using a Vario Macro Cube elemental analyser (Figure 2.5). The process involved burning the sample, after which the resulting gases (e.g., carbon dioxide, water vapour, and nitrogen oxide) were detected using a thermal conductivity detector that emitted an electrical signal proportional to the content of the respective gas. The oxygen content was then estimated from the difference between the original weight and the analysed content of hydrogen, carbon, and hydrogen (oxygen content = 100 % - (% H + % C + % N)).

Figure 2.5. Elemental analyser

2.3.3. Thermogravimetric analysis

Thermal stability refers to the susceptibility of materials to degradation at exceptionally high temperatures, which are considerably above the ambient temperature. This concept is especially pertinent to biofuels, as fuel temperatures may increase during the operation of engine fuel injection systems because of fuel recirculation through the system and back to the fuel tank.

Thermogravimetric analysis (utilising Mettler-Toledo TGA, Figure 2.6) assesses thermal stability by monitoring changes in the sample's mass as the temperature varies in a controlled environment (nitrogen or air). This method facilitates the investigation of degradation and the prediction of CNSL's thermal stability. The thermogravimetric curve provides parameters such as the initial decomposition temperature (Ti), peak decomposition temperature (Tmax), carbon residue at 700 °C, and integral decomposition temperature (IPDT).

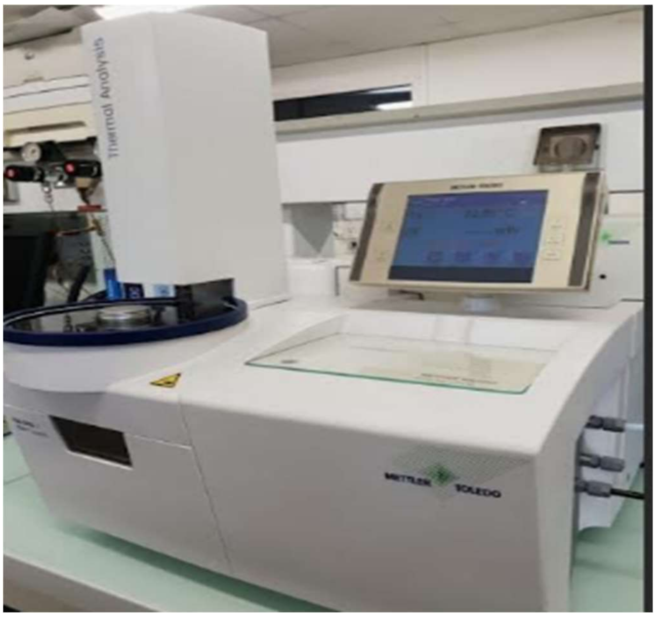

Figure 2.6. Thermogravimetric Analyser (Mettler-Toledo).

2.4. Physicochemical characterisation of samples

Biofuels must satisfy specific criteria for use in diesel engines, including density, viscosity, heating value, moisture content, acid number, and cetane number. These parameters influence diesel engines' performance, emission characteristics, and longevity. The assessment procedure for fuel parameters is detailed in the following section.

2.4.1. Kinematic viscosity

Viscosity is an important fuel characteristic that significantly influences fuel atomisation efficiency and injection in combustion units, as well as the performance and emission characteristics of diesel engines.

The dynamic viscosities of the fuel were initially evaluated using a programmable Brookfield LV-DVII viscometer (Figure 2.7) connected to a temperature controller.

Figure 2.7. Brookfield Viscosimeter

The kinematic viscosities were calculated theoretically using Equation 2.1.

$$\nu = \frac{\mu}{\rho} \qquad \textbf{(Equation 2.1)}$$

Where:

ρ is the density ($kg.m^{-3}$),

μ is the dynamic viscosity (mPa. s),

and ν is the kinematic viscosity ($mm^2.s$).

2.4.2. Density

Fuel density indicates the mass-to-volume ratio, and this parameter can affect the time between fuel injection and combustion in a diesel engine, which influences the efficiency of fuel atomisation. The densities of all fuels were measured at 20 °C using a pycnometer (Blaubrand, Germany) in accordance with the DIN ISO 3507 standard and were calculated using the following formula (Equation 2.2):

$$\rho = \frac{m_{sample}}{V} \qquad \textbf{(Equation 2.2)}$$

Where:

ρ: density of sample (kg/m^3),

V: volume of pycnometer (5mL),

m_{sample} : mass of sample (g).

2.4.3. Higher heating value

The heating value represents the quantity of heat obtained from the complete combustion of a unit mass of fuel. This is an essential property for selecting liquid fuels for engine applications, as a higher heating value leads to greater engine power output. The heating value of biofuel must be as high as possible, as it directly relates to the conversion of chemical energy into mechanical energy. This heating value depends on the chemical constituents, particularly the carbon and hydrogen content in the sample. There are two heating values: the higher heating value (HHV) and the lower heating value (LHV). HHV represents the total energy released when a material (combustible) is burnt, including the latent heat of water vapour. In contrast, LHV, often more significant, refers solely to the heat released during combustion. However, it is important to note that most scientific articles present the HHV rather than the LHV. Many authors do not specify this, merely using the term "heating value".

The HHV of the samples was evaluated using a Parr calorimeter (Figure 2.8) in accordance with the ASTM D240 standard. This process involves measuring the heat of combustion of a fuel sample that can cause a temperature rise of at least one degree (with a mass typically between 0.5 g and 0.8 g for liquid fuels). The sample is combusted in the presence of oxygen (25 bar) within a calorimetric bomb submerged in a known volume of water. The HHV is, therefore, initially calculated based on the rise in temperature of the water in the calorimeter vessel, factoring in the average heat capacity of the equipment used (gelatin capsule and ignition wire).

Figure 2.8. Parr 6200 calorimeter

The HHV is calculated using the equation 2.3:

$$\mathbf{HHV} = \frac{\mathbf{K_1 \times E_{cal}(T_m - T_i) - K_1 \times E_{pt}(L_i - L_f) - K_1 \times HHV_{capsule} \times m_{capsule}}}{\mathbf{m_{sample}}} \qquad \textbf{(Equation 2.3)}$$

Where:

K_1 : conversion factor 4.1855 J/cal,

E_{cal} : The calorimetric equivalent of the calorimeter, the bomb, its accessories and the water introduced into the bomb ($E_{cal} = 2674$ cal/°C),

T_m : maximum temperature in °C,

T_i : initial temperature in °C,

L_i : initial platinum wire length in cm,

L_f : remaining platinum wire length in cm,

E_{pt} : calorific value of platinum wire ($E_{pt} = 2{,}3$ cal/cm);

$HHV_{capsule}$: calorific value of the empty capsule, in cal/g (It is determined by taking the average of three (3) concurring determinations of the HHV of the empty gelatin capsule. $HHV_{capsule} = 5059$ cal/g,

$m_{capsule}$: Mass of the capsule (g),

m_{sample} : Mass of the test portion of the sample to be analysed (g).

The HHV of the fuel blends was determined as a function of the volume concentration of each blend component using the Kay blending rule [95].

$$\mathbf{HHV = \sum_i HHV_i \; X_i} \; \textbf{(Equation 2.4)}$$

Where:

HHVi and Xi are the calorific value and volumetric fraction of each component, respectively.

2.4.4. The acid number

The acid number indicates the quantity of carboxylic acid groups present in the product. A high acid number in fuel can lead to engine corrosion, particularly in injection systems and tanks. Therefore, this parameter should remain low and comply with the requirements for conventional fuels to avoid damage to engines during prolonged use.

The acid numbers of the samples were determined through acid-base titration in accordance with ASTM D664. Approximately 0.1 g of the sample was weighed into an Erlenmeyer flask, to which a mixture of ethanol and ethyl ether (50/50) and a few drops of phenolphthalein were added. The mixture was titrated with ethanolic potassium hydroxide solution (0.1 N) until the colour indicator changed to pink. The acid numbers were calculated using the following Equation 2.5:

$$\textbf{Acid number} = V_{\mathrm{KOH}} \times C_{\mathrm{KOH}} \times \mathrm{M})/(10 \times \mathrm{m}) \textbf{ (Equation 2.5)}$$

Where:

V_{KOH}: volume (mL) of the titrated potassium hydroxide solution,

C_{KOH}: concentration of the titrated potassium hydroxide solution,

M: molar mass in grams per mole of oleic acid (282 g/mol),

m: sample mass (g).

2.4.5. Moisture content

The moisture content of the samples was determined using a Karl Fischer titrator (Mettler Toledo V20) (Figure 2.9) in accordance with ASTM E203.

Karl–Fisher titration is a chemical method used to determine the water content in a sample at concentrations ranging from 0.01 % to 100 % v/v. It involves taking a sample mass with a disposable plastic syringe and introducing it into the titrator. Following this, the sample mass is introduced, and the instrument begins the measurement. Once the measurement is complete, the potential returns to 100 mV and drifts below the preset value (generally 25 µg/min), after which the instrument provides the result and resets for a new analysis. The measurements were repeated three times for each sample, and the average of these measurements was calculated.

Figure 2.9. Karl Fisher Titrator

2.4.6. Cetane number

The cetane number (CN) measures the quality of fuel combustion. A higher CN indicates that the fuel ignites more readily and improves combustion. According to ASTM D6751-07, the

CN of diesel fuel for compression-ignition diesel engines should exceed 47 to ensure an appropriate ignition delay [97].

CN is conventionally determined for petroleum products by a standardised method (ASTM D 613) using a variable compression ratio engine known as a CFR (Cooperative Fuel Research) diesel engine [98]. The test involves determining the ketone percentage in a mixture of 2-methylnaphthalene and n-ketone with the same ignition delay as the CFR engine fuel. The indices 0 and 100 are assigned to 2-methylnaphthalene and n-ketone, respectively.

Due to a lack of equipment for evaluating the CN, we used a calculating method to evaluate the studied samples. As CNSL has fuel properties such as density and viscosity identical to those of heavy fuel oil (HFO), and as we do not have a modern apparatus to evaluate it, we calculate CN for CNSL based on a theoretical formula for HFO. For heavy fuels, the cetane index provides an alternative formulation of the CN. The calculated cetane index, developed by British Petroleum, provides values in the order of those associated with the CN. Autoignition tendencies depend on fuel density and viscosity. The CN of CNSL was evaluated using the following equation proposed by Espadafor et al. [99]:

$$\mathbf{CN = (270,795 + 0,1038\,T) - 0,2545\,D + 23,708\,log\,(log\,(V + 0,7))} \textbf{ (Equation 2.6)}$$

where:

D: density of the sample measured at 15 °C (kg/m^3),

V: kinematic viscosity measured at temperature T=40 °C.

The cetane number of fuel blend was estimated using the relation:

$$\mathbf{CN = \sum_i CN_i\ X_i} \textbf{ (Equation 2.7)}$$

Where:

CNi: cetane number of each component,

Xi: volumetric fraction of every element.

2.4.7. Carbon residue content

The carbon residue test indicates the extent of carbon deposits from fuel combustion. Carbon residue formed by the decomposition and subsequent pyrolysis of the fuel components can clog the fuel injectors. It was determined by analysing the TGA of CNSL at 900 °C using the following method used by Rodrigues et al. [42].

2.5. Preparation of fuel blends and suitable blends for stationary diesel engines

CNSL was filtered before the experiments to remove extraction residues. Commercial diesel was obtained once from Total Energies Station (Burkina Faso) to ensure consistent properties throughout the experiments.

While the literature recommends limiting CNSL to 20 % in fuel blends for use efficiently operated in diesel engines, this study examines the feasibility of utilising higher proportions of CNSL. By investigating CNSL in fuel blends beyond this threshold, we aim to assess their feasibility as fuels for stationary diesel engines and explore ways to enhance their fuel characteristics. A higher CNSL content could potentially increase the biofuel components in the blends and decrease reliance on fossil fuels; however, it may introduce challenges related to viscosity, ignition quality, and engine compatibility.

The CNSL–diesel blends were prepared by mixing 10 %–90 % CNSL with commercial diesel. The mixture was magnetically stirred at 1,500 rpm for 7 to 8 hours and then allowed to stand at room temperature for approximately four hours. A 100 mL fuel blend was prepared for each sample in a 250 mL Erlenmeyer flask (Figure 2.10).

Figure 2.10. Preparation of fuel blends

2.6. Storage and accelerated ageing of fuel blends

Prolonged storage can result in the degradation of the properties of biofuels, including the density, viscosity and acid number. Therefore, storage stability and accelerated ageing tests were conducted on the fuel blends with key properties similar to those of diesel. The storage stabilities were examined using a method adapted from Bora et al. [100]. The blends were visually inspected after storage for 1–4 weeks in a desiccator at room temperature (Figure 2.11). The fuel blends that maintained a single phase were assumed to be stable and suitable for diesel engines. The initial values of the parameters (density, viscosity, and acid number) were evaluated and compared with those at the end of storage to identify any changes.

Figure 2.11. Formulated fuel blend in a desiccator

Accelerated ageing tests were conducted using the method described by Lehto et al. [101]. The fuel blends were maintained at 80 °C for 24 h, and their stability was assessed based on changes in viscosity measurement at 40 °C. The system employed to test the ageing of fuel blends is shown in Figure 2.12.

Figure 2.12. System used for accelerated ageing of fuel blends.

Finally, the characteristics of the stable fuel blends were analysed and compared with the requirements for diesel, including density, viscosity, heating value, acid number, moisture content, and cetane number. Diesel engines powered by vegetable oils provide satisfactory engine performance and emissions [102], the diesel requirements in this study were established based on the specifications for diesel fuel and straight vegetable oils (SVO) proposed by Blin et al. [7]. The cetane number of fuel blends was evaluated based on calculations of the cetane index using the equations proposed by Espadafor et al. [99] and Aguado-Deblas et al. [95].

2.7. Purification of CNSL with various solvents (acetone, butanol, ethanol, and ABE)

The literature reviews indicate that CNSL has a higher acidity than the specifications for diesel. This elevated acidity can shorten the engine's lifespan when used for extended periods. Therefore, it is crucial to lower the acid number of CNSL before incorporating it into a blend with diesel or additives. This study aims to purify CNSL using various solvents, including acetone, butanol, ethanol, and an ABE (361) mixture.

The purification process entails several steps to improve CNSL's fuel characteristics (acidity, density, and viscosity). The purification steps are outlined below.

- 50 mL of various solvents (acetone, butanol, ethanol, and ABE) were mixed with CNSL.
- Each mixture was stirred using a vortex mixer for 5 minutes at a frequency of 20 Hz. The mixtures (CNSL-solvent) were centrifuged for 15 minutes at 1000 rpm, and no deposits were observed; therefore, the filtering process was not conducted.
- The mixtures were evaporated using a rotary evaporator at their boiling points for 45 to 60 minutes. The boiling points of acetone, ethanol, and butanol are 56 °C, 79 °C, and 120 °C, respectively. An evaporation temperature of 120 °C was selected for ABE (361) due to its high butanol content.
- The fuel properties of the purified CNSLs, such as density, kinematic viscosity, and acid number, were evaluated according to standard methods.

2.8. Performance of a diesel engine fuelled with appropriate fuel blends

The performance characteristics of a diesel engine were analysed on a single-cylinder, four-stroke, direct-injection diesel engine with a power output of 2.2 kW at a rated speed of 2,000 rpm. Table 2.1 presents the specifications of the experimental diesel engine at the 2iE engine platform.

2.8.1. Description of the test engine bench bed

The test bench engine comprised two principal components: the motor part and the instrumental chassis. The diesel engine is mounted on a trolley with lockable wheels and is directly coupled to a hydraulic dynamometer, which enables adjustments of various loading conditions (Figure 2.13). The power provided by the motor is subsequently dissipated in the water flowing through the dynamometer. It applies a load related to the flow rate and water level, which can be adjusted using a precise needle valve.

The engine test bench was equipped with various sensors, including K-type thermocouples, speed sensors, and torque sensors, to measure the exhaust gas temperature, torque, and engine speed under different loads. The air consumption flow meter determines the air-to-fuel ratio, which can influence the engine's overall performance and efficiency. The data obtained from the sensors were transferred to the data acquisition system and recorded using VDAS software installed on the computer to assess the engine's performance.

2.8.2. Benchtop instrumentation frame

Three display modules are mounted on a sturdy frame of the instrument chassis, and they display values of speed, torque, pressure, fuel consumption, and temperature and allow regulation of the engine operating under specific conditions (loads and speeds). The separation of the instrumental chassis (Figure 2.14) from the test bed engine prevents the transmission of vibrations from the engine to the measuring devices, thereby ensuring the integrity of the collected data and the life of the display modules. To ensure accurate results, all measurement equipment was calibrated using standard methods before the commencement of experimental work.

Table 2.1. Technical details of four-stroke diesel engine

Make	**Hatz**
General Details	diesel engine, single-cylinder, four-stroke, air-cooled
Bore / Stroke	69 mm/62 mm
Fuel Type	Diesel to minimum specifications: EN 590
Engine capacity	232 cm^3
Stroke/crank radius	62 mm/31 mm
Connecting rod length	104 mm
Compression ratio	22: 1
Rated power output	2.2 kW@ 2,000 rpm 1,1 KW @1,500 rpm
Oil type	Multigrade SAE 5W-40
Oil capacity	0.9 Liter
Torque maximal	15 Nm at 2,000 rpm
Weight	300 kg

The fuel system was modified to accommodate various fuel blends by adding two supplementary fuel tanks, a prefilter, and a three-way, hand-operated, two-position directional control valve to the existing tank. This valve enables quick and seamless switching between standard diesel and tested fuels.

Torque is measured with utmost precision using a strain-gauged load cell, strategically placed on the side of the dynamometer. When subjected to torque, the load cell generates a strain that is converted into an electrical signal. This signal is displayed on the digital screen, allowing for the precise measurement of torque values.

The engine speed was detected precisely using optical (photo) sensors and measured by a digital RPM indicator. The voltage pulses from the sensor were transmitted to a digital RPM meter for pulse conversion and display of engine speed with the utmost accuracy, ensuring the equipment's reliability in providing precise data.

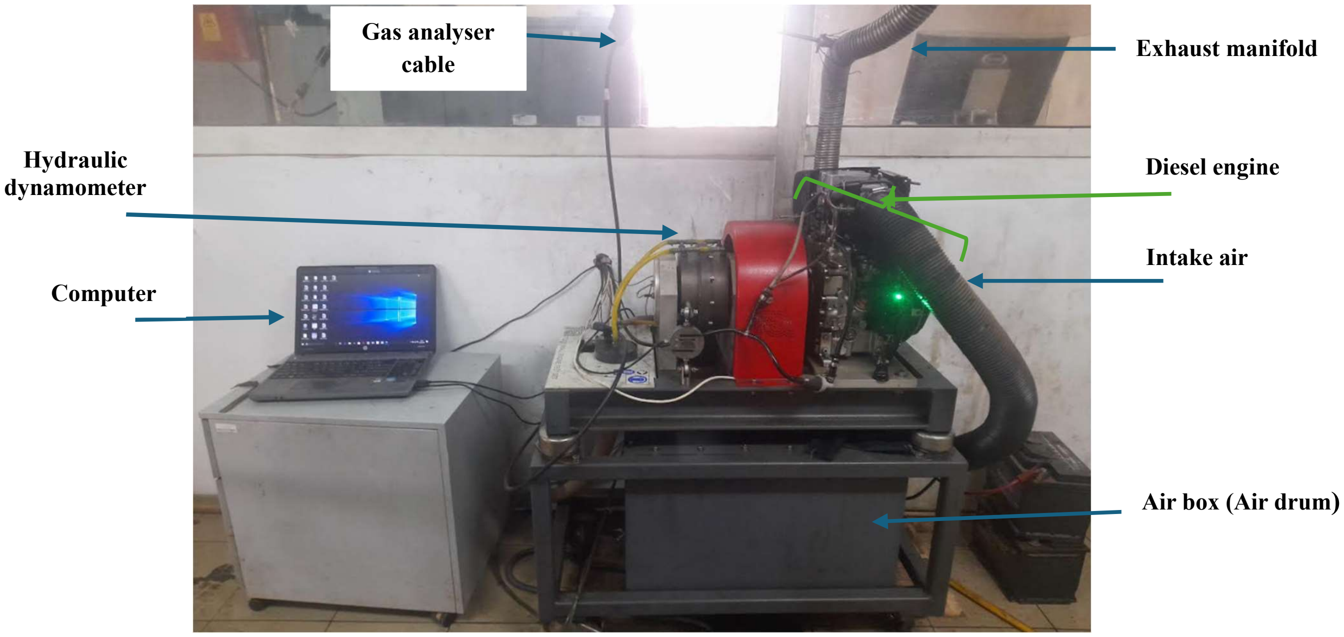

Figure 2.13. Photographic view of the experimental setup

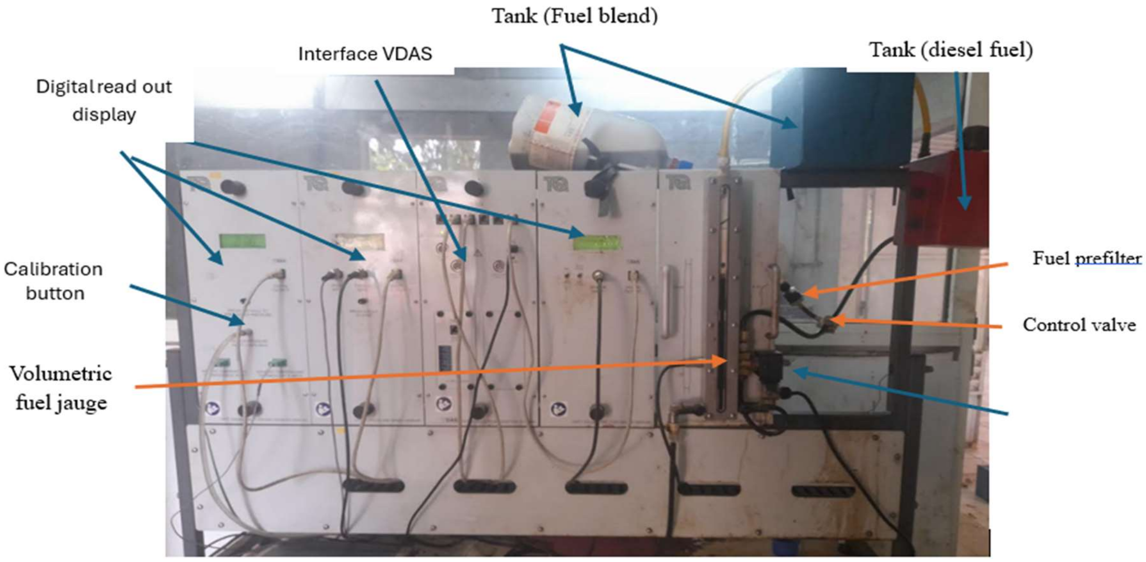

Figure 2.14. Benchtop instrumentation frame

The output power is determined by the product of speed and torque, which is shown on the digital display. It can be adjusted by varying both speed and torque. Users can swiftly adapt it to optimise power output by monitoring the digital readout.

The assessment of fuel consumption was conducted using a high-precision volumetric gauge (8 mL) fitted with two optical position sensors. The timer begins precisely when the fuel level reaches the upper optical sensor and halts at the lower position sensor, thus ensuring an accurate measurement of the time (in seconds) between the two positions.

A highly accurate K-type thermocouple was employed to measure the exhaust gas temperature in the flue gas output. A thermocouple is an electrical sensor made up of two metals or alloys joined at two junctions to form a closed loop. When these junctions are exposed to differing temperatures, a voltage is generated, the magnitude of which is determined by the specific materials and the temperature difference between the junctions. In this configuration, the thermocouple's output is linked to temperature transmitters that relay the signals to the VDAS® (Versatile Data Acquisition System). The test temperature is recorded with a variation of ±2 °C. The data acquisition system processes the signals and displays real-time temperature readings on the measurement module, ensuring continuous monitoring of the exhaust gas temperature.

In this study, we have assumed the stability of measurements to investigate engine performance, with accuracies of ±5 W for output power, ±50 rpm for engine speed, and ±0.5 N·m for torque.

Mathematical formulas were used to calculate the brake thermal efficiency and brake-specific fuel consumption of the diesel engine, providing essential insights into engine performance. Brake-specific fuel consumption (BSFC) measures the amount of fuel consumed in one hour to generate one kilowatt of brake power at the shaft. It is assessed according to equation 2.8:

$$\mathbf{BSFC\ (kg/KWh)} = \frac{\mathbf{36\times Cv}}{\mathbf{600\times P_m}} \times\ \mathbf{D\ (Equation\ 2.8)}$$

With Cv: fuel flow rate (mL/min),
D: fuel density (kg/m^3),
and Pm: output power (W).

Brake thermal efficiency (BTE) is evaluated by calculating the ratio of the thermal energy produced from combustion to the mechanical power generated by the engine, as shown in Equation 2.9:

$$\mathbf{BTE}\ (\%) = \frac{\mathbf{P_m}}{\mathbf{Q}} \times\ \mathbf{100}\ \ \mathbf{(Equation\ 2.9)}$$

Where Pm is the power developed by the engine,
and Q is the heat of combustion.

2.8.3. Procedure for evaluating performance characteristics in a diesel engine

The initial operation of the diesel engine using commercial diesel was crucial for generating reference data (BTE, BSFC, and EGT) before testing the fuel blends. The test bench allows for assessments of engine performance at various load values while maintaining a constant engine speed. The operating parameters of the diesel engine, rated at 2.2 kW (100 % load) with a speed of 2,000 rpm, were chosen as the reference point for determining the load ratio applied to the engine shaft (Table 2.2). The fuel blend operated in a diesel engine was analysed under identical conditions to those of the commercial diesel (standard pressure and timing), with the constant speed maintained at 2,000 rpm across different engine loads (20, 40, 60, 80, and 100 %).

Table 2.2. Engine test for fuel blends

Engine load	20 %	40 %	60 %	80 %	100 %
Output power (W)	440	880	1320	1600	2200
Engine speed (rpm)	2,000				

After each experiment, the diesel engine was run for approximately 15 minutes under a low load to ensure that no residual fuel remained in the engine's fuel system. Once parameters, such as torque, speed, and developed power, stabilised, data were recorded for 10 minutes and saved in an Excel file on a computer. The saved data include performance characteristics such as BTE, BSFC, and EGT.

The experimental procedure for assessing the performance of fuel blends in a diesel engine is as follows:

- Step 1. Start the engine with commercial diesel and allow it to run for 15 minutes to reach optimal operating conditions.
- Step 2. Set the engine load to 100 % and at a rated speed, waiting for parameters such as power, motor speed, and torque to stabilise (5–10 min). Then, a series of data (specific fuel consumption, thermal efficiency, gas temperature, etc.) are recorded using the VDAS software.
- Step 3. Change to the fuel mixture and repeat the procedure.

For the mixture test, switch to the fuel blend and allow the engine to stabilise before beginning data recording. Engine performance is evaluated using key metrics, including BTE, BSFC, and EGT. This systematic approach ensures accurate comparisons between conventional diesel and fuel blend performance.

Recording experimental data manually can be challenging, time-consuming, and repetitive. Some engine tests require the operator to take multiple readings from different instruments simultaneously, while others may necessitate gathering readings over several hours or days. Adjusting the settings and instruments during measurements is also required. There is a risk of errors, such as misreading values, incorrectly noting them down, or inaccurately recording them into the computer. These mistakes can lead to significant discrepancies in the measurements, compromising the reliability of the data.

In this study, the test bench bed featured the VDAS® acquisition system, a tool commonly used with most TecQuipment products. It helps eliminate the possibility of human error during manual readings and ensures immediate recording of a substantial amount of data. It automatically takes readings over several hours and stores data in a digital format (Excel files), enabling users to review it later and convert it into graphs and tables with utmost precision and accuracy.

2.8.4. Procedure for evaluating emissions characteristics of a diesel engine

The emission characteristics are investigated to elucidate the performance of a diesel engine operating with fuel blends compared to commercial diesel. By analysing the exhaust gas emissions from diesel engines run on various fuels, we can identify potential pollutants and propose strategies to mitigate emissions and improve combustion. The Testo 340 gas analyser (Figure 2.15) is utilised to examine the exhaust gases from diesel engines using different fuels.

Figure 2.15. Testo 340 gas analyser

The gases measured by the Testo 340 include CO, CO_2, and O_2. The exhaust sample to be evaluated was passed through a filter element to prevent water vapour and particulates from entering the analyser. This gas analyser is primarily equipped with a standard O_2 sensor, while three additional gas sensors can be configured individually at any time. However, this analyser lacks modules for measuring NOx and unburnt hydrocarbons.

The Testo 340 was connected to the engine's exhaust pipe. The emissions characteristics were continuously recorded manually up to the maximum levels and were acquired digitally.

Before each measurement, the gas analyser was calibrated using the calibration button to ensure accurate and reliable readings. The Testo gas analyser continuously recorded data for 3 to 5 minutes after adjusting the diesel engine to a specific load condition (75 %). This ongoing data collection enabled us to capture the peak values of various exhaust gas emissions. The emission characteristics of the diesel engine operating on fuel blends were assessed at the optimal engine load of 75 %, providing valuable insights into the behaviour and performance of diesel engines with different fuel blends.

CO_2 emissions are calculated from the fuel's characteristics, such as the maximum CO_2 rate given for the fuel and the residual oxygen measured in the flue gases, as shown below.

$$\boldsymbol{CO_{2max}} = \frac{\boldsymbol{CO_{2max}}}{\boldsymbol{O_{2base}}} \boldsymbol{x}\ (O_{2base} - O_2) \qquad \textbf{(Equation 2.10)}$$

With:

CO_{2max}: Fuel-specific carbon dioxide value,

O_{2base}: O_2 reference value,

O_2: Measured oxygen content (%).

The specifications of the Testo 340 gas analyser are listed in Table 2.3.

Table 2.3. Testo gas analyser specifications

Parameters	Accuracy	Range
CO	±10 % of mv ppm	0-10,000 ppm
CO_2	±0.3	0-50 vol %
O_2	±0.2	0-25 vol %

Chapter 3. Optimisation study of cashew nut shell liquid blended with diesel as alternative fuels in stationary diesel engines

3.1. Introduction

This chapter evaluates the feasibility of utilising CNSL as a biofuel component in diesel engines. CNSL, a dark-brown liquid extracted from cashew shells (an abundant and underutilised biomass resource in SSA) via mechanical pressing, holds the potential as a partial or total replacement for conventional fuels. However, its direct application is hindered by high viscosity and acidity. To address these limitations, this study investigates the blending of CNSL with commercial diesel. The chapter is structured as follows: First, the physicochemical composition of pressed CNSL, including its structure, elemental analysis, and key fuel properties, is characterised. Second, CNSL-diesel blends, ranging from 10 % to 90 % CNSL, are prepared, and their fuel properties are evaluated according to established standards. Third, the effect of temperature on both neat CNSL and the formulated blends is investigated. Finally, based on the preceding analyses, appropriate CNSL-diesel blends suitable for diesel engine applications are identified, and their performance characteristics are assessed. Blending CNSL with diesel fuel is expected to improve key fuel properties such as density, viscosity, and cetane number.

3.2. Results and discussions

3.2.1. Composition and elemental analysis of CNSL

The chemical composition of pressed CNSL in cardanols, cardols and anacardic acids is presented in Table 3.1. Pressed CNSL contains 5.5 % cardanols, close to the values observed in previous studies [42,103]. Phenolic lipids comprise anacardic acids, cardols and methyl cardols. This assessment is limited because it does not allow us to know the totality of anacardic acids and cardols to compare these with previous results. The chromatogram of pressed CNSL is presented in Appendix H1.

Table 3.1. Composition of CNSL using HPLC

Constituents	Pressed CNSL (in this study)	CNSL [42,103]
Cardols	1.7	34-42.0
Anacardic acids	15.2	47-51.84
Cardanols	5.5	3-8.11
Others phenolic lipids	78.8	-

The CNSL samples contained 76 % carbon, 9.41 % hydrogen, and 14.17 % oxygen (Table 3.2). However, commercial diesel has carbon, hydrogen, and nitrogen contents of 86.13:13.39:0.38, respectively. The high oxygen content could explain the lower HHV of CNSL compared to that of commercial diesel. Srinivasan et al. [28] reported carbon: hydrogen: oxygen contents of 81.02:8.50:8.62 (in %) for pressed CNSL. There were significant differences between carbon and oxygen contents of CNSL (in this study) and those observed in an above previous study. The enhancement of the elemental composition in the previous study can be explained by the heat treatment, which improves the carbon content by decreasing the oxygen content of natural CNSL [28,32]. Therefore, it appears that CNSL was extracted by pressing the cashew nutshell at a lower temperature than that reported by Srinivasan et al. [28].

Vegetable oils mainly comprise carbon, hydrogen, and oxygen, with a carbon: hydrogen: oxygen content of 78:12:10 (%). This makes vegetable oils a viable biofuel alternative fuel for diesel engines. The chemical composition of CNSL was found to close this ratio, with marginally higher carbon and hydrogen content and a lower proportion of oxygen. This composition of CNSL indicates that it could match essential properties with vegetable oils, specifically in terms of its ability to release energy during combustion.

The higher carbon content in CNSL suggests that it may offer a greater energy density compared to straight vegetable oils. This is particularly important in fuel applications, as a higher carbon concentration often translates to more significant heat release during the combustion process. Similarly, the elevated hydrogen content in CNSL could further enhance its suitability as a biofuel, as hydrogen is a critical element in achieving clean and efficient combustion. The relatively low oxygen content in CNSL, while slightly lower than that found in vegetable oils, is not necessarily a disadvantage. In fact, the decreased oxygen content may reduce the formation of certain combustion by-products, such as nitrogen oxides (NOx), which are linked to higher oxygen availability in the combustion chamber.

Because of its chemical composition, CNSL has the potential to serve as a viable alternative to straight vegetable oils (SVO) as a biofuel. SVOs, such as soybean, sunflower, and rapeseed oils, are currently used in biodiesel production and offer a renewable, biodegradable option to traditional fossil fuels. However, one of the key challenges associated with SVOs is their competition with food supplies. Using edible oils in fuel production often sparks concerns about food security, especially in regions where these oils serve as primary dietary staples. CNSL, derived from agricultural waste from cashew nut shells, avoids this issue entirely. It provides a non-edible alternative that can be leveraged for energy production without impacting the availability of food resources. According to the elemental analysis of pressed CNSL, it can replace SVO as a biofuel. Provided from a non-edible feedstock, CNSL offers a compelling solution to the food versus fuel dilemma by avoiding competition with food crops. This inherent characteristic positions CNSL as a sustainable and promising substitute fuel in various biofuel applications. CNSL differs from certain biofuel sources, which are derived from edible resources or arable land suitable for food production, such as Jatropha or cottonseed oil. A CNSL-based alternative fuel could reduce reliance on conventional diesel in the transportation sector. In addition, CNSL can be used in agriculture as a fuel source for powering machinery and equipment.

Table 3.2. Elemental composition of CNSL, SVO, and commercial diesel

Composition	**Carbon (%)**	**Hydrogen (%)**	**Oxygen (%)***	**Nitrogen (%)**
CNSL (in this study)	75.96±0.1	9.41±0.1	14.1±0	0.40±0.15
Commercial diesel	86.13±0.05	13.39±0.2	0.38±0	0.07±0.05
CNSL [28]	81.02	8.50	8.62	0.30
Straight vegetable oil [11]	78.00	12.00	10.00	-

*Oxygen (%) is calculated using this formula: 100- (% H+% C+% N)

- **Thermogravimetric analysis of CNSL**

The thermogravimetric curve (Figure 3.1) was obtained for 10 mg of CNSL under a nitrogen atmosphere (50 mL/min) at a heating rate of 10 °C/min.

The degradation of CNSL began at 157 °C, with a high initial peak degradation temperature (IPDT) of 410 °C (Table 3.3). This indicates that CNSL (in this study) has greater thermo-oxidative stability than the technical CNSL reported by Rodrigues et al. [42]. The variation may be attributed to the pressing temperature used during the extraction of CNSL, which can significantly influence its chemical composition. Elevated temperatures can alter the molecular structure of CNSL, potentially affecting its quality and properties. Therefore, maintaining precise control over the pressing temperature during CNSL extraction is critical to preserving its desired characteristics. Temperature fluctuations can lead to changes in viscosity, acidity, or the concentration of key compounds within CNSL, impacting its overall performance and effectiveness in various applications. The greater thermal stability of CNSL indicates the potential of its use as a stable biofuel with promising thermal properties for energy applications.

Additionally, the carbon residue content of CNSL was 6.45 %, which is similar to the results of Srinivasan et al. [28].

The high residue in CNSL signifies the presence of a significant amount of impurities and non-volatile materials. This indicates that CNSL contains higher levels of complex organic compounds or impurities that do not readily evaporate or decompose at lower temperatures. A high carbon residue can negatively impact combustion characteristics, as these impurities may lead to incomplete combustion, increased emissions, and the build-up of deposits in engine systems, particularly on injector heads. Moreover, these deposits can reduce engine efficiency and shorten its lifespan. The presence of these components implies the need for further processing or refinement of CNSL to enhance its suitability as a biofuel.

Table 3.3. Variables in the thermal degradation process of CNSL in a synthetic air atmosphere at a flow rate of 10 °C/min.

Parameters	**CNSL (in this study)**	**Technical CNSL** [42]
Ti °C	157±0.1	148
Tf °C	620±0.1	580
IPDT (°C)	410±0.1	309
Residue (900 °C) (% wt.)	6±0.0	2.2

Ti: Initial decomposition temperature
Tf: Final decomposition temperature
IPDT: Integral procedural decomposition temperature.

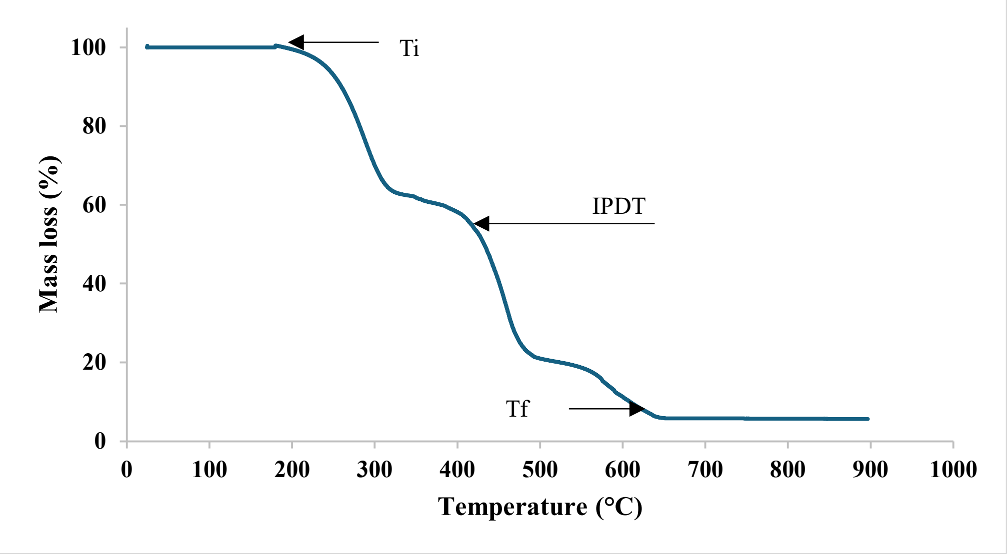

Figure 3.1. Thermogravimetric curve of CNSL (10 °C/min).

3.2.2. Analysis of physicochemical properties of CNSL

CNSL and diesel fuel were characterised by analysing their physicochemical properties, including density, viscosity, heating value, acid number, and moisture content (Table 3.4).

The density of CNSL is 985 kg/m^3, consistent with the results reported by Srinivasan et al. [28], but significantly higher than that of commercial diesel (822 kg/m^3). The density of CNSL is nearly comparable to several findings in the literature. For instance, Bangjang et al. [38], and da Silva et al. [104] reported CNSL density values of 965 and 973 kg/m^3, respectively. Notably, CNSL's density is approximately 1.24 times greater than that of commercial diesel. The higher density of CNSL may influence its application in fuel systems, affecting combustion characteristics and efficiency. The density of CNSL is similar to that of heavy fuel oil (HFO) used in stationary combustion applications, and it can be used as an alternative to conventional fuels in certain applications. A high density of CNSL poses challenges for direct use in diesel engines, as it can reduce fuel atomization efficiency. this results in incomplete combustion, which may lead to higher emissions and decreased engine efficacy performance. On the other hand, the increased density also results in a higher energy content per unit volume, which can be advantageous in energy-intensive applications.

The viscosity of CNSL was 249.10 mm^2/s, approximately 42 times higher than the maximum value specified for diesel (5.9 mm^2/s). The long carbon chains and aromatic rings contributed to the high viscosity of the CNSL. The CNSL viscosity was lower than that reported in the literature [38,104]. The observed difference can be attributed to the extraction methods and post-treatment processes of CNSL. Different extraction methods can significantly affect the quality of CNSL by influencing its purity, yield, and chemical composition. High viscosity can lead to issues with fuel flow injection, resulting in pumping inefficiencies and atomisation problems. If the fuel is excessively viscous, it may struggle to flow easily through the fuel injection systems, potentially causing premature wear and mechanical failure of both the pump and injector. Therefore, enhancing the fuel characteristics of CNSL is essential to optimise its properties for engine use. One method involves combining CNSL with low-viscosity fuels, such as commercial diesel or fuel additives, to attain desirable fuel flow properties.

The HHV of CNSL (36.34 MJ/kg) was found to be 20% lower than that of commercial diesel (45.45 MJ/kg). When assessed in terms of energy per unit volume, the HHV of CNSL was 4.2 % lower than that of commercial diesel. This result indicates that CNSL provides less energy per unit in mass and volume, which could affect fuel consumption.

The heating value of CNSL was identical to that reported by Srinivasan et al. [28] for mechanically extracted CNSL (raw CNSL). Other studies have reported higher HHV for CNSL owing to differences in the extraction method and thermal treatment. An increase in carbon content during the pyrolysis of CNSL was observed by Das et al. [31], which increased the heating value. Srinivasan et al. [28] also found that the thermal cracking of CNSL has improved its heating value by about 6 MJ/kg. In contrast, the heating value of CNSL is almost identical to that of *Jatropha oil*, making it a promising alternative fuel source for diesel engines, as demonstrated in numerous studies.

The moisture content of CNSL was measured at approximately 1.12 %, exceeding the maximum acceptable threshold for diesel engines. Fuel standards impose strict limits on moisture content to prevent issues such as tank and filter corrosion. Excess moisture in fuel can also negatively impact combustion efficiency, leading to engine performance problems and increased wear over time. Therefore, while CNSL may have potential as an alternative fuel, its higher moisture content poses a significant challenge that must be addressed to meet diesel engine requirements and ensure long-term engine durability. The moisture content of CNSL can be reduced by heating it to 105 °C. However, thermal treatment of CNSL can lead to an increase in polymeric materials, which are not suitable for use in fuel blending because of the separate phases that may occur. The high moisture content also contributed to a reduction in the heating value of fuel.

The higher acid number of CNSL (124.65 mg KOH/g) was attributed to the higher concentration of anacardic acid (61.4 %) resulting from the low-temperature extraction. However, the acidic pH (5.7) of CNSL was close to that reported by Srinivasan et al. [28] for thermally cracked CNSL. A high acid number of fuel indicates a high risk of corrosion of metal engine parts, such as tanks, filtration systems, seals, and pipes. This can negatively impact the engine lifespan and requires major repairs. It is recommended that biofuels should have an acceptable acid number to reduce maintenance costs.

The calculated cetane number (CN) for pressed CNSL was found to be 33, which is consistent with the value reported in [65]. The CN of pressed CNSL, however, is significantly lower compared to that of conventional diesel fuel, which generally has a cetane number of 47. The lower CN of CNSL suggests that it may have a longer ignition delay and reduced combustion efficiency compared to diesel. CN is a key indicator of combustion quality in compression-ignition engines. A higher CN values typically lead to more efficient combustion. The lower CN of CNSL indicates that it may not perform as efficiently as diesel in standard engines, potentially requiring additives or blending with other fuels to improve its ignition properties. Despite its lower cetane rating, CNSL remains a promising biofuel due to its abundance and renewable nature. Its CN can be improved by incorporating cetane enhancers such as ethyl 2-

hexyl nitrate to enhance its viability as a biofuel in diesel engines. The calculated CN of CNSL was identical to the recommended minimum value (30) for stationary diesel engines [99]. By boosting its CN, CNSL can achieve better combustion efficiency and performance in diesel applications, making it a more practical alternative to conventional fuels while leveraging its renewable advantages.

Table 3.4. Comparative of physicochemical properties of CNSL and commercial diesel

Proprieties	**Limit values**	**Pressed CNSL**	**Commercial diesel**	**CNSL** [28,65]	**Limit values**
Density, 15 °C (kg/m^3)	≤ 890 [105]	985±1.01	822±2.5	960–961	≤ 890 [105]
Viscosity, 40 °C (mm^2/s)	≤ 5.9 [7]	249.10±1.9	2.65±0.1	55.30–77.00	≤ 5.9 [7]
Higher heating value (MJ/kg)	≥ 44 [105]	36.34±1.0	45.45±1.45	35.80	≥ 44 [105]
Moisture content (% wt.)	< 0.05 [7]	1.13±0.2	0.02±0	3.20	< 0.05 [7]
Acid number (mg KOH/g)	≤ 3 [7]	124.65±1.5	0.50±0.1	_	≤ 3 [7]
Cetane number	≥ 47 [99]	33.37±0.0	45–55	33. 41	≥ 47 [99]
pH	_	5.70±1.2	_	4.10	_
Refractive index	_	1.45±0.05	1.52±0.05	_	_
Carbon residue	_	6±0.0	< 0.15	6.45–6.74	_
Ash content (%)	_	_	_	0.9-1.3	_

Based on the analysis of the fuel properties, CNSL can be used as an alternative fuel for stationary diesel engines. However, its high density and viscosity can overload the fuel injection pump and cause it to stop operating, resulting in engine stall and failure. Therefore, it is necessary to optimise the flow characteristics to ensure that diesel engines operate correctly. Fuel can be pre-heated before being injected into a diesel engine. Preheating improves fuel flow properties, making it easier for the fuel injection pump to inject fuel into the engine. This also enhances the engine performance and decreases engine damage.

3.2.3. Effect of preheating on CNSL

The effects of temperature on the viscosities of pressed CNSL, commercial diesel and HFO are presented in Figure 3.2. The viscosity of the CNSL decreased with increasing temperature, and a sharp reduction was observed at 100 °C. With an increase in temperature from 40 to 100 °C, a viscosity reduction of 91 % was observed. The viscosity of CNSL (preheated to 100 °C) was 3.65 times the maximum specified value for diesel fuel. Most diesel engines are designed to comply with diesel specifications for high-speed diesel engines. However, at a temperature of 100 °C, the viscosity of CNSL falls outside the specified range. This viscosity value is slightly higher than the maximum recommended value at the inlet of the injection pump of a stationary diesel engine. When preheated to 80 °C, the viscosity of CNSL was lower than the maximum limit specified for vegetable oil [7].

The viscosity of CNSL (measured at 40 °C) was lower than that of HFO. A viscosity of 20–40 mm^2/s is required for the proper atomisation of HFO, which is achieved by heating it to 90–100 °C. However, as CNSL requires heating to 80 °C to obtain the same viscosity, its use diminishes the demand for the heating device, facilitating fuel conditioning. Moreover, with a viscosity lower than HFO, all operations related to transport and pumping between tanks are easier, thereby reducing the energy consumption of the auxiliary equipment.

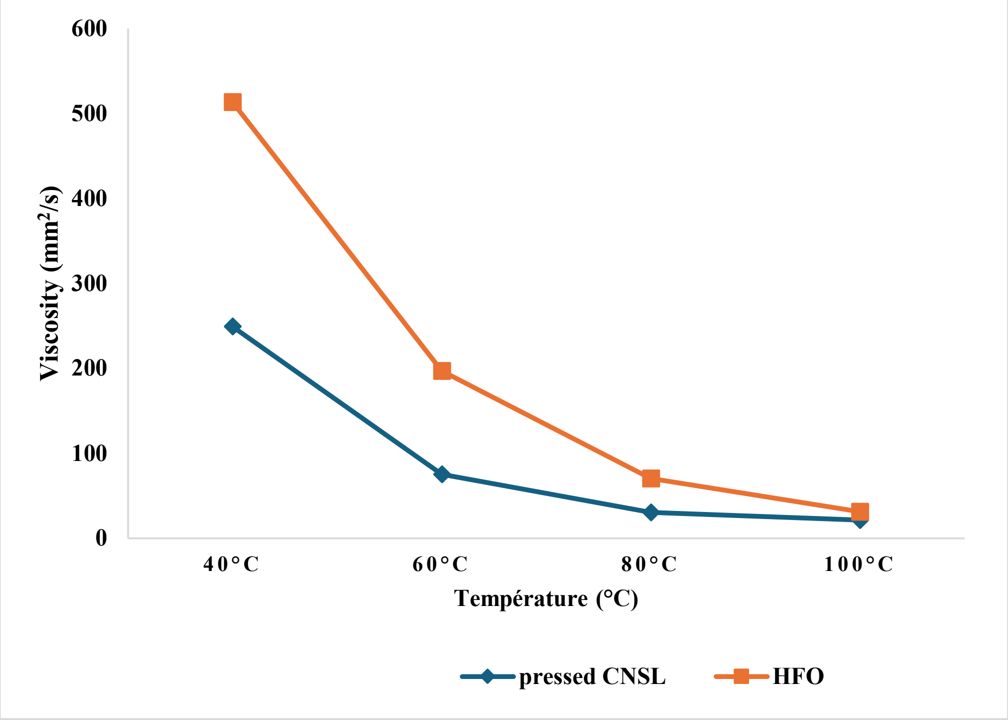

Figure 3.2. Effect of temperature on viscosity of pressed CNSL and HFO

3.2.4. Physicochemical properties and specification of fuel blends for diesel engines

Fuel blends can be selected based on kinematic viscosity, density, heating value, acid number, and CN. Assessing fuel characteristics is important to determine the optimal proportion of CNSL in diesel blends to provide acceptable properties for diesel engines.

Figure 3.2 illustrates the configurations and proportions of the prepared CNSL-diesel.

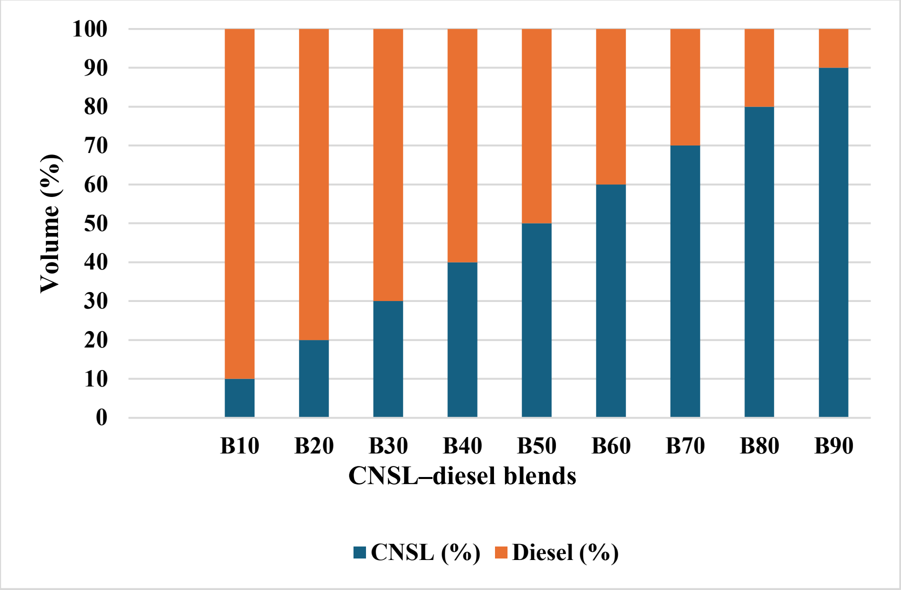

Figure 3.3. Proportion of CNSL-diesel blends

3.2.4.1. Viscosity of the CNSL–diesel blend

Kinematic viscosity is an essential fuel characteristic that provides information regarding flow resistance. A higher value can lead to poor atomisation and affect fuel combustion in the combustion chamber. The viscosity of the fuel (biofuel or fuel blend) must comply with the ranges recommended by diesel engine manufacturers, or the values specified for conventional fuels.

Figure 3.4 shows the evolution of the viscosity of the CNSL–diesel blends. The viscosity of the CNSL–diesel blend increased as the percentage of CNSL in the mixture rose, displaying a linear relationship with the volume proportion of CNSL. Since viscosity significantly impacts the performance of the fuel delivery system, excessively high viscosity can lead to issues such as injection pump malfunction and fuel filter blockage. To prevent such problems, the blend's viscosity must not exceed 5.9 mm^2/s. The addition of higher proportions of diesel to CNSL effectively reduces viscosity, which aligns with the general understanding that diesel has a much lower viscosity compared to CNSL. This reduction in viscosity is critical for ensuring smooth engine operation. Thomas et al. [106] have similarly shown that blending diesel with high-viscosity vegetable oils reduces their viscosity, improving their usability in diesel engines. Therefore, the appropriate blending of CNSL with diesel ensures the fuel's viscosity remains within acceptable limits and enhances the engine system's overall performance and longevity.

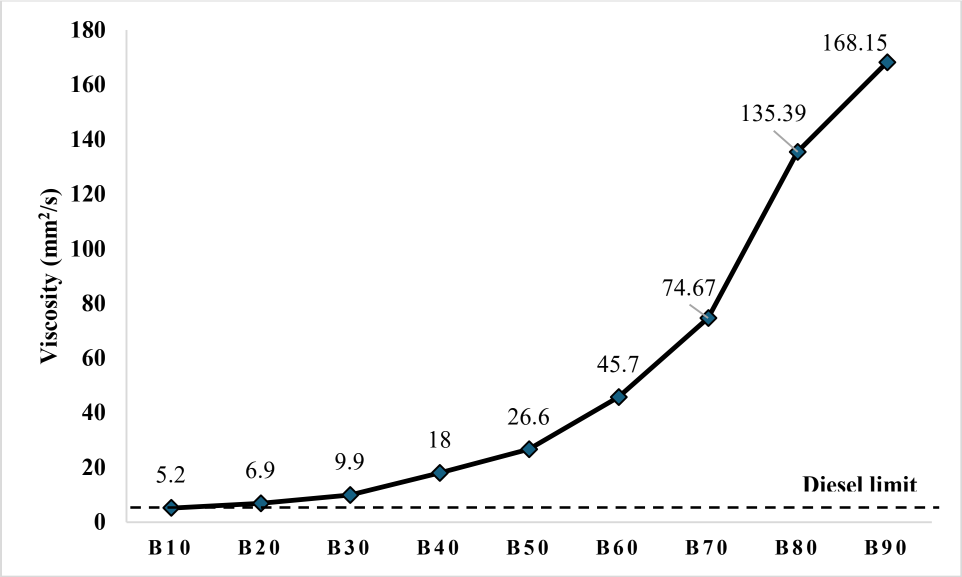

Figure 3.4. Viscosity of CNSL-diesel blends

Only the B10 blend met the diesel fuel requirements regarding key performance parameters. Similarly, Sanjeeva et al. [34] found that a 10 % CNSL blend in diesel exhibited characteristics almost identical to pure diesel fuel. According to engine manufacturers, low-speed engines require fuel with a kinematic viscosity between 13 and 17 mm²/s before entering the fuel pump. Blends containing up to 30 % CNSL meet this viscosity range, making them suitable for low-speed diesel engines. This demonstrates that a lower percentage of CNSL in the blend, like B10, can be an effective alternative to conventional diesel without compromising engine performance.

3.2.4.2. The density of the CNSL–diesel blends

Fuel density affects the fuel injection pressure, which also influences the combustion characteristics and engine performance. High-density fuels generally require higher injection pressures to ensure adequate atomisation. To optimise the combustion in a diesel engine when using a fuel with a high density, the injection pressure and timing must be adjusted, thereby requiring supplemental engine adaptations. A higher density results in higher energy content per unit volume and greater energy delivered per cycle because the pump is a volumetric device [99].

Figure 3.5 depicts the evolution of the density of CNSL-diesel blends. The densities of the blends increased with the proportion of CNSL in the fuel blend because CNSL has a higher density than diesel. Sivakumar [107] observed similar effects when CNSL was blended with diesel fuel. They found that the density increased linearly with the proportion of CNSL, as observed in this study. The densities of the CNSL–diesel blends with up to 40 % CNSL matched the diesel specifications.

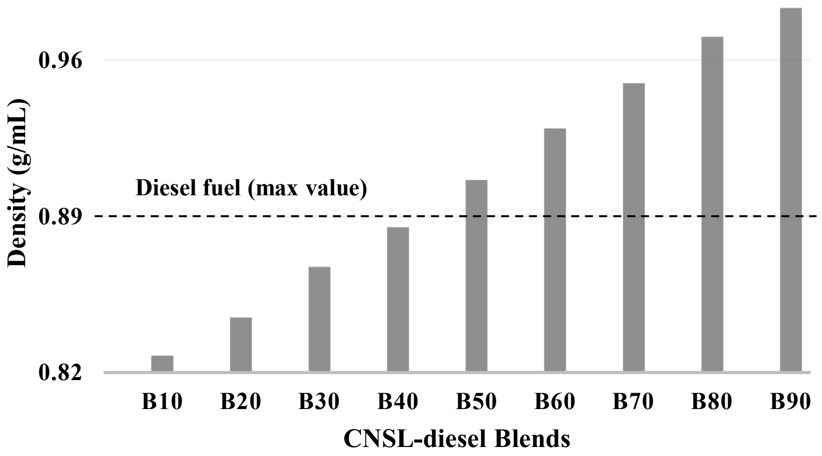

Figure 3.5. Density of CNSL–diesel blends

The densities of the blends increased with the proportion of CNSL in the fuel blend because CNSL has a higher density than diesel. Similar effects were observed when CNSL was blended with diesel fuel [107]. They found that the density increased linearly with the proportion of CNSL, as observed in this study. The densities of the CNSL–diesel blends with up to 40 % CNSL matched the diesel specifications.

3.2.4.3. Heating value of CNSL–diesel blends

The physicochemical properties of fuel blends are presented in Table 3.5.

Table 3.5. Fuel properties of CNSL-diesel blends

Fuel blends	Density (kg/m^3) [a]	Viscosity (mm^2/s)[b]	HHV (MJ/kg)	Cetane number	Moisture Content (%)	Acid number (mg KOH/g)
B10	812.6	5.26	45.18	52.84	0.13	15.62
B20	827.6	6.95	44.22	50.70	0.24	26.24
B30	844.7	9.90	43.27	48.52	0.34	52.01
B40	867.3	18.04	42.31	46.37	0.46	56.65
B50	885.1	26.61	41.36	44.20	0.56	62.73
CNSL	985.50	249.1	36.59	33.41	1.10	124.65
Diesel specifications	820-890	1.6-5.9	>45	>50	0.075	<3

[a] value measured at 20 °C;

[b] value measured at 40 °C.

The heating value of a fuel is the amount of heat released by combustion under standard conditions. A high heating value improves the engine efficiency and specific fuel consumption. The heating values of the fuel blends decrease as the CNSL volume proportion increases (Table 3.6). This is because the heating value of CNSL is lower than that of commercial diesel. Blend B10 has a higher heating value because of its high proportion of diesel fuel. The blends containing 10 %–50 % CNSL had heating values that met the diesel specifications (40.50 MJ/kg). This study found that the heating value of CNSL was lower than that of the fuel specifications.

3.2.4.4. Acid number of CNSL–diesel blends

The acid number of fuel is a critical parameter that must be kept low to meet the requirements of the fuel injection system, as high acid levels can lead to corrosion and damage to engine components. Table 3.6 presents the acid numbers of blends containing 10 % to 50 % CNSL with diesel. The fuel blends in this study exhibited acid numbers higher than the vegetable oil specifications reported by Blin et al. [7]. This indicates that prolonged use of these fuel blends could potentially corrode the metal components of engines, especially under long-term operational conditions. However, it is important to note that these results are consistent with observations from other studies. For example, Park et al. [56] reported that bio-oils intended for power generation industries exhibited acidities ranging between 0.39 and 35.43 mg KOH/g, showing that formulated biofuels in this study can still perform effectively within this range.

Among the blends tested, those containing 10 % and 20 % CNSL fall within this acceptable acidity range, suggesting that these blends are less likely to cause significant engine wear and corrosion. Therefore, blends with lower CNSL content, such as B10 and B20, can be considered viable substitutes for diesel fuel in stationary engines, particularly in power generation applications. By reducing the CNSL content, these blends can minimize the risk of acid-related damage while maintaining their biofuel benefits.

3.2.4.5. Cetane number of the CNSL–diesel blends

The CN affects engine start-up, combustion control, and engine performance. CNs were evaluated using the equations proposed by Espadafor et al. [99] and Aguado-Deblas et al. [95]. The CNs of the blends with 10 %–50 % CNSL and diesel fuel are shown in Table 3.6. Increasing the volume proportion of CNSL decreased the CN of the fuel blend. This is because of the relatively low CN of CNSL compared with that of diesel fuel. The results indicated that the B10, B20, B30, and B40 diesel fuels exceeded the minimum CN requirement of 45. The CN of B50 was below the limit for diesel fuel because of the large amount of CNSL. A high cetane number (CN) is an important parameter in enhancing engine performance. Allawi et al. [108] found that an increase in CN led to improvements across various performance parameters, highlighting a positive correlation between high CN and engine efficiency. Higher CN fuels tend to ignite more efficiently, resulting in smoother combustion and improved engine performance. Similarly, Sapra et al. [109] demonstrated that energy-assisted compression ignition using fuels with higher CN significantly boosted combustion efficiency. Given these findings, CN is a crucial parameter to consider when selecting fuels for diesel engines, as it directly influences ignition delay, fuel combustion quality, and overall engine efficiency. Choosing fuels with a higher CN makes it possible to achieve more efficient and reliable engine operations, particularly in compression ignition engines, which rely heavily on the fuel's ability to ignite promptly under pressure.

3.2.5. Selection of fuel blends for stationary diesel engines

Fuel blends containing 10 %–40 % CNSL satisfy this viscosity requirement as well as the density and calorific value within the range recommended for stationary diesel engines (Table 2.7). However, it is also necessary to consider other parameters, such as the acid number to avoid engine corrosion and abrasion. The acid number should be as low as possible to avoid damaging engine fuel systems. The fuel blends B10 and B20 matched the proposed specifications in terms of density, viscosity, heating value, and cetane number. Owing to these properties, these fuel blends can be used as alternative fuels for stationary diesel engines.

3.2.6. Prolonged stability of fuel blends suitable for diesel engines

Fuel stability is an important property for ensuring uniform and even miscibility of biofuels in diesel. As discussed in the previous sections, B10 and B20 blends exhibit physicochemical characteristics that position them as viable substitutes for diesel fuel. For biofuels to be practical alternatives, their properties, such as viscosity, density, and acid number, must remain consistent during extended storage.

The prolonged storage was studied using a method adapted from ASTM D4625. The blends were stored at room temperature (25–35 °C) for 12 weeks (three months), and parameters such as viscosity, density, and acid number were evaluated at the beginning and end of storage. The physical stability was studied by visually observing the phase separation of the mixtures.

The viscosities, densities, and acid numbers of the B10 and B20 blends remained constant during prolonged storage (Table 3.6). No phase separation was observed, indicating that these fuel blends retained homogeneity over time. These results are exhibited with the observations of Sanjeeva et al. [49], who reported that CNSL-diesel blends containing up to 20 % CNSL remained stable and homogeneous for at least three months. Furthermore, the key properties of the B10 and B20 blends, such as viscosity, density, and acid number, were consistent with their initial values and met the recommended specifications for stationary diesel engines, ensuring their suitability for extended use without compromising engine performance.

Table 3.6. Properties of appropriate fuel blends (B10 and B20) after three months of storage

Blends	**Density (kg/m^3)**	**Viscosity (mm^2/s)**	**Acid number (mg KOH/g)**
B10 (10 % CNSL, 90 % diesel)	825.3±1.54	5.19±0.45	15.62±0.35
B20 (20 % CNSL, 80 % diesel)	835.1±2.01	6.92±0.53	26.24±1.49
Diesel specifications	≤ 890 [105]	≤ 5.9	≤ 3

The elemental composition of the B20 blend remained stable even after ageing at 80 °C for 24 hours. Due to evaporation during the ageing test, the moisture content for both B20 and CNSL decreased due to the high temperature, as shown in Table 3.7. Despite this, the density and viscosity of the fuel blend remained minimally changed, indicating that the ageing process largely unaffected the fuel properties. This stability is crucial for maintaining consistent performance and emissions in diesel engine applications for prolonged use.

Table 3.7. Comparison of properties of diesel, CNSL, and B20 after the ageing test

Fuel	Viscosity, 40 °C (mm^2/s)	Density, 20 °C (Kg/m^3)	Moisture content (% wt.)	C:H: N:O (% wt.)
Commercial diesel (RT)	2.65	822.37	0.02	86.13:13.39:0.07:0.38
Commercial diesel (24 h, 80 °C)	2.73	809.20	0.02	84.17:13.01:2.72:0.08
B20 (RT)	5.55	840.06	0.22	84.83:12.80:2.22:0.13
B20 (24 h, 80 °C)	5.17	840.57	0.14	84.56:12.61:2.69:0.12
CNSL (RT)	249.1	985.50	1.10	75.96:9.41:14.17:0.40
CNSL (24 h, 80 °C)	253.4±0.01	986.80	0.6±0.01	76.70:9.49:13.17:0.62
RT: room temperature (25–35 °C				

3.2.7. Specification of appropriate CNSL-diesel blends for testing in a diesel engine

Fuel specifications are essential in determining the suitability of fuel blends for engine use. Key fuel properties, including density, viscosity, heating value, cetane number (CN), and acid number, directly impact engine performance, combustion efficiency, and emissions. To ensure the blends met the necessary performance and stability criteria, CNSL-diesel blends were formulated based on commercial diesel standards.

Fuel specifications were established using literature data on key fuel parameters identified through extensive research. Espadafor et al. [99] reported that diesel engines can operate efficiently at low speeds (< 1500 rpm) when fuel viscosities range between 13 and 17 mm²/s. The density of commercial diesel served as a reference value for selecting CNSL-diesel blends. A stationary diesel engine (2iE platform test bench) successfully operated using *Jatropha curcas* as a biofuel, establishing its acid number and heating value as baselines for selecting suitable fuel blends.

The B10 blend exhibited a lower acid number than B20 and a value close to that of *Jatropha oil*. Furthermore, the B10 acid number is lower than that reported by Park et al. [56] for bio-oil used in power generation, indicating its potential as a viable alternative to commercial diesel fuel. Additionally, B10 has a viscosity, density, and heating value very similar to those of diesel. The performance and suitability of a B10 fuel blend will be evaluated in a stationary diesel engine by analysing thermal efficiency, fuel consumption, and exhaust gas temperature. Results will be compared to standard diesel fuel to determine the blend's viability as a biofuel alternative for widespread use.

3.2.8. Analysis of performance parameters of CNSL-diesel blends

3.2.8.1. Brake thermal efficiency

Brake thermal efficiency (BTE) generally specifies the useful amount of energy obtained by combusting fuel. Figure 3.6 shows the BTE of the diesel engine as a function of load for the tested fuels. As the engine load increased, the BTE improved for all tested fuels. Higher loads enhance combustion performance due to increased fuel concentration and reactivity in the cylinder. This leads to a more effective conversion of the fuel's energy potential into mechanical output. The BTE of the diesel engine fuelled with commercial diesel was 20.74 % and 39.16 %, respectively, at low load (20 %) and full load (100 %). For the B10 blend, BTE was 16.84 % at 20 % load and increased to 35.11 % at full load. This mainly implies that the combustion temperature in the combustion chamber is higher at 100 % engine load than at 20 % load. This was because more fuel is injected into the combustion chamber at higher engine loads, resulting in a more complete combustion and higher temperatures. This was primarily due to reduced heat loss and increased output power at higher loads. The trend of increasing BTE with engine load aligns with observations reported in the literature.

However, the BTE of the B10 blend was slightly lower than that of commercial diesel at all load conditions (20 %, 40 %, 60 %, 80 %, and 100 %). This reduction is attributed to the lower calorific value and the poor air-fuel mixture formation caused by its lower volatility, higher viscosity, and higher density. These fuel properties significantly influence combustion behaviour, as the viscosity and boiling point of the fuel play critical roles in determining combustion efficiency [88]. These factors contribute to the observed differences in BTE between the B10 blend and commercial diesel, offering insight into the technical challenges associated with biofuel blends.

The maximum BTE was achieved with commercial diesel at 80-100 % load. For the B10 blend, BTE was 18.8 % lower at a small load (20 %) and 10 % lower at a full load (100 %) than commercial diesel. The B10 blend exhibited limitations at higher loads, as its efficiency decreased at 80 % and full load. This indicates that the B10 mixture may not be suitable for engine operation at loads exceeding 60 % due to its reduced performance under high-load conditions.

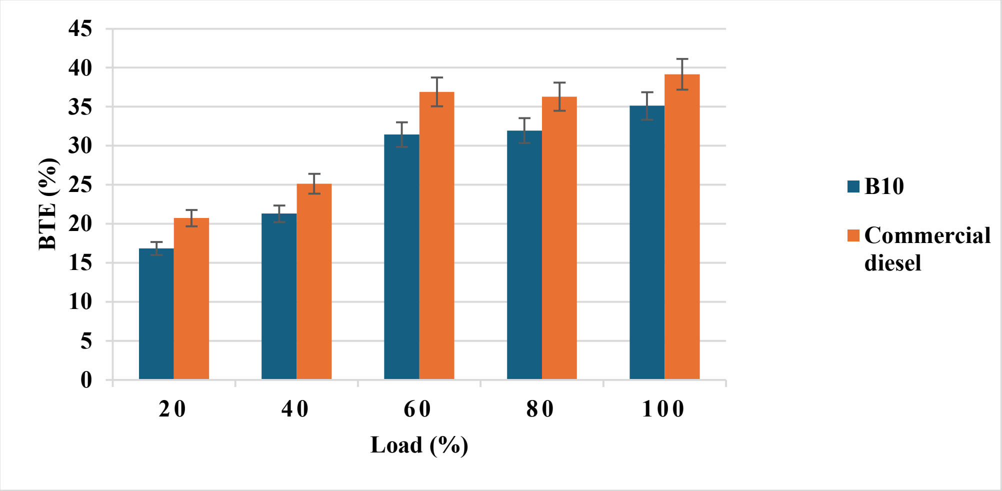

Figure 3.6. Comparison between BTE for B10 vs commercial diesel

The B10 blend demonstrated a higher BTE than diesel at 60 % engine load, indicating potential for efficient operation at moderate loads. However, the blend does not allow the engine to operate effectively at nominal speed and full load. This limitation is likely due to its lower calorific value, which provides insufficient energy to maintain full load performance at the rated engine speed of 2,000 rpm. As a result, B10 may be better suited for applications requiring lower speeds (less than 1,500 rpm). Stationary diesel engines typically operate at lower rotational speeds, making B10 a more viable option for such applications. The higher viscosity and density of B10 also contribute to poor atomisation and combustion efficiency at higher speeds, further justifying its use in slower-speed engines.

3.2.8.2. Brake-specific fuel consumption

The mass of the fuel injected into the combustion chamber determines the engine's power and torque at any load. Brake-specific fuel consumption (BSFC) is mainly based on parameters like proper atomisation of fuel blends, desired fuel quantity for complete combustion, swirl generated by the nozzle, etc., along with the proper propagation of fuel combustion and angle of injection.

Figure 3.7 depicts the variation in BSFC as a function of engine load for diverse fuels. The BSFC decreases with increasing engine load for all tested fuels because of the significant amount of fuel required to produce the same amount of power [69,73,79]. The high engine load leads to high combustion temperature in the chamber, reducing fuel consumption and improving the BTE [110]. As the engine load increases, more fuel is required to produce the same power output, which explains the overall reduction in BSFC. For the B10 blend, the BSFC was 0.27 kg/kWh, compared to 0.21 kg/kWh for diesel at full load. This indicates that the BSFC for B10 is higher than that for commercial diesel.

The BSFC of B10 is higher than that of diesel at all engine loads. B10 has a lower calorific value and higher viscosity and density than commercial diesel (Table 3.6), resulting in less efficient combustion and, consequently, increased fuel consumption. Literature reports indicate that the BSFC of CNSL (and its blends) exceeds that of diesel, which can be attributed to the low calorific value of CNSL and its blends [79,80]. In their study, Sanjeeva et al. [50] reported that the BSFC of DT-CNSL blends (B5, B10, and B15) was comparable to those for diesel. In contrast, Krishnamoorthi et al. [64] reported higher BSFC for a B20 CNSL blend preheated to 70 °C, demonstrating that preheating or higher biofuel content can further impact fuel consumption.

The increased BSFC observed for B10 highlights the need for optimisation in fuel blends to achieve performance closer to commercial diesel. The higher BSFC of the B10 blend compared to conventional diesel is mainly due to the difference in heating values between the two fuels. Commercial diesel has an approximately 0.5% higher heating value than B10, which means that a greater B10 blend is required to produce the same power output in the engine. Additionally, the high viscosity and density of the B10 blend further contribute to the BSFC. Pramanik [111] explains that the elevated BSFC in biofuel blends can be attributed to their higher viscosity, lower heating value, and higher density, which hinder efficient combustion and lead to increased fuel use. Together, these fuel parameters contribute to diminishing energy conversion efficiency, necessitating a greater volume of biofuel blends that reach performance levels akin to conventional diesel.

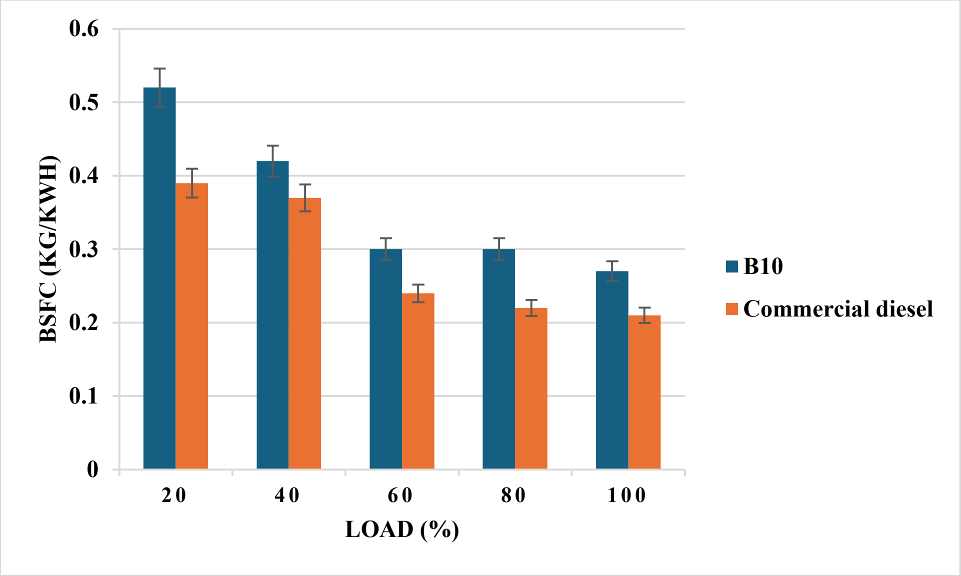

Figure 3.7. Comparison BSFC for B10 vs commercial diesel

The difference in BSFC between commercial diesel and the B10 blend decreases as engine load increases, decreasing from approximately 25 % at low loads to around 22 % at higher loads. This trend can be attributed to the elevated combustion chamber temperatures at higher loads, which improves the fuel flow properties of the fuel mixture. The lower viscosity enhances fuel atomisation, leading to more efficient combustion within the cylinder.

3.2.8.3. Exhaust gas temperature

Figure 3.8 presents the variation in exhaust gas temperature (EGT) with load for different fuels. The EGT increased with the rise in engine load, a trend that aligns with the findings of Sanjeeva et al. [49]. High engine loads are associated with increased power and torque, leading to a continuous rise in EGT as the power output of the engine increases [110]. This phenomenon can be attributed to the increased fuel consumption at higher engine loads [81], which results in more energy being released during combustion, thus raising the EGT.

At full load, the EGT of the B10 blend was observed to be approximately 5 % higher than that of pure diesel. This increase in EGT indicates poorer engine efficiency and overconsumption, particularly in the case of the 10 % CNSL blend with diesel. The elevated EGT for the B10 blend is likely attributable to inefficient combustion, in which a significant portion of the fuel's energy is lost as heat through the exhaust gases rather than being effectively utilised to generate mechanically. This inefficiency can be worsened by the fuel's physical properties, including its higher viscosity, density, and lower volatility compared to standard diesel. These characteristics negatively impact fuel atomisation and spray formation, resulting in incomplete combustion and elevated exhaust temperatures.

In contrast, Vedharaj et al. [39] reported lower EGT values for CNSL-diesel blends than diesel. This may be due to the fuel properties of CC-CNSL, which exhibited improved combustion characteristics during the combustion phase. This underscores the important role that the chemical composition and fuel properties of CNSL have in its combustion performance.

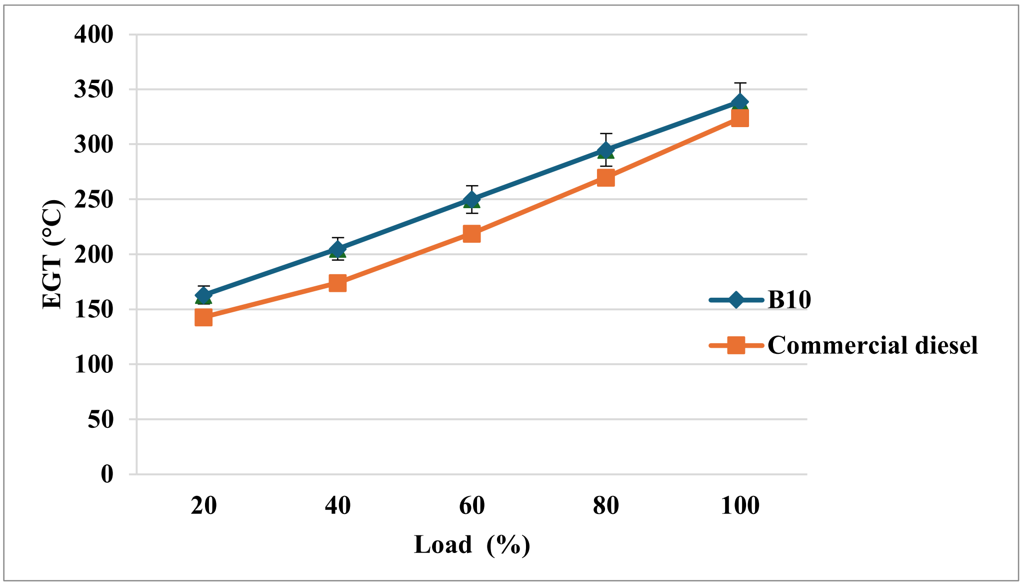

Figure 3. 8. EGT for B10 vs commercial diesel

Thus, the higher EGT observed for the B10 blend in this study underlines the need to further optimise CNSL properties to enhance its combustion efficiency. Modifying the blend ratio by reducing it or employing pre-treatment techniques, such as preheating or refining the biofuel, needs to be investigated. It may help to mitigate the adverse effects of high viscosity and low volatility, ultimately enhancing fuel performance and reducing EGT to levels comparable with commercial diesel.

3.2.8.4. Air fuel ratio

The air-fuel ratio (AFR) is crucial for combustion because it ensures enough oxygen to burn the fuel completely. This results in higher energy output and lower emissions. An optimal AFR can also prevent engine knocking and improve overall performance.

The air-fuel ratio (AFR) tends to decrease with increasing engine load, regardless of the type of fuel used (Figure 3.9). The AFR was consistently higher for diesel fuel than that observed for the B10 blend. A higher AFR is typically associated with improved BTE and reduced fuel consumption, indicating a great mixture allowing more efficient combustion.

When operating with diesel fuel, the AFR was approximately 28 % higher at low engine loads (20 %) and decreased to around 10 % at full load. This variation is due to the different demands on the engine at varying loads. At low loads, diesel engines require a higher AFR to ensure sufficient oxygen for complete combustion, thereby preventing soot formation and improving combustion efficiency. This results in a leaner mixture, reducing unburned hydrocarbons and CO emissions and contributing to lower fuel consumption and higher thermal efficiency.

As the engine load increases, more fuel is injected to meet the increased power demand, naturally leading to a lower AFR. This shift towards a richer mixture helps maximise power output but can result in slightly less efficient combustion. The decrease in AFR at higher loads is necessary to maintain optimal engine performance, as the combustion process requires more fuel to produce the necessary torque and power. However, this also implies that engines running on the B10 blend at higher loads do not achieve the same efficiency level as diesel due to the blend's lower AFR and possible combustion properties. Thus, it is crucial to maintain an appropriate AFR for different engine loads to optimise performance, mainly when using alternative biofuel blends.

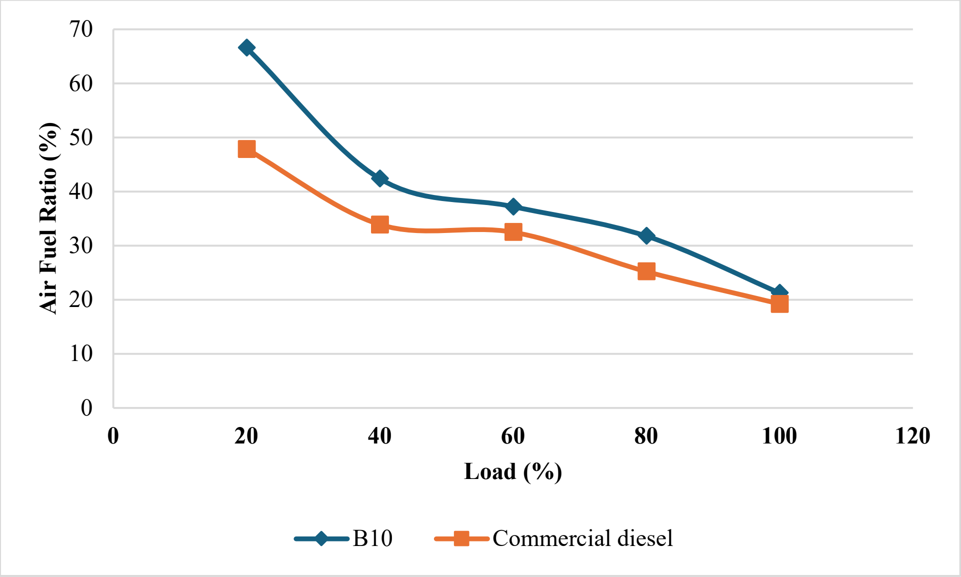

Figure 3.9. Air fuel ratio for B10 and diesel fuel vs engine load

The higher air-fuel ratio for diesel fuel leads to an efficient engine combustion process compared to fuel blend. This results in better engine performance and higher power output. Maintaining an optimal AFR can significantly enhance fuel efficiency by ensuring the engine operates at its most effective combustion level. When the AFR is appropriately balanced, the engine burns fuel more completely, reducing energy loss. This saves on fuel costs and contributes to a more environmentally friendly operation.

3.3. Summary

The fuel properties of CNSL biofuel, including density, viscosity, and heating value, are reliably similar to those of HFO. This consistent similarity makes CNSL an attractive and dependable alternative for stationary diesel engines and power plants that operate on heavy fuel oils. CNSL and diesel can be blended effortlessly, making them completely miscible, and no phase separation was observed in fuel blends. It is worth noting that CNSL has a higher viscosity and density than commercial diesel, limiting its direct use in diesel engines. These properties improved when blended with diesel at a higher blend ratio. The heating value of CNSL decreased as the blend ratio increased and was much closer to that of vegetable oil for neat CNSL. The calculated cetane index of CNSL was lower than that of commercial diesel but close to that of heavy fuel oil. The result showed that the B10 blend matched the specifications defined in this study and was successfully tested in a diesel engine. The performance characteristics of diesel engines fuelled with 10 % CNSL in diesel have shown smaller efficiency than commercial diesel at most of the load. The performance of the B10 blend was acceptable compared to conventional diesel. This indicates that CNSL-diesel blends can be used in diesel engines without any modifications. Incorporating CNSL into diesel fuel has substantial potential to reduce petroleum imports, especially in countries without significant fossil fuel resources. This approach presents a promising opportunity for fostering a more sustainable and energy-independent future.

However, further improvements in the fuel properties of neat CNSL are essential before blending, as this would enhance its performance in diesel engines. It is also crucial to explore techniques that allow for a higher percentage of CNSL in the blend, using appropriate additives such as acetone, butanol, or ethanol. These additives can help improve fuel characteristics, such as viscosity, density and combustion efficiency, and enhance the overall performance of diesel engines running on CNSL-diesel blends.

Chapter 4. Formulation and storage stability study of cashew nut shell liquid, diesel fuel and ABE (361) blend as alternative fuel for stationary diesel engines

4.1. Introduction

This chapter details the formulation of fuel blends from converting wastes that have not been extensively used to date and whose production rates are continually increasing in the region. Formulation involves developing and manufacturing a product to meet specific criteria and utility. First, the method of formulation of fuel blends based on CNSL, diesel, and ABE (361) is described, and the physicochemical properties of fuel blends are evaluated. Then, the best blends were selected based on their fuel properties that matched diesel specifications, and their performance and emission characteristics were investigated in a diesel engine. Finally, an economic analysis of appropriate blends was estimated to evaluate feasibility in the context of sub-Saharan Africa, particularly in Burkina Faso.

4.2. Methodology for fuel blend formulation

Biofuels must meet certain specifications for use in diesel engines, including density, viscosity, heating value, moisture content, and acid number. Biofuels with a high acid number may corrode engine parts, and those with a low heating value have insufficient output power. The physicochemical properties of the CNSL samples were evaluated using the standard testing methods listed in Table 4.1. The acid numbers of samples were evaluated by acid-base titration according to ASTM D664.

4.2.1. Preparation of fuel blends and specifications

Based on the acid number, moisture content, and heating value results, CNSLT was selected as the optimal biofuel for obtaining suitable blends for diesel engines. The fuel blends were prepared in conical tubes (50 mL) with vigorous stirring for 10 min at room temperature. Three independent batches of each blend were prepared and tested.

Table 4.1. Equipment and standards used to assess the physicochemical properties of fuel.

Property	Equipment	Standard	Accuracy
Density at 20 °C	Pycnometer (Blaubrand)	NF ISO 4787	±0.01 kg/m^3
Viscosity at 40 °C	Viscosimeter (Pro. Brookfield DV-II)	ASTM D445	±0.01 mm^2/s
Heating value	Calorimeter (Parr 6200)	ASTM D240	±0.001 MJ/kg
Moisture content	Karl Fischer Titrator (Mettler Toledo)	ASTM E203	±0.01 wt.%

Twenty blends were prepared: CNSLT–diesel blends containing 10, 20, 30, 40, and 50 vol% CNSLT (designated as B10, B20, B30, B40, and B50, respectively); CNSLT–ABE (361) blends containing 70, 80, and 90 vol% CNSLT (designated as C70ABE30, C80ABE20, and C90ABE10, respectively); and CNSLT–diesel–ABE blends containing *x* vol% CNSLT and *y* vol% ABE (361) (designated as B*x*ABE*y*, where *x* = 20, 30, 40, and 50 vol% and *y* = 10, 20, and 30 vol%). For example, B20ABE10 comprises 20 vol% CNSLT, 10 vol% ABE, and 70 vol% diesel, and B30ABE30 comprises 30 vol% CNSLT, 30 vol% ABE, and 40 vol% diesel. The fuel blends were centrifuged at 6000 rpm for 5 min to be separated from the unfiltered CNSL impurities. The density, viscosity, and heating value of the blends were measured as described in Section 4.2.1.

Heating values of blends were calculated based on the component ratios [95]. For the CNSLT–diesel–ABE blends, the results are only given for those that met the diesel requirements. Fuel blends must exhibit consistent properties to be suitable for engine testing and evaluation. To select the blends that best satisfied the diesel specifications, the physical properties, such as density, viscosity, and heating value, were evaluated and compared to the requirements for diesel fuel, straight vegetable oil (SVO), and heavy fuel oil (HFO), as listed in Table 4.2. Because preheating can reduce the viscosity, the fuel blends that exceeded the viscosity requirement at 40 °C were retested after preheating to 60 and 80 °C.

Table 4.2. Physicochemical properties and their limits for biofuels in accordance with standard specifications for conventional fuels.

Property	Viscosity, 40 °C (mm^2/s)	Density 20 °C (kg/m^3)	Heating value (MJ/kg)	Acid number (mg KOH/g)	Moisture Content (% wt.)	References
Diesel fuel	1.6–5.9	820–890	40[b]	≤ 1	≤0.05	SONABHY; [7]
SVO	50	900–960	≥ 36	≤ 3.00	≤ 0.075	[7]
HFO	≤ 420[a]	960–990	≥ 40.6	4.31	≤ 0.50	SONABHY [7]; [112]; [56]

[a] Value measured at 50 °C;

[b] Estimated minimum value [113].

SONABHY: ‘Société Burkinabé des hydrocarbures’.

4.3. Results and Discussion

The physicochemical properties of the CNSL samples were analysed before the preparation of the fuel blends. Twenty fuel blends were prepared from CNSLT, diesel, and ABE (361), of which three (B10, B20ABE10, and B30ABE30) were selected for stability testing because their physical properties were similar to those of diesel fuel.

4.3.1. CNSLP and CNSLT composition

The anacardic acid, cardanol, and cardol contents of CNSLP and CNSLT are listed in Table 4.3. CNSLP contained 26.7 % cardanols, 20.8 % cardols, 43.8 % anacardic acids, and 8.7 % other components, similarly to previous reports [28,103]. By comparison, CNSLT contained less anacardic acids (17.6 %) and more other components (25.9 %). CNSLP is thermally treated at 160 °C to form CNSLT, which causes the decarboxylation of the anacardic acids. This led to the slight increase in cardanol content [29]. Similarly, the increase in other components is attributed to the formation of polymeric material during thermal treatment. Notably, HPLC only enables the analysis of low-molecular-weight components.

Table 4.3. Chemical composition of CNSLP[a] and CNSLT[b] using HPLC[c]

Constituent	Content (wt.%)			
	CNSLP	**CNSLT**	Oliveira et al. [103]	Srinivasan et al. [28]
Cardols	20.8	28.8	7.0	33.7
Anacardic acids	43.8	17.6	47.0	51.8
Cardanols	26.7	27.7	42.0	8.1
Other	8.7	25.9	8.0	6.0

[a] CNSLP: Natural cashew nut shell liquid extracted from cashew nut shells (CNSs) via mechanical pressing;
[b] CNSLT: Technical cashew nut shell liquid obtained by heating CNSLP at 160 °C for 4 h;
[c] HPLC: High performance liquid chromatography.

Table 4.4 lists the elemental compositions of the CNSL samples and commercial diesel in terms of the relative percentages of carbon, hydrogen, oxygen, and nitrogen.

Table 4.4. Elemental composition of CNSLP, CNSLT, and commercial diesel.

Composition	Content (%)			
	Carbon	Hydrogen	Oxygen	Nitrogen
CNSLP	76.51	8.55	14.60	0.34
CNSLT	80.85	9.83	8.90	0.42
Commercial diesel	86.13	13.39	0.38	0.07

The CNSLT indicated a high carbon content, whereas the CNSLP showed a high oxygen content. The carbon and hydrogen contents in CNSLT increased after the thermal treatment, which is attributable to decarboxylation reactions. The C:H:O ratio in vegetable oil is typically 78:12:10 [11], whereas that in technical CNSLT is approximately 81:10:9. Therefore, the high carbon content of the CNSLT may explain its higher heating value than that of vegetable oil.

4.3.2. Physicochemical properties of CNSL samples, diesel fuel, and ABE (361)

The properties of CNSLP, CNSLT, and ABE (361), such as density, viscosity, heating value, moisture content, and acid number, are summarised in Table 4.5.

A difference of approximately 0.5 % was observed between the densities of the CNSLT (985 kg/m^3) and CNSLP (991 kg/m^3), which was approximately 17 % higher than that of diesel. The low density of the CNSLT is attributable to the molar mass of their components. It contains slightly more cardanols than the CNSLP with a low molar mass and less anacardic acid with a medium molar mass.

Table 4.5. Fuel properties of each pre-blended component.

Components	Viscosity, 40 °C (mm^2/s)	Density, 20 °C (kg/m^3)	Heating value (MJ/kg)	Acid number (mg KOH/g)	Moisture Content (% wt.)
CNSLT	738.25	985.48	40.34	20.30	0.87
CNSLP	184.70	991.04	36.17	113.24	1.12
ABE (361)	1.79	800.00	33.56	n/a	n/a
Diesel fuel	2.76	822.37	45.45	0.50	0.02

n/a: Not available.

The viscosities of the CNSLP (184.70 mm^2/s) and CNSLT (738.25 mm^2/s) differed significantly, which were 66 and 267 times higher than those of diesel, respectively. Heat treatment resulted in more polymerised materials in CNSLT than in CNSLP. Polymerised materials have higher viscosities than other components (cardanols and cardols), which explains the high viscosity of the CNSLT. A viscosity difference was observed between the CNSLP (obtained from Anatrans) and pressed CNSL (obtained at 2iE). This variation is likely attributable to the type of mechanical pressing employed and subsequent post-treatment processes, such as filtration. The viscosity of the CNSLT was slightly higher than that reported in the literature [42]. The use of CNSLT in diesel engines is limited because of issues related to the engine’s fuel injection system (pump and injector) arising from its high viscosity.

The heating values of the CNSLP (36.17 MJ/kg) and CNSLT (40.34 MJ/kg) differed by approximately 10 %. The heating value of the CNSLT was approximately 11 % lower than that of diesel. The presence of oxygen atoms in the CNSL samples contributed to the lower heating value compared with that of diesel. The CNSLT indicated a significantly higher heating value than CNSLP because of thermal treatment, which increased the carbon content and reduced the oxygen and moisture contents. The oxygen content of the CNSLP (14.60 %) was higher than that of the CNSLT (8.90 %). Oxygen-rich fuels typically exhibit lower heating values, as the presence of oxygen results in reduced carbon and hydrogen. It was noted that the heating value of CNSLP was similar to that of CNSL obtained through mechanical pressing at 2iE (36.34 MJ/kg).

The acid numbers of the CNSLT (20.30 mg KOH/g) and CNSLP (113.24 mg KOH/g) differed significantly. The high anacardic acid content of CNSLP (43.8 %) rendered it more acidic than the CNSLT. There is a correlation between anacardic acids and acid number, and higher concentrations of anacardic acids are associated with a higher acid number in CNSL. Heat treatment helps to reduce the acid value, in contrast to heating vegetable oils at elevated temperatures, which can negatively affect the acid value. The acid number of CNSLT was approximately seven times higher than that of diesel. Thus, CNSLT is unsuitable for direct use in diesel engines as it can cause high corrosion of engine components.

The CNSLP exhibited a moisture content of approximately 1.12 %, which exceeded that of CNSLT (0.87 %). Nevertheless, both values surpassed the maximum allowable limit for diesel engine fuels. The lower moisture content observed in the CNSLT likely results from thermal treatment at 160 °C, which evaporated a certain amount of water.

The following section discusses the use of CNSLT as their properties (acid number, moisture content, and heating value) are the most appropriate for the current study. However, the values of its flow properties exceed the diesel specifications; therefore, it must be blended with diesel to improve its physical properties and satisfy the diesel requirements.

4.3.3. Study of CNSLT–diesel blends

4.3.3.1. Properties of CNSLT–diesel blends

The physical properties of the CNSLT–diesel blends are listed in Table 4.6.

Table 4.6. Properties of CNSLT–diesel blends.

Fuel blends	Viscosity, 40 °C (mm^2/s)	Density, 20 °C (kg/m^3)	Heating value (MJ/kg)
B10 (10 % CNSLT, 90 % diesel)	4.56	842.17	44.94
B20 (20 % CNSLT, 80 % diesel)	7.50	856.87	44.42
B30 (30 % CNSLT, 70 % diesel)	13.88	871.58	43.91
B40 (40 % CNSLT, 60 % diesel)	23.60	885.53	43.40
B50 (50 % CNSLT, 50 % diesel)	44.03	897.01	42.90
Diesel fuel	2.76	822.37	45.45

The viscosities and densities of the fuel blends increased as the diesel ratio decreased, in particular, B10, which was the only blend that satisfied the diesel requirements, indicated the most significant decrease in viscosity. A similar study by Chatterjee et al. [29] showed that the B10 blend indicated a viscosity of 2.71 cSt, which exhibited diesel specifications.

The density of fuel blends used in diesel engines should be between 820 and 889 kg/m^3, and all fuel blends with up to 40 % CNSLT should satisfy this requirement. The B10 blend indicated a higher heating value compared with other blends owing to its higher diesel ratio. Therefore, the amount of CNSLT affected the heating values of the fuel blends. The CNSLT–diesel blends indicated heating values that were 2–6 % lower than that of diesel but higher than the diesel requirements.

The physical properties of the B10 blend satisfied the diesel specifications, thus implying that it is likely to perform similarly to diesel fuel in diesel engines. By contrast, the viscosities of the B20, B30, B40, and B50 blends exceeded the required range, which implies that they must be preheated because their viscosity decreases as temperature increases. Therefore, the effect of the preheating temperature on these blends was investigated.

4.3.3.2. Effect of temperature on CNSLT–diesel blends

The viscosity of a liquid is defined as its ability to resist flow, which affects its level of fluidity. This property determines the resistance when the liquid passes through a pump, orifice or pipe. An increase in the temperature of fuel blends reduces its viscosity, making the liquid more fluid. On the other hand, a decrease in temperature results in higher viscosity and less fluidity. The temperature plays a critical role in influencing the viscosity of the fluid entering the injection pump. Lower viscosity facilitates pumping and improves fuel atomisation. Improved atomisation produces a finer spray, which optimises the air/fuel mixture and promotes more efficient combustion. This section of the study aims to identify the preheating temperature required for CNSL and its blends with diesel to achieve a viscosity comparable to diesel specifications before injection into the engine.

The viscosities of the CNSLT–diesel blends as a function of the preheating temperature are shown in Figure 4.1. For each fuel blend (CNSL-diesel blends: B20, B30, B40, and B50), the kinematic viscosity was measured at varying temperatures of 40 °C, 60 °C, and 80 °C.

The kinematic viscosity of the fuel blends decreased significantly as the preheating temperature increased. To achieve a kinematic viscosity of less than 5.9 mm^2/s, the B30 blend had to be preheated at 80 °C. However, B20 required preheating at 60 °C to achieve the same viscosity; its use obviates the necessity for the heating device, thereby facilitating fuel conditioning. Therefore, the B20 and B30 blends can be preheated to achieve flow characteristics similar to those required for diesel engines. A similar study showed that 20 % CNSL mixed with diesel and preheated to 80 °C can be used as fuel for diesel engines without any modifications [73].

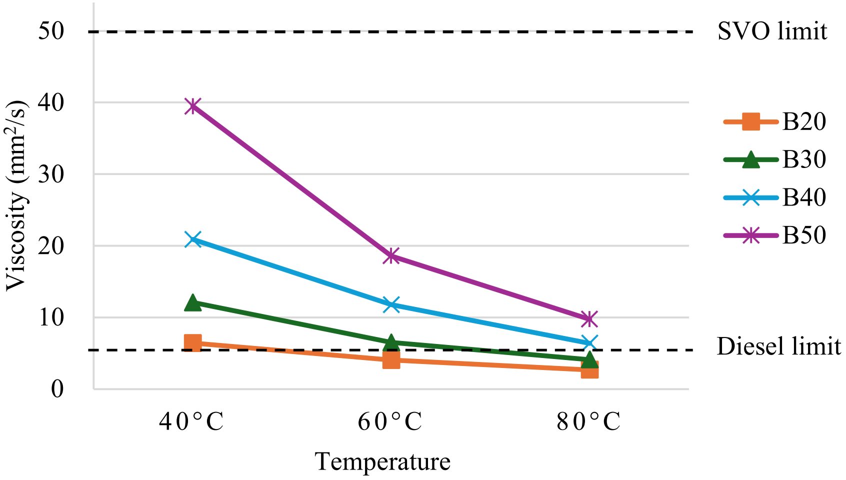

Figure 4.1. Viscosity for CNSLT–diesel blends as function of temperature.

By contrast, the B40 and B50 blends exhibited viscosities in the range of 20–40 mm^2/s, which is the range required to achieve the appropriate atomisation at the burner nozzle of an oil-fired boiler [56]. Therefore, the B40 and B50 blends can be used as burner fuels instead of HFO.

4.3.4. Study of CNSLT–ABE blends

4.3.4.1. Properties of CNSLT–ABE blends

The physical properties of the CNSLT and its blends with different ABE ratios are listed in Table 4.7.

Table 4.7. Properties of CNSLT–ABE blends.

Biofuel blends	Viscosity, 40 °C (mm^2/s)	Density, 20 °C (kg/m^3)	Heating value (MJ/kg)
C90ABE10 (90 % CNSLT, 10 % ABE)	270.96	976.03	39.67
C80ABE20 (80 % CNSLT, 20 % ABE)	99.28	955.92	38.99
C70ABE30 (70 % CNSLT, 30 % ABE)	53.70	940.55	38.31
Diesel fuel	2.76	822.37	45.45
Straight vegetable oil specifications [7]	50	900–960	≥ 36
Heavy fuel oil specifications (SONABHY, [7]; [112]; [56])	≤ 420	960–990	≥ 40.6

The kinematic viscosity of the CNSLT decreases by adding ABE (361) at different ratios (10 %, 20 %, and 30 %). C70ABE30, C80ABE20, and C90ABE10 exhibits viscosity reductions of 92.27 %, 86.55 % and 63.30 %, respectively. Despite the greater reduction in the viscosity of C70ABE30, it is approximately 7 % higher than the SVO specification, but its density satisfies the SVO requirements. This blend indicates a heating value of approximately 6 %, slightly higher than the SVO specifications. The density and viscosity of the C80ABE20 blend satisfy the HFO requirements; however, it indicates a heating value of approximately 4 %, which was slightly lower than that of HFO. Meanwhile, the energy density of C80ABE20 (40.79 MJ/L) is slightly higher than that of HFO (39.50 MJ/L). Therefore, the addition of 20 % and 30 % ABE (361) to the CNSLT results in fuel blends comparable to those of HFO and SVO, respectively.

4.3.4.2. Effect of temperature on CNSLT–ABE blends

The viscosities of the CNSLT–ABE blends as functions of the preheating temperature are shown in Figure 4.2.

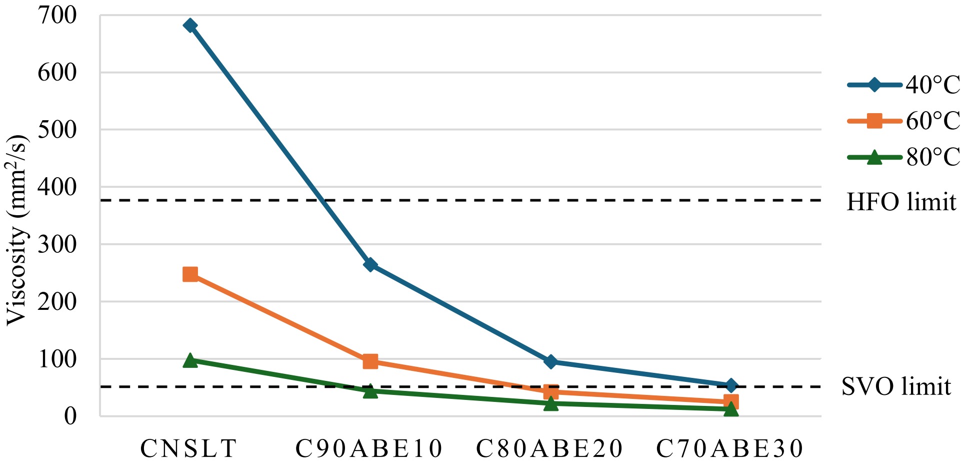

Figure 4.2. Viscosity of CNSLT–ABE blends as a function of temperature

As the preheating temperature and ABE ratio increased, the viscosity of the fuel blends decreased. A more significant decrease in viscosity was observed in the CNSLT with 30 % ABE (361); however, its viscosity remained significantly higher than that of diesel. The C70ABE30 blend preheated to 80 °C indicated a viscosity of 12.5 mm^2/s, which was lower than the maximum value of 17 mm^2/s recommended for stationary diesel engines [7]. In fact, the density and heating value of this fuel blend satisfied the SVO requirements. Therefore, they can be used as an alternative to SVO in diesel engines. However, when preheated to 60 °C, the C70ABE30 and C80ABE20 blends exhibited viscosities between 20 and 40 mm^2/s, which were the values required to achieve adequate atomisation at the burner nozzle of an oil-fired boiler. Therefore, the C70ABE30 and C80ABE20 blends can be used as burner fuels instead of HFO.

4.3.5. Analysis of CNSLT–diesel–ABE blends

4..3.5.1. Properties of CNSLT–diesel–ABE blends

To satisfy diesel specifications, fuel blends must exhibit a viscosity of less than 5.9 mm^2/s. In this regard, B20ABE10, B20ABE20, B20ABE30, and B30ABE30 satisfied this requirement, as shown in Figure 4.3.

The viscosity decreased as the ABE (361) ratio increased, and a significant decrease was observed for fuel blends with 30 % ABE (361). For all the fuel blends, the viscosity decreased linearly as the ABE ratio increased.

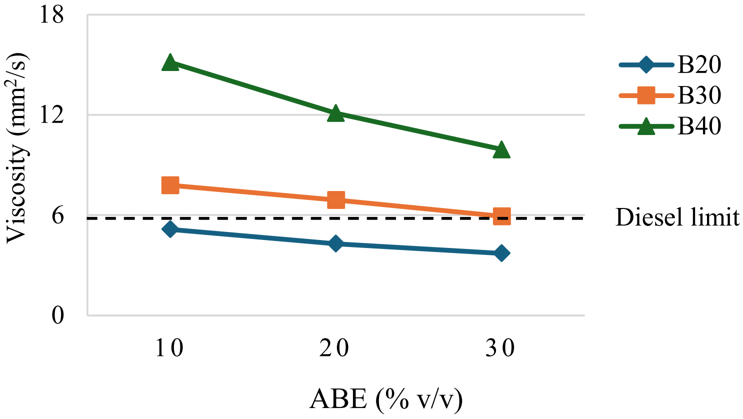

Figure 4.3. Viscosity of CNSLT–diesel blends vs. ABE ratio

The physical properties of the CNSLT–diesel–ABE blend that satisfied the diesel requirements are listed in Table 4.8.

An increase in the ABE ratio decreased the density, viscosity, and heating value of the fuel blend. A difference of approximately 5 % was observed between the heating values of B20ABE10 and B20ABE30 blends with the same volume of CNSLT. Owing to its higher ABE ratio (30 %), B30ABE30 indicated the lowest heating value of 40.81 MJ/kg, which is higher than the diesel requirement. Thus, the B20ABE10 and B30ABE30 blends can be used instead of B20 and B30 blends, which require heating to 60 °C and 80 °C, respectively.

Table 4.8. Properties of CNSLT–diesel with ABE.

Fuel blends	Viscosity, 40 °C (mm^2/s)	Density, 20 °C (kg/m^3)	Heating value (MJ/kg)
B20ABE10 (20 % CNSLT, 10 % ABE, 70 % diesel)	5.06	849.04	43.34
B20ABE20 (20 % CNSLT, 20 % ABE, 60 % diesel)	4.22	842.89	42.25
B20ABE30 (20 % CNSLT, 30 % ABE, 50 % diesel)	3.65	834.39	41.17
B30ABE30 (30 % CNSLT, 30 % ABE, 40 % diesel)	5.83	849.02	40.81
Diesel fuel	2.76	822.37	45.45

4.3.5.2. Effect of temperature on CNSLT–diesel–ABE blends

The effect of the heating temperature on the viscosity of CNSLT–diesel with ABE blends is shown in Figure 4.4.

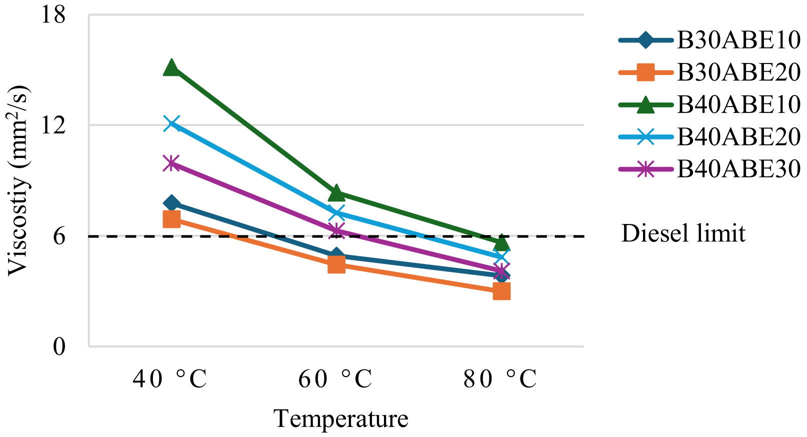

Figure 4.4. Viscosity of CNSLT–diesel–ABE blends as function of preheating temperature.

The viscosity decreased as the preheating temperature of the fuel blend increased. Blends B30ABE10 (CNSLT/ABE (361)/diesel=30:10:60 v/v) and B30ABE20 (30:20:50 v/v) preheated at 60 °C satisfied the diesel viscosity requirements. Consequently, starting the engine in cold conditions with these fuel blends will be challenging. Meanwhile, blends B40ABE10 (40:10:50 v/v), B40ABE20 (40:20:40 v/v), and B40ABE30 (40:30:30 v/v) required heating at 80 °C to satisfy the diesel requirements. The B30ABE10 blend was more suitable than other fuel blends because of its high heating value and low preheating temperature (60 °C).

4.3.6. Stability of the most appropriate fuel blends

4.3.6.1. Selection of fuel blends

Based on the results, B10, B20ABE10, and B30ABE30 possess physicochemical properties that render them suitable substitutes for diesel fuel. However, these fuel blends must remain stable during their transport and prolonged storage.

4.3.6.2. Stability analysis of fuel blends

Storage stability and ageing tests were conducted on fuel blends B10, B20ABE10, and B30ABE30. Their physical stability was assessed by visually observing the phase separation of the fuel blends at room temperature. The B10 blend exhibited no phase separation during the first month of storage. The miscibility of CNSL and diesel blends can be explained by how they interact in a mixture. CNSL contains phenolic compounds such as anacardic acids, cardanols, and cardols, which exhibit both polar and non-polar characteristics due to their molecular structure. The aromatic ring and hydroxyl groups contribute to the polar nature, while the long aliphatic side chain imparts non-polar properties [114]. Substances with similar polarities are more likely to be miscible. Since diesel is nonpolar, and CNSL contains both polar and nonpolar components, the nonpolar portions of CNSL can mix well with diesel. Moreover, stabilisers in diesel prevent the formation of undesirable compounds such as gums or sediments and improve miscibility [115]. A study has shown that stabilisers can effectively decrease the content of unstable components in diesel fuel and improve storage stability.

Furthermore, B20ABE10 and B30ABE30 exhibited no phase separation because of the high solubility of CNSLT in diesel and ABE (361). This can be explained by the miscibility of CNSLT with each ABE component (acetone, butanol, and ethanol).

As shown in Figure 4.5, the viscosities of B10, B20ABE10, and B30ABE30 blends varied only slightly with storage time, and their densities were 841, 849, and 850 kg/m^3, respectively. The viscosities and densities of these blends were within acceptable limits for diesel engines during one month of storage.

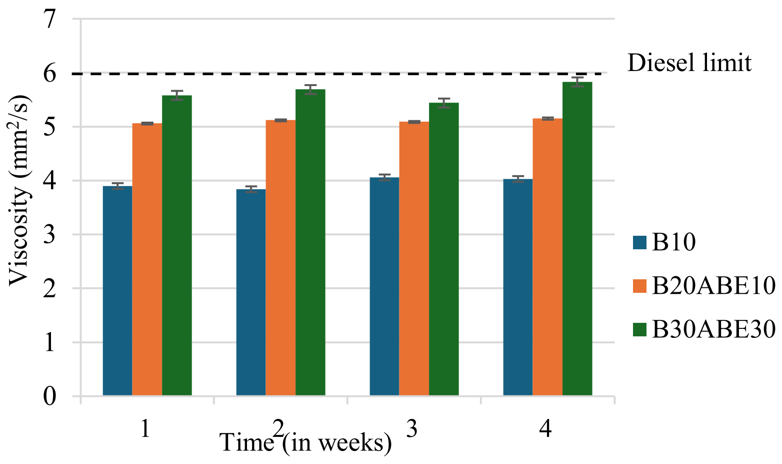

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Figure 4.5. Viscosity of fuel blends (stored at room temperature)

The viscosities of B10, B20ABE10, and B30ABE30 blends exhibited an increase after the ageing test at 80 °C for 24 h, and they were comparable to those stored at room temperature (Figure 4.6). After the ageing test, the viscosities of the blends were almost identical to the diesel requirements. As a result, these fuel blends can be stored for about one year because the ageing test changes in fuel properties that could occur in one year, as reported by [112].

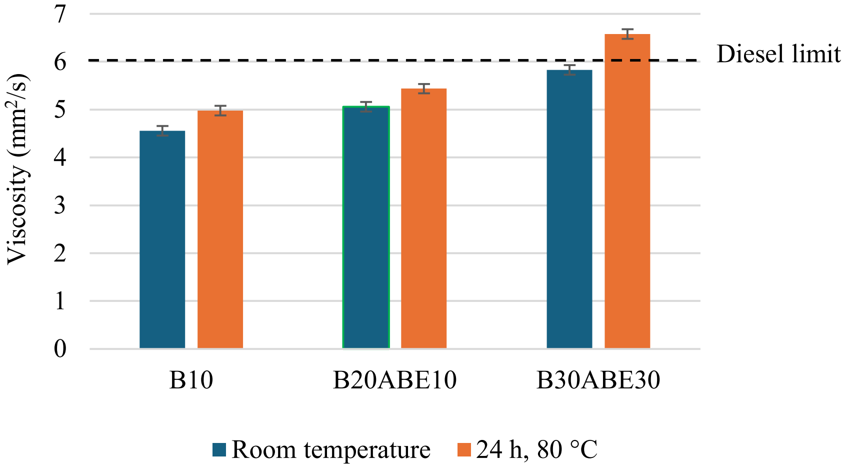

Figure 4.6. Viscosity of fuel blends (stored at room temperature and after the ageing test)

The acid numbers of the B10, B20ABE10, and B30ABE30 blends remained practically constant after one month of storage at room temperature (Figure 4.7). In addition, the values of the acid number were within acceptable limits (< 15 mg KOH/g) and can avoid the corrosion of the engine parts for prolonged usage.

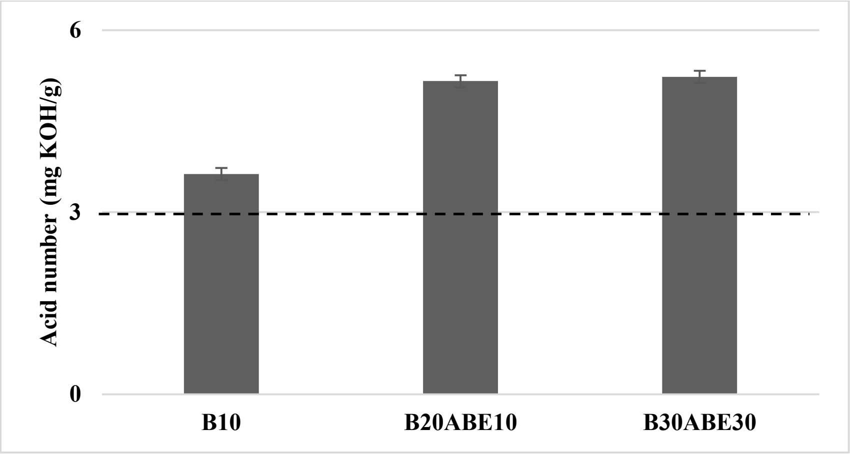

Figure 4.7. Acid number of fuel blend (after one month of storage)

4.3.6.3. Characteristics of the most suitable fuel blends for diesel applications

The physicochemical characteristics of the fuel blends were compared with the diesel specifications to ensure that they satisfied the diesel requirements, as summarised in Table 3.9. The density, viscosity, and heating value of B10 were within the standard limits for diesel engines. However, the B20ABE10 and B30ABE30 blends exhibited acid numbers ranging from 4.92 to 6.60 mg KOH/g, which were higher than the diesel specifications. According to

Blin et al. [7], some engine manufacturers accept acid numbers of up to 15 mg KOH/g, which are higher than those of suitable fuel blends.

The moisture content of the B20ABE10 and B30ABE30 blends varied from 0.24 % to 0.41 %, which was higher than the diesel specifications and slightly lower than that of HFO. Manufacturers of low-speed diesel engines recommend a cetane index (which indicates the ignition quality of the fuel) exceeding 30 [99]. This requirement was fulfilled by B10, B20ABE10 and B30ABE30 blends (Table 4.9). Although the heating values of the blends were lower than those of diesel, they were higher than those specified for diesel in this study.

Table 4.9. Properties of the most suitable fuel blends.

Properties		B20ABE10	B30ABE30	B10	Requirements
Viscosity at 40 °C (mm^2/s)		5.02	5.83	4.56	1.6–5.9
Density at 20 °C (kg/m^3)		850.00	849.02	842.17	820–890
Heating value (MJ/kg)		42.20	40.81	44.94	≥ 40
Acid number (mg KOH/g)		4.92	6.60	3.25	≤ 3
Moisture content (% wt.)		0.24	0.41	0.11	≤ 0.05
Cetane number		40.80	35.40	44.00	45–55
Elemental analysis	C (%)	82.7	80.4	84.80	
	H (%)	10.89	10.72	12.80	
	O (%)	6.41	8.88	2.21	

4.3.6.4. Fuel properties of purified CNSLs

The high acidity of the formulated fuel blends, exceeding the limits for standard diesel fuel, presents a key challenge. This is directly attributable to the high acid number (20.30 mg KOH/g) of CNSLT used in their preparation. To mitigate this issue, treatments with different solvents (acetone, butanol, ethanol, and ABE) are employed to reduce the acid number of CNSLT.

The acid number of purified CNSLs is depicted in Figure 4.8. The acid numbers of CNSL purified with ethanol and ABE (361) were 3.32 and 2.39 mg KOH/g, respectively. CNSL contains free fatty acids (FFAs) [116]. When alcohols such as butanol or ethanol are added to CNSL, a transesterification reaction can occur, producing ethyl esters or butyl esters, depending on the alcohol used. These reactions reduce the FFA content in CNSL. The acid number comprises the acidity from free fatty acids (FFA) as well as any other acidic compounds present. Consequently, the significant reduction of FFA during the transesterification process decreases the acid value, as evidenced by the properties of CNSL biodiesel in various studies. The acid number of purified CNSL-ABE met diesel specifications (3 mg KOH/g).

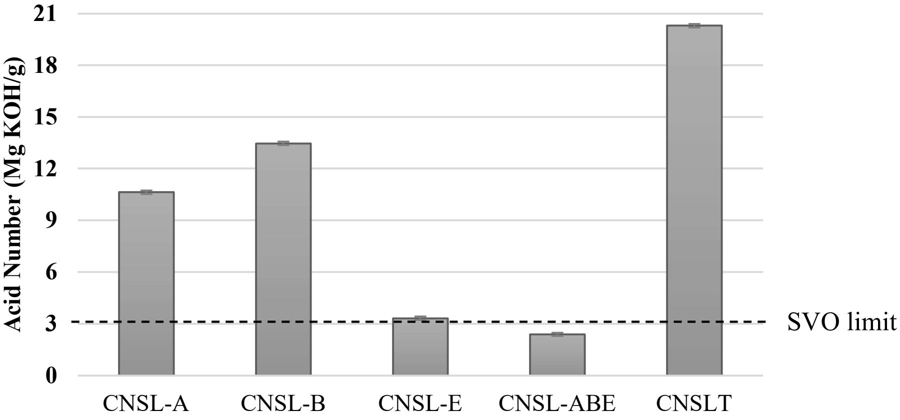

Figure 4.8. Acid numbers of CNSLs purified with different solvents (CNSL-A: CNSLT purified with acetone, CNSL-B: CNSLT purified with butanol, CNSL-E: CNSL purified with ethanol, CNSL-ABE. CNSL purified with ABE (361), CNSLT: technical CNSL)

Other fuel properties, such as viscosity and density, must be assessed to determine their suitability as a direct biofuel for diesel engines. Figure 4.9 shows the viscosity values of purified CNSLs.

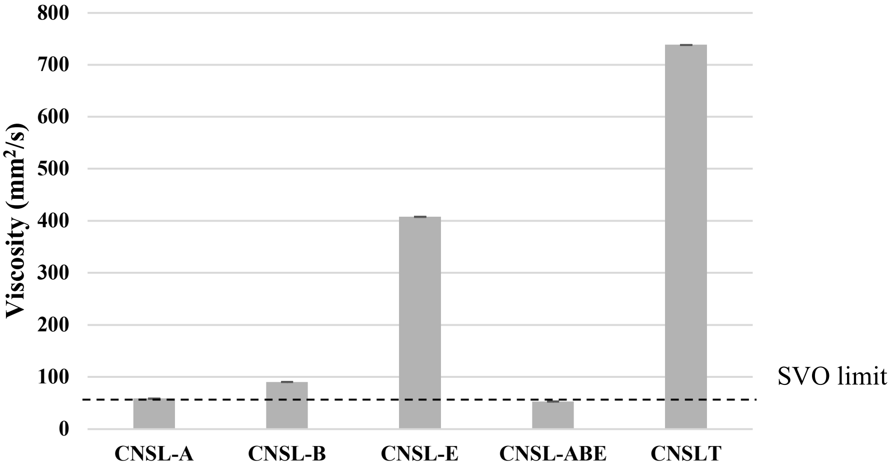

Figure 4.9. Viscosity values of CNSLs purified with different solvents

Purified CNSLs have a high viscosity, exceeding 5.9 mm²/s, which makes them unsuitable for direct use in engines. However, treating CNSL with an ABE (acetone-butanol-ethanol) solvent mixture can significantly reduce its viscosity by approximately 93 %, bringing it closer to that of vegetable oils commonly used as biofuels (50 mm²/s). This substantial reduction in viscosity, along with decreases in density (Figure 4.10) and acid number (figure 4.9), positions ABE as an ideal solvent for optimising CNSL as a biofuel. By lowering these key properties, CNSL purified with ABE allows for higher proportions of biofuel to be incorporated into fuel blends, making it more feasible for use in engines while maintaining fuel performance.

The density values of purified CNSLs are shown in Figure 4.10.

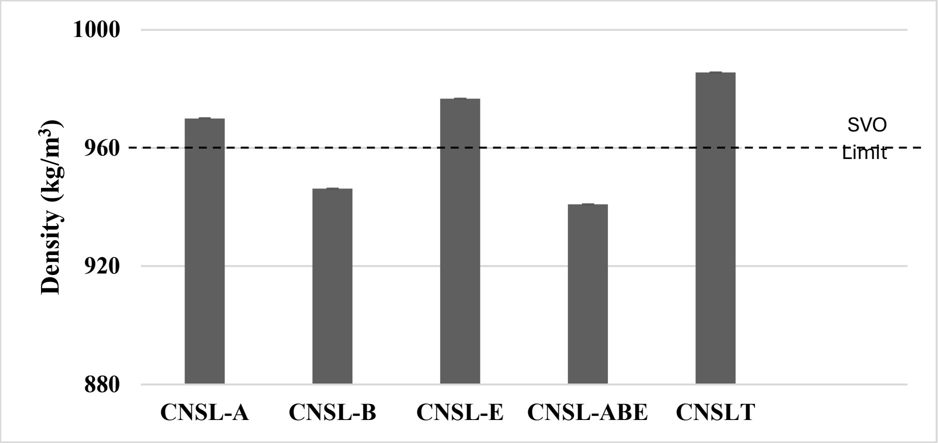

Figure 4.10. Density values of CNSLs purified with different solvents (CNSL-A: CNSL purified with acetone, CNSL-B: CNSL purified with butanol, CNSL-E: CNSL purified with ethanol, CNSL-ABE: CNSL purified with ABE)

CNSL samples purified with acetone and ethanol exhibited higher density values, likely due to the near-complete evaporation of both solvents during the purification process. As relatively volatile solvents, acetone and ethanol evaporate quickly, failing to reduce the density or viscosity of the CNSL effectively. This residual high density may limit CNSL's potential in fuel blends, where lower-density fuels are typically favoured for performance reasons. Therefore, to enhance the suitability of CNSL as a biofuel, alternative solvents must be explored to achieve better reductions in density and viscosity.

CNSL purified with ABE (361) showed a reduction in density to 940.85 kg/m^3, which is within the vegetable oil specification of 960 kg/m^3. However, its density remains slightly higher than the diesel standard of 890 kg/m^3. The physicochemical characterization of various purified CNSL samples shows that ABE (361) purification yields favourable density, viscosity, and acid number results, closely aligning with straight vegetable oil (SVO) used as biofuel. Notably, the acid number dropped significantly from 20.30 mg KOH/g in its crude form to 2.39 mg KOH/g after purification. This reduction in acidity enhances CNSL's suitability as a biofuel and helps mitigate the potential risk of engine corrosion, making it a safer alternative for use in fuel blends.

4.4. Analysis of performances and emissions characteristics of diesel engine fuelled with appropriate fuel blends

This section analyses the performance and emission characteristics of a diesel engine powered by the most suitable blends of B20ABE10 and B30ABE30, which exhibit fuel characteristics that align with diesel specifications. After replacing the injector and pump, achieving full load proved challenging, even with diesel fuel, leading to a limitation of tests to a maximum fixed load. In fact, the investigation of the performance of a diesel engine using suitable CNSL-diesel blends indicated that the performance was optimal at loads of 60 to 80 %. As a result, we chose to use the maximum load of 75 % for the remainder of the investigation.

Due to difficulties in loading the engine at high rotational speeds (2,000 rpm) and full load (100 %), tests were conducted on a diesel engine (as described in Chapter 2) with a rated power output of 1.1 kW at 1,500 rpm. This adjustment is also ideal for electricity generation, as it ensures a consistent output of 50 Hz, which is standard for electrical devices. The test bench analyses engine performance at various loads while maintaining constant speeds. The fuel blends were evaluated under the same conditions as commercial diesel, specifically at standard pressure and timing, with the engine speed held steady at 1,500 rpm across varying loads of 25 %, 50 %, and 75 %. The performance of a diesel engine operated with different fuel blends is assessed by analysing parameters such as BTE, BSFC, and EGT.

4.4.1. Brake thermal efficiency

BTE usually indicates the useful amount of energy obtained from fuel combustion. The combustion of fuel blends mainly relies on characteristics such as viscosity and boiling point. Figure 4.11 indicates the variation of BTE for commercial diesel and appropriate fuel blends at various loading conditions (25, 50, and 75 %). It was observed that the BTE increased with engine load. The reasons are the reduction of heat loss and development in power with increased load. At a 25 % engine load, BTEs for commercial diesel, B20ABE10 and B30ABE30 were 13.22 %, 10.54 %, and 10.03 %, respectively. Similar results were observed by Govindan et al. [73] for CNSL-diesel blends with ethanol fumigation at all engine loads. In contrast, Sivakumar [107] observed high BTEs for fuel blends compared to diesel fuel at low loads.

At a higher load (75 %), BTEs increased to 22.49 % for B20ABE10 and 23.79 % for B30ABE30. The BTEs of B20ABE10 and B30ABE30 were lower at all engine loads than those of commercial diesel due to the poor spray formations resulting from the higher viscosities, lower CV, and higher densities. Aguado-Deblas [95] explained the reduction in the BTE of ternary blends (SVO/diesel/ABE), which diminished as the percentage of ABE/SVO biofuel increased due to the lower energy content of the blends compared to commercial diesel. The reduced BTE of fuel blends can be attributable to poor combustion efficiency due to poor fuel mixture, and low in-cylinder temperatures [117] and may lead to a substantial portion of the fuel remaining unburned, negatively impacting the BTE. The BTE of the B20ABE10 blend (at 75 % engine load) was comparable to that reported for B20 [28].

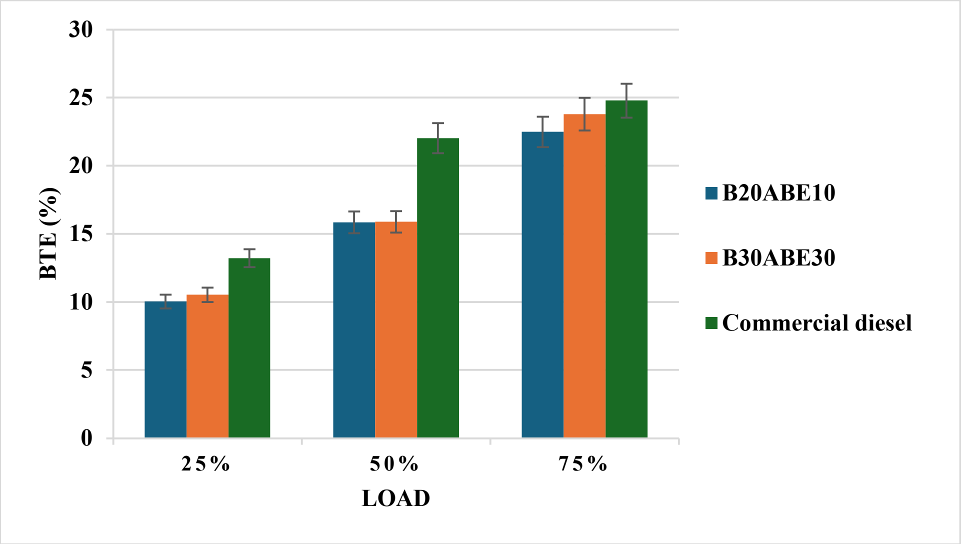

Figure 4.11. Brake-thermal efficiency (BTE) of fuel blends vs diesel

Other strategies can be employed to enhance the BTE of diesel engines when using fuel blends. For example, preheating biofuel can improve fuel properties and combustion efficiency, optimise engine characteristics, reduce specific fuel consumption, and raise the BTE [118]. This optimisation can enhance the energy conversion of fuel blends, bringing them closer to the performance of commercial diesel. For this test bench diesel engine, the fuel filter has been positioned near the heated part of the engine. The engine heats up under high engine load and improves the flow properties of the fuel. As the temperature increases, both the density and viscosity of the fuel decrease. This strategic placement leverages the heat generated by the engine. By reducing its viscosity, the fuel can be delivered more easily to the combustion chamber, which leads to better atomisation and combustion efficiency. The improved flow properties have resulted in superior engine operation with B30ABE30 at 75 % engine load, which was very close to that of commercial diesel. Moreover, the BTE of B20ABE10 was observed to be lower than that of B30ABE30. In terms of oxygen content, B30ABE30 possesses a higher oxygen concentration, which enhances combustion within the engine.

A study by Masimalai et al. [65] demonstrated that increasing the oxygen content in the intake of a CI engine improves combustion efficiency

Many studies have demonstrated that acetone, butanol, and ethanol at certain proportions added to CNSL or CNSL-diesel blends improve efficiency and reduce emission characteristics. Kasiraman [15] found that adding 30 % of butanol to CNSL improved engine efficiency. Another study found a slight increase in the BTE because of combustion improvement [73]. Shantharaman et al. [17] added acetone (4 %, 8 %, and 12 %) as an additive to CNSL–diesel blends (B20) and the results revealed that 12 % acetone with a B20 blend serves as a better alternative fuel for diesel engines. Thanigaivelan et al. [18] found that a 10 % ethanol-blended B20 blend with a hydrogen flow rate of 8 L/min exhibited the highest brake thermal efficiency and reduced CO and HC emissions.

The literature revealed that acetone, butanol, and ethanol improve the efficiency of CNSL and its blends in diesel engines. This might explain the improvement in diesel engine efficiency when the three components (ABE) are combined and blended with CNSL and diesel, especially for B30ABE30. The acceptable thermal efficiency of B30ABE30 presents a promising outlook for alternative fuels.

4.4.2. Brake-specific fuel consumption

BSFC indicates engine performance in relation to fuel economy [69]. It measures the quantity of fuel consumed per unit of time to achieve one unit of brake power output. Figure 4.12 illustrates the variations in the BSFC of commercial diesel and suitable fuel blends under different engine loading conditions.

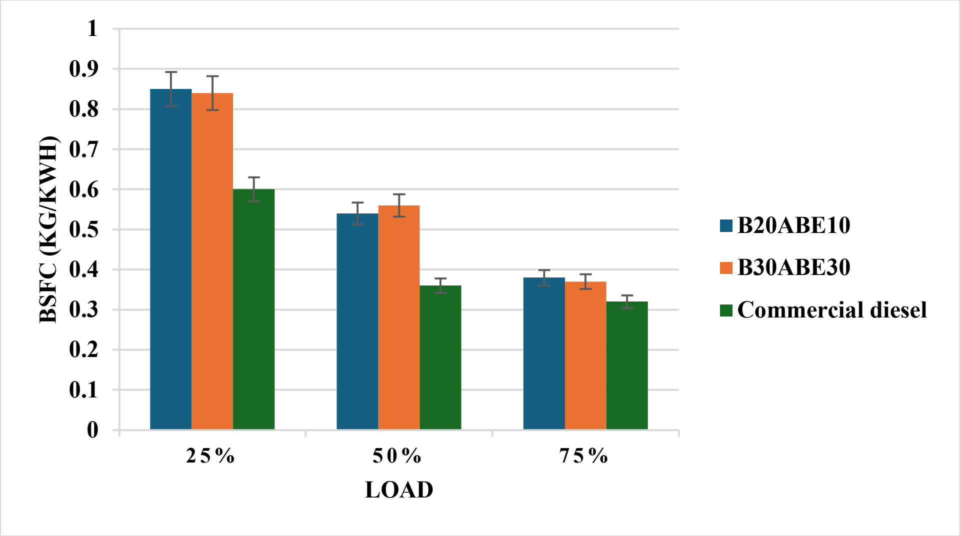

Figure 4.12. Brake-specific fuel consumption (BSFC) of fuel blends

The BSFC decreases as the engine load increases. Sivakumar [107] observed the same trend for BSFC for CNSL-diesel blends (B20, B40, and B60). The BSFC for B20ABE10 and B30ABE30 were smaller than for commercial diesel (at 25, 50, and 75 % loads). The BSFC of B20ABE10 and B30ABE30 were approximately 12 % higher than that of diesel fuel. In their study, Venkatesan [69] reported that the increase in BSFC for fuel blends compared to diesel fuel may be related to their lower calorific values, higher viscosity, and densities. Pramanik [111] stated that the increased specific fuel consumption of different biofuel blends was mainly due to factors like higher viscosity, lower heating value, and relative fuel density of different blends.

The higher BSFC for fuel blends (B20ABE10 and B30ABE30) is also due to the lower energy content of ABE (361) and CNSL, which decreases the heating value of fuel blends compared to that of commercial diesel. It has been observed that the heating value of diesel fuel is 7 to 10 % higher than that of fuel blends. Notably, Srinivasan et al. [28] reported an increase of approximately 5.46 % in BSFC for fuel blends containing 20 % CNSL in diesel fuel, underscoring the influence of fuel blends on fuel consumption.

It is also observed that the BSFC for B20ABE10 is 2 % higher than that for B30ABE30 (75% load). Although both fuel blends possess similar viscosity and density values, since the heating value of B20ABE10 is greater than that of B30ABE30, we would expect B20ABE10 to consume less fuel. This finding challenges the assumption that a higher calorific value leads to lower fuel consumption. The reduction in BSFC for B30ABE30 is probably due to the higher oxygen content, which improves combustion and engine efficiency.

4.4.3. Exhaust gas temperature

EGT refers to the energy lost through the exhaust or the effective utilisation of energy. As shown in Figure 4.13, EGT rose as the engine load increased for all tested fuels. A higher load implies more fuel is being injected to produce greater power, resulting in an increase in exhaust gas temperature.

Fuel blends exhibit high EGT at all engine loads (25, 50 and 75 %). This can be attributed to the presence of higher-boiling-point CNSL components that did not evaporate sufficiently during the main combustion phase and continued to burn in the later combustion phase. The fuel characteristics, such as higher viscosity and density than commercial diesel, can lead to incomplete combustion [74], and result in a delayed and prolonged burn of fuel blends, thereby increasing the EGT. Other studies attribute the high EGT to the inefficient combustion of biofuel compared to diesel [119].

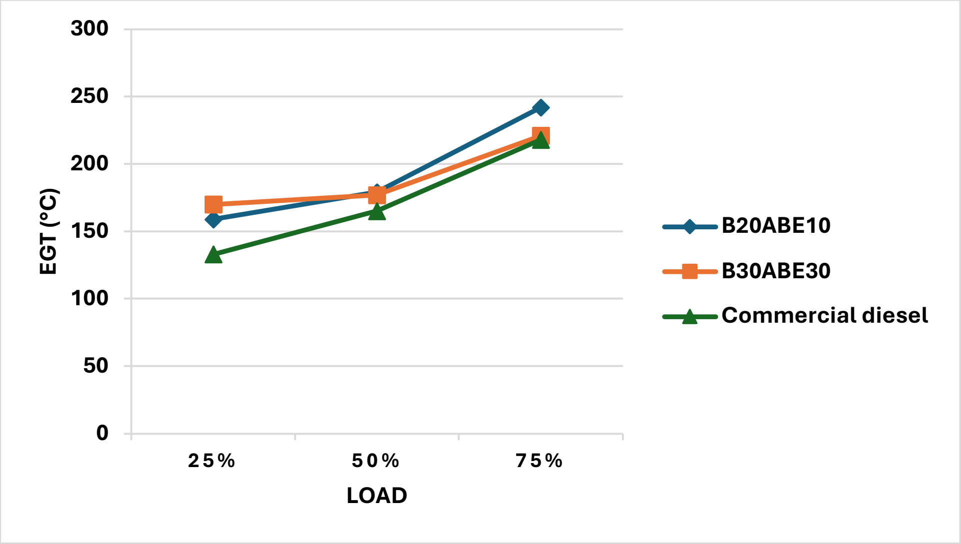

Figure 4.13. Exhaust gas temperature (EGT) of fuel blends and commercial diesel

At a low engine load of 25 %, commercial diesel exhibited a lower EGT (133 °C) compared to B20ABE10 (159 °C) and B30ABE30 (170 °C). A greater load implies the engine is working harder, generating more heat and increasing EGT. The EGT at a high engine load of 75 % for commercial diesel, B20ABE10, and B30ABE30 were 218 °C, 242 °C and 221°C, respectively. The EGT of B30ABE30 was slightly higher than that of commercial diesel, indicating a small reduction in fuel chemical energy. This observation correlates with the BTE, which was nearly identical for commercial diesel and B30ABE30 at 75 % engine load. The high proportion of ABE content contributed to improving the combustion process.

The EGT for B20ABE10 exceeded that of the other fuels (diesel and B30ABE30) under all load conditions. The overconsumption of B20ABE10 appears to result in an elevated engine exhaust temperature, as reported by Sidibé concerning the EGT for oil and oil-diesel mixtures [119]. A higher EGT correlates with a decrease in engine efficiency. In contrast, it has been reported that a higher exhaust temperature signifies improved combustion of vegetable oil, indicated by enhanced engine performance and reduced emissions [119].

The EGT can affect the emission characteristics of diesel engines. The temperature significantly impacts the formation of nitrogen oxides (NOx). They form inside the combustion chamber at high temperatures [107]. The higher EGT in the fuel blend can lead to increased NOx formation. Furthermore, the EGT may impact the durability of the exhaust pipe components. High EGT can potentially damage engine components, including the exhaust manifold and catalytic converter, increasing wear and tear. It may also impact the performance of emission control systems, such as catalytic converters. While some catalysts may perform effectively at high temperatures, others can even damage, and they can depend on the quality of the materials used in their manufacture.

4.4.4. Evaluating emissions characteristics of a diesel engine running with fuel blends

Analysing emission characteristics is essential for understanding combustion quality, which may be complete or incomplete. The Testo 340 allows for measuring CO, O_2, and CO_2 levels, as well as the temperature of exhaust gas, which aids in explaining fuel combustion in engines. Table 4.10 presents the exhaust gas emissions of a diesel engine fuelled with various suitable fuel blends operating at 75 % engine load and 1,500 rpm.

The emissions characteristics are evaluated using suitable fuel blends like B20ABE10 and B30ABE30. The emission characteristics are compared with those of the commercial diesel used in a diesel engine under identical conditions (75 % load, 1,500 rpm).

Table 4. 10. Exhaust gas emissions in a diesel engine (75 % engine load)

Parameters	Commercial diesel	B20ABE10	B30ABE30
Carbon dioxide CO_2 (%)	4.85	4.31	5.05
Carbon monoxide CO (ppm)	321	1368	411
Oxygen O_2 (%)	14.87	15.06	14.46
Fume temperature (°C)	168.1	193.4	180.8

- **Analysis of CO emission**

CO emission is generated by the incomplete combustion of fuel, which can occur due to a lack of oxygen. According to [120], CO emission in the exhaust gas of diesel engines is negligibly tiny when a homogeneous mixture is burned at a stoichiometric air-fuel ratio mixture or on the lean side. The CO emission of the B30ABE30 blend was smaller (411 ppm) compared to those of B20ABE10 (1368 ppm) (Table 4.10). In contrast, the CO emissions of B30ABE30 were close to those of commercial diesel (321 ppm). The literature revealed that the primary source of CO emission is incomplete fuel burning in the combustion chamber, i.e., the combustion in a poor oxygen environment. The elemental analysis revealed that B30ABE30 contained higher oxygen content than B20ABE10. The high oxygen content likely contributed to improving the combustion of B30ABE30 rather than B20ABE10. CO emission increases when oxygen availability is insufficient and mainly depends on the air-fuel ratio relative to the stoichiometric proportions [107]. This phenomenon is mainly observed in a diesel engine fuelled with

B20ABE10, and high CO emission is a matter of urgent concern in diesel engine emissions. A high percentage of ABE in fuel blends contributed to significantly reduced CO emissions by offering a promising solution to this pressing issue. An increase in the emission level of CO may result in fuel blends due to the rich air-fuel mixture, which produces more CO during combustion [107].

Commercial diesel produces lower CO emissions than other fuel blends such as B20ABE10 and B30ABE30. This is partly because these fuel blends have lower cetane numbers than diesel fuel (Table 3.9), underscoring the importance of cetane numbers in selecting fuel blends as fuel for diesel engines. The combustion of the fuel blends results in poor combustion due to specific characteristics, such as the cetane number [119]. For B20ABE10 at 75 % load, the CO emission was 22 % higher than those of diesel fuel. At 75 % engine load, the CO emission level for B20 is marginally higher than that of diesel fuel, at a value of 20 % [107].

From the discussions, it was noted that B20ABE10 produces a higher level of CO emissions than commercial diesel. The emission level of B30ABE30 reflects that of diesel, showing a slight increase. As CO is a toxic intermediate product generated during the combustion of hydrocarbon fuels, the environmental impact becomes critical when using various fuel blends, highlighting the complexity of choosing suitable blends.

- **Analysis of CO_2 emission**

When the carbon from the fuel is fully oxidised during combustion, CO_2 is produced as a by-product instead of CO. CO_2 is generated due to the combustion of hydrocarbon atoms within the fuel molecules. According to Table 4.10, B30ABE30 exhibits higher CO_2 emissions (5.05 %) than B20ABE10 (4.31 %). It is important to note that B30ABE30 emitted approximately 13 % more CO_2 than commercial diesel. In their study, Srinivasan [28] observed that the CO_2 emissions fuel blend (B20) is 20 % higher than diesel fuel. At a load of 75 %, the fuel blend B20ABE10 emitted 4.31% CO_2, which is lower than the emissions from B20 (20 % CNSL, 80 % diesel) reported by Sivakumar [107].

The CO_2 emissions of B30ABE30 were slightly higher than those of diesel fuel. The greater energy content of diesel fuel means that less fuel is required to generate the same amount of energy compared to B30ABE30, thus reducing CO_2 emissions.

The analysis of emissions characteristics indicates that blends of B30ABE30 emit levels of emissions comparable to diesel while maintaining acceptable thermal efficiency. This observation is particularly significant because alternative fuels can greatly reduce emissions and enhance air quality. While our study has outlined the composition of exhaust gases in terms of CO, O_2, and CO_2, there is still much to explore. Evaluating NOx and unburnt hydrocarbon (HC) emissions is a critical next step. Unfortunately, due to the limitations of our gas analyser, we were only able to analyse three gases. This research did not examine the heat release rate, an important aspect of combustion, due to a faulty sensor.

It is important to note that no other studies have investigated the emission characteristics of diesel engines using CNSL blended with diesel and ABE blend, which limited the comparison of our results with those of previous studies. The absence of prior research highlights the novelty and significance of our study, which seeks to address this gap and offer valuable insights into the potential of these alternative fuels.

The results have demonstrated that incorporating ABE (361) into CNSL and diesel can significantly enhance performance and emission characteristics, especially for B30ABE30. We observed that ABE (361) when mixed with CNSL and diesel fuel in various proportions, produced fuel formulations that optimise combustion efficiency. Incorporating this additive in viscous biofuel enhanced the volatility and combustibility, facilitating better atomisation and mixing within the combustion chamber. Fuel blend B30ABE30 exhibited improved BTE, particularly under high engine load (75 %). Furthermore, using such fuel blends can help alleviate issues related to the higher viscosity and density in neat CNSL, enabling it to perform more comparably to conventional diesel fuel. This enhancement in fuel properties and performance is crucial for accepting biofuels in combustion applications. The synergistic effects of these additives not only improve overall fuel blend properties but also contribute to improving the performance of diesel engines in emissions. This positions ABE as a sustainable additive in the search for cleaner energy solutions.

4.4.5. Economic analysis of appropriate fuel blends

The economic analysis aims to estimate the cost of different fuel blends and compare them to commercial diesel to demonstrate their feasibility. The cost of the fuel blend was assessed using a methodology from Bangjang et al. [38], which involves calculating the cost of fuel blends by evaluating the price of each component and subsequently using the blending ratio to estimate the costs of fuel blends (B10, B20ABE10, and B30ABE30).

The economic analysis also showed that the B10 blend was 6.25 % cheaper (1.05 \$) than commercial diesel (1.12 \$). In contrast, the cost of blends B20ABE10 and B30ABE20, are \$5.81 and \$14.98 per litre, respectively (Table 4.11). Due to their high production costs, using them as alternative fuels for diesel engines in Sub-Saharan Africa is unappealing. Producing fuel blends is quite expensive due to the high cost of the imported ABE component (361).

Reducing the quantity of ABE (361) in the blend could lower fuel costs; however, this approach would alter fuel properties and may not meet diesel standards specifications as a result. Therefore, using B10 as an alternative fuel could result in significant cost savings and consequently decrease the importation of commercial diesel, particularly in Burkina Faso, which lacks domestic petroleum production.

Table 4.11. Estimation and comparison price of fuel blend (Price ($/L)

Fuel	**Price ($/L)**
Commercial diesel [a]	1.12
Acetone*	40
Butanol*	50
Ethanol*	56.60
ABE (30 % acetone, 60 % butanol, 10 % ethanol)	47.70
CNSL[b]	0.44
B10 (10 % CNSL, 90 % diesel)	1.05
B20ABE10 (20 % CNSL, 10 % ABE, 70 % diesel)	5.81
B30ABE30 (30 % CNSL, 30 % ABE, 70 % diesel)	14.98

*Local price for 1L (calculated from the price of 2.5L, for ethanol=85,000 XOF, butanol=75,000 XOF, and acetone=60,000 XOF, with1 $=601 XOF 28/07/2024)

[a] Local price for 1L of commercial diesel

[b] Calculated from 450 $ per tonne [121]

In 2018, Burkina Faso imported approximately 1,500 kilotons of oil equivalent (ktoe) of petroleum products, including diesel, distillate diesel oil, and heavy fuel oil (HFO) (Appendix F). Diesel fuel accounted for approximately 34.5 % of the total imported petroleum products [7], consequently, 517.5 ktoe of diesel[1] was imported in 2018. It has been observed that the potential for CNSL production is approximately 15.18 ktoe[2]. This quantity of CNSL does not allow for blending with up to 10 % diesel for total consumption. On the other hand, this potential could replace up to 3 % of the total imported commercial diesel, marking a significant step towards reducing energy independence.

This study demonstrates that CNSL can replace HFO in stationary applications, such as diesel engines or boilers. The imported HFO in Burkina, as mentioned in [7], representing about 13.7 % of total petroleum products. This resulted in an estimated value of 205.5 ktoe for HFO in

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[1] Calculated from Appendix F and [7]

[2] Evaluated from ((Com Cashew Report, 2019) and Appendix G).

2018[3]. While the potential for CNSL production may not currently match that of imported HFO, it could still significantly reduce HFO imports by approximately 7%. This observation highlights the potential of CNSL as a viable alternative for sustainable development.

4.5. Summary

The combination of CNSL with commercial diesel and ABE (361) has resulted in fuel blends with properties similar to those of diesel fuel. Blends B20ABE10 and B30ABE30 meet diesel specifications. Moreover, the fuel properties of these blends (density, viscosity, and acid number) remained stable over 30 days of storage, with no phase separation detected. Consequently, each blend of 20% CNSL with 10% ABE (361) and 30% CNSL with 30% ABE (361) in diesel fuel can serve as fuels for acceptable performance in diesel engines without any modifications. Furthermore, the purification of CNSL using an ABE blend has produced a high-quality product that could serve as a substitute for SVO as biofuel for diesel engines. However, it is essential to consider specific properties of ABE, such as boiling temperature, to optimise the evaporation step and purification process. Consequently, the purified CNSL blend may serve as a promising biofuel for diesel engines.

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[3] Detailed calculations from Appendix F and [7]

General conclusion and outlooks

The primary objective of this thesis was to enhance the fuel properties of CNSL to match those of conventional diesel, which is widely used in direct-injection diesel engines. While CNSL demonstrated potential as an alternative to diesel fuel, its high viscosity and density currently limit its direct application in engines. Therefore, it is essential to pursue further research and development to improve CNSL's properties for use as a biofuel.

The first part of the thesis discusses various types of CNSL and methods to enhance its fuel properties. It critically evaluates different strategies for improving these properties. Among the proposed strategies, preheating and blending CNSL with diesel fuel are the most feasible options. However, current methods for producing CNSL biofuels necessitate high temperatures, catalysts, or chemical reagents. Additionally, CNSL biofuels need to be blended with other secondary fuels in small percentages to match the performance of diesel fuel. This study selected locally available technical CNSL due to its easy accessibility in small cashew nut processing units across Africa.

The density, viscosity, moisture content, cetane index, acid number, and heating value are essential factors to consider when investigating fuels for diesel engines. CNSL possesses an advantageous property, specifically a high calorific value. However, its higher viscosity and density make it unsuitable for direct application as a biofuel in diesel engines. Due to its fuel flow characteristics, using CNSL as a biofuel can result in challenges with fuel flow that may obstruct the pump and injection system. This issue can be mitigated by blending CNSL with commercial diesel in varying proportions to improve its fuel flow properties.

The investigation into the fuel properties of the CNSL-diesel blend has revealed that fuel B10 (CNSL/diesel = 10:90 v/v) meets the diesel specifications. For other fuel blends, such as B20 (CNSL/diesel = 20:80 v/v) and B30 (CNSL/diesel = 30:70 v/v), preheating at 60–80 °C is necessary to optimise the fuel flow properties. The preheating of different fuel blends presents several challenges:

- It requires additional energy, which may offset the environmental benefits of biofuel use.
- The availability and compatibility of preheating systems for small diesel engines may limit users from adopting these fuel blends.
- The temperature requirements for preheating blends may elevate wear and tear on the engine components, potentially affecting the engine's long-term durability.

A fuel additive was used to enhance fuel blends that did not match diesel specifications, avoiding the need for preheating fuel. An acetone/butanol/ethanol (ABE) mixture (30:60:10 v/v) applied to B20 and B30 produced appropriate fuel blends, B20ABE10 (CNSLT/ABE/diesel=20:10:70 v/v) and B30ABE30 (30:30:40 v/v), which were stable over one month of storage and satisfied diesel specifications (density, viscosity, heating value, cetane number). However, these fuel blends have a higher acid number, exceeding the limits established for diesel fuel. The high acid value of the fuel blend may be due to the elevated acid value of the CNSL used in its preparation. To reduce the acid value, CNSL was purified using various solvents (acetone, butanol, ethanol, ABE (361)). The purification of CNSL using ABE (361) decreased the acid number of CNSL, making it comparable to diesel specifications. The fuel blends B10, B20ABE10, and B30ABE30 also have cetane numbers that are lower than those of diesel fuel; however, they meet the recommendations for stationary diesel engines.

The performance and emission characteristics of a diesel engine operated with suitable fuel blends at various loads (25 %, 50 %, and 75 %) were examined. The results revealed that the thermal efficiency and fuel consumption of B30ABE30 are comparable to those of diesel at 75 % load. In contrast, B20ABE10 exhibited higher fuel consumption than diesel and B30ABE30, along with poorer efficiency.

The emission characteristics of the diesel engine were assessed using a gas analyser (Testo 340), which measured two types of pollutants (CO and CO_2) at a 75 % engine load. The commercial diesel emitted a low level of CO (321 ppm) compared to the fuel blends and was similar to that of the B30ABE30 blend (411 ppm). The B30ABE30 emitted 13 % more CO_2 than commercial diesel, which was less than that of B20ABE10. Regarding performance and emissions characteristics, the B20ABE10 and B30ABE30 blends can serve as alternative fuels for low-speed diesel engines without requiring modifications. Additionally, the B10 demonstrated acceptable performance as an alternative to diesel engines.

The economic analysis revealed that the estimated cost of the B10 blend was 6.25 % cheaper ($1.05/L) than commercial diesel ($1.12/L). In contrast, the estimated costs of B20ABE10 and B30ABE30 were $5.81 and $14.98/L, respectively, higher than diesel. The cost of the imported ABE component (361) has contributed to the rising cost of fuel blends. The B10 blend offers an attractive alternative fuel, which could lead to considerable cost savings. Utilising this fuel blend could diminish the necessity to import commercial diesel, especially in Burkina Faso, which does not manufacture petroleum products.

Considering the significant potential of CNSL in sub-Saharan Africa, using these formulated fuel blends could diminish the reliance on petroleum diesel imports and reduce greenhouse gas emissions. However, the cost of the necessary reagents (acetone, butanol, and ethanol) may limit the feasibility of using these fuel blends. The use of cashew apples in the production of ABE (361) could enhance the value of cashew by-products. Further research is required to confirm the feasibility of this strategy. Cashew trees are a unique source of food (cashew nuts) and biofuels (CNSL and ABE) from single crops.

Our results revealed that C70ABE20 (CNSLT/ABE (361) = 70:30 v/v) and C80ABE20 (80:20 v/v) blends may be used as burner fuels instead of HFO. Furthermore, C70ABE30 can substitute for SVO as fuel in diesel engines. An extensive study of the physicochemical properties of these blends, along with performance tests in a diesel engine or burner, must be carried out to confirm the suitability of these systems as alternative fuels.

This study evaluated the cetane number of fuel blends using a calculation method that incorporated variables such as density, viscosity, and temperature. Although this calculation method offered a rough estimate of the cetane number of fuel blends, it lacked the precision and accuracy that direct measurements could provide. It would be intriguing to employ methods that consider all the environmental variables.

The study involved using fuel blends in a diesel engine without any modifications. Further investigations are necessary to optimise the use of these fuel blends by adjusting injection pressure and preheating fuel, thereby impacting diesel engines' performance and emission characteristics. Furthermore, studying the evaporation of droplets from these fuels is necessary to fully explain the combustion process. It is also crucial to assess the impact of these fuel blends on diesel engine components, including the piston, valve head, and injector head.

The investigation of the emissions characteristics poses significant challenges due to the complex composition of exhaust gases. The study of exhaust gas emissions from a diesel engine operating on various fuel blends was confined to measuring CO and CO_2 levels. Indeed, the lack of measurement modules for nitrogen oxides (NO/NOx), particulate matter, and hydrocarbons (HC) hindered a more comprehensive assessment of the engine's environmental impact and necessitates thorough evaluation for further research.

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Appendix

Appendix A. Tests parameters of diesel engine fuelled with B10

Time (s)		Fuel Consumption (mL.min^{-1})	Exhaust Gas Temperature (°C)	Torque (Nm)	Speed (rev.min^{-1})	Power (W)	Specific Consumption (kg. kWh^{-1})	Thermal Efficiency (%)
B10 (10 % CNSL, 90 % diesel): 100 % load								
0		11.4	339	10.6	2034	2251	0.27	35.12
30		11.4	340	10.6	2028	2244	0.27	35.01
60		11.4	339	10.6	2034	2256	0.27	35.20
B10 (10 % CNSL, 90% diesel): 80 % load								
0		9.0	303	7.6	2036	1613	0.31	30.80
30		9.0	294	7.6	2043	1628	0.31	30.85
60		8.6	289	7.6	2037	1618	0.29	33.01
B10 (10 % CNSL, 90 % diesel): 60 % load								
0		6.7	251	6.3	1990	1303	0.29	31.56
30		6.7	250	6.8	1953	1385	0.31	31.32
B10 (10 % CNSL, 90 % diesel): 60 % load								
0		6.4	217	5.9	2000	1235	0.29	32.76
30		6.4	220	6.4	1962	1319	0.27	34.99
60		7.1	222	6.3	1972	1304	0.30	31.44
B10 (10 % CNSL, 90 % diesel): 40 % load								
0		7.1	212	3.8	2047	822	0.48	19.82
30		6.4	205	4.0	2037	849	0.42	22.52
60		6.4	200	3.8	2047	813	0.44	21.56
B10 (10 % CNSL, 90 % diesel): 20 % load								
0		5.1	170	2.3	2042	481	0.60	15.95
30		5.1	166	2.3	2046	486	0.59	16.11
60		4.5	163	2.3	2047	487	0.52	18.45

Appendix B. Tests parameters of diesel engine fuelled with commercial diesel.

Time (s)	Fuel Consumption (mL.min^{-1})	Exhaust Gas Temperature (°C)	Torque (Nm)	Speed (rev.min^{-1})	Power (W)	Specific Consumption (kg. kWh^{-1})	Thermal Efficiency (%)
Commercial diesel: 100 % load							
0	11.0	329	10.3	1998	2159	0.20	39.21
30	10.9	330	10.4	1999	2186	0.21	39.10
60	10.9	330	10.4	1999	2182	0.21	39.17
Commercial diesel: 80 % load							

Table continues in next page

0	8.1	267	8.2	1990	1698	0.21	36.30
30	8.2	266	7.9	1995	1642	0.22	36.45
60	8.2	265	7.9	1997	1652	0.22	36.14
Commercial diesel: 60 % load							
0	7.1	227	6.3	2042	1342	0.24	36.98
30	6.9	223	6.8	2012	1440	0.24	36.80
Commercial diesel: 40 % load							
0	6.3	207	4.1	2028	881	0.37	25.14
30	6.2	201	4.1	2034	874	0.36	25.19
60	6.3	197	4.1	2025	879	0.37	25.09
Commercial diesel: 20 % load							
0	5.1	146	2.1	1990	443	0.39	20.90
30	4.8	144	2.1	1989	447	0.38	20.74
60	5.0	143	2.1	1995	448	0.39	20.62

Appendix C. Tests parameters of diesel engine fuelled with B20ABE10, B30ABE30 and commercial diesel at various loads (25 %, 50 %, and 75 %)

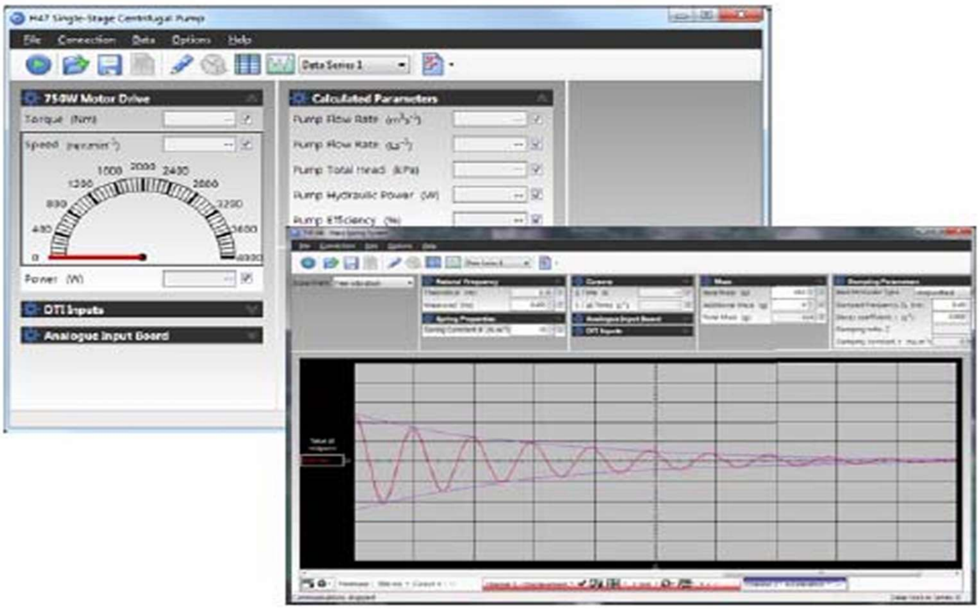
Time (s)	**Fuel Consumption (mL.min^{-1})**	**Exhaust Gas Temperature (°C)**	**Torque (N.m)**	**Speed (rev.min^{-1})**	**Power (W)**	**Specific Consumption (kg. kWh^{-1})**	**Thermal Efficiency (%)**
B20 ABE10 (20 % CNSL, 70 % diesel, 10% ABE): 75 % load							
0	5.5	209	4.2	1548	850	0.38	22.49
30	5.5	209	4.2	1547	845	0.37	22.27
60	5.5	209	4.1	1561	864	0.38	22.17
B20 ABE10 (20 % CNSL, 70 % diesel, 10 % ABE): 50 % load							
0	4.4	179	3.7	1511	582	0.54	15.85
30	4.4	179	3.8	1512	589	0.54	15.93
60	4.4	179	3.7	1514	591	0.55	15.38
B20 ABE10 (20 % CNSL, 70 % diesel, 10 % ABE): 25 % load							
0	3.4	137	1.7	1534	300	0.85	10.03
30	3.4	137	1.8	1529	297	0.83	10.27
60	3.4	137	1.8	1532	300	0.83	10.29
B30 ABE30 (30 % CNSL, 40 % diesel, 30 % ABE): 75 % load							
0	6.4	221	4.5	1571	837	0.37	23.69
30	6.3	221	4.5	1575	838	0.37	23.82
60	6.4	222	4.5	1577	842	0.39	22.93
B30 ABE30 (30 % CNSL, 40 % diesel, 30 % ABE): 50 % load							
0	4.3	179	3.4	1463	452	0.56	15.89
30	4.3	179	3.3	1392	459	0.55	15.99
60	4.3	179	3.3	1487	447	0.58	15.28

Table continues in next page

B30 ABE30 (30 % CNSL, 40 % diesel, 30 % ABE): 25 % load							
0	3.4	180	1.7	1556	300	0.84	10.54
30	3.5	181	1.8	1559	304	0.83	10.64
60	3.4	180	1.7	1559	301	0.85	10.40

Time (s)	Fuel Consumption (mL.min^{-1})	Exhaust Gas Temperature (°C)	Torque (N.m)	Speed (rev.min^{-1})	Power (W)	Specific Consumption (kg. kWh^{-1})	Thermal Efficiency (%)
Commercial diesel: 75 % load							
0	5.86	216	4.9	1551	949	0.30	26.13
30	5.85	217	4.9	1555	955	0.30	26.29
60	5.86	217	4.9	1555	943	0.31	25.96
Commercial diesel: 50 % load							
0	4.3	166	4.0	1522	634	0.34	23.27
30	4.4	166	4.0	1524	632	0.34	23.20
60	4.4	166	4.0	1524	635	0.34	23.31
Commercial diesel: 25 % load							
0	3.65	156	2.0	1530	319	0.56	14.02
30	3.65	156	2.0	1534	320	0.56	14.07
60	3.65	156	2.0	1539	321	0.56	14.11

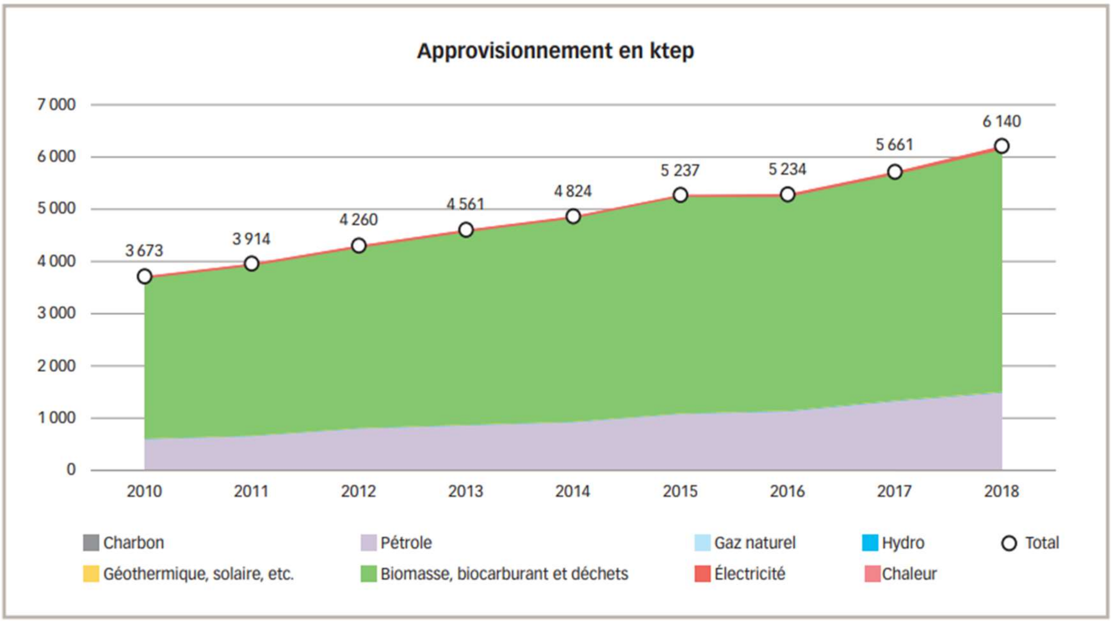
Appendix D. Interface of VDAS software



Appendix E. Steps for using VDAS software

- **Step 1**: Starting software VDAS on the computer
- **Step 2**: Put the density and heating value of the fuel in the software.
- **Step 3**: Define the time and range of data-saving
- **Step 4:** Save data and export in Excel file.

Appendix F. Trends in Burkina Faso's energy supplies from 2010 to 2018 (Source : Rapport-2019_SIE_UEMOA_Chiffres_Cles_BURKINA_FASO_web.pdf (francophonie.org))

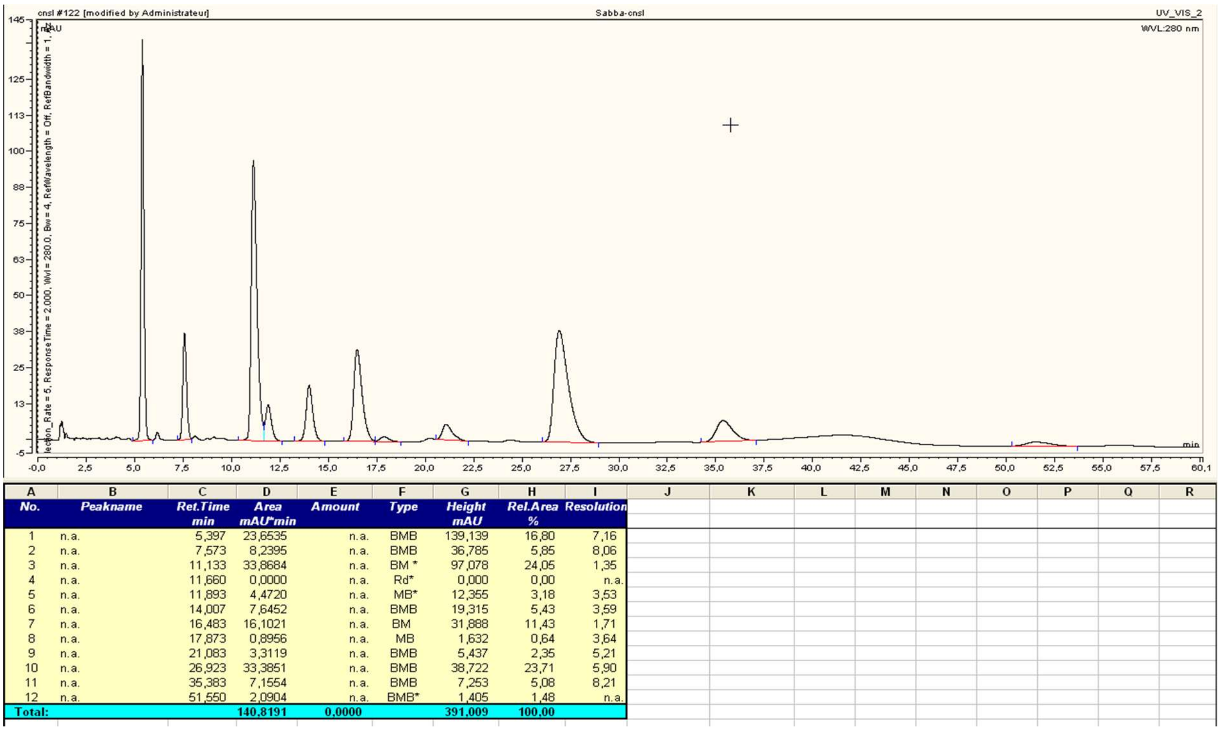


Appendix G. Conversion of tonnes metrics of CNSL to tonnes of oil equivalent (toe)

- First, convert the mass of CNSL to kg
- Next, calculate the total energy content of the CNSL in MJ:
- Total energy (MJ)= Mass (kg)×Heating value (MJ/kg)
- Convert the total energy from megajoules (MJ) to GJ, with 1 GJ=1,000 MJ
- Finally, convert the total energy from GJ to toe:
- 1 toe=41.868 GJ

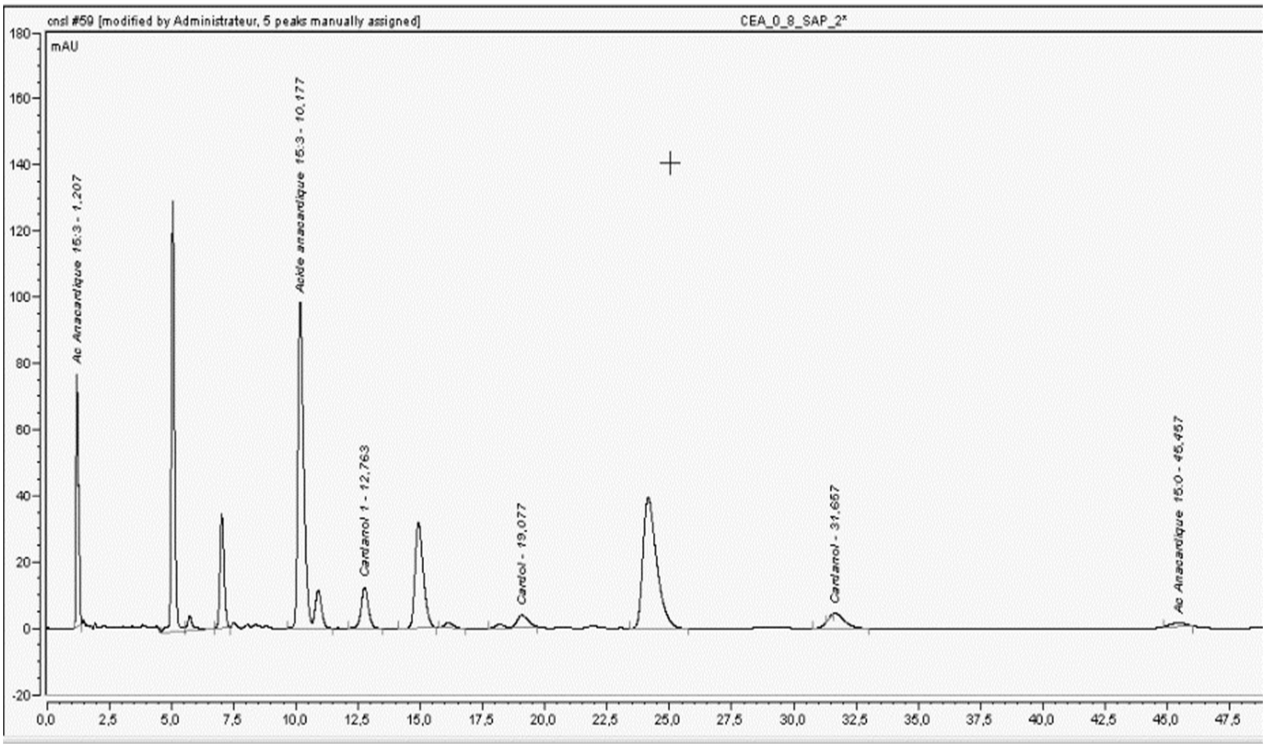
Appendix H. Chromatogram of CNSLs components using the HPLC technique

Appendix H1. Chromatogram of natural CNSL

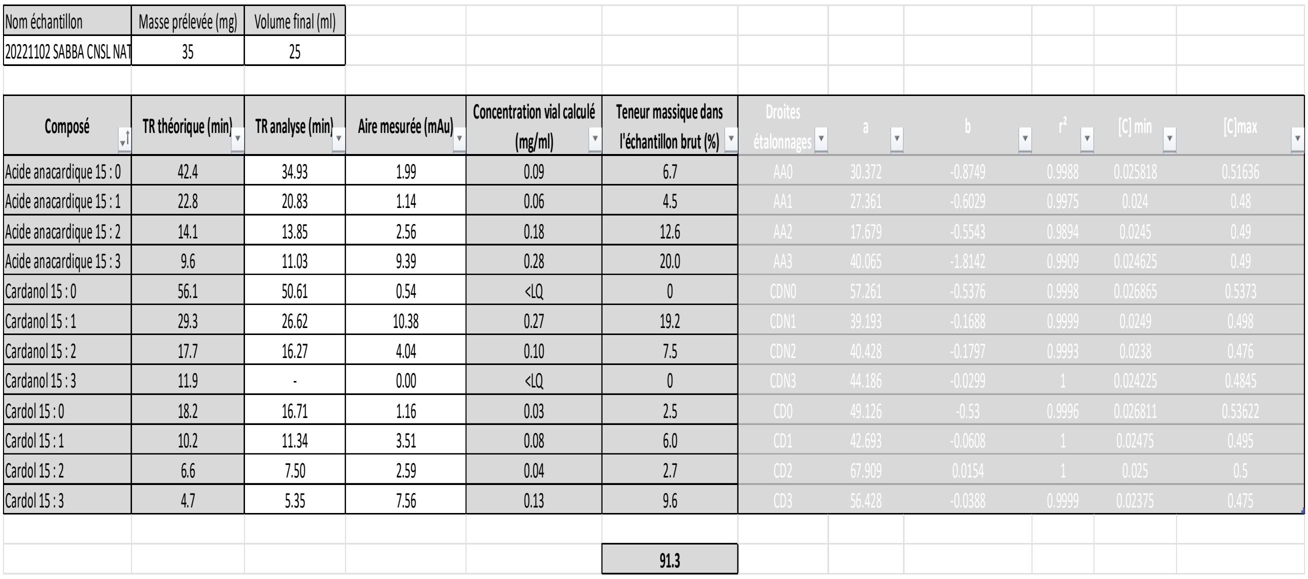


A	B	C	D	E	F	G	H	I
No.	Peakname	Ret.Time min	Area mAU*min	Amount	Type	Height mAU	Rel.Area %	Resolution
1	n.a.	5,397	23,6535	n.a.	BMB	139,139	16,80	7,16
2	n.a.	7,573	8,2395	n.a.	BMB	36,785	5,85	8,06
3	n.a.	11,133	33,8684	n.a.	BM *	97,078	24,05	1,35
4	n.a.	11,660	0,0000	n.a.	Rd*	0,000	0,00	n.a.
5	n.a.	11,893	4,4720	n.a.	MB*	12,355	3,18	3,53
6	n.a.	14,007	7,6452	n.a.	BMB	19,315	5,43	3,59
7	n.a.	16,483	16,1021	n.a.	BM	31,888	11,43	1,71
8	n.a.	17,873	0,8956	n.a.	MB	1,632	0,64	3,64
9	n.a.	21,083	3,3119	n.a.	BMB	5,437	2,35	5,21
10	n.a.	26,923	33,3851	n.a.	BMB	38,722	23,71	5,90
11	n.a.	35,383	7,1554	n.a.	BMB	7,253	5,08	8,21
12	n.a.	51,550	2,0904	n.a.	BMB*	1,405	1,48	n.a.
Total:			140,8191	0,0000		391,009	100,00	

Appendix H2. Typical CNSL chromatogram

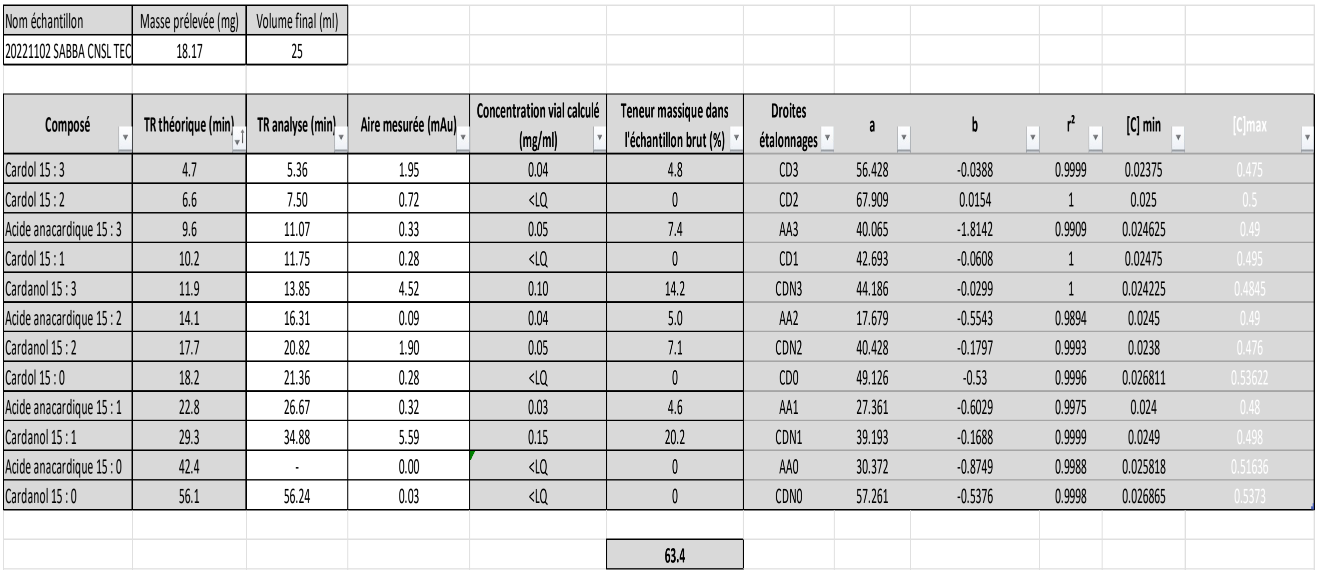


Appendix H3. Constituent of natural CNSL by HPLC



Nom échantillon	Masse prélevée (mg)	Volume final (ml)
20221102 SABBA CNSL NAT	35	25

Composé	TR théorique (min)	TR analyse (min)	Aire mesurée (mAu)	Concentration vial calculé (mg/ml)	Teneur massique dans l'échantillon brut (%)	Droites étalonnages	a	b	r²	[C] min	[C]max
Acide anacardique 15 : 0	42.4	34.93	1.99	0.09	6.7	AA0	30.372	-0.8749	0.9988	0.025818	0.51636
Acide anacardique 15 : 1	22.8	20.83	1.14	0.06	4.5	AA1	27.361	-0.6029	0.9975	0.024	0.48
Acide anacardique 15 : 2	14.1	13.85	2.56	0.18	12.6	AA2	17.679	-0.5543	0.9894	0.0245	0.49
Acide anacardique 15 : 3	9.6	11.03	9.39	0.28	20.0	AA3	40.065	-1.8142	0.9909	0.024625	0.49
Cardanol 15 : 0	56.1	50.61	0.54	<LQ	0	CDN0	57.261	-0.5376	0.9998	0.026865	0.5373
Cardanol 15 : 1	29.3	26.62	10.38	0.27	19.2	CDN1	39.193	-0.1688	0.9999	0.0249	0.498
Cardanol 15 : 2	17.7	16.27	4.04	0.10	7.5	CDN2	40.428	-0.1797	0.9993	0.0238	0.476
Cardanol 15 : 3	11.9	-	0.00	<LQ	0	CDN3	44.186	-0.0299	1	0.024225	0.4845
Cardol 15 : 0	18.2	16.71	1.16	0.03	2.5	CD0	49.126	-0.53	0.9996	0.026811	0.53622
Cardol 15 : 1	10.2	11.34	3.51	0.08	6.0	CD1	42.693	-0.0608	1	0.02475	0.495
Cardol 15 : 2	6.6	7.50	2.59	0.04	2.7	CD2	67.909	0.0154	1	0.025	0.5
Cardol 15 : 3	4.7	5.35	7.56	0.13	9.6	CD3	56.428	-0.0388	0.9999	0.02375	0.475
					91.3						



Nom échantillon	Masse prélevée (mg)	Volume final (ml)
20221102 SABBA CNSL TEC	18.17	25

Composé	TR théorique (min)	TR analyse (min)	Aire mesurée (mAu)	Concentration vial calculé (mg/ml)	Teneur massique dans l'échantillon brut (%)	Droites étalonnages	a	b	r²	[C] min	[C]max
Cardol 15 : 3	4.7	5.36	1.95	0.04	4.8	CD3	56.428	-0.0388	0.9999	0.02375	0.475
Cardol 15 : 2	6.6	7.50	0.72	<LQ	0	CD2	67.909	0.0154	1	0.025	0.5
Acide anacardique 15 : 3	9.6	11.07	0.33	0.05	7.4	AA3	40.065	-1.8142	0.9909	0.024625	0.49
Cardol 15 : 1	10.2	11.75	0.28	<LQ	0	CD1	42.693	-0.0608	1	0.02475	0.495
Cardanol 15 : 3	11.9	13.85	4.52	0.10	14.2	CDN3	44.186	-0.0299	1	0.024225	0.4845
Acide anacardique 15 : 2	14.1	16.31	0.09	0.04	5.0	AA2	17.679	-0.5543	0.9894	0.0245	0.49
Cardanol 15 : 2	17.7	20.82	1.90	0.05	7.1	CDN2	40.428	-0.1797	0.9993	0.0238	0.476
Cardol 15 : 0	18.2	21.36	0.28	<LQ	0	CD0	49.126	-0.53	0.9996	0.026811	0.53622
Acide anacardique 15 : 1	22.8	26.67	0.32	0.03	4.6	AA1	27.361	-0.6029	0.9975	0.024	0.48
Cardanol 15 : 1	29.3	34.88	5.59	0.15	20.2	CDN1	39.193	-0.1688	0.9999	0.0249	0.498
Acide anacardique 15 : 0	42.4	-	0.00	<LQ	0	AA0	30.372	-0.8749	0.9988	0.025818	0.51636
Cardanol 15 : 0	56.1	56.24	0.03	<LQ	0	CDN0	57.261	-0.5376	0.9998	0.026865	0.5373
					63.4						

Appendix I. Publications and oral communications at international conferences

This section presents articles and communications at international conferences that form part of the research presented in this thesis. One paper has been published, and another is being reviewed for publication, including:

Sabba Gwoda, Valette J., Sidibé SS., Piriou B., Blin J., & Ouédraogo Igor W. K. (2024). Use of cashew nut shell liquid as biofuel blended in diesel: Optimisation of blends using additive acetone–butanol–ethanol (ABE (361)). Cleaner Chemical Engineering, 9, 100117. https://doi.org/10.1016/j.clce.2024.100117.

In this study, the feasibility of increasing the proportion of cashew nut shell liquid (CNSL)-based biofuels in diesel was assessed. Biofuel–diesel blends with different percentages of CNSL were prepared, and their physical properties, including the density, viscosity, and heating value, were determined. B10 (CNSL/diesel = 10:90 v/v) satisfied the diesel specifications without preheating, whereas B20 (20:80 v/v) and B30 (30:70 v/v) met the specifications only after preheating to 60 and 80 ◦C, respectively. To avoid preheating B20 and B30, an acetone/ butanol/ethanol (ABE) mixture (30:60:10 v/v) was added to the fuel blends to improve their flow characteristics. The blends with CNSL/ABE (361)/diesel ratios of 20:10:70 and 30:30:40 (v/v) exhibited properties comparable to those of diesel and remained stable for one month of storage. These fuel blends allow up to 30 vol% CNSL and 30 vol% ABE (361) to be incorporated into diesel and can be used as alternative fuels in diesel engines.

Manuscript under review for publication:

Biofuels from cashew nut shells for diesel engines: A comparative review

Participation in international conferences

1. **Sabba Gwoda,** Sayon dit Sadio Sidibé, Igor W. K. Ouédraogo**.** Performance Characteristics of Diesel Engine Fuelled with Cashew Nut Shell Liquid blended with Acetone-Butanol-Ethanol (ABE (361)). Semaine des Energies et Energies Renouvelables d'Afrique (SEERA) 2024, Ouagadougou (Burkina Faso), 17 mai 2024.

Abstract: This study aims to assess the feasibility of using locally technical cashew nutshell liquid biofuel as an alternative to diesel engines. Fuel blends were prepared by blending various proportions of biofuel–diesel blends with a mixture comprising 30 % acetone, 60 % butanol, and 10 % ethanol (ABE (361)) as an additive, and their physical characteristics, including

density, viscosity, heating value, cetane index, and moisture content, were determined. Among the prepared fuel blends, B20ABE10 (CNSL/diesel/ABE:20:70:10 %) and B30ABE30 (30:40:30 %) satisfied the diesel requirements and remained stable over a month of storage. The results of performance in a diesel engine showed that the thermal efficiencies of B20ABE10 and B30ABE30 were reduced by 3.75 % and 9.16 %, respectively, compared with that of diesel fuel. However, the specific fuel consumption of B20ABE10 was very close to that of diesel, while it was 5 % higher for B30ABE30 compared to that of diesel. B20ABE10 blend can be used as an alternative fuel for low-speed diesel engines without any modifications.

Keywords: Cashew Nutshell Liquid; acetone–butanol–ethanol (ABE361); fuel blends; diesel engine.

2. **Sabba Gwoda,** Sayon dit Sadio Sidibé, Igor W. K. Ouédraogo. Development of Biofuel using Cashew Nutshell Liquid (CNSL) and Acetone–Butanol–Ethanol (ABE (361)) for replacement of Heavy fuel oil (HFO). Communication, 5th SOAPHYS congress, MALI (Bamako), 18-22nd December 2023.

Abstract: This study aimed to assess the feasibility of using locally technical cashew nutshell liquid (CNSL) as an alternative for heavy fuel oil. Fuel blends were prepared by blending various proportions of CNSL with a mixture comprising 30 % acetone, 60 % butanol, and 10 % ethanol (ABE (361)) as an additive, and their physical characteristics including density, viscosity, and heating value were determined. The viscosity and density of CNSL were decreased by blending with ABE (361), and C90ABE10 (90 % CNSL, 10 % ABE), C80ABEB20 (80 % CNSL, 20 % ABE), and C70ABE30 (70 % CNSL, 30 % ABE) blends satisfied HFO flow requirements and remained stable over a month of storage. Among these fuel blends, C90ABE10 blends satisfies the recommended viscosity for burner nozzles of an oil-fueled boiler. Therefore, it can be used as an alternative fuel in boiler applications and low speed diesel engines.

Keywords: Cashew Nutshell Liquid (CNSL), acetone–butanol–ethanol (ABE361), Heavy Fuel Oil (HFO), boiler applications, requirements.

3. **Sabba Gwoda**, Sayon dit Sadio Sidibé, Igor W. K. Ouédraogo, Joel Blin, Bruno Piriou. Etude de formulation de mélanges CNSL-diesel comme carburant alternatif au gazole pour moteur diesel stationnaire. Communication, 4ème Congrès SOAPHYS, TOGO (LOME), 05-10th December 2022.

Abstract : La majorité des pays africains sont dans l'incapacité de produire suffisamment de biocarburants pour répondre aux besoins énergétiques de leurs populations. Ce travail se concentre donc sur l'étude de formulation et de stabilité de mélanges du CNSL (Cashew Nut Shell Liquid) avec du gazole. La formulation des différents mélanges est effectuée en utilisant une quantité variable du CNSL (de 5 à 20 %) dans le gazole. L'étude de stabilité des mélanges carburants est effectuée par les essais de vieillissement accéléré (80 °C pendant 24 h). L'évaluation des propriétés physico-chimiques des mélanges CNSL-gazole avant et après le vieillissement permettent de prévoir l'évolution chimique de ces mélanges dans le temps. L'étude de performance du moteur en utilisant les mélanges formulés a été effectuée sur un moteur diesel stationnaire, monocylindrique et à injection directe de puissance nominale de 2,2 KW à une vitesse nominale de 2000 tr/min. Les propriétés physico-chimiques des mélanges CNSL-gazole telles que la densité, la viscosité, et le pouvoir calorique respectaient les spécifications du gazole (Burkina Faso). Les résultats de tests sur un banc moteur ont montré que les mélanges de 5 à 20 % CNSL dans du gazole présentaient des performances (rendement global, consommation spécifique en carburant) comparables à celles du gazole. Ces mélanges peuvent être utilisés comme des alternatives au gazole pour les moteurs diesel stationnaires sans modification.

Mots clés : CNSL, mélanges CNSL-gazole, stabilité, performance, moteur diesel stationnaire.