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Biodiesel-Based Ternary Fuel Blends in Compression Ignition Engines: A Comprehensive Review of Combustion, Performance, and Emission Characteristics

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Abstract: The increasing dependence on fossil diesel fuel and the associated environmental and energy security concerns have intensified research efforts toward sustainable and renewable alternatives for compression ignition (CI) engines. Biodiesel derived from non-edible oils and waste cooking oil has emerged as a promising substitute due to its renewable nature, biodegradability, and favorable combustion characteristics.

However, the widespread application of biodiesel is constrained by inherent drawbacks such as higher viscosity, lower calorific value, increased brake-specific fuel consumption, and a tendency to elevate nitrogen oxide emissions. To overcome these limitations, the present research investigates the performance, combustion, and emission characteristics of ternary fuel blends comprising diesel, biodiesel, and higher alcohols. In this study, biodiesel produced from selected non-edible and waste-based feedstocks is blended with diesel and higher alcohols such as butanol, pentanol, hexanol and n-octanol in varying proportions. Experimental investigations are conducted on a single-cylinder, four-stroke, water-cooled compression ignition engine under different load conditions.

Key performance parameters, including brake thermal efficiency and brake-specific fuel consumption, are evaluated alongside detailed combustion analysis involving in-cylinder pressure, ignition delay, and heat release rate. Exhaust emissions such as carbon monoxide, unburned hydrocarbons, nitrogen oxides, and smoke opacity are also analyzed and compared with baseline diesel operation.

Furthermore, statistical optimization techniques such as the Taguchi method and Response Surface Methodology are employed to identify optimal blend compositions that achieve a balanced trade-off between engine performance, combustion stability, and emission reduction.

The outcomes of this research are expected to provide comprehensive experimental insights into the feasibility of ternary biofuel blends and contribute to the development of cleaner and more efficient CI engine fuel strategies.

Keywords: Compression Ignition Engine, Biodiesel, Ternary Fuel Blends, Alcohol Fuels, Combustion Characteristics.

I. INTRODUCTION

The world energy situation is now becoming threatened by the growing energy demand, the exhaustion of traditional fossil fuel resources, and the growing geopolitical uncertainties linked to petroleum supply chains, especially within transportation, agriculture, construction, and power generation, whose systems rely on diesel.

A large portion of diesel production worldwide goes into compression ignition (CI) engines, as they are more thermally efficient and durable and thus dominate heavy-duty and stationary applications, adding pressure to the long-term energy security concerns, particularly in the case of the developing economies that heavily depend on imported petroleum fuels (Heywood, 2018; Knothe, 2010).

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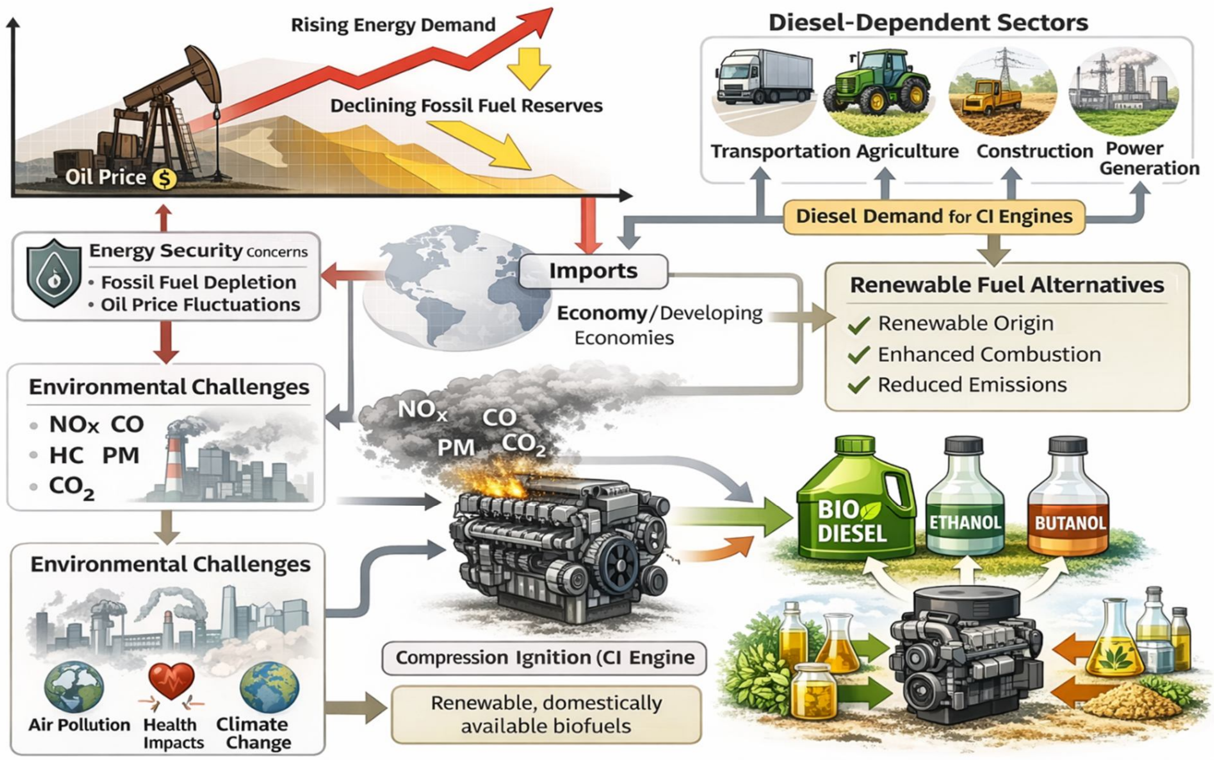
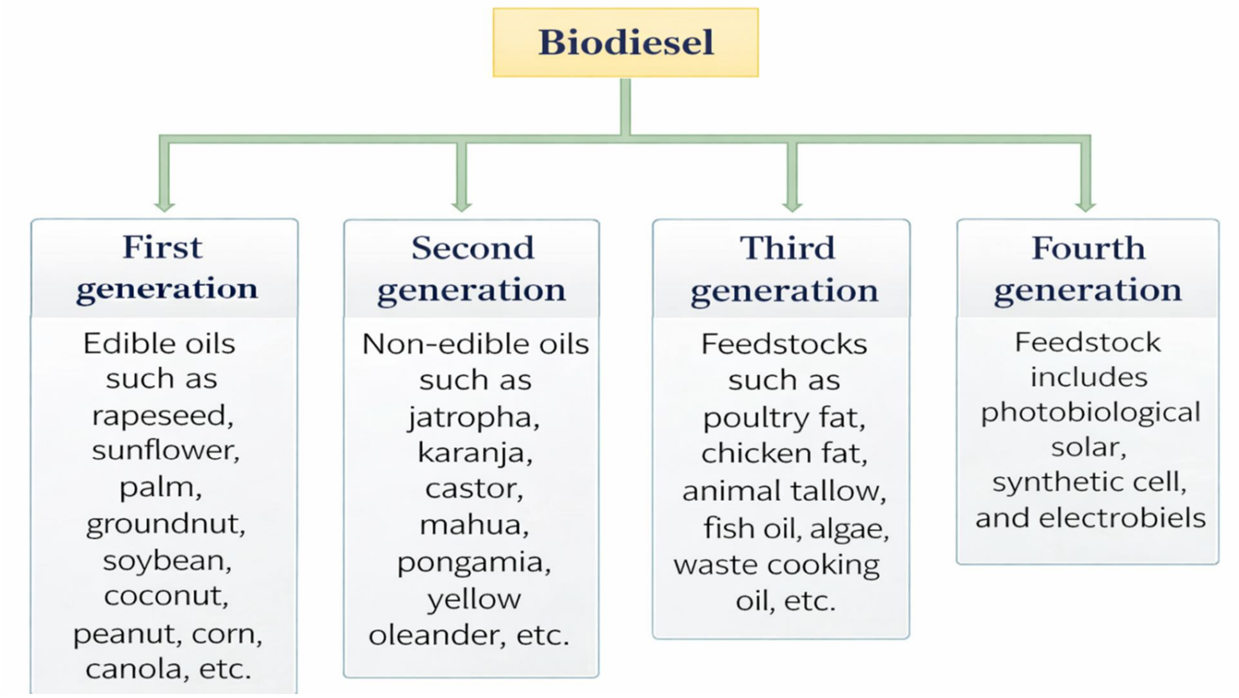


Figure 1: Schematic representation of energy challenges and the transition toward renewable fuel strategies for CI engines (self generated)

The rise and fall in the crude oil prices also contribute to the misbalance of the economy and raise the cost of conducting operations, which supports the fact that diversification of fuel search in CI engines is an urgent matter requiring the inclusion of renewable energy sources and domestically sourced energy into the portfolio. Diesel engines are also a considerable threat to the environment since the burning of fossil diesel leads to considerable emission of nitrogen oxides (NO[?]) and carbon monoxide (CO), unburned hydrocarbons (HC), particulate matter (PM), and carbon dioxide (CO2) that cause air pollution, negative health outcomes, and global warming (Lapuerta et al., 2008; Demirbas, 2009). Even though there has been an introduction of advanced exhaust after-treatment technologies like diesel particulates filters and selective catalytic reduction system which are capable of ensuring high emission regulations have been achieved, high costs, complexity, maintenance needs have aroused greater interest in fuel-based emission reduction methods. In this regard biodiesel, alcohols and vegetable oils are some of the renewable fuels that have become prospects because of their renewable nature and good combustion properties. Biodiesel specifically has been widely accepted due to its biodegradability, increased cetane number and its inherent oxygen content that improves combustion efficiency and decreases CO, HC and smoke emissions; but its higher viscosity, reduced calorific value, cold flow properties and its tendency to increase NO; emissions limit its application in further blends (Atabani et al., 2012; Mofijur et al., 2013). Such alcohols as ethanol and butanol have a high oxygen content and better volatility to enhance the spray atomization and mixing of fuels with air, however, they have low cetane number and worsen the solubility in diesel, thus affecting negatively the ignition stability and engine performance (Zheng et al., 2008). These restrictions suggest that there is no single alternative fuel that can meet the combined needs of performance, emissions and engine compatibility in CI engines. Therefore, there has been a continuous development of research that is less neater in the form of neat biodiesel and diesel-biodiesel binary combinations; more sophisticated in formulation of ternary fuels which incorporate diesel, biodiesel and oxygenated additives like higher alcohols. In these ternary blends, biodiesel acts as a medium ad between diesel and alcohols, where alcohols are known to increase the miscibility between alcohols and diesel, lower the viscosity, elevate the volatility and further lead to synergistic increase in combustion efficiency and emission reduction (Balat & Balat, 2008; Lapuerta et al., 2008). Recent experimental studies have obtained results showing that ternary blends when optimized appropriately can provide engine performance comparable to standard diesel with much reduction in regulated emissions, thus changing the focus of research to systematic experimental assessment and statistical optimization of ternary fuel systems to support sustainable CI engine operation.

II. BIODIESEL AS AN ALTERNATIVE FUEL FOR CI ENGINES

Because of its renewable nature, biodegradability and the ability to use it with current diesel engine systems, biodiesel has become one of the most widely studied renewable replacement to traditional diesel fuel used in compression ignition (CI) engines. It is mainly prepared by transesterifying triglycerides that are formed in vegetable oils, animal fat or waste cooking oil with alcohols like methanol or ethanol in the presence of alkaline or acidic catalysts. Jatropha curcas, Pongamia pinnata (Karanja), Mahua, and waste cooking oil are particular non-edible feedstocks that are gaining particular attention especially in developing nations because they do not directly compete with food supplies and because cultivation in marginal land can lead to increased energy security and sustainability (Knothe, 2010; Atabani et al., 2012). The physicochemical characteristics of biodiesel can be distinguished significantly compared to petroleum diesel; its features are higher density, higher viscosity, lower calorific value, higher flash point, and higher oxygen concentration, as well as elevated cetane number which facilitates consistent auto-ignition in CI engines. As much as higher cetane number will reduce ignition delay and improve the smoothness of the combustion, increased viscosity will negatively impact spray atomization and evaporation that may result in increased fuel consumption and new combustion timing (Lapuerta et al., 2008). Experimental studies are in full agreement that biodiesel-powered CI engines, at least at low blend ratios of B10 and B20, have the same brake thermal efficiency as when operated using diesel, but the brake-specific fuel consumption is generally high since biodiesel has a lower heating value (Mofijur et al., 2013).



As indicated by a combustion analysis of the bio-diesel, the combustion of bio-diesel is too with a shorter ignition delay, lower premixed combustion fraction and with a slightly advanced heat release, due to an increased cetane number and oxygenated molecular structure, but slower evaporation rates may increase diffusion combustion phase, especially at higher blend ratios. Biodiesel has great benefits in terms of reduction in carbon monoxide, unburnt hydrocarbons and particulate matter emissions due to improved oxidation reactions because it contains intrinsic oxygen and does not have any aromatic compounds (Demirbas, 2009). On the other hand, it is stated that in numerous studies, there is a modest rise in the emissions of nitrogen oxides, which is associated with the increase in the in-cylinder temperature and the availability of oxygen during combustion, though this tendency is also affected by the type of feedstock, engine operation regime, and injection parameters (Lapuerta et al., 2008). However, in spite of these merits, there is a number of limitations to the extensive use of biodiesel which includes greater viscosity, cold flow issues, reduced energy content, possible material incompatibility problems, and NO8 emissions penalties in case of more biodiesels are used. These issues illustrate that biodiesel is not a renewable fuel suitable to be used independently to achieve the required performance and emission in CI engines and that therefore highly organized fuel blending methods like binary and ternary blends must be used to harness the synergistic effect of fuel interactions and eliminate the natural disadvantages.

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III. ALCOHOL FUELS IN CI ENGINES

There is growing interest in alcohol fuels as possible renewable additives or as supplementary renewable fuels in compression ignition (CI) engines because of their oxygenated natures, great volatility, and ability to enhance combustion efficiency when mixed with diesel or biodiesel. Alcohols of interest as CI engine fuel can be categorized by their length of carbon chain (where shorter alcohols like ethanol (C_2H_5OH) and longer alcohols like butanol (C_4H_9OH), pentanol ($C_5H_{11}OH$) or hexanol ($C_6H_{13}OH$) and others are investigated). Ethanol is high in availability and can be easily refilled and it has low cetane number, high latent heat of vaporization as well as low miscibility with diesel which negatively impacts the ignition quality and cold-start performance. Higher alcohols, especially Butanol and pentanol, are more compatible with diesel and biodiesel, exhibit higher energy density, lower vapour pressure and have comparably higher cetane numbers thus making them better suited to CI engine usage (Knothe, 2010; Atmanli and Yilmaz, 2017). Alcohols are commonly used in the CI engines in either alcohol-diesel or alcohol-biodiesel mixtures, where the latter is typically a co-solvent that helps to improve the stability of blends and reduce the effects of phase separation caused by polar alcohol molecules (Zheng et al., 2008).

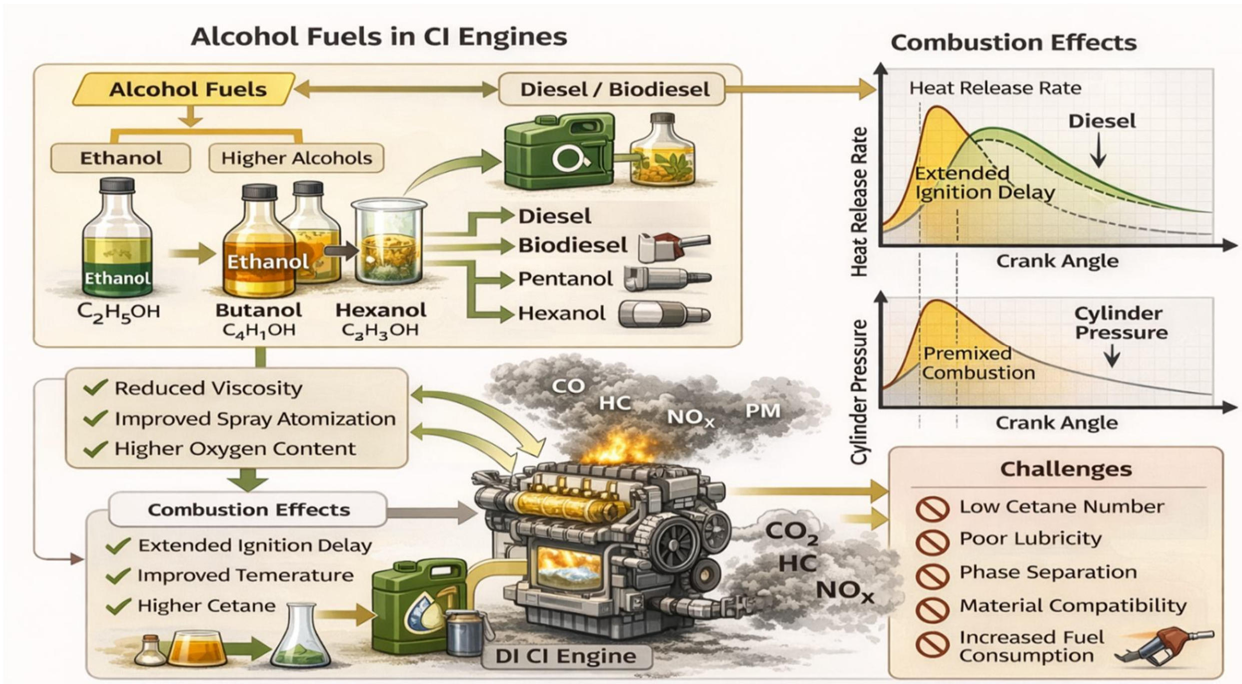

Figure 2: Schematic overview of alcohol fuels and their effects in compression ignition (CI) engines.

The experimental studies show that the addition of alcohols tends to decrease the viscosity and density of fuels, increasing the spray atomization, accelerating the mixing of air and fuels, and decreasing the homogeneity of the combustion, which can cause slight improvements or similar thermo-efficiency of the brakes at the optimum blend ratios, though the calorific value of alcohols is usually lower (Lapuerta et al., 2008). Analysis of alcohol blends by combustion existing mixtures results in a prolonged ignition delay due to the low cetane number of alcohols which elevates the premixed portion of the combustion fraction, and distorts the heat release properties, possibly causing higher rates of peak pressure growth at some operating conditions, but the high alcohols would temper this effect in contrast to ethanol because of superior ignition quality (Heywood, 2018). Emission wise, there are continuous decreases in carbon monoxide and unburnt hydrocarbons and smoke opinion because of increased oxidation of the high oxygen content of the alcohols and decreased high density of combustion areas caused by the high oxygen content in the alcohols. Effects on nitrogen oxide emissions are observed to be varied, showing that some studies have found a reduced emission and others have shown a slight increase depending on the type of alcohol and the proportion of the blends (Demirbas, 2009; Mofijur et al., 2013). In spite of these advantages, CI engines using alcohol fuels have a number of challenges, which include low cetane number, low lubricity, low temperatures phase separation, materials compatibility issue, and high consumption of fuels at high blending ratios. These shortcomings suggest the independent use of alcohol fuels is limited and also indicate the need to undertake optimized blending strategies, especially ternary fuel systems, to benefit substantially the impact of alcohols and still have stable combustion and acceptable engine operations.

IV. TERNARY FUEL BLENDS IN CI ENGINES

Blends of diesel, biodiesel and a third oxygenated element, usually alcohols or vegetable oils have become a new frontier fuel approach towards compression ignition (CI) engines, and they seek to exploit the strengths of the individual fuels in a synergistic approach, and overcome their limitations. The main explanation of ternary blending is the balancing of the important fuel characteristics based on cetane number, viscosity, volatility, calorific value, and oxygen content to have a stable combustion with better performance and lower emissions. The ester functional groups in biodiesel make it an essential bridging component in such systems to increase miscibility between the non-polar diesel and polar alcohols with the help of the functional groups, and thus improve stability of the blends and minimize the chances of phase separation, especially under varied ambient conditions (Zheng et al., 2008; Atabani et al., 2012). However, stability of blends is still one of the most important technical issues, as variations in Poland, density, and volatility of three components may result in stratification at low temperatures or during extended storage that requires a careful choice of alcohol type, blending ratio, and co-solvents or mild heating in some cases. Experimental studies on ternary blends all announce comparable brake thermal efficiency of optimized blends with neat diesel, mainly attributed to better atomization, enhanced air-fuel mixing, and increased oxygen accessibility during combustion; nevertheless, brake-specific fuel consumption tends to rise slightly owing to lower calorific value of alcohol blends (Lapuerta et al., 2008; Mofijur et al., 2013).

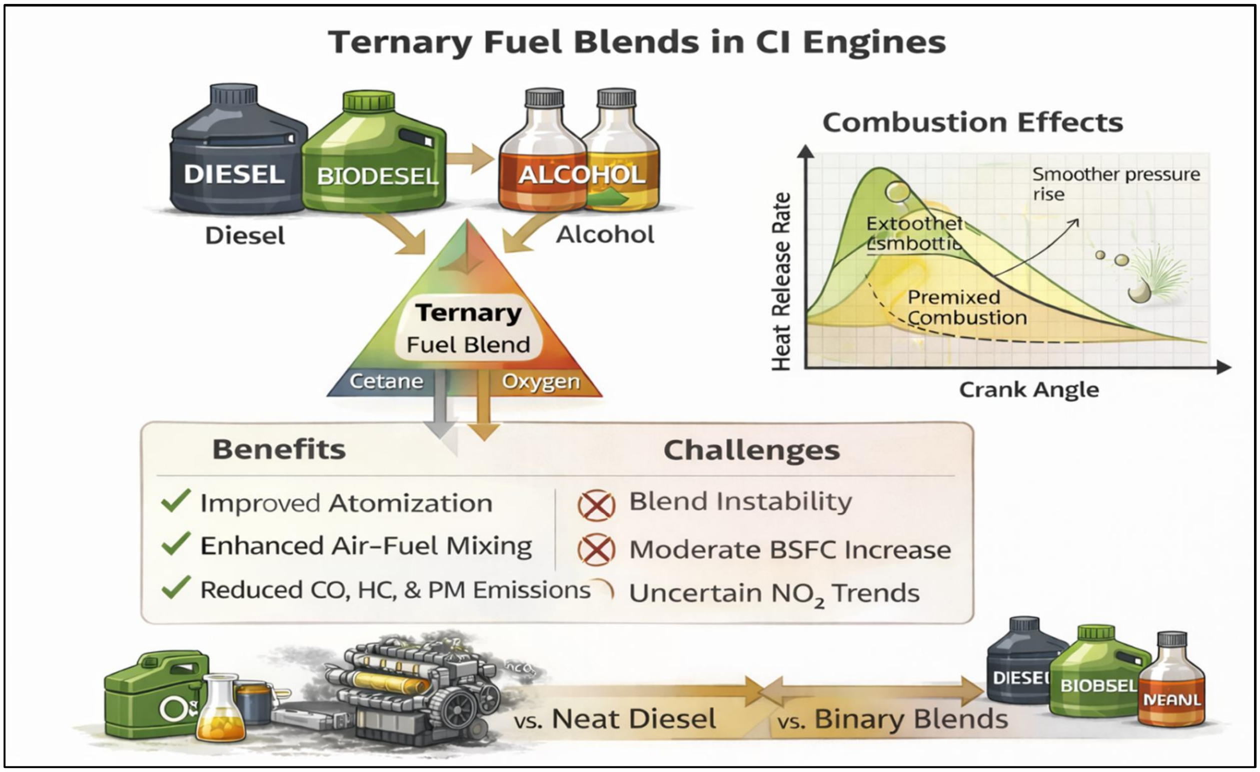

Figure 3: Schematic representation of ternary fuel blends in compression ignition (CI) engines.

Ternary blends have been shown by the combustion analysis to show altered ignition delay and heat release characteristics with the higher cetane number of the biodiesel over-compensating the ignition-retarding effects of the alcohols, leading to a controlled premixed combustion phase and smoother rates of pressure rise than with alcohol-diesel binary blends. Also, volatility differences in ternary fuels can cause micro-explosion and secondary atomization, which increases the fuel-air contact and combustion efficiency of the fuel further (Heywood, 2018). Emission wise, ternary blends exhibit substantial carbon monoxide, unburned hydrocarbons, and PM emission reductions due to the combined effects of oxygen enrichment and lowering the proportion of aromatics, whereas the trends in nitrogen oxide emissions range over slight increases and others have noticed a decline in nitrogen oxide emissions in comparison to diesel operation (Demirbas, 2009). In comparison to neat diesel and binary blends, ternary fuel system is typically a better trade-off between performance and emissions because it eliminates the high viscosity and cold flow of biodiesel and low ignition quality of alcohols, which can make ternary fuel systems a technically viable and environmentally friendly fuel choice in future CI engine applications.

V. SPRAY, IGNITION, AND HEAT RELEASE BEHAVIOR

The formation of the spray, the ignition process, and the heat delivery nature is a decisive factor in controlling the combustion efficiency, engine performance, and the formation of emissions in the compression ignition (CI) engines which use alternative fuels and blended fuels. Fuel properties including volatility, surface tension, density, and viscosity affect the process of spray atomization and fuel-air mixing to a great extent, which differs greatly between diesel, biodiesel, the alcohols, and the ternary blends. The fuels obtained by using vegetable oils, which have a higher viscosity and surface tension, are more likely to form larger fuel droplets with longer penetration distances, which leads to slower evaporation and higher heterogeneity in the fuel-air mixture. It is also found that ternary blends containing alcohols are effective in reducing the total blend viscosity and density and also facilitate better atomization, increases the spray breakup and also enhances a more uniform fuel-air mixing in the combustion chamber (Lapuerta et al., 2008; Atabani et al., 2012). Ignition delay that can be defined as the duration between injection and combustion onset is a significant parameter that controls the phasing and pressure formation of combustion. Valuable properties of biodiesel are that, it tends to reduce the ignition delay as compared to alcohols which tend to increase the ignition delay because of greater cetane number and less latent heat of vapour respectively. These conflicting effects usually offset one another in ternary blends, which causes moderate ignition delay values that enable stable combustion and a lower cyclic variability than alcohol-diesel binary blends (Heywood, 2018).

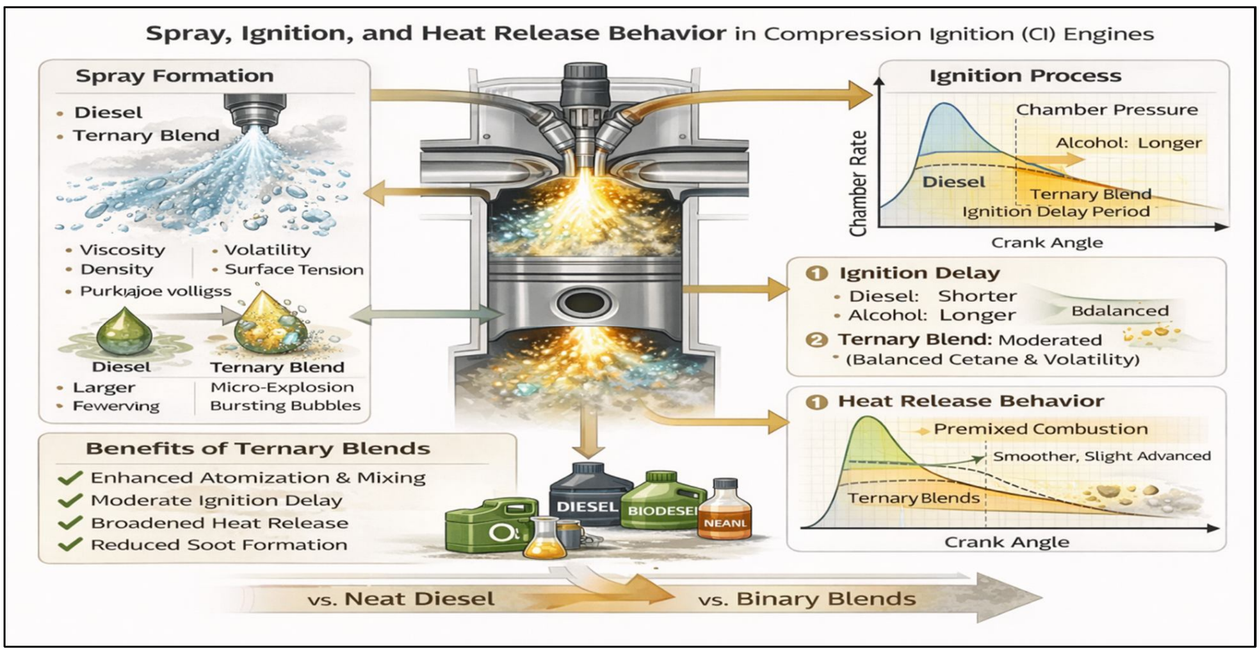

Figure 4: Schematic illustration of spray formation, ignition delay, and heat release behavior in compression ignition (CI) engines fueled with ternary blends.

Delay of ignition is directly proportional to the pre-mixed and diffusion stages of combustion since long delay of ignition generates high percentages of pre-mixed combustion, steep heat release rate and less delays to generate smoother diffusion-controlled combustion. In-cylinder pressure development and heat release rate (HRR) profiles of ternary blends have tended to slightly increase heat release as compared to diesel, to further enhance better mixing and accessibility of oxygen but peak pressures may vary as well depending on the blend composition and engine load (Mofijur et al., 2013). Moreover, the emergence of micro-explosion and the secondary atomization processes may commence by the ternary mixing with multi-component fuel droplets especially when the highly volatile alcohols are trapped within the ternary blends of less volatile droplets of either biodiesel or vegetable oil. It is an accelerated internal vaporization that results in the dispersion of droplets into small sizes and that can greatly increase the secondary atomization, rate of evaporation and optimal mixing of air and fuel in the local region which helps in increasing the thorough combustion and lessening formation of soot (Demirbas, 2009). The combination of all of these spray, ignition and heat release properties highlights the complicated yet beneficial combustion properties of ternary fuel mixtures, and their potential in providing superior performance in terms of combustion efficiency and emissions control in CI engines when optimized.

VI. OPTIMIZATION TECHNIQUES USED IN TERNARY BLEND STUDIES

The growing sophistication of ternary fuel mixtures in compression ignition (CI) engines has led to the incorporation of sophisticated optimization methodologies to systematically examine the combined effect of the fuel composition and engine operating conditions on performance, combustion and emissions. The Taguchi method is one of the most utilized methods as a powerful design-of-experiments (DoE) methodology to minimize the experimental trials and determine the most significant control factors which are blend ratio, injection pressure, engine load, and injection timing. The Taguchi method allows effective screening of the parameters and calculation of optimal operating conditions at the lowest cost of experimentation; however, it is not effective in reflecting the complex nonlinear interactions between variables (Taguchi, 1986; Lapuerta et al., 2008).

Table: A comparative overview of optimization techniques

Optimization Method	Purpose	Modeling Capability	Strengths	Limitations
Taguchi Method	Factor screening	Linear / limited	Fewer experiments, simple	Poor nonlinear modeling
RSM	Predictive optimization	Nonlinear (polynomial)	Interpretable, multi-objective	Moderate experimental effort
ANN	System prediction	Highly nonlinear	High accuracy	Black-box, data intensive

In order to address these shortcomings, Response Surface Methodology (RSM) has been progressively used in ternary blend studies as it can be used to describe nonlinear relationships among multiple input variables and response parameters using a series of polynomials. RSM supports the establishment of predictive models of the key responses like brake thermal efficiency, brake-specific fuel consumption, and regulated emissions, as well as allows the multi-objective optimization through desirability functions to find the balance between the conflicting performance and emission targets (Atabani et al., 2012; Mofijur et al., 2013). Over the last couple of years, artificial neural networks (ANN) have become a widely-used data-driven methodology, which is capable of modelling very nonlinear and complex interactions involved in the processes of CI engines burning ternary blends. The models of ANN are also better prediction models of the engine responses when well trained on adequate and experimental data, especially when under different loads and blends although the black-box nature and high dependency on large data sets do not permit physical interpretability (Demirbas, 2009). In comparison tests in the literature, it is described that, although the Taguchi technique is best suited to the initial optimization and screening of factors, RSM has a balanced structure between predictive ability and interpretability and ANN is best suited to predict complex systems at the cost of transparency. Recent research is, therefore, progressively promoting hybrid approaches to optimization, involving experimental design, statistical and machine-learned-based models to provide trustworthy, effective and thorough optimization of ternary fuel blends to operate CI engines on a sustainable basis.

VII. N-OCTANOL AS A THIRD ADDITIVE IN TERNARY FUEL BLENDS FOR CI ENGINES

However, n-octanol (C8H17OH) has shown itself as a promising higher-chain alcohol additive in compression ignition (CI) engines in recent years as it has relatively good physicochemical and combustion properties compared to lower alcohols, e.g. ethanol and butanol. Being a higher alcohol, n-octanol is comparatively more cetane number, higher density of energy, lower vapour pressure, higher miscible with both diesel and biodiesel and hence it finds its niche in CI engines where ignition quality and stability of blend is the most significant. The increased carbon length of the n-octanol chain minimizes discrepancies in polarity between the alcohol and hydrocarbon fuels, and minimizes phase separation challenges that can occur with short-chain alcohols and increases the long-term storage stability of ternary fuel blends. Regarding fuel characteristics, addition of n-octanol to diesel-biodiesel mixtures leads to moderate decrease in viscosity and density that will enhance spray atomization and better fuel-air mixing without leading to too much ignition delay. Unlike ethanol, n-octanol has both a higher cetane number and a lower latent heat of vaporization, which reduces both cold-start problems and excessive ignition delay constraints resulting in more controlled combustion timing. Moreover, the calorific value of n-octanol is significantly greater than that of lower alcohols and, thus, it diminishes the rise in brake-specific fuel consumption commonly experienced with alcohol-based blends. The literature on combustion studies has shown that, ternary blends of diesel, biodiesel, and n-octanol usually have stable ignition behaviour, lower pressure rise rates, and extended heat release characteristics than alcohol-diesel binary blends. In such systems, biodiesel compensates the ignition-retarding nature of the alcohols, n-octanol increases volatility and oxygen supply and leads to a balanced input of the premixed and diffusion combustion phases.

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Furthermore, multicomponent droplets that carry n-octanol could be used to enhance the effect of micro-explosion and secondary atomization because of variations in the volatility of blend components, thus enhancing evaporation, local mixing of fuels and air, and overall combustion efficiency. Regarding emission properties, ternary blends with n-octanol have been demonstrated to bring about a reduction in carbon monoxide, unburned hydrocarbons and particulate matter emissions in comparison to the traditional operation with diesel. These are largely due to the oxygenated character of n- octanol and the consequent decrease in locally rich combustion regions. The character of nitrogen oxide emissions also continues to be influenced by the blend composition and engine operating condition with certain researchers finding marginal increases with higher in-cylinder temperatures and others finding marginal decreases with delayed combustion timing and enhanced heat distribution. Comprehensively, the nitrogen oxide-particulate matter trade-off as is the case of the n-octanol based ternary blends tends to be at best more positive than that is the case of blends with lower alcohols. Although these benefits exist, the use of n-octanol as a fuel additive is limited by factors, including increased cost of production, small-scale production, and critical optimization of the proportion of blends in order to attain the desired balance between performance, emissions, and fuel economy. However, when incorporated as a third ingredient in ternary fuel systems that are based on biodiesel, n-octanol presents a viable trade-off between the stability of blends, ignition quality, and reduction of emissions. As a result, n-octanol-assisted ternary blends are a technically feasible and eco-friendly fuel concept of the future CI engines that should be considered additionally through systematic experimental research and optimization.

VIII. COMPARATIVE ANALYSIS OF REPORTED STUDIES

It is necessary to conduct a comparative evaluation of the reported experimental studies to critically analyze the usefulness of binary and ternary fuel blends of biodiesel in compression ignition (CI) engines. The available literature is diverse with respect to the choice of feedstock, type of alcohol, blends, engine type, and operating conditions and hence different levels of performance and emissions. However, there are patterns that emerge on a regular basis when there is systematic comparison of results. The vast majority of studies have been performed in terms of single cycle or multi-cylinder, four stroke CI engines and under different load conditions to allow a meaningful comparison of the brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), combustion behavior, and exhaust emission. The general characteristics of binary biodiesel-diesel blends are fewer carbon monoxide, unburnt hydrocarbons, and smoke emissions with slight rise in fuel consumption levels and a slight rise in nitrogen oxides emissions. These trends are further altered through the use of the alcohols in the ternary blends to enhance the degree of atomization and the degree of homogeneity in the combustion resulting into higher capability of reducing emissions. The benefits of performance are however very sensitive to the blend composition and type of alcohol. A summary of the major reported works is provided in Table 7, which reveals critical information on the fuel type, engine characteristics, blend ratios, performance data, and emission dynamics, thus resulting in a holistic picture of the prevailing level of research and the necessity to establish ternary blend blending.

Table: Comparative Summary of Reported Studies on Biodiesel and Ternary Fuel Blends in CI Engines

Study / Reference	Fuel Type	Engine Specifications	Blend Ratios Investigated	Performance Outcomes	Emission Trends
Agarwal et al. (2010)	Biodiesel–Diesel	Single-cylinder, 4-stroke, DI CI engine	B10, B20, B50	BTE comparable to diesel at B20; BSFC increased with blend ratio	↓ CO, ↓ HC, ↓ Smoke; ↑ NO_x
Lapuerta et al. (2008)	Biodiesel–Diesel	4-cylinder DI CI engine	B5–B30	Slight reduction in BTE; higher BSFC	↓ CO, ↓ PM; slight ↑ NO_x
Zheng et al. (2008)	Diesel–Biodiesel–Ethanol	Single-cylinder CI engine	D–B–E (up to 10% ethanol)	Improved combustion stability at low ethanol levels; BSFC ↑	↓ CO, ↓ Smoke; mixed NO_x trend
Atmanli & Yilmaz (2017)	Diesel–Biodiesel–Butanol	Single-cylinder DI CI engine	D70B20Bu10, D60B20Bu20	Comparable or slightly ↑ BTE; BSFC moderately ↑	↓ CO, ↓ HC, ↓ Smoke; marginal NO_x variation
Swarna et al. (2021)	Diesel–Hybrid Biodiesel–Alcohol	Naturally aspirated CI engine	B20H10, B20H20	Improved BTE for higher alcohol blends; reduced BSFC	↓ CO, ↓ HC, ↓ Smoke; slight ↑ NO_x

Kumar et al. (2023)	WCO Biodiesel–Alcohol (Binary/Ternary)	Single-cylinder Kirloskar CI engine	Multiple binary and ternary blends	Optimized ternary blends showed higher BTE than binary blends	Significant ↓ CO and HC; NO_x controlled
Sudarsanam et al. (2024)	Diesel–WCO Biodiesel–Pentanol (+nano-additives)	CRDI CI engine	D70B20Pe10	↑ BTE, ↓ BSFC with optimized blends	↓ CO, ↓ HC, ↓ Smoke; NO_x marginally affected
Gaur et al. (2025)	WCO & Karanja Biodiesel–Diesel	Single-cylinder CI engine	B10–B30	BTE close to diesel; BSFC ↑ with blend ratio	↓ CO, ↓ Smoke; NO_x slightly ↑

IX. IDENTIFIED RESEARCH GAPS

Although the topic of biodiesel, alcohol fuels, and ternary fuel blends in compression ignition (CI) engines has received much literature, there are still many blatant research gaps that restrain its wide-scale adoption and put it into practice. There is a significant experimental gap in the amount of research being limited to the blend ratios, restricted operating conditions, and limited-duration tests next to the full scope of load and speed of CI engines (Lapuerta et al., 2008). Also, there is generally no consistency in engine structure, injection conditions, and test regimen with experimental comparisons, cross-study validation is challenging. The drawbacks are also apparent in the combustion and emission studies because some studies mainly concentrate on the performance and controlled emission but provide little information on the in-cylinder combustion processes including detailed heat release mechanisms, pressure increase rates, periodic variability, and micro-explosion behavior which are fundamental to the long-term engine stability and durability (Heywood, 2018). Moreover, despite the existence of sophisticated diagnostic methods, their use in ternary blend studies is still intermittent and, as a consequence, the characterization of ignition chemistry and spray-combustion interactions is still not complete. Another major gap is the lack of optimization-focused methods; although limited studies use simple tools of statistics, multi-objective optimization where performance, emissions, and combustion stability are combined and implemented by means of multi-dimensional and multi-level methods like Response Surface Methodology, artificial neural networks, or hybrid models is still scarce, especially with ternary fuel systems whose interactions are highly nonlinear (Atabani et al., 2012; Demirbas, 2009). Furthermore, there is a strong demand of a geographically oriented research, in particular, in Indian context, whereby the presence of non-edible feedstocks, including Jatropha curcas, Pongamia pinnata, Mahua, and waste cooking oil, is offering its own opportunities in terms of producing sustainable fuels. The majority of the current research base its investigation on feedstocks or engine platforms that apply to the other geographical locations, and as such, its research is less applicable to Indian operating conditions that are characterized by changing fuel quality, climatic conditions, and usage patterns (Mofijur et al., 2013). The systematic experimental testing, combustion diagnostics examination, and strong optimization structures of ternary blends of Indian feedstock to address these gaps are thus crucial in the development and enhancement of the practicality and economic stability of alternative fuels in CI engines.

X. FUTURE RESEARCH DIRECTIONS

Future studies in alternative fuels to compression ignition (CI) engines ought to advance to the development of multicomponent fuel formulations and the system-level integration in order to achieve the full potential of renewable energy sources. The future in this direction is the enhancement of ternary and quaternary fuel blends that include diesel, biodiesel, higher alcohols, and other substances like vegetable oils or artificial oxygenates to provide a high degree of combustion stability, performance, and further reduction in emissions as the fuel interaction synergies (Atabani et al., 2012). These multicomponent mixtures need to be optimized in a systematic way to manage the issues concerning the stability of the blends, ignition, and energy density. Adding nano-additives to ternary blends is another up-and-coming research direction because the more recent studies suggest that nanoparticles can be used to increase heat transfer, catalytic oxidation, and spray atomization by a significant margin, which leads to better brake thermal efficiency, shorter ignition delay, and lower CO, HC, and particulate matter emissions (Jin et al., 2023; Muteeb et al., 2024). Nonetheless, the problems of nanoparticle dispersion stability, cost of production, possible health effects, and post-treatment of exhausts contradict the need to carry out additional research. Durability and reliability studies of the long-term engine performance also represent a research priority since the majority of the current studies are centered on the short-term performance and emission testing without sufficient emphasis on the injector fouling, deposition formation, lubricant degradation, material compatibility, and wear behavior related to the long-term use of biodiesel-based ternary fuels (Heywood, 2018).

Moreover, the future work to be performed should focus on incorporating the optimized ternary fuel blends and improved technologies of emissions control, including exhaust gas recirculation, diesel particulate filters, and selective catalytic reduction systems, to examine the combined fuel-engine-after-treatment interactions under the real working conditions. These combined solutions are necessary towards achieving regulatory compliance, operating reliability, and environmental sustainability to enable massive use of renewable multicomponent fuels in the contemporary CI engine uses (Demirbas, 2009; Lapuerta et al., 2008).

XI. CONCLUSION

In this review, the literature on the use of bio-diesel and alcohol fuels as well as ternary mixtures as fuels in compression ignition (CI) engines have been thoroughly reviewed, with special focus on fuel properties, combustion behavior, engine performance, emission properties and optimization strategies. According to the big results, non-edible and waste products as feedstocks to biodiesel have an immense contribution to the environment by reducing carbon monoxide, unburned hydrocarbons, and particulate matter emissions, and engine performance, when blended with petrol, was as good as conventional diesel. Alcohol fuels and, in particular, higher alcohols, including butanol and pentanol, also increase the quality of combustion (by improving atomization and mixing of air and fuel) but have low cetane number and low calorific value that negatively impact ignition stability and fuel consumption in pure form. Consensus Ternary fuel blends that incorporate diesel, biodiesel, and alcohols have become a good option in that fuel characteristics are well balanced to ensure the desired effects of fuel efficiency, lowering smoke emission, and satisfactory level of performance when optimized accordingly. Although these developments are made, a critical evaluation of the literature produced has shown that there are various shortcomings that prevent ternary blends to be used widely in CI engines. Numerous research has been focused on small-scale blend mixtures and operating conditions, and less attention has been paid to finer combustion diagnostics, long-term engine performance, and scalability across engines. Also, variation in experimental approaches, engine designs, and standards of reporting makes it difficult to compare and generalize results of different studies. The use of statistical and data-driven optimization methods like Taguchi method, Response Surface Methodology and artificial neural networks have been applied but their implementation has been in isolated cases without unified multi-objective optimization models to cater to performance, emissions and combustion stability at a given time. Moreover, studies that are region-specific, especially those based on Indian non-edible feedstock, and region-specific operating conditions are relatively few, restricting the practical usefulness of available results. Considering the above gaps, the current experimental studies are highly warranted, as it will be intended to investigate in a systematic fashion the biodiesel-based ternary fuel blends under controlled experimental conditions, detailed combustion analysis, and rigorous optimization tools. The target of the proposed study to produce credible, application-oriented findings by ensuring the engine performance is tested under a significant range of load conditions using non-edible and waste-based biodiesel feeds is expected to provide solutions to the technical and environmental issues. It is hoped that the results of this study will be helpful in the future of optimized, sustainable fuel policies to CI engines contributing to a cleaner burn, greater energy security and knowledgeable policy and engineering decisions.

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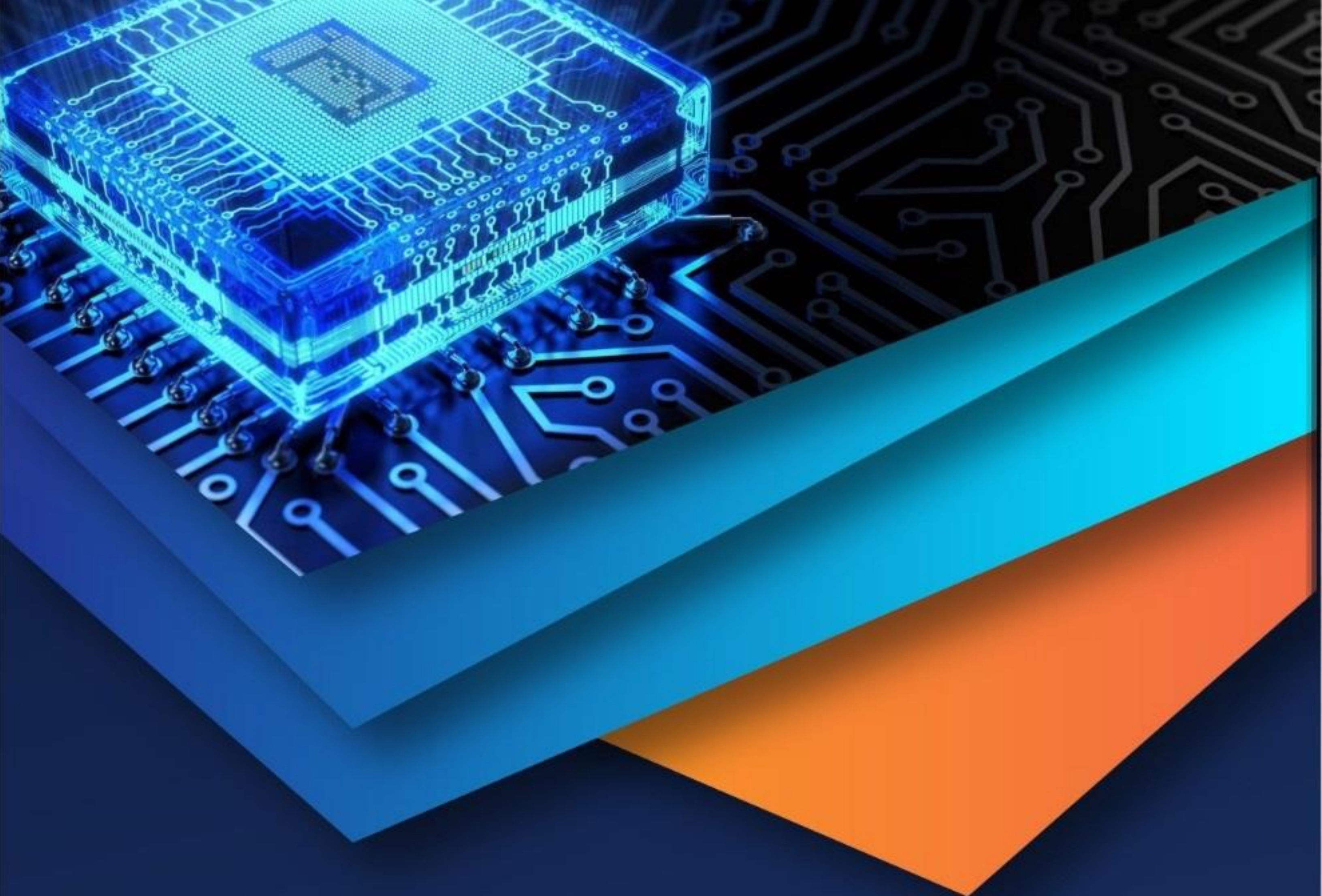

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