BIODIESEL AT THE CROSSROADS OF CLEAN ENERGY AND CANCER PREVENTION: A DOUBLE-EDGED SWORD IN SUSTAINABLE TRANSPORT

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HIGHLIGHTS

- Biodiesel reduces emissions of PM, UHC and CO linked to cancer development.
- Intrinsic oxygen content improves combustion and lowers formation of toxic pollutants.
- However, biodiesel tends to increase NO_X emission, raising secondary cancer risks.
- Health risks may also arise from production and processing stages.
- Balancing emission benefits and risks is essential for biodiesel's safe application.

GRAPHICAL ABSTRACT
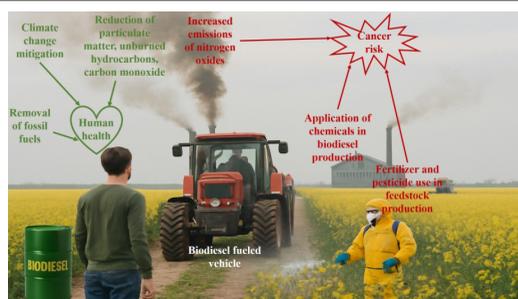
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ABSTRACT

Air pollution is a significant environmental risk for cancer, primarily driven by emissions from the transportation sector. Biodiesel, a renewable alternative to petro-diesel, has emerged as a promising strategy to reduce toxic emissions from diesel engines. This review critically examines the relationship between biodiesel use and cancer risk, evaluating its impact across key pollutants, including Particulate Matter (PM), Unburned Hydrocarbons (UHC), carbon monoxide (CO) and Nitrogen Oxides (NOx). Biodiesel combustion generally results in lower emissions of PM, UHC and CO, pollutants known to induce DNA damage, oxidative stress and chronic inflammation and all of which contribute to carcinogenesis. These benefits are attributed mainly to the fuel's intrinsic oxygen content, absence of aromatic compounds and high cetane number, which collectively promote complete combustion. However, biodiesel is consistently associated with increased NOx emissions, which can lead to the formation of secondary

carcinogenic pollutants, such as ozone and Polycyclic Aromatic Hydrocarbons (PAH). Additionally, potential cancer risks may also arise during the production and processing of biodiesel. This review uniquely integrates toxicological, environmental and life cycle perspectives to assess biodiesel's role in cancer risk, an area that remains underexplored. The paper concludes that while biodiesel significantly improves air quality and reduces several cancer-related exposures, optimising its formulation and combustion conditions are essential to minimise unintended health trade-offs. Biodiesel thus represents both an opportunity and a challenge in the broader effort to achieve clean energy and cancer prevention.

Introduction

Cancer is characterised by the dysregulated proliferation and unchecked growth of cells originating from tissues and organs of the body, ultimately resulting in organ dysfunction and mortality (AlDosari *et al*., 2023). This pathological process is often initiated by genetic lesions that affect the cell cycle, or by somatic mutations in upstream signalling pathways controlling cellular homeostasis. Despite considerable advances in biomedical research and therapeutic innovation, effective cancer treatment remains a formidable challenge (Nguyen *et al*., 2023). The intrinsic complexity of malignancies, including cellular heterogeneity, metastatic potential and resistance to conventional therapies, such as chemotherapy and radiotherapy, continues to hinder clinical outcomes. Additionally, the capacity of cancer cells to evade immune surveillance poses a significant obstacle to achieving long-term remission. These factors collectively undermine the efficacy of traditional therapeutic strategies, which frequently yield suboptimal and transient responses (Yahya & Alqadhi, 2021).

Cancer persists as one of the foremost causes of mortality globally, accounting for nearly 10 million deaths in 2020 alone. In the same year, approximately nine million new cases were diagnosed worldwide (Madsen *et al*., 2023). According to estimates from the Global Cancer Observatory of the International Agency for Research on Cancer (IARC/WHO), one in five individuals will develop cancer during their lifetime, with one in eight men and one in 11 women expected to die from the disease. Alarmingly, the global cancer burden is projected to rise by at least 67%, reaching an estimated 24 million new cases annually by 2040 (Espina *et al*., 2023). These trends underscore an urgent need for more comprehensive, targeted and proactive cancer prevention strategies.

While genetic predisposition and lifestyle choices are well-established determinants of cancer risk, growing evidence implicates environmental pollution as a significant and under-recognised contributor to the global cancer burden (Bonfiglio *et al*., 2023) (Figure 1). Chronic exposure to hazardous airborne pollutants, including ozone, sulphur dioxide, nitrogen oxides (NOx) and particulate matter (PM), has been identified as a significant risk factor for multiple cancer types (Liang *et al*., 2023). In fact, the International Agency for Research on Cancer (IARC) classifies outdoor

air pollution, specifically PM, as carcinogenic to humans (Group 1). Beyond respiratory malignancies, air pollutants may exert systemic effects through oxidative stress and endocrine disruption. Oxidative stress arises from an imbalance between the production of Reactive Oxygen Species (ROS) and the cellular capacity to neutralise or repair the resulting damage. In pulmonary tissues, one of the primary targets of airborne PM, this imbalance can trigger the release of inflammatory mediators by lung epithelial cells, initiating pathways implicated in tumourigenesis (Poulsen *et al.*, 2023) (Figure 2). Notably, some PM components also exhibit estrogenic activity, further broadening the spectrum of potential oncogenic effects.
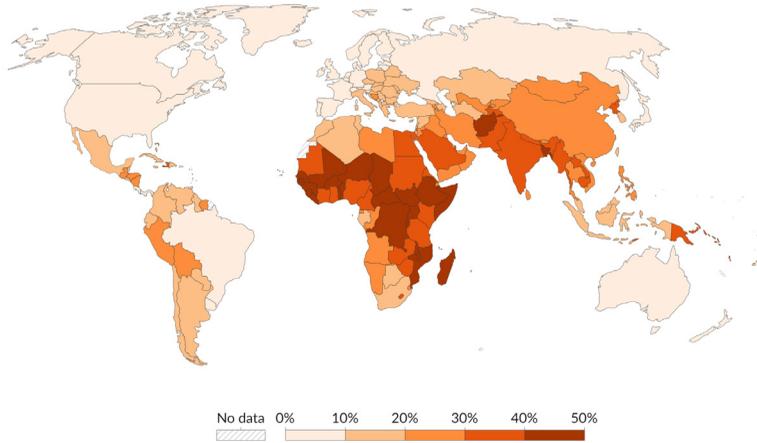

Figure 1: Share of lung cancer deaths attributed to air pollution, 2021. IHME, Global Burden of Disease (2024) – processed by Our World in Data (https://ourworldindata.org/)
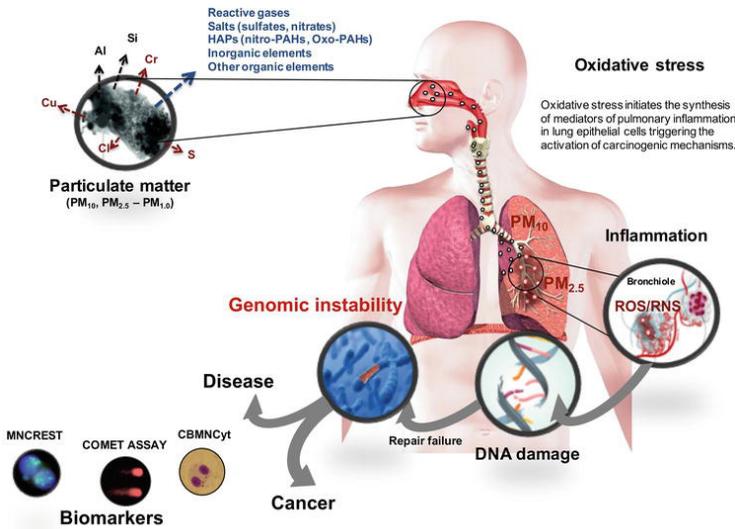

Figure 2: Main processes and biomarkers associated with genomic instability, inflammation and cancer risk induced by particulate matter exposure.
Source: Perez *et al.* (2019)

Air pollution has long commanded the attention of researchers and policymakers alike, driven by its profound implications for public health and environmental sustainability. A primary contributor to deteriorating air quality is the rapid increase in population and the growing reliance on motorised transport. Escalating vehicle ownership, the decline of non-motorised transport modes, the prevalence of aging fleets and insufficient vehicle maintenance together pose formidable challenges for regulatory agencies tasked with ensuring clean air (Kebede *et al*., 2022). Although there is a gradual shift towards low- and zero-emission technologies, this transition remains in its infancy and will require time for widespread implementation. In the meantime, internal combustion engine vehicles remain a dominant source of urban air pollutants. Recent studies have highlighted that on-road traffic is a significant source of key pollutants, including PM, NO_X and carbon monoxide (CO), particularly in rapidly urbanising regions (Dhital *et al*., 2021). These emissions not only compromise air quality but also contribute to a growing body of evidence linking traffic-related air pollution to adverse health outcomes, including cancer.

The transport sector is not only a major facilitator of global mobility, but also a significant driver of energy consumption and pollutant emission. It accounts for approximately 29% of global final energy use and consumes nearly 65% of the world's oil, positioning it as a key contributor to anthropogenic carbon emissions, which make up approximately 24% of the global total, primarily due to fuel combustion (Solaymani, 2019). The health repercussions of this environmental burden are increasingly evident. Prolonged exposure to traffic air pollution is projected to drive a continued rise in lung cancer incidence. Simultaneously, climate change is expected to intensify ultraviolet (UV) radiation exposure, leading to an increase in skin cancer cases. Gastrointestinal malignancies

are also expected to rise, influenced by factors such as industrial toxins, food insecurity and compromised water supplies.

Beyond direct health impacts, climate change threatens to deepen social vulnerabilities, particularly among economically disadvantaged populations. An estimated 100 million people are projected to fall into poverty by 2030, further exacerbating health inequities and cancer mortality in resource-limited settings. Moreover, the complex infrastructure required for comprehensive oncology care is increasingly at risk from climate-induced disruptions, including extreme weather events and global health crises such as pandemics, which may divert critical resources and attention away from cancer treatment (Zimta *et al*., 2021).

Multiple technological interventions have been explored to mitigate diesel engine emissions, including PM, such as strategies like low-temperature combustion, ultra-high fuel injection pressures and the incorporation of diesel particulate filters (Geng *et al*., 2014). Among the various emission-reduction approaches, the adoption of alternative fuels has garnered increasing global attention. Biodiesel has emerged as a promising substitute for conventional diesel. Composed of fatty acid alkyl esters produced via transesterification of triglycerides found in vegetable oils and animal fats, biodiesel offers numerous advantages over petro-diesel (Agarwal *et al*., 2015). Chemically, it is compatible with existing diesel infrastructure and can be blended with conventional diesel at virtually any ratio without requiring engine modifications (Giakoumis *et al*., 2012).

Crucially, biodiesel's intrinsic oxygen content enhances combustion efficiency during fuel spray ignition, thereby minimising incomplete combustion and PM formation (Shi *et al*., 2006; Rajak *et al*., 2018). Furthermore, the absence of aromatic compounds in biodiesel reduces its sooting tendency compared to

petro-diesel, contributing to markedly lower PM emission (Nabi *et al*., 2017). This benefit is also supported by the high cetane number of biodiesel, which shortens the ignition delay and prolongs combustion duration, facilitating more complete fuel combustion (Kumar *et al*., 2013). Notably, toxicological studies have shown that the carcinogenic potential of PM emitted from pure biodiesel combustion is approximately 94% lower than that of petro-diesel-derived PM, highlighting biodiesel's role as a cleaner and safer alternative fuel (Elling, 2001).

However, biodiesel combustion is consistently associated with elevated NOx emissions (Figure 3), primarily due to the same combustion characteristics responsible for PM reduction. The high-oxygen content of biodiesel enhances combustion efficiency, resulting in elevated in-cylinder temperatures under both premixed and diffusion-controlled combustion regimes, thereby promoting thermal NOx formation via the Zeldovich mechanism (Adi *et al*., 2009; Mueller *et al*., 2009). In addition, the lower soot concentration within the combustion chamber diminishes radiative heat loss, further increasing flame temperature and exacerbating NOx generation. Biodiesel's molecular structure also plays a role: Higher degrees of unsaturation and shorter carbon chain lengths, which correlate with increased cetane numbers, have been shown to elevate NOx emissions (Graboski *et al*., 2003). Unlike PM, NOx emissions will increase with a higher cetane number due to the shortened ignition delay, which permits an extended residence time of combustion products at elevated temperatures (Hoekman *et al*., 2012).
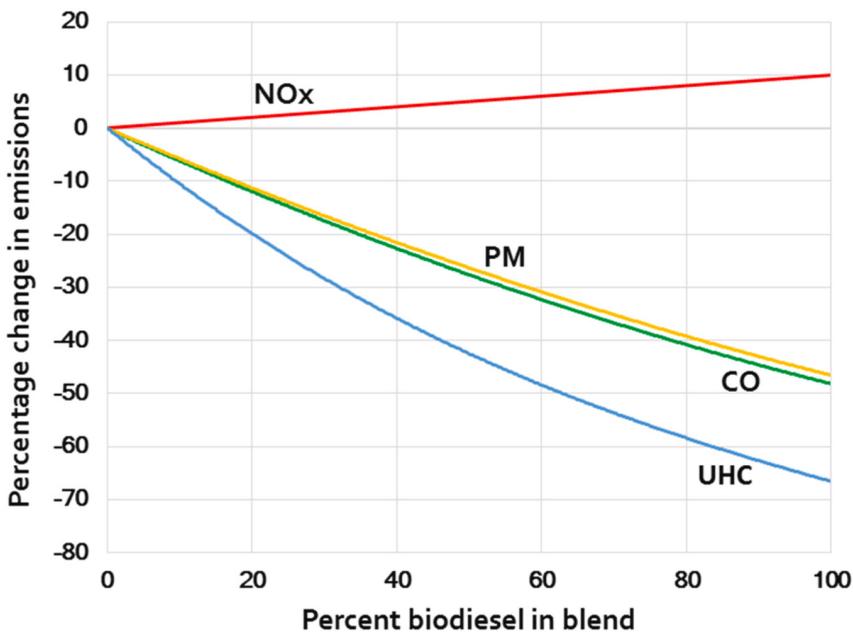

Figure 3: Average emission of diesel engines running on different biodiesel blend ratios compared with neat petro-diesel. Used with permission from Elsevier. Copyright©2022, Licence Number: 6035550713313
Source: Khalife *et al*. (2017)

Traffic-related NOx has been significantly associated with increased lung cancer in women, exhibiting a Pearson correlation coefficient of 0.33 ($p = 0.03$) (Liaw *et al*., 2008). Beyond direct carcinogenicity, NOx compounds also contribute to the formation of secondary pollutants; in the presence of hydrocarbons and sunlight, they react to generate photochemical oxidants, such as ozone and peroxyacetyl nitrate (PAN). NOx also undergoes oxidisation to form nitrogen dioxide (NO_2), a pollutant with well-documented long-term impacts on respiratory health, particularly among children (Kousoulidou *et al*., 2008). Notably, data from the Multiethnic Cohort Study involving 57,589 women revealed significant associations between NOx, NO_2, $PM_{2.5}$, and PM_{10} exposure with increased breast cancer incidence, particularly among individuals residing within 500 metres of major roads. These associations were especially pronounced among African American and Japanese American women, with NOx and NO_2 emerging as the most strongly linked pollutants (Cheng *et al*., 2020).
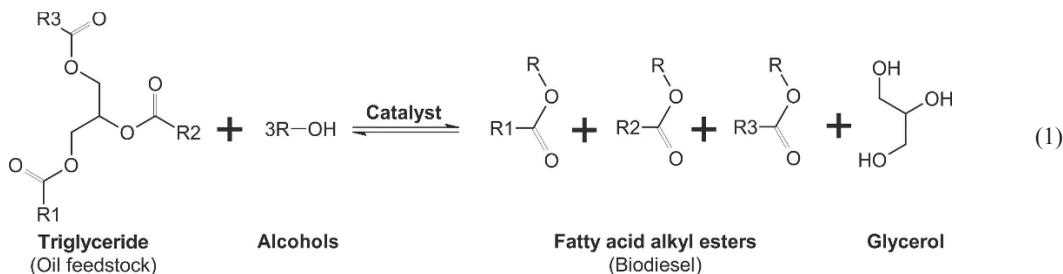
While numerous studies have explored the environmental and health impacts of biodiesel, few have critically examined its potential role in cancer risk across the entire life cycle of production and use. This review uniquely synthesises current evidence at the intersection of biodiesel emissions and carcinogenesis, providing a comprehensive evaluation of both the mitigating and risk-enhancing effects of its emission. By bridging environmental science and oncology, this work provides novel insights to inform the implementation of safer biofuels and public health strategies.

Biodiesel

Vegetable oils and animal fats represent promising renewable substitutes for petro-diesel in compression ignition engines. However, their inherently high viscosity poses significant challenges for direct application in diesel engines (Kumar *et al*., 2020). To address this limitation, several strategies have been employed, including dilution, microemulsification, pyrolysis and transesterification (Aghbashlo *et al*., 2021). Among these, pyrolysis and hydrothermal liquefaction are notable thermochemical conversion processes that transform biomass into liquid fuels, commonly known as "bio-oil" or "biocrude" (Leng *et al*., 2018). Despite their potential, these bio-oils often exhibit unfavourable properties, such as high viscosity, low volatility, elevated ash content, reduced heating value and corrosive nature. Dilution is a straightforward approach, yet it can lead to carbon deposits in the engine cylinder and incomplete combustion. Similarly, microemulsification, while offering partial improvement, still suffers from drawbacks. including limited volatility, poor stability and persistently high viscosity (Digambar Singh *et al*., 2020)

Transesterification of vegetable oil is the most widely adopted method as it effectively converts long-chain, high molecular weight triglycerides into smaller, more volatile fatty acid methyl-esters (FAMEs), commonly known as biodiesel (Nayab *et al*., 2022). As shown in Equation 1, the transesterification reaction typically involves the stoichiometric reaction of one mole of triglyceride with three moles of methanol, yielding three moles of biodiesel and one mole of glycerol as a by-product. Glycerol, the secondary product of this process, holds significant value in various applications. It is utilised in the formulation of glycerol-based fuels and the cosmetics industry, and has recently gained attention for its potential use in water electrolysis systems as an alternative to the oxygen evolution reaction (Oyekunle *et al*., 2023).

Triglyceride + Alcohols → Fatty acid alkyl esters + Glycerol

(1)

Triglyceride (Oil feedstock) **Alcohols** **Fatty acid alkyl esters** (Biodiesel) **Glycerol**

Biodiesel, derived from biomass, is a renewable energy source with the potential to provide continuous and sustainable energy supply. Notably, the production of biodiesel, particularly second-generation biodiesel synthesised from domestic and industrial waste, can contribute to environmental preservation (Mahlia *et al*., 2020). In contrast to conventional diesel production, biodiesel synthesis generates minimal to no waste. Chemically, biodiesel typically contains 10% to 11% oxygen, trace amounts of nitrogen and is virtually free of sulphur (Demirbas, 2007). The intrinsic oxygen content enhances engine combustion efficiency and lowers the oxidation potential of the fuel (Mofijur *et al*., 2014). Furthermore, the combustion of biodiesel significantly reduces harmful emissions, with total unburned hydrocarbons (UHCs) and polycyclic aromatic hydrocarbons (PAHs) decreasing by approximately 90% and 75% to 90%, respectively, compared with conventional diesel emissions (Demirbas, 2007).

Beyond its emissions benefits, biodiesel offers superior lubricating properties, ensuring smoother engine performance, reducing component wear and extending engine life (Ong *et al*., 2019). Its profile as a renewable, biodegradable, non-toxic, non-flammable and environmentally friendly fuel makes it an ideal candidate for addressing the growing demand for cleaner energy sources (Hosseinzadeh-Bandbafha *et al*., 2018). These qualities not only underscore biodiesel's practical advantages. but also its role in building a sustainable energy future. Remarkably, the vision of using vegetable oils as engine fuel dates back to 1893, when Rudolf Diesel, the inventor of the diesel engine, foresaw their potential in powering agricultural machinery. His foresight materialised in 1900, when he successfully ran an engine on peanut oil at the World Exhibition in Paris. This early innovation laid the groundwork for future developments, including the world's first industrial biodiesel production process, developed by Brazilian scientist Expedito Parente in 1977. Just over a decade later, in 1989, Austria launched the first biodiesel plant using rapeseed oil, marking a pivotal moment in the global shift toward bio-based fuels (Mathew *et al*., 2021). Top of Form

According to the EASAC (2012) report, biodiesel is broadly categorised into first, second and third generations, based primarily on the origin of the feedstocks. A fourth generation, still in its infancy, emerges from cutting-edge synthetic biology and genetic engineering, which holds exciting promise for the future (Digambar Singh *et al*., 2020). First-generation biodiesel, derived from edible crops, such as palm oil, soybean, rapeseed and corn, had sparked both enthusiasm and ethical concerns. While it addresses growing energy demands, its reliance on food-based feedstocks make it a direct competitor to global food demand, driving up food prices and straining food security in low-income countries (Kiehbadroudinezhad, Merabet, *et al*., 2023). This "food vs fuel" dilemma has galvanised scientific efforts to develop sustainable biofuels

as innovative solutions to balance energy needs with humanitarian and environmental priorities.

Second-generation biodiesel is derived from feedstocks that are unsuitable for human consumption (Kiehbadroudinezhad, Hosseinzadeh-Bandbafha, *et al*., 2023). Sources like plant oils and agricultural waste are processed to produce a more sustainable form of biodiesel. Notable examples include oils from neem, jatropha, nagchampa, karanja, oil nut (*Calophyllum inophyllum*), rubber seeds and the Mahua tree (*Mahua indica*) (Takase *et al*., 2015). This generation of biodiesel offers several compelling advantages: It is more eco-friendly, significantly reduces production costs, avoids competition with the global food supply and demands less arable land for cultivation. As such, second-generation biodiesel presents a promising solution to the food-versus-fuel dilemma while contributing to a more balanced and equitable energy landscape (Digambar Singh *et al*., 2020).

Building on this momentum, third-generation biodiesel takes innovation a step further by utilising microalgae as its primary feedstock (Jacob *et al*., 2021). Unlike traditional crops, algae can thrive in saline water, wastewater, or even on non-arable land, and possess a remarkably high lipid content, making them a highly efficient fuel source (Tahir *et al*., 2024). Their rapid growth rate and ability to capture carbon dioxide further enhance their appeal, positioning algal biodiesel as a scalable, environmentally responsible solution. Moreover, microalgae can be cultivated year-round and tailored to produce specific biodiesel profiles, offering both versatility and sustainability. Despite current challenges in scaling up and cost-effectiveness, third-generation biodiesel holds significant promise for transforming the bioenergy landscape.

Biodiesel's Role in Cancer Risk

Biodiesel, Particulate Matter and Cancer Risk

Fine and ultrafine PM can be inhaled and deposited in the lungs, where it evades mucociliary clearance and induces localised and systemic effects (Mack *et al*., 2020). PM is a complex mixture that often carries adsorbed carcinogenic compounds, such as PAH (Larrea Valdivia *et al*., 2020), Volatile Organic Compounds (VOC) (Zhang *et al*., 2021) and transition metals (Sørensen *et al*., 2005). These components can generate reactive oxygen species (ROS), inducing oxidative stress that damages key cellular macromolecules, especially DNA.

Figure 4 illustrates the oxidative stress-related pathways triggered by PM, as reported in recent literature (Vilas-Boas *et al*., 2024). In parallel, PM exposure activates pro-inflammatory signalling pathways (e.g., NF-κB, MAPK), leading to chronic inflammation (Li *et al*., 2020), which in turn contributes to a pro-carcinogenic microenvironment by promoting cellular proliferation, inhibiting apoptosis, and increasing angiogenesis. Epigenetic alterations, including DNA methylation and histone modification, have also been observed in response to PM exposure (Shukla *et al*., 2019), suggesting additional mechanisms by which PM can dysregulate gene expression and facilitate oncogenesis. Collectively, these processes may initiate and promote the development of malignancies, particularly lung cancer, in populations with prolonged exposure.
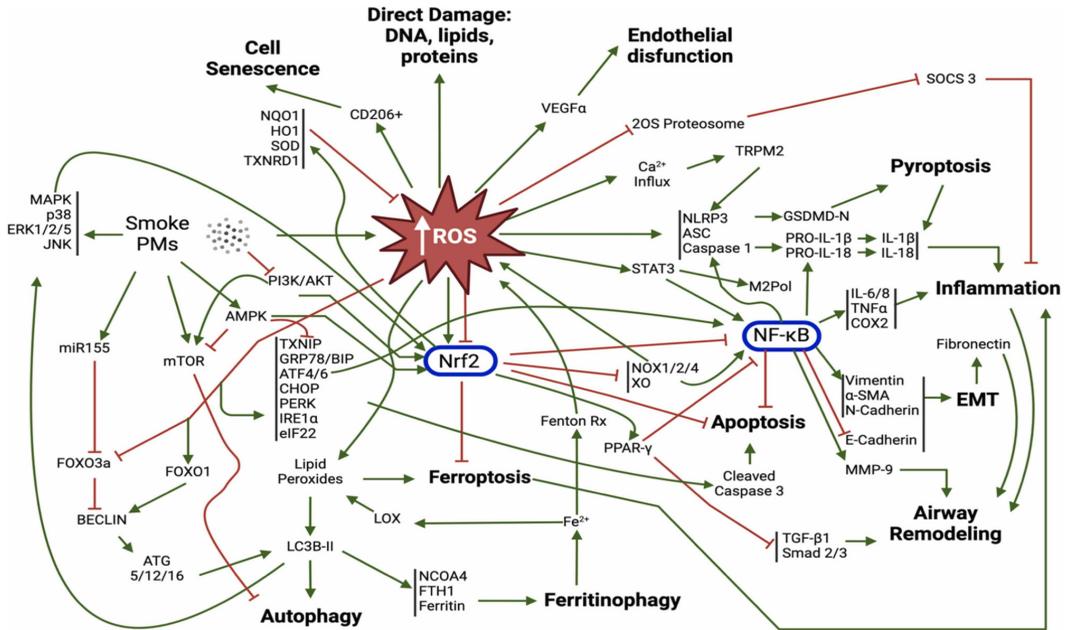
Figure 4: Oxidative stress pathways are triggered by exposure to particulate matter. A schematic representation of key molecular pathways activated by fine and ultrafine particulate matter, highlighting the role of reactive oxygen species (ROS) in oxidative stress, DNA damage, inflammation and carcinogenesis. Source: Vilas-Boas *et al.* (2024)

PM is widely recognised as one of the most hazardous pollutants emitted from diesel engines. These fine particles are predominantly formed in the fuel-rich zones of the combustion chamber, especially under high temperatures and pressures near the core of the fuel spray (Pang *et al.*, 2006). However, an increasingly compelling body of research demonstrates that biodiesel can significantly mitigate PM emissions compared with conventional diesel (Reyes *et al.*, 2006; Kumar *et al.*, 2013; Devendra Singh *et al.*, 2015; Rajak *et al.*, 2018).

One of the most promising aspects of biodiesel lies in its inherent oxygen content. Oxygen facilitates more complete combustion by enriching the pyrolysis region of the fuel spray, thereby reducing soot formation and leading to cleaner exhaust (Shi *et al.*, 2006). Essentially, biodiesel promotes a more efficient combustion process, thereby minimising the conditions under which PM is typically formed (Rajak *et al.*, 2018). Furthermore, biodiesel contains negligible aromatic compounds, unlike petro-diesel, which substantially lowers its sooting tendency (Nabi *et al.*, 2017). The higher cetane number further supports this advantage by shortening ignition delay and extending the combustion duration, ensuring a smoother and complete burn (Kumar *et al.*, 2013).

Therefore, since PM is a significant carrier of carcinogenic compounds, the reduction of its formation will directly lower the inhalation exposure to these harmful substances. By minimising the generation of ROS and inflammation associated with PM, biodiesel combustion may play a role in the reduction of DNA damage, mutagenesis and other cancer-related processes.

Biodiesel, Unburned Hydrocarbons and Cancer Risk

UHC represent a hidden yet serious public health concern. Released during the incomplete combustion, UHC comprise a complex mix of VOC (Dhamodaran *et al*., 2023), many of which are well-established carcinogens. Notably, substances like benzene, 1,3-butadiene, toluene and xylene (Kumar *et al*., 2020) are among the most carcinogenic organic compounds.

While some studies have noted a rise in UHC emission with biodiesel blends, often linked to its high viscosity, density and low energy content, a growing body of research has also highlighted the opposite trend. Numerous studies have demonstrated that biodiesel can significantly mitigate UHC emission (Altaie *et al*., 2015; Man *et al*., 2016; Bueno *et al*., 2017; Manigandan *et al*., 2019). This reduction is primarily attributed to the intrinsic oxygen content of biodiesel, which enhances post-flame oxidation and increases flame speed, particularly in fuel-rich zones (Fattah *et al*., 2014). Such properties promote more complete combustion and facilitate the oxidation of hydrocarbon intermediates, thus lowering UHC output. The absence of aromatic hydrocarbons in biodiesel further suppresses UHC formation by limiting the generation of persistent organic pollutants (Giakoumis *et al*., 2012). Additionally, the high cetane number advances combustion phasing, contributing to more thorough fuel oxidation (Kwanchareon *et al*., 2007). Therefore, by lowering UHC emissions, this will reduce the quantity of carcinogenic VOC into the atmosphere.

Biodiesel, Carbon Monoxide and Cancer Risk

Unlike classical carcinogens, CO is not directly genotoxic and does not initiate cancer. However, chronic exposure reduces the efficiency of oxygen delivery to tissues and organs as the gas binds to haemoglobin with an affinity of 200 to 300 times more than oxygen (McGrath *et al*.,

1993; Patel *et al*., 2023). The resulting hypoxic condition can activate hypoxia-inducible factors (HIFs) (Pawlus *et al*., 2013), which affect genes involved in angiogenesis, cell survival and metabolic adaptation — processes that support tumour growth and progression. Furthermore, chronic CO exposure can exacerbate oxidative stress, also an established hallmark of tumour progression. Emerging evidence suggests that CO, particularly when endogenously produced via heme oxygenase activity, may contribute to a pro-oxidant microenvironment in aerobic mammalian cells (Piantadosi, 2008). This environment not only disrupts redox homeostasis, but also triggers signalling cascades associated with ROS generation, potentially fostering conditions favourable for tumour development and progression.

In the context of biodiesel combustion, few studies have reported increased CO emission due to poor atomisation and incomplete combustion linked to biodiesel's high viscosity and density (Nalgundwar *et al*., 2016; Bueno *et al*., 2017). A more consistent body of evidence supports a CO-reducing effect. Numerous studies have demonstrated that biodiesel's inherent oxygen content enhances combustion efficiency, enabling the more complete oxidation of carbon species and thereby significantly reducing CO emission (Özener *et al*., 2014; Al-lwayzy *et al*., 2017; Dhamodaran *et al*., 2017; Pandian *et al*., 2017; Manigandan *et al*., 2019). This improved combustion profile not only supports cleaner air, but may also reduce the cumulative cancer risk associated with chronic exposure to CO and other co-emitted toxicants.

Biodiesel, Nitrogen Oxides and Cancer Risk

NOx, primarily comprising nitric oxide (NO) and nitrogen dioxide (NO_2), are reactive gases produced during high-temperature combustion processes, such as those in vehicle engines. Although NOx compounds are not classified as primary carcinogens, they contribute to cancer

risk through indirect mechanisms. NO_2 is a strong oxidant that can induce oxidative stress and lower lung tissue antioxidant defences (Raz-Maman *et al*., 2025). These conditions promote a tumour-supportive microenvironment by enhancing cell proliferation, inhibiting apoptosis and generating reactive oxygen and nitrogen species (ROS/RNS) that can damage DNA. Furthermore, NOx is involved in the atmospheric formation of ozone and secondary PM, which contains PAH and heavy metals. Long-term exposure to NOx, especially in urban and traffic-dense environments, has been epidemiologically linked to an increased incidence of lung cancer and other respiratory diseases. Thus, while NOx may not directly initiate carcinogenesis, it plays a significant contributory role in the risk of air pollution-related cancers.

NOx represents the most deleterious pollutants emitted from diesel engines, with profound implications for both human health and the environment (Palash *et al*., 2013). Based on Agarwal *et al*. (2006), NOx formation is inherently linked to the elevated flame temperatures typical of diesel combustion in oxygen and nitrogen-rich conditions. Intriguingly, while biodiesel is often hailed for its sustainability benefits, numerous studies, such as those by Mosarof *et al*. (2016), Aldhaidhawi *et al*. (2017) and Manigandan *et al*. (2019) suggest that it can exacerbate NOx emissions. This paradox stems from the inherent properties of biodiesel: Its structural oxygen content enhances combustion completeness, elevating in-cylinder temperatures (Chen *et al*., 2018).

The higher degree of unsaturation in biodiesel fuels has similarly been implicated in further temperature elevation during combustion (Ban-Weiss *et al*., 2007). Moreover, the oxygenated nature of biodiesel reduces soot formation, when compared when petro-diesel, will inadvertently raise flame temperatures by diminishing radiative heat losses (Mueller *et al*., 2009). Additionally, its shortened ignition delay due to high cetane number will increase the residence time of reactants and combustion intermediates at high temperatures (Senthil *et al*., 2019). As a result, despite its renewable nature, biodiesel's tendency to elevate NOx emissions may indirectly heighten long-term cancer risk in populations exposed to traffic-related air pollution.

Biodiesel Production and Cancer Risk

In terms of hazards, the life cycle of biodiesel reveals hidden health risks, particularly in relation to carcinogenic exposure. At the feedstock level, particularly in first-generation crops, the intensive use of pesticides and fertilisers can release hazardous agrochemicals, such as atrazine and glyphosate, both of which have been linked to carcinogenicity (Figure 5). During oil extraction and processing, workers may be exposed to VOC and PM, including methanol and formaldehyde, well-known for their toxic and potentially carcinogenic properties. Toxic vapours are also produced in transesterification, where vegetable oils are reacted with alcohols and a base catalyst to produce biodiesel esters and glycerol. Moreover, inadequate purification may leave residual chemicals in the final product, further increasing potential exposure and health concerns. These overlooked stages warrant critical attention when assessing the full carcinogenic footprint of biodiesel production.

Finally, biodiesel has the potential to mitigate climate change, a global crisis increasingly linked to cancer risk. Rising temperatures accelerate the formation of ground-level ozone and prolong the persistence of airborne pollutants like $PM_{2.5}$ and PAH (Ebi *et al*., 2008). Wildfires, intensified by heatwaves and prolonged droughts, release a complex cocktail of toxic compounds associated with lung cancer and brain tumours (Korsiak *et al*.,

2022). Recent studies show that people living within 50 km of wildfires had a 4.9% higher risk of lung cancer and a 10% higher risk of brain tumours compared to those unexposed (Korsiak *et al*., 2022). Additionally, shifting climate patterns are expanding the range of pathogens and vectors, increasing the incidence of virus-related cancers, such as those linked to hepatitis B and C (Ribeiro *et al*., 2024).
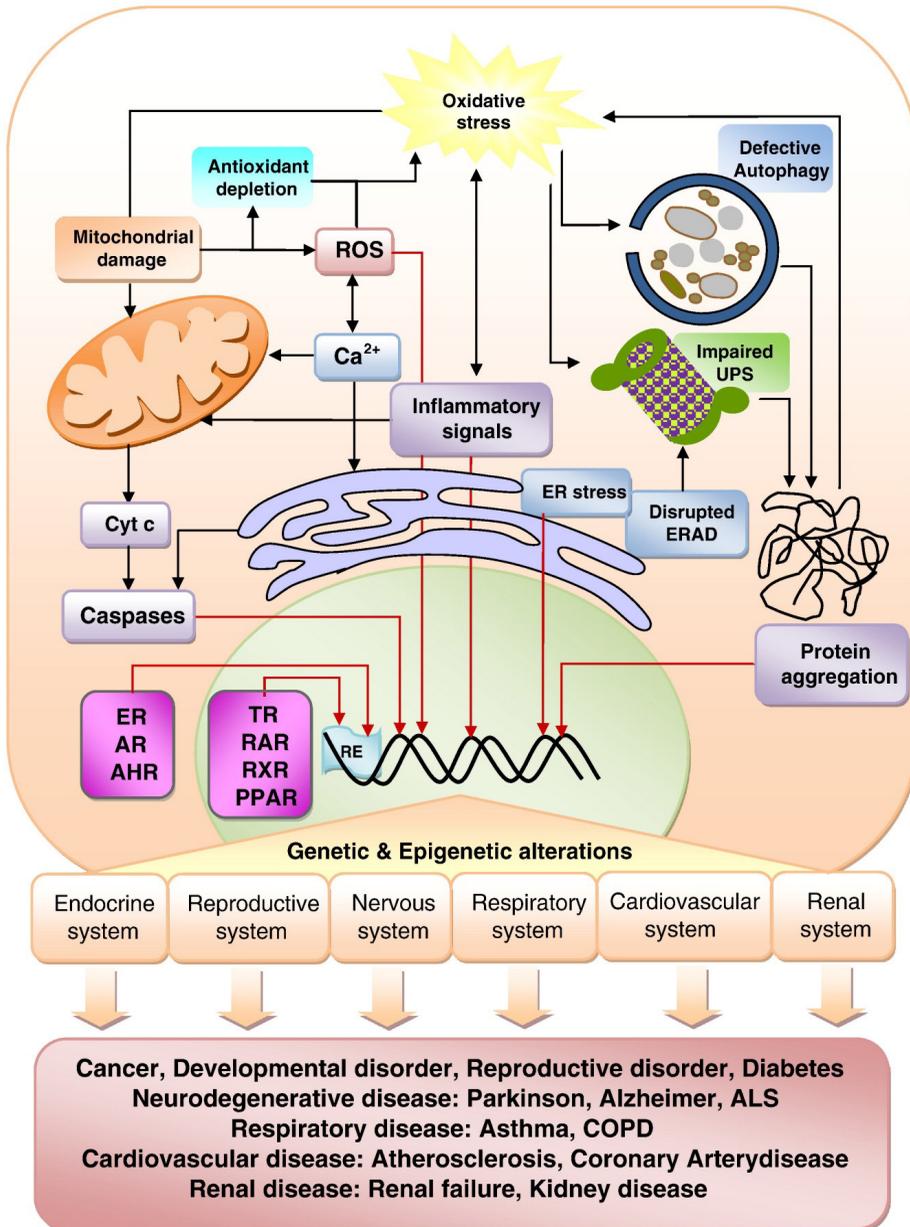

Figure 5: A simplified model for mechanisms by which pesticides induce and develop chronic disease. Used with permission from Elsevier. Copyright©2022, Licence Number: 6035551148807
Source: Mostafalou *et al*. (2013)

Conclusions

This review underscores the dualistic role of biodiesel in shaping the landscape of environmental carcinogenesis. As a renewable and clean-burning alternative to petro-diesel, biodiesel offers significant potential to mitigate key air pollutants, particularly PM, UHC and CO, which may be directly or indirectly implicated in cancer development. Its intrinsic oxygen content, higher cetane number and lack of aromatic hydrocarbons contribute to more complete combustion, reducing emissions of several compounds known to induce oxidative stress, chronic inflammation, DNA damage and tumour-promoting microenvironments. These features make biodiesel a promising ally in efforts to reduce the cancer burden associated with traffic-related air pollution.

However, the widespread adoption of biodiesel is not without challenges. Elevated NOx emissions, driven by biodiesel's combustion characteristics, present a persistent concern, given NOx's role in the formation of secondary pollutants such as ozone and carcinogenic particulate matter. Additionally, potential health risks may arise across biodiesel's life cycle, including exposure to hazardous chemicals during feedstock cultivation, fuel processing and combustion, particularly in the absence of stringent emission controls and industrial safety protocols.

Ultimately, the transition toward biodiesel and other biofuels must be carefully managed within a broader framework of clean fuel innovation, emissions regulation and public health protection. When integrated with cleaner engine technologies, advanced after-treatment systems, and sustainable feedstock selection, biodiesel can serve as a viable tool not only for reducing carbon emissions and addressing climate change, but also for lowering the incidence of environmentally linked cancers. As global energy systems evolve in response to climate and health imperatives, biodiesel stands at a critical intersection of renewable energy advancement and cancer prevention strategy. To this end, we recommend that future research prioritise comprehensive toxicological evaluations of biodiesel life cycle and the formulation of clear regulatory standards to balance the environmental benefits of biodiesel with its potential health impacts.

Acknowledgements

References

Adi, G., Hall, C., Snyder, D., Bunce, M., Satkoski, C., Kumar, S., Garimella, P., Stanton, D., & Shaver, G. (2009). Soy-biodiesel impact on NOx emissions and fuel economy for diffusion-dominated combustion in a turbo-diesel engine incorporating exhaust gas recirculation and common rail fuel injection. *Energy and Fuels*, *23*(12), 5821-5829. https://doi.org/10.1021/ef9006609

Agarwal, A. K., Gupta, T., Shukla, P. C., & Dhar, A. (2015). Particulate emissions from biodiesel fuelled CI engines. *Energy Conversion and Management*, *94*, 311-330. https://doi.org/10.1016/j.enconman.2014.12.094

Agarwal, D., Sinha, S., & Agarwal, A. K. (2006). Experimental investigation of control of NOx emissions in biodiesel-fueled

compression ignition engine. *Renewable Energy*, *31*(14), 2356-2369 https://doi.org/10.1016/j.renene.2005.12.003.

Aghbashlo, M., Peng, W., Tabatabaei, M., Kalogirou, S. A., Soltanian, S., Hosseinzadeh-Bandbafha, H., Mahian, O., & Lam, S. S. (2021). Machine learning technology in biodiesel research: A review. *Progress in Energy and Combustion Science*, *85*, Article 100904. https://doi.org/10.1016/j.pecs.2021.100904

Al-lwayzy, S. H., & Yusaf, T. (2017). Diesel engine performance and exhaust gas emissions using Microalgae Chlorella protothecoides biodiesel. *Renewable Energy*, *101*, 690-701. https://doi.org/10.1016/j.renene.2016.09.035

Aldhaidhawi, M., Chiriac, R., & Badescu, V. (2017). Ignition delay, combustion and emission characteristics of Diesel engine fueled with rapeseed biodiesel - A literature review. *Renewable and Sustainable Energy Reviews*, *73*, 178-186. Retrieved from https://doi.org/10.1016/j.rser.2017.01.129

AlDosari, S. M., Banawas, S., Ghafour, H. S., Tlili, I., & Le, Q. H. (2023). Drug release using nanoparticles in the cancer cells on 2-D materials in order to target drug delivery: A numerical simulation via molecular dynamics method. *Engineering Analysis with Boundary Elements*, *148*, 34-40. https://doi.org/10.1016/j.enganabound.2022.12.020

Altaie, M. A. H., Janius, R. B., Rashid, U., Taufiq-Yap, Y. H., Yunus, R., Zakaria, R., & Adam, N. M. (2015). Performance and exhaust emission characteristics of direct-injection diesel engine fueled with enriched biodiesel. *Energy Conversion and Management*, *106*, 365-372. https://doi.org/10.1016/j.enconman.2015.09.050

Ban-Weiss, G. A., Chen, J. Y., Buchholz, B. A., & Dibble, R. W. (2007). A numerical investigation into the anomalous slight NO x increase when burning biodiesel; a new (old) theory. *Fuel Processing Technology*, *88*(7), 659-667. https://doi.org/10.1016/j.fuproc.2007.01.007

Bonfiglio, R., Scimeca, M., & Mauriello, A. (2023). The impact of environmental pollution on cancer: Risk mitigation strategies to consider. *Science of The Total Environment*, *902*, Article 166219. https://doi.org/10.1016/j.scitotenv.2023.166219

Bueno, A. V., Pereira, M. P. B., de Oliveira Pontes, J. V., de Luna, F. M. T., & Cavalcante Jr, C. L. (2017). Performance and emissions characteristics of castor oil biodiesel fuel blends. *Applied Thermal Engineering*, *125*, 559-566. https://doi.org/10.1016/j.applthermaleng.2017.06.114

Chen, H., Xie, B., Ma, J., & Chen, Y. (2018). NOx emission of biodiesel compared to diesel: Higher or lower? *Applied Thermal Engineering*, *137*, 584-593. https://doi.org/10.1016/j.applthermaleng.2018.04.022

Cheng, I., Tseng, C., Wu, J., Yang, J., Conroy, S. M., Shariff Marco, S., Li, L., Hertz, A., Gomez, S. L., & Le Marchand, L. (2020). Association between ambient air pollution and breast cancer risk: the multiethnic cohort study. *International Journal of Cancer*, *146*(3), 699-711. https://doi.org/10.1002/ijc.32308

Demirbas, A. (2007). Importance of biodiesel as transportation fuel. *Energy Policy*, *35*(9), 4661-4670. https://doi.org/10.1016/j.enpol.2007.04.003

Dhamodaran, G., Esakkimuthu, G. S., Palani, T., & Sundaraganesan, A. (2023). Reducing gasoline engine emissions using novel bio-based oxygenates: A review. *Emergent*

Materials, *6*(5), 1393-1413. https://doi.org/10.1007/s42247-023-00470-7

Dhamodaran, G., Krishnan, R., Pochareddy, Y. K., Pyarelal, H. M., Sivasubramanian, H., & Ganeshram, A. K. (2017). A comparative study of combustion, emission, and performance characteristics of rice-bran-, neem-, and cottonseed-oil biodiesels with varying degree of unsaturation. *Fuel*, *187*, 296-305. https://doi.org/10.1016/j.fuel.2016.09.062

Dhital, N. B., Wang, S.-X., Lee, C.-H., Su, J., Tsai, M.-Y., Jhou, Y.-J., & Yang, H.-H. (2021). Effects of driving behavior on real-world emissions of particulate matter, gaseous pollutants and particle-bound PAHs for diesel trucks. *Environmental Pollution*, *286*, 117292. https://doi.org/10.1016/j.envpol.2021.117292

Ebi, K. L., & McGregor, G. (2008). Climate change, tropospheric ozone and particulate matter, and health impacts. *Environmental Health Perspectives*, *116*(11), 1449-1455. https://doi.org/10.1289/ehp.11463

Elling, J. (2001). *Biodiesel Offers Fleets a Better Alternative to Petroleum Diesel: Clean cities technical assistance fact sheet*. National Renewable Energy Lab. (NREL), Golden, CO (United States).

Espina, C., Feliu, A., Maza, M., Almonte, M., Ferreccio, C., Finck, C., Herrero, R., Dommarco, J. R., de Almeida, L. M., & Arrossi, S. (2023). Latin America and the Caribbean code against cancer 1st edition: 17 cancer prevention recommendations to the public and to policy-makers (World Code Against Cancer Framework). *Cancer Epidemiology*, *86*, Article 102402. https://doi.org/10.1016/j.canep.2023.102402

Fattah, I. M. R., Masjuki, H. H., Kalam, M. A., Mofijur, M., & Abedin, M. J. (2014). Effect of antioxidant on the performance and emission characteristics of a diesel engine fueled with palm biodiesel blends. *Energy Conversion and Management*, *79*, 265-272. https://doi.org/10.1016/j.enconman.2013.12.024

Geng, P., Yao, C., Wei, L., Liu, J., Wang, Q., Pan, W., & Wang, J. (2014). Reduction of PM emissions from a heavy-duty diesel engine with diesel/methanol dual fuel. *Fuel*, *123*, 1-11. https://doi.org/10.1016/j.fuel.2014.01.056

Giakoumis, E. G., Rakopoulos, C. D., Dimaratos, A. M., & Rakopoulos, D. C. (2012). Exhaust emissions of diesel engines operating under transient conditions with biodiesel fuel blends. *Progress in Energy and Combustion Science*, *38*(5), 691-715. https://doi.org/10.1016/j.pecs.2012.05.002

Graboski, M. S., McCormick, R. L., Alleman, T. L., & Herring, A. M. (2003). The effect of biodiesel composition on engine emissions from a DDC series 60 diesel engine. In National Renewable Energy Laboratory (Report No: NREL/SR-510-31461). National Renewable Energy Laboratory (Report No: NREL/SR-510-31461).

Hoekman, S. K., & Robbins, C. (2012). Review of the effects of biodiesel on NOx emissions. *Fuel Processing Technology*, *96*, 237-249. https://doi.org/10.1016/j.fuproc.2011.12.036

Hosseinzadeh-Bandbafha, H., Tabatabaei, M., Aghbashlo, M., Khanali, M., & Demirbas, A. (2018). A comprehensive review on the environmental impacts of diesel/biodiesel additives. *Energy Conversion and Management*, *174*, 579-614. https://doi.org/10.1016/j.enconman.2018.08.050

Jacob, A., Ashok, B., Alagumalai, A., Chyuan, O. H., & Le, P. T. K. (2021). Critical review on third generation micro algae biodiesel production and its feasibility as future bioenergy for IC engine

applications. *Energy Conversion and Management*, *228*, Article 113655. https://doi.org/10.1016/j.enconman.2020.113655

Kebede, L., Tulu, G. S., & Lisinge, R. T. (2022). Diesel-fueled public transport vehicles and air pollution in Addis Ababa, Ethiopia: Effects of vehicle size, age and kilometers travelled. *Atmospheric Environment: X, 13*, Article 100144. https://doi.org/10.1016/j.aeaoa.2021.100144

Khalife, E., Tabatabaei, M., Demirbas, A., & Aghbashlo, M. (2017). Impacts of additives on performance and emission characteristics of diesel engines during steady state operation. *Progress in Energy and Combustion Science*, *59*, 32-78. https://doi.org/10.1016/j.pecs.2016.10.001

Kiehbadroudinezhad, M., Hosseinzadeh-Bandbafha, H., Pan, J., Peng, W., Wang, Y., Aghbashlo, M., & Tabatabaei, M. (2023). The potential of aquatic weed as a resource for sustainable bioenergy sources and bioproducts production. *Energy*, *278*, Article 127871. https://doi.org/10.1016/j.energy.2023.127871

Kiehbadroudinezhad, M., Merabet, A., & Hosseinzadeh-Bandbafha, H. (2023). A life cycle assessment perspective on biodiesel production from fish wastes for green microgrids in a circular bioeconomy. *Bioresource Technology Reports*, *21*, Article 101303. https://doi.org/10.1016/j.biteb.2022.101303

Korsiak, J., Pinault, L., Christidis, T., Burnett, R. T., Abrahamowicz, M., & Weichenthal, S. (2022). Long-term exposure to wildfires and cancer incidence in Canada: A population-based observational cohort study. *The Lancet Planetary Health*, *6*(5), e400–e409. https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(22)00067-5/fulltext#

Kousoulidou, M., Ntziachristos, L., Mellios, G., & Samaras, Z. (2008). Road-transport emission projections to 2020 in European urban environments. *Atmospheric Environment*, *42*(32), 7465-7475. https://doi.org/10.1016/j.atmosenv.2008.06.002

Kumar, D., & Singh, B. (2020). Effect of winterization and plant phenolic-additives on the cold-flow properties and oxidative stability of Karanja biodiesel. *Fuel*, *262*, Article 116631. https://doi.org/10.1016/j.fuel.2019.116631

Kumar, N., Varun, & Chauhan, S. R. (2013). Performance and emission characteristics of biodiesel from different origins: A review. *Renewable and Sustainable Energy Reviews*, *21*, 633-658. https://doi:10.1016/j.rser.2013.01.006

Kumar, R. P., Kashyap, P., Kumar, R., Pandey, A. K., Kumar, A., & Kumar, K. (2020). Cancer and non-cancer health risk assessment associated with exposure to non-methane hydrocarbons among roadside vendors in Delhi, India. *Human and Ecological Risk Assessment: An International Journal*, *26*(5), 1285-1299. https://doi.org/10.1080/10807039.2019.1570077

Kwanchareon, P., Luengnaruemitchai, A., & Jai-In, S. (2007). Solubility of a diesel–biodiesel–ethanol blend, its fuel properties, and its emission characteristics from diesel engine. *Fuel*, *86*(7-8), 1053-1061. https://doi.org/10.1016/j.fuel.2006.09.034

Larrea Valdivia, A. E., Reyes Larico, J. A., Salcedo Peña, J., & Wannaz, E. D. (2020). Health risk assessment of Polycyclic Aromatic Hydrocarbons (PAHs) adsorbed in PM 2.5 and PM 10 in a region of Arequipa, Peru. *Environmental Science and Pollution Research*, *27*, 3065-3075. https://doi.org/10.1007/s11356-019-07185-5

Leng, L., Li, H., Yuan, X., Zhou, W., & Huang, H. (2018). Bio-oil upgrading by emulsification/microemulsification: A review. *Energy*, *161*, 214-232. https://doi.org/10.1016/j.energy.2018.07.117

Li, J., Wang, T., Wang, Y., Xu, M., Zhang, L., Li, X., Liu, Z., Gao, S., Jia, Q., & Fan, Y. (2020). Particulate matter air pollution and the expression of microRNAs and pro-inflammatory genes: association and mediation among children in Jinan, China. *Journal of Hazardous Materials*, *389*, Article 121843. https://doi.org/10.1016/j.jhazmat.2019.121843

Liang, H., Zhou, X., Zhu, Y., Li, D., Jing, D., Su, X., Pan, P., Liu, H., & Zhang, Y. (2023). Association of outdoor air pollution, lifestyle, genetic factors with the risk of lung cancer: A prospective cohort study. *Environmental Research*, *218*, Article 114996. https://doi.org/10.1016/j.envres.2022.114996

Liaw, Y.-P., Ting, T.-F., Ho, K.-K., & Yang, C.-F. (2008). Cell type specificity of lung cancer associated with air pollution. *Science of the Total Environment*, *395*(1), 23-27. https://doi.org/10.1016/j.scitotenv.2008.01.053

Mack, S. M., Madl, A. K., & Pinkerton, K. E. (2020). Respiratory health effects of exposure to ambient particulate matter and bioaerosols. *Comprehensive Physiology*, *10*(1), 1-20. https://doi.org/10.1002/j.2040-4603.2020.tb00103.x

Madsen, R., Larsen, P., Carlsen, A. M. F., & Marcussen, J. (2023). Nursing care and nurses' understandings of grief and bereavement among patients and families during cancer illness and death – A scoping review. *European Journal of Oncology Nursing*, *62*, Article 102260. https://doi.org/10.1016/j.ejon.2022.102260

Mahlia, T. M. I., Syazmi, Z., Mofijur, M., Abas, A. E. P., Bilad, M. R., Ong, H. C., & Silitonga, A. S. (2020). Patent landscape review on biodiesel production: Technology updates. *Renewable and Sustainable Energy Reviews*, *118*, Article 109526. https://doi.org/10.1016/j.rser.2019.109526

Man, X. J., Cheung, C. S., Ning, Z., Wei, L., & Huang, Z. H. (2016). Influence of engine load and speed on regulated and unregulated emissions of a diesel engine fueled with diesel fuel blended with waste cooking oil biodiesel. *Fuel*, *180*, 41-49. https://doi.org/10.1016/j.fuel.2016.04.007

Manigandan, S., Gunasekar, P., Devipriya, J., & Nithya, S. (2019). Emission and injection characteristics of corn biodiesel blends in diesel engine. *Fuel*, *235*, 723-735. https://doi.org/10.1016/j.fuel.2018.08.071

Mathew, G. M., Raina, D., Narisetty, V., Kumar, V., Saran, S., Pugazhendi, A., Sindhu, R., Pandey, A., & Binod, P. (2021). Recent advances in biodiesel production: Challenges and solutions. *Science of the Total Environment*, *794*, Article 148751. https://doi.org/10.1016/j.scitotenv.2021.148751

McGrath, J. J., Schreck, R. M., & Lee, P. S. (1993). Carboxyhemoglobin levels in humans: Effects of altitude. *Inhalation Toxicology*, *5*(2), 241-249. https://doi.org/10.3109/08958379309034504

Mofijur, M., Masjuki, H. H., Kalam, M. A., Atabani, A. E., Fattah, I. M. R., & Mobarak, H. M. (2014). Comparative evaluation of performance and emission characteristics of Moringa oleifera and Palm oil based biodiesel in a diesel engine. *Industrial Crops and Products*, *53*, 78-84. https://doi.org/10.1016/j.indcrop.2013.12.011

Mosarof, M. H., Kalam, M. A., Masjuki, H. H., Alabdulkarem, A., Ashraful, A. M., Arslan, A., Rashedul, H. K., & Monirul, I. M. (2016). Optimization of performance, emission, friction and wear characteristics of palm and Calophyllum inophyllum biodiesel blends. *Energy Conversion and Management*, *118*, 119-134. https://doi.org/10.1016/j.enconman.2016.03.081

Mostafalou, S., & Abdollahi, M. (2013). Pesticides and human chronic diseases: Evidences, mechanisms, and perspectives. *Toxicology and Applied Pharmacology*, *268*(2), 157-177. https://doi.org/10.1016/j.taap.2013.01.025

Mueller, C. J., Boehman, A. L., & Martin, G. C. (2009). An experimental investigation of the origin of increased NO x emissions when fueling a heavy-duty compression-ignition engine with soy biodiesel. *SAE International Journal of Fuels and Lubricants*, *2*(1), 789-816. https://doi.org/10.4271/2009-01-1792

Nabi, M. N., Zare, A., Hossain, F. M., Ristovski, Z. D., & Brown, R. J. (2017). Reductions in diesel emissions including PM and PN emissions with diesel-biodiesel blends. *Journal of Cleaner Production*, *166*, 860-868. https://doi.org/10.1016/j.jclepro.2017.08.096

Nalgundwar, A., Paul, B., & Sharma, S. K. (2016). Comparison of performance and emissions characteristics of DI CI engine fueled with dual biodiesel blends of palm and jatropha. *Fuel*, *173*, 172-179. https://doi.org/10.1016/j.fuel.2016.01.022

Nayab, R., Imran, M., Ramzan, M., Tariq, M., Taj, M. B., Akhtar, M. N., & Iqbal, H. M. N. (2022). Sustainable biodiesel production via catalytic and non-catalytic transesterification of feedstock materials - A review. *Fuel*, *328*, Article 125254. https://doi.org/10.1016/j.fuel.2022.125254

Nguyen, V.-N., Dao, T. N. T., Cho, M., Jeong, H., Nguyen-Le, M.-T., Shin, Y., & Yoon, J. (2023). Recent advances in extracellular vesicle-based organic nanotherapeutic drugs for precision cancer therapy. *Coordination Chemistry Reviews*, *479*, Article 215006. https://doi.org/10.1016/j.ccr.2022.215006

Ong, H. C., Milano, J., Silitonga, A. S., Hassan, M. H., Wang, C.-T., Mahlia, T. M. I., Siswantoro, J., Kusumo, F., & Sutrisno, J. (2019). Biodiesel production from Calophyllum inophyllum-Ceiba pentandra oil mixture: Optimization and characterization. *Journal of Cleaner Production*, *219*, 183-198. https://doi.org/10.1016/j.jclepro.2019.02.048

Oyekunle, D. T., Barasa, M., Gendy, E. A., & Tiong, S. K. (2023). Heterogeneous catalytic transesterification for biodiesel production: Feedstock properties, catalysts and process parameters. *Process Safety and Environmental Protection*, *177*, 844-867. https://doi.org/10.1016/j.psep.2023.07.064

Özener, O., Yüksek, L., Ergenç, A. T., & Özkan, M. (2014). Effects of soybean biodiesel on a DI diesel engine performance, emission and combustion characteristics. *Fuel*, *115*, 875-883. https://doi.org/10.1016/j.fuel.2012.10.081

Palash, S. M., Kalam, M. A., Masjuki, H. H., Masum, B. M., Fattah, I. M. R., & Mofijur, M. (2013). Impacts of biodiesel combustion on NOx emissions and their reduction approaches. *Renewable and Sustainable Energy Reviews*, *23*, 473-490. https://doi.org/10.1016/j.rser.2013.03.003

Pandian, A. K., Ramakrishnan, R. B. B., & Devarajan, Y. (2017). Emission analysis on the effect of nanoparticles on neat biodiesel in unmodified diesel engine. *Environmental Science and Pollution Research*, *24*(29), 23273-23278.

Pang, X., Shi, X., Mu, Y., He, H., Shuai, S., Chen, H., & Li, R. (2006). Characteristics of carbonyl compounds emission from a diesel-engine using biodiesel-ethanol-diesel as fuel. *Atmospheric Environment*, *40*(36), 7057-7065. https://doi.org/10.1016/j.atmosenv.2006.06.010

Patel, S., Jose, A., & Mohiuddin, S. S. (2023). *Physiology, oxygen transport and carbon dioxide dissociation curve*. In StatPearls [Internet]. StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK539815/

Pawlus, M. R., & Hu, C.-J. (2013). Enhanceosomes as integrators of hypoxia inducible factor (HIF) and other transcription factors in the hypoxic transcriptional response. *Cellular Signalling*, *25*(9), 1895-1903. https://www.ncbi.nlm.nih.gov/sites/books/NBK539815/

Perez, L. E., Vidal, L. J., & Perez, P. J. E. (2019). *Particulate matter exposure: Genomic instability, disease, and cancer risk*. IntechOpen. https://doi.org/10.5772/intechopen.86536

Piantadosi, C. A. (2008). Carbon monoxide, reactive oxygen signaling, and oxidative stress. *Free Radical Biology and Medicine*, *45*(5), 562-569. https://doi.org/10.1016/j.freeradbiomed.2008.05.013

Poulsen, A. H., Hvidtfeldt, U. A., Sørensen, M., Pedersen, J. E., Ketzel, M., Brandt, J., Geels, C., Christensen, J. H., & Raaschou-Nielsen, O. (2023). Air pollution with NO2, PM2. 5, and elemental carbon in relation to risk of breast cancer - A nationwide case-control study from Denmark. *Environmental Research*, *216*, Article 114740. https://doi.org/10.1016/j.envres.2022.114740

Rajak, U., & Verma, T. N. (2018). Effect of emission from ethylic biodiesel of edible and non-edible vegetable oil, animal fats, waste oil and alcohol in CI engine. *Energy Conversion and Management*, *166*, 704-718. https://doi.org/10.1016/j.enconman.2018.04.070

Raz-Maman, C., Borochov-Greenberg, N., Lefkowitz, R. Y., & Portnov, B. A. (2025). Ambient exposure to nitrogen dioxide and lung function: A multi-metric approach. *Environmental Monitoring and Assessment*, *197*(4), 1-13. https://doi.org/10.1007/s10661-025-13871-4

Reyes, J. F., & Sepulveda, M. A. (2006). PM-10 emissions and power of a diesel engine fueled with crude and refined biodiesel from salmon oil. *Fuel*, *85*(12), 1714-1719. https://doi.org/10.1016/j.fuel.2006.02.001

Ribeiro, T., & Macedo, G. (2024). Climate change and liver disease: A mini review. *Frontiers in Gastroenterology*, *3*, Article 1334877. https://doi.org/10.3389/fgstr.2024.1334877

Senthil, R., Pranesh, G., & Silambarasan, R. (2019). Leaf extract additives: A solution for reduction of NOx emission in a biodiesel operated compression ignition engine. *Energy*, *175*, 862-878. https://doi.org/10.1016/j.energy.2019.03.039

Shi, X., Pang, X., Mu, Y., He, H., Shuai, S., Wang, J., Chen, H., & Li, R. (2006). Emission reduction potential of using ethanol-biodiesel-diesel fuel blend on a heavy-duty diesel engine. *Atmospheric Environment*, *40*(14), 2567-2574. https://doi.org/10.1016/j.atmosenv.2005.12.026

Shukla, A., Bunkar, N., Kumar, R., Bhargava, A., Tiwari, R., Chaudhury, K., Goryacheva, I. Y., & Mishra, P. K. (2019). Air pollution associated epigenetic modifications: Transgenerational inheritance and

underlying molecular mechanisms. *Science of the Total Environment*, *656*, 760-777. https://doi.org/10.1016/j.scitotenv.2018.11.381

Singh, Devendra, Singal, S. K., Garg, M. O., Maiti, P., Mishra, S., & Ghosh, P. K. (2015). Transient performance and emission characteristics of a heavy-duty diesel engine fuelled with microalga Chlorella variabilis and Jatropha curcas biodiesels. *Energy Conversion and Management*, *106*, 892-900. https://doi.org/10.1016/j.enconman.2015.10.023

Singh, Digambar, Sharma, D., Soni, S. L., Sharma, S., Sharma, P. K., & Jhalani, A. (2020). A review on feedstocks, production processes, and yield for different generations of biodiesel. *Fuel*, *262*, Article 116553. https://doi.org/10.1016/j.fuel.2019.116553

Solaymani, S. (2019). CO2 emissions patterns in 7 top carbon emitter economies: The case of transport sector. *Energy*, *168*, 989-1001. https://doi.org/10.1016/j.energy.2018.11.145

Sørensen, M., Schins, R. P. F., Hertel, O., & Loft, S. (2005). Transition metals in personal samples of PM2. 5 and oxidative stress in human volunteers. *Cancer Epidemiology Biomarkers & Prevention*, *14*(5), 1340-1343. https://doi.org/10.1158/1055-9965.EPI-04-0899

Tahir, F., Ashfaq, H., Khan, A. Z., Amin, M., Akbar, I., Malik, H. A., Abdullah, M., Alessa, A. H., Alsaigh, A. A., & Ralph, P. J. (2024). Emerging trends in algae farming on non-arable lands for resource reclamation, recycling, and mitigation of climate change-driven food security challenges. *Reviews in Environmental Science and Bio/Technology*, *23*(3), 869-896. https://doi.org/10.1007/s11157-024-09697-0

Takase, M., Zhao, T., Zhang, M., Chen, Y., Liu, H., Yang, L., & Wu, X. (2015). An expatiate review of neem, jatropha, rubber and karanja as multipurpose non-edible biodiesel resources and comparison of their fuel, engine and emission properties. *Renewable and Sustainable Energy Reviews*, *43*, 495-520. https://doi.org/10.1016/j.rser.2014.11.049

Vilas-Boas, V., Chatterjee, N., Carvalho, A., & Alfaro-Moreno, E. (2024). Particulate matter-induced oxidative stress-mechanistic insights and antioxidant approaches reported in in vitro studies. *Environmental Toxicology and Pharmacology*, Article 104529. https://doi.org/10.1016/j.etap.2024.104529

Yahya, E. B., & Alqadhi, A. M. (2021). Recent trends in cancer therapy: A review on the current state of gene delivery. *Life Sciences*, *269*, Article 119087. https://doi.org/10.1016/j.lfs.2021.119087

Zhang, Z., Li, Y., Zhang, X., Zhang, H., & Wang, L. (2021). Review of hazardous materials in condensable particulate matter. *Fuel Processing Technology*, *220*, Article 106892. https://doi.org/10.1016/j.fuproc.2021.106892

Zimta, A.-A., Gulei, D., Stefan, D. C., & Tomuleasa, C. (2021). The impact of climate change and land use on the cancer burden in the 21st century. In *Climate and land use impacts on natural and artificial systems* (pp. 49-71). Elsevier. https://doi.org/10.1016/B978-0-12-822184-6.00010-7