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WASTE COOKING OIL TO BIOFUEL: A SUSTAINABLE POWER SOURCE FOR A GREENER FUTURE

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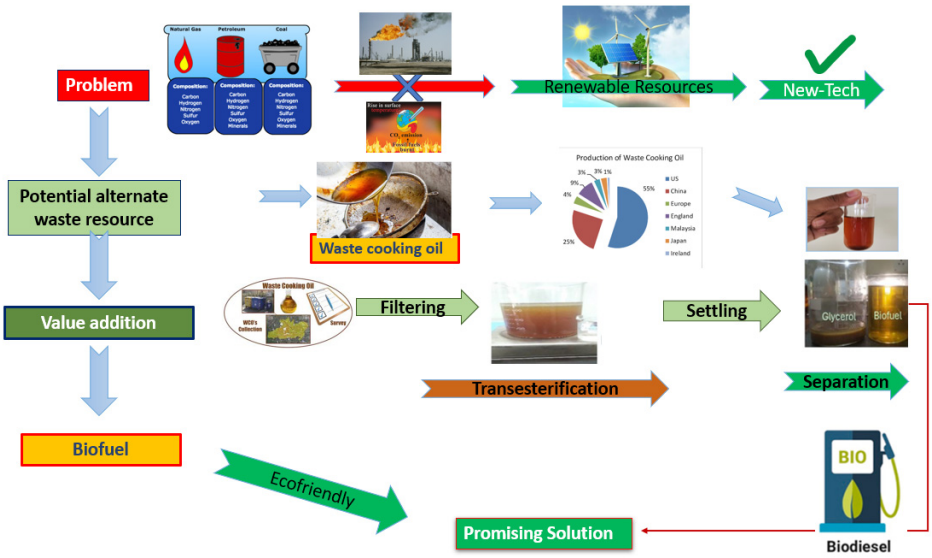
Graphical Abstract



ABSTRACT

Achieving a sustainable energy future is greatly aided by biofuels, especially in terms of easing to switch from fossil fuels to renewable energy sources. The environmental problems that conventional fuels create particularly in the transportation sector highlight the significance of biofuels as a workable alternative. First-generation biofuels come from food crops, while advanced generations make use of biomass that is not intended for human consumption. Among these, waste cooking oil (WCO) biodiesel stands out as a potentially useful substitute. WCO-based biodiesel is an attempt to develop a more ecologically friendly and sustainable energy system because of lower pollution levels in the environment and provides a practical means of managing oil and grease waste. Supportive policies, including incentives and research, are vital for advancing biofuel adoption and addressing challenges like feedstock supply and environmental impact.

KEY WORDS : Waste cooking oil, Biofuel, biodiesel, Sustainable energy system.

INTRODUCTION TO FUELS

Fuels are important because they make combustion possible, which produces energy and at the same time using them makes the state of the environment worse. A sustainable future requires a shift to sustainable alternative energy resources (Dale, 2008). Numerous development opportunities exist for worldwide markets for petroleum and other liquid fuels, some of which are incompatible. There are alternating scenarios with optimistic and pessimistic assumptions. Either way, significant adjustments are needed for the future energy supply. Crude oil is the most important energy source globally among conventional sources, accounting for around 33% of primary energy consumption. While oil consumption expanded by 2.5% in 2013, oil output surged by 1.6% to a new high of approximately 4.2 billion tons.It is undeniable that conventional oil reserves are finite, even though there are still relatively substantial geological quantities of energy resources available (Duwe *et al*., 2019; Shree Raksha Yadav *et al.,* 2024). Transportation is significantly shaped by liquid fuels, and vehicles are becoming major users of these fuels. Liquid propane, diesel oil, gasoline, and alcohol (methyl and ethyl) are the primary liquid fuels for transportation and other liquid fuel such as hydrazine and ammonia are used. Fuel efficiency and availability have a significant influence on energy policy and transportation infrastructure, which in turn affects environmental sustainability and societal mobility.

Need for biofuels

The utilization of biomass resources to produce biofuels has gained attention globally due to climate change and rising oil prices. Researchers are concentrating on renewable technologies to address these problems (Lhawang *et al*., 2021). Biofuel is made from biomass and offers traditional fuels as a sustainable alternative because they are non-toxic, biodegradable, and economically feasible, which offer a good substitute for reducing reliance on fossil fuels. Furthermore, their abundance of biomass ensures widespread availability and supports environmental sustainability as well as energy security. As a sustainable energy source, biofuels are crucial to lowering global warming and promoting ecologically responsible energy practices (Malik *et al*., 2024). Temperature, catalyst type, chemical selection, and catalytic reaction time are just a few of the many factors that are carefully considered when producing biofuels. These elements are necessary to ensure that the processes utilized in the production of biofuels as environmentally friendly and sustainable. By optimizing these conditions, it is possible to maximize the production of biofuel while minimizing the impact on the environment, leading to a more sustainable energy future (Puri *et al.,* 2012).

Types of biofuels

Numerous techniques and technologies are available for transforming energy derived from a range of biomass sources, applicable for both experimental and extensive biofuel manufacturing. Biofuels are generally divided into two categories: conventional (first generation) and advanced (second and third generation), according to the International Energy Agency (Malik *et al*., 2024). Traditional biofuels are made by extracting vegetable oil and animal fats, or by fermenting crops like maize, sugarcane, and soybeans.These biofuels are made by well-established methods: biodiesel is produced by trans-esterifying vegetable or edible oils, while bioethanol is produced by fermentation from sugars and starchy feed stocks (Nisar *et al*., 2024). Yet, the move toward greener options is being driven by growing worries about carbon emissions, land use, and food security (Sirigeri *et al*., 2022).

Advanced biofuels, encompassing both second and third generations, utilize non- edible sources such as algae or agricultural residues, employing sophisticated conversion techniques to enhance sustainability and mitigate competition with food resources (Malik *et al.,* 2024). Second-generation bioethanol can be made from lignocellulosic biomass, which includes wood, forestry waste, agricultural residues, and organic wastes. Thermochemical methods yield petroleum-diesel alternatives like dimethyl ether (a propane substitute), green diesel, and Fischer-Tropsch diesel, as well as petroleum substitutes like methanol, mixed alcohols, and Fischer-Tropsch gasoline (Saini *et al*., 2015; Shree Raksha Yadav *et al*., 2024). Third-generation Algae, seaweed, and other microorganisms are becoming feedstocks for biofuels that have benefits like not requiring cultivable land (Chia *et al*., 2022; Hinduja *et al*., 2024).

Why biodiesel?

The world's economy is about to face a severe

shortage of fossil fuels as reserves of crude oil run out due to increase in energy demand. It is clear from the current situation that using fossil fuels alone will not fulfil the world's energy demand in the coming future (Dhawane *et al*., 2018; Rhithuparna *et al*., 2024). Diesel fuel is frequently used because on complete combustion, it produces carbon dioxide and water but in real life condition, burns partially and releases a variety of gases, liquids, and solid particles. Diesel engines emit significantly less carbon monoxide when compared to gasoline engines, but they produce more nitrogen oxides and aldehydes, which are especially known to irritate the upper respiratory tract. Diesel exhaust particles (DEPs) make up a major portion of the air pollutants produced by motor vehicles that are released into numerous towns and cities. Submicron soot particles from diesel engines are thought to mediate a number of negative consequences that have been reported (Long and Carlsten, 2022). As petroleum reserves are depleting and environmental awareness is rising, there is a growing focus on renewable energy sources.

Vegetable-based oils are among the main renewable energy sources that may be converted to biodiesel, a substitute fuel for diesel engines (Lin and Wu, 2022). Biodiesel can be used either exclusively or in conjunction with diesel fuels derived from petroleum. It is a naturally decomposing, non-toxic fuel that is renewable. When compared to diesel-based fuels, biodiesel offers significant advantages. Compared to diesel fuel, it has a greater cetane number, and its weight percentage is 10-12% oxygen, nearly zero sulfur, and no aromatics. Compared to petroleum diesel-fueled engines, combustion engines running on biodiesel emit fewer CO, HC, and particulates (Graboski and McCormick, 1998).

Identification of various alternatives

In order to meet future energy needs and maintain sustainability, research and development of alternative, renewable energy sources have intensified due to the excessive use of fossil fuels and rising greenhouse gas emissions (Callegari *et al.,* 2020; Kusumo *et al*., 2022). Table 1 lists the normal fatty acid distribution in different vegetable oils. Since the local soil and climate determine the feedstock needed to produce biodiesel, different locations are concentrating on different kinds of oils. A new industry has had to be established in order to accommodate the growth of biofuel. About 1,500 petrol stations in Germany currently sell biodiesel. Official biodiesel guidelines were issued in 2000; however criteria were set by ASTM D6751 in 1996 (Benny *et al.,* 2024).

Importance of waste cooking oil in biodiesel

The synthesis of biodiesel to serve as a diesel substitute has received a lot of interest as plant, vegetable, and animal fats are sources of renewable biomass. Biodiesel fuel has gained popularity due to its positive environmental effects (Demirba°, 2003). Waste or used cooking oil (WCO) is a common source of trans fats that are linked to several non-communicable disorders, including diabetes, hypertension, cardiovascular disease, stroke, and cancer (Manikandan *et al*., 2023). Using WCO for biodiesel production can avoid food supply chain associated harmful diseases and can also offer a reasonably priced alternative to fossil fuels, meeting the increasing demand for renewable energy sources (Gaur *et al*., 2021), thus production of biodiesel from this WCO has the potential is profitable. First and second used cooking oils are the two varieties of used cooking oils that are available, where first-used cooking oil is frequently produced by fast food establishments and are usually from vegetable sources. On the other hand, street food vendors frequently generate second-used cooking oil, which is leftover oil from first frying oil. These days, this oil frequently ends up in the trash without any care and thus, if done nothing about it, the ecosystem will get contaminated (Kawentar and Budiman, 2013;

Table 1. The typical distribution of fatty acids in various vegetable oils (Benny *et al.,* 2024).

Fatty acid	Coconut	Palm	Peanut	Tallow	Used Cooking Oil
Lauric	46.5	0.1	0.1	0.1	0.34
Myristic	19.2	1	0.3	2.8	0.9
Palmitic	9.8	42.8	12.3	23.3	20.4
Stearic	3	4.5	4.6	19.4	4.8
Oleic	6.9	40.5	53.6	42.4	52.9
Linoleic	2.2	10.1	29	2.9	13.5
Linolenic	0	0.2	0.1	0.9	0.8

Rastegari and Ghaziaskar, 2023). Producing biodiesel from the leftover cooking oil is one way to handle it and substitute will be advantageous both financially and ecologically. Since used cooking oil is less expensive as a raw material and doesn't require much maintenance, can solve the problem of raw mater availability without any seasonal break (Maheshwari *et al.*, 2022). Studies conducted recently showed that using WCOs instead of food-grade vegetable oil could cut the price of producing biodiesel by nearly half (Escobar *et al.*, 2009).

It was estimated that 15 million tons of used cooking oil are disposed of on land or in water each year worldwide. Since it might fill a sizable gap in the existing worldwide demand for biodiesel, such a large amount of poor-quality non-edible oil warrants special investigation as a substitute for low-cost raw material (Lee *et al.*, 2014).

Biofuel Synthesis process

Waste cooking oil is first collected and pre-treated, then filtered to eliminate particles of food, water, and contaminants. Transesterification process is carried out for the conversion of the oil's triglycerides into fatty acid methyl esters (FAME), which are the building blocks of biofuel, and glycerol as a byproduct as presented in the Figure 1. A catalyst, typically sodium or potassium hydroxide, combined with methanol or ethanol to produce methoxide or ethoxide solution, facilitates this process. To start the reaction, this solution is mixed with oil that has already been pre-treated, heated, with constant stirring. After an hour of reaction time, the mixture was allowed to settle and separate into layers of biofuel in the top layer and glycerol. After this, biofuel is separated and washed by distilled water to remove water soluble contaminants, dried at 70^0C to get rid of moisture. It is possible to treat the glycerol byproduct further to make it useful in a variety of sectors, including medicine and cosmetics (Suzihaque *et al.*, 2022).

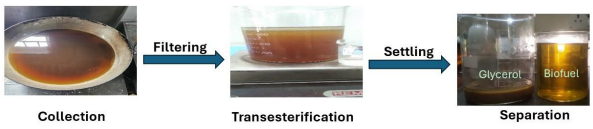


Fig. 1. Transesterification of oil to produce biofuel

Stages of biodiesel

Transesterification, also referred to as methanolysis, is the most popular and practical way to produce biodiesel. It is the result of an induced reaction between vegetable oil and alcohol to produces both glycerol and biodiesel. Short-chain alcohol takes the place of glycerol in triglycerides during transesterification (Figure 2). Three successive reversible steps begin the process, converting triglycerides to diglycerides, which are subsequently converted to monoglycerides, and finally to glycerol (Suzihaque *et al.*, 2022). Alcohol is used in the transesterification process (such as methanol, or ethanol). Potassium hydroxide (KOH) and sodium hydroxide (NaOH), two of the most often used catalysts, are both extremely sensitive to the quantity of water and free fatty acids in the chemical reaction as well as its purity (Negm *et al.*, 2024).

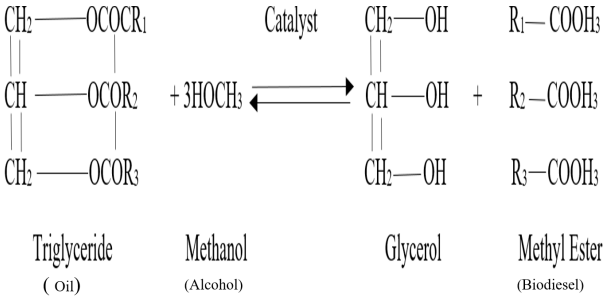


Fig. 2. Transesterification reaction

The use of biodiesel as diesel fuel has some disadvantages, such as higher viscosity. Lower energy content, higher pour and cloud points, higher nitrogen oxide emissions, lower engine power and speed, injector coking, engine compatibility, high cost, and increased engine wear. Compared to diesel fuel made from petroleum, which has a flash point of 350 K, biodiesel has a flash point of over 423 K. making it far less flammable and safer. Biodiesel has 10-11% more oxygen by weight, has a greater cetane number (around 50) than diesel fuel, and is free of sulfur and aromatics. Cetane number is one widely used indicator for evaluating diesel fuel quality, especially ignition quality. It determines the degree of fuel readiness for self-starting when the engine is injected. The ignition quality of biodiesel is one property that is impacted by the makeup of the fatty acid methyl ester (FAME) component. The most important feature of biodiesel is its viscosity, which affects the operation of fuel injectors. Particularly at lower temperatures when a higher viscosity affects the fuel's fluidity. Diesel fuels and biodiesel both have similar viscosities. Elevated viscosity results in less precision from the fuel injectors and poor atomization of the fuel spray (Balat and Balat, 2010; Wan Osman *et al.*, 2024). The

elemental makeup and relative amounts of the compounds included in diesel and biodiesel fuel are shown in Table 2. Biodiesel has a greater viscositythen diesel fuel because it is somewhat more polar than diesel fuel due to the presence of the electronegative ingredient oxygen. The inclusion of elemental oxygen in biodiesel lowers its heating value relative to diesel fuel. The lower heating value (LHV) is the most widely used number for engine applications. It acts as a barometer for the energy content of the fuel. Biodiesel usually has an LHV that is 12% less than the figure (Devale *et al.,* 2023).

Table 2. Properties of biodiesel and diesel (Demirbas, 2009)

Fuel properties	Biodiesel	Diesel
Density at 15ºC/cm^3	0.8834	0.8340
Viscosity at 40 ºC, mm^2/s	4.47	2.83
Sulphur content, %	<0.005	0.034
Carbon content, %	76.1	86.2
Hydrogen, %	11.8	13.8
Oxygen, %	12.1	-
Flash point, ºC	178	62
Cetane number	56	47
Net calorific value, kJ/kg	37,243	42,588
Cloud point ·	270–285	258–278

Biofuel policy

Policies for biofuels have been developed and put into action to encourage the production and consumption of biofuels. These regulations can take many different forms, including public funding, requirements for renewable or low-carbon fuels, incentives, exemptions from excise taxes, and blending mandates. The various stages of biofuel production and consumption are impacted by each policy tool. There are two sorts of biofuel policies: market-pull and technology-push. Policies that drive technology forward are intended to assist in the early stages of technology development, such as research and development (R&D), commercialization, and demonstration of biofuels. They seek to lower R&D expenses and promote innovation (Anil *et al.,* 2024; Ashra, 2010; Ebadian *et al.,* 2020). As a key player in policymaking, the government has an important role in how far biodiesel technology advances as well as how quickly they progress. Price caps, tax breaks, direct subsidies, and goal setting are a few examples of strategies that are used to exert as powerful incentives. To encourage the expansion and development of the biodiesel business, the government can now provide a variety of incentives (Ashra, 2010; Khan *et al.*, 2022).

Indian biodiesel policy

A framework for creating a sustainable biofuel economy in India was outlined in the National Policy on Biofuels (NPB) 2018, with a particular emphasis on biodiesel. Because of the difficulties in production and adoption, the program has changed its aim of blending 5% biofuel with diesel by 2030 from the previous target of 20% by 2017. The main challenges are the restricted supply of feedstock and the 18% Goods and Services Tax (GST) that raises the price of biodiesel over regular fuel. Further hindering development are limitations on the interstate transportation of raw material like WCO, a possible feedstock for biodiesel, which upset the supply chain. Additionally, the legislation forbids the import and export of biofuels, which restricts business expansion and economic efficiency. Additionally, there is a restriction on the use of food grains as a feedstock for biofuel production to protect food security. Due to these obstacles, blending goals have been lowered, and increasing biodiesel production in India continues to present issues (Ashra, 2010; Ebadian *et al.,* 2020).

The Food Safety and Standards Authority of India (FSSAI) reports that India uses 225 lakh tons of vegetable oil each year, of which thirty percent is wasted. This waste oil offers a great chance to be used as a raw feedstock for the manufacturing of biodiesel. According to the 2018 biofuel strategy, the Indian government wants to prevent leftover cooking oil (WCO) from being used for cooking and instead create a reliable system for collecting WCO to guarantee a consistent supply for the manufacturing of biodiesel. Additionally, according to the FSSAI, 101 places in India-64 businesses, 200 aggregators, 350 hubs, and 26 plant initiatives have the authorization to gather WCO and turn it into biodiesel (Gaur *et al.,* 2021).

INTERNATIONAL CASE STUDY

China

China generates over five million tons of WCO, also known as gutter oil, every year as a result of rising urbanization and dietary changes. This presents a serious dilemma for the country. 40% to 60% of waste materials may find their way back into the food supply due to improper disposal, which

includes unlawful sewer discharge and food reuse. These practices represent major threats to the environment and human health. Even though biodiesel production increased from 2.33 million tons in 2006 to 9.66 million tons in 2014, there are still several obstacles to overcome, as evidenced by recent declines in China's biodiesel output. These include declining oil prices, high production costs, and significant environmental impacts from the production process, such as resource depletion, carbon emissions, and health risks. Jinlihai Biodiesel Co. Ltd is a prime example of the industry's promise as well as its limitations. To overcome these obstacles and optimize the benefits of WCO-to-biodiesel conversion, more legislative support and technology breakthroughs are required (Irawan *et al*., 2024; Zhao *et al*., 2021).

Policies in the US and EU favor the conversion of WCO to biodiesel, which has advantages including waste reduction, environmental protection, and energy security.

CASE STUDY IN INDIA

Maharashtra

The case study focuses on the functioning and results of a pilot plant at YMC, Yava, Maharashtra. The plant was built to produce biodiesel from a range of raw materials. In particular, the factory used five different kinds of feedstocks: palmoline oil, jatropha oil, Karanja oil, acid oil, and WCO. To satisfy India's need for alternative fuels, these materials were selected based on their availability and potential as sustainable sources for the manufacturing of biodiesel. The pilot plant was set up as a part of a larger project to investigate the viability of producing biodiesel locally, especially in rural locations where access to traditional fuel sources can be scarce. The study focused on waste resources, such as discarded cooking oil and acid oil, and non-edible oils, such as palmoline, Karanja, and jatropha. The goal was to create low-cost techniques that could be repeated in comparable environments around the nation. The manufacturing of biodiesel was faced with distinct challenges and characteristics from each of the five feedstocks used. WCO and acid oil, byproducts of the refining of vegetable oil, are two low-cost, high-FFA (free fatty acid) sources that are generally regarded as inappropriate for conventional biodiesel production due to their greater processing requirements and contaminants. Nevertheless, these oils could be transformed into high-grade biodiesel that complied with industry requirements because of the pioneer plant's creative method, which comprised stages like esterification and transesterification. The YMC, Yava plant was essential in confirming the viability of producing biodiesel from these many sources of raw materials. Its operations shown that decentralized biodiesel production can be a workable plan for India, promoting rural development and assisting in the country's decrease in dependency on imported fossil fuels. The case study demonstrates how pilot-scale initiatives can help close the knowledge gap between lab research and large-scale industrial applications, providing a sustainable fuel production model that could be more broadly embraced throughout the nation(Shah *et al*., 2010).

Bangalore

The study of availability of WCO in Bengaluru city looks at WCO's potential as a sustainable feedstock for biodiesel production. WCO is mostly produced by the hotel industry. The research underscores the importance of WCO, which is frequently disposed of inappropriately, causing health and environmental hazards, in light of the Indian government's efforts to reduce reliance on fossil fuels and environmental pollution through biodiesel mixing. The study, which was carried out in Ward No. 65, Kadu Malleswara, Bengaluru, comprised a thorough assessment of different food business operators (FBOs), such as lodging facilities, eateries, and street vendors. Results show that approximately 29% of cooking oil used by FBOs ends up as WCO, with large FBOs contributing approximately 60% of the total WCO generated, amounting to an average of 2,650 liters per month. A large portion of this WCO is collected by agents of the biodiesel industry, and a significant amount is either improperly disposed of (poured into drains, for example) or reused domestically by FBO owners, indicating a lack of awareness regarding proper disposal practices. To quantify and spatially analyze the WCO generated, potential hotspots were identified, and collection routes were optimized using GIS-based mapping of FBOs. The significant potential for WCO to aid in the manufacturing of biodiesel-it is predicted that Ward No. 65 alone produces 54,300 liters of WCO per year. The report also highlights the need for FBOs to be more informed about the environmental advantages of safe WCO disposal as well as the health risks associated with frequent cooking oil use.

Additionally, it suggests creating a structured network for the collecting and recycling of WCO to optimize its use in the manufacturing of biodiesel. Through the integration of survey data and GIS mapping, the study offers a comprehensive framework for comprehending WCO availability and its consequences for sustainable energy production. It highlights the significance of expanding comparable initiatives throughout Bengaluru to fully realize the city's potential as a major player in the biodiesel sector (Hemanth Kumar *et al.*, 2020).

CONCLUSION

Biodiesel produced from used cooking oil sticks out as a strong option for resolving the energy industry's fiscal and environmental Issues. WCO is converted into biofuel using a process known as transesterification, which not only creates an environmentally benign energy source but also provides a useful way to handle waste. There are a number of noteworthy benefits associated with producing biodiesel from used cooking oil. In comparison to conventional fossil fuels, it aids in the reduction of greenhouse gas emissions. This procedure reduces the overall carbon footprint by reusing used cooking oil that may otherwise wind up in landfills or cause contamination in the environment. This encourages a decrease in the use of non-renewable energy sources and is in line with international efforts to address climate change. Since the emissions emitted during the combustion of the biodiesel are balanced by the CO_2 absorbed by the plants used to create the oil, biodiesel made from waste cooking oil is frequently linked to lower net carbon dioxide emissions. Producing biodiesel from leftover cooking oil has the potential to be more cost-effective than using virgin vegetable oils. Since feedstock is a waste product, it is typically less expensive and more accessible. This aids the local economy by perhaps creating jobs in the trash collection, processing, and biodiesel production sectors, in addition to helping to create a more affordable biofuel. Additionally, it helps to improve energy security by lowering reliance on imported fossil fuels for energy. However, in order to fully utilize this biodiesel, certain issues must be resolved. It's important to address issues including the requirement for effective waste collecting systems, the variation in feedstock quality, and the advancement of cutting-edge processing technology. Widespread acceptance will depend on how inexpensive and scalable the production process can be made. Furthermore, continuous research and development can enhance the effectiveness and functionality of biodiesel produced from leftover cooking oil.

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Ethics approval and consent to participate

No Ethical approval needed for this research.
Consent for publication

No Needed
Availability of data and material
The datasets supporting the current studies are available with the corresponding author on reasonable request

Competing interests

The authors confirm that they have no competing financial interest.

Author Contribution

1. Srithejas Kadumanadka: Formal Analysis, Investigation, methodology, Writing original draft preparation.
2. Pallavi Nagaraju: Validation, Resource, Writing review and Editing
3. Nadarajah Kannan: Validation, Visualization,
4. Kandiah Pakeerathan: Supervision, Visualization, Writing review and Editing
5. Kalya Tulasidas Vadiraj: Conceptualization, Fund acquisition, methodology, project administration, supervision, Writing original draft preparation

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