Effect on saturated and unsaturated fatty acids on various vegetable oils on droplet combustion characteristic

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ABSTRACT

Vegetable oils have composed of triglycerides, which one consist of 3 fatty acids combined with glycerol. Each saturated and unsaturated fatty acid has a different effect on burning characteristics. This study aimed to investigated effect of fatty acids at ceiba pentandra and jatropha oils on the flame behavior of the droplet combustion process. The combustion characteristic was observed by an ignited droplet at the junction using a thermocouple and a high-speed camera (120 fps). Results showed that a higher saturated fatty acid content resulted in long-life and steady flames. This is because more oleic and linoleic acid carbon atoms leave the droplet area and react with air. Jatropha oil produces a higher temperature of 780 °C than ceiba pentandra oil. Temperature of a vegetable oils flame is influenced by number of carbon chains, double bond, and heating value. Ceiba pentandra oil has a higher burning rate of 0.185 mm/s than jatropha oil at 0.155 mm/s. The chain content of polyunsaturated fatty acids has significant effect on rate of combustion, which is due to the weak van der Waals dispersion forces, such that heat absorption is more active and energetic. The highest flame height for ceiba pentandra oil is 55.03 mm compared to for jatropha oil it is 46.82 mm. Long-chain unsaturated double bonds and glycerol cause micro-explosions. This micro-explosion caused the shape of the flame to split and expand so that evaporation occurred faster, thus increasing the size of the flame.

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1. INTRODUCTION

Currently, fossil fuel are most important sources of energy for human civilization worldwide. Increasing energy consumption has had an impact fossil fuels resources, leading to early scarcity [1]. Tighter emission regulations, increased oils price, and a limited supply fossil fuel have makes it necessary to seek sustainable and environmentally friendly energy sources [2]. Various attempt has made to researchers to find alternative fuel to substitute these fossil fuels, one of which is the use of alternative fuels for vegetable oil and animal fat [3]. To overcome the problem of reduced fuel reserves and toxic emissions caused by fossil fuels, alternative solutions for vegetable oil are potential renewable and environmentally friendly energy source [4], [5]. The advantages of using vegetable oils are the availability of resources in large quantities, renewability, low sulfur content, and biodegradability [6]. On the contrary, the disadvantages are the highest density, highest viscosity, lower evaporation rates, and highest levels reactivity of unsaturated hydrocarbon chains [6]-[8]. Vegetable oils are generally triglyceride molecule consisting in glycerols and three carbons chain, such as backbone and branching [9], [10]. The long carbon chain structures of fatty acids resemble the molecular structure of diesel fuels [11]. Therefore, fatty acid has potential sources on diesel. However, directing the applications of these vegetable oils causes more problems in engines because of their higher density and viscosity than diesel [12]. Various studies on the physicochemical properties of biodiesel have shown that biodiesel generally consist five main-chains carbon: methyl linolenic (C18:3, C17H32O2), linoleate (C18:2, C19H34O2), and oleate (C18:1, C19H36O2), such as unsaturated FAMEs; stearate (C18:0, C19H38O2); and palmitate (C16:0, C17H34O2), such as saturated FAME [13], [14].

Several researchers have founding direct correlations between emission and chemical structures of FAME, suggesting that NOx increases with increasing degrees of unsaturation and average degradation in carbon chain length. Unsaturated show poor oxidation stability and release more NOx than saturated fatty acid [15]. Owing to strict emissions control, although biodiesel originating from saturated fatty acids has lower temperature, lower NOx emissions, and lower oxidation stability, researchers around the world are starting to search for biodiesel derived on saturated fatty acids [16].

Many researchers have argued that increased fuel saturation leads to lower greenhouse gas emissions, higher cetane numbers, higher thermal efficiency, and good combustion properties. Increases in the degree of unsaturation result on shorter ignition delays and burning durations, but high temperatures, permanent burn rates, certain power, and flame dimensions [17]. Burning unsaturated fatty acids has the longest combustions and results in the highest pressure than to saturated fatty acids [18]. Linseed oil methyl esters with the highest linolenic acid content (unsaturated fatty acid esters) are not suitable to diesel engines because they have the highest nitrogen oxide content and lowest thermal efficiency [19]. Highest unsaturated fatty acids, highest NOx, and lowest CO emissions [20]. The saturated acid component and longer carbon chain cause a higher flame temperature in an open flame [21]. Testing unsaturated fatty acid biodiesel and emission characteristics of direct injection diesel engines resulted in the following conclusions: i) excessive unsaturated fatty acids have highest density but lower viscosity; ii) excessive unsaturated fatty acid have lower cetane number, highest activation energy, and longest ignition delays; iii) excessive unsaturated fatty acids result in higher HC, CO, and smoke; iv) excessive unsaturated fatty acids result in higher NO due to longest ignition delays and fast injection fuel times; and v) exhaust gas temperatures, pressure gas, and heat release rates were higher for unsaturated biodiesel [18]. In unsaturated biodiesel fuels, NOx emission increase by 10% and particle mass emissions decrease at 20% [22].

From the studies mentioned above, effects of fatty acid at vegetable oil and flame behavior, which play important roles in combustion stability and affect engine performance, have not been discussed. Particular attention should be paid to the chemical-physical properties of vegetable oil as alternative fuel. Hence, further research is required, particularly on the role of fatty acids in the stabilization of combustions. This studies provide data of stability of burning fatty acids through droplet combustion. The information disclosed provides an overview of how combustions process on vegetable oils on engines becomes more efficient. It is necessary of study impact on fuel in the combustions chamber, mainly the internal combustion equipment, during long-term used. Those study aimed to reveal role of fatty acids on engine internal combustion of various pure vegetable oils.

2. METHOD

2.1. Vegetable oil chemical structures and properties

Vegetable oils tested included ceiba pentandra and jatropha oils. Its vegetable oil was obtained from the market. Fatty acid compositions, physical properties, glycerol, gums, and water in vegetable oil have described on our previous research [23].

2.2. Experimental apparatus

Study have carried out experimentally equipment used was shows schematically on Figure 1. The oils droplet of ceiba pentandra and jatropha oils were hung at the junction a type-K thermocouple with a diameter of 0.1 mm (5). Single fuel droplets were prepared using a conventional syringe (1 mL) at 100 strips, which showed volume of liquid on syringe so that's each strip was 10 µL (0.00001 L). The droplets size were fixed at diameter of approximately 0.3-0.6 mm (4). These droplets are ignited by a 0.3 mm diameter electric coil heater made from Ni-Cr wire (3). The 30 mm long wire had a resistance of 1.02 Ω with voltage 6 V and current 5 A. This research was conducted in the combustion chamber (6). Data collection was repeated five times.

2.3. Data acquisition

The thermocouple signal indicating the temperature evolution on middle of droplets were obtained using personal computer connected to Arduino UNO R3 Atmega 328 as a data logger (7). Data acquisition began at the same time that the heater was turned on by a 6 V 5 A DC power source (2). Arduino UNO data recorder with frequency of 0.01 Hz sends flame temperature signal to laptop (8). Image data of flames were recorded by a high-speed camera 120 fps (9) from droplets that began to burn and saved on a sim card, then process used on free video to JPG converter application and Image J bundled with 64-bit Java 1.8.0-112 by converting the image file into multiple frames. The droplet diameter, flame length, and evolution were measured using the CorelDraw application.

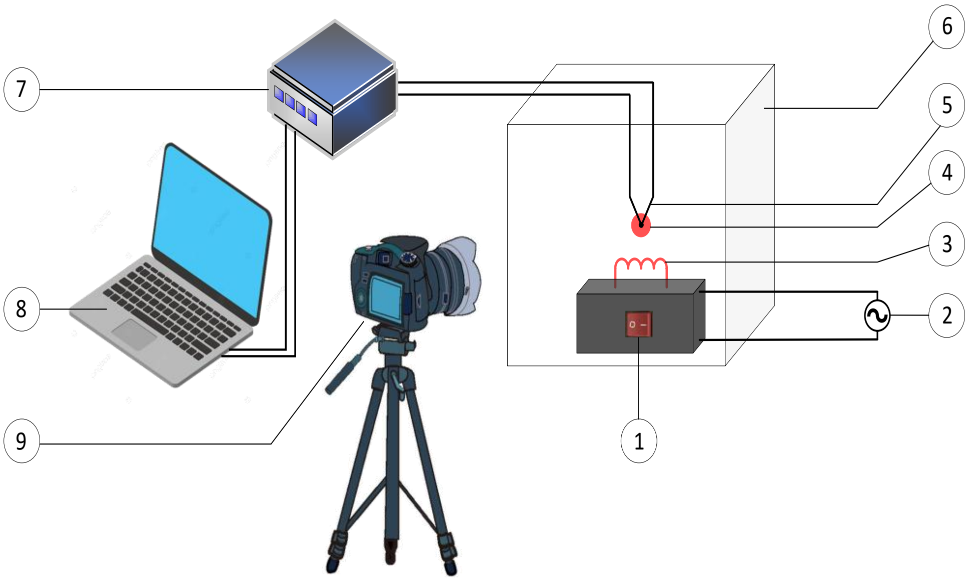


Figure 1. Experimental apparatus: (1) push on switch, (2) power supply, (3) electrical heater, (4) droplet, (5) thermocouple, (6) combustions chamber, (7) data loggers, (8) laptop, and (9) high speed cameras

3. RESULTS AND DISCUSSION

3.1. Stability and flame characteristics of various vegetable oils and time of evolution

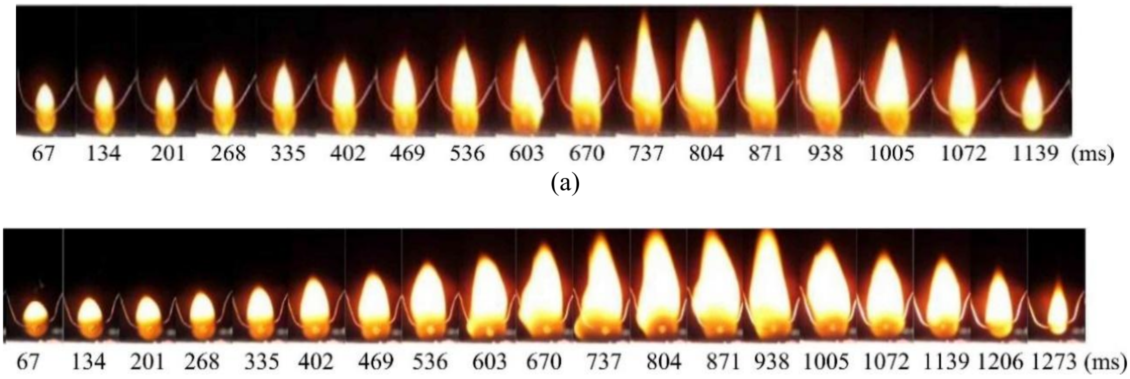
Figure 2 shown stability and shape of flames at different combustion rates. The burning mechanism of pure vegetable oil under the same treatment has different flame characteristics. Figure 2 shows two things. First, the type of ceiba pentandra oil shows that the flame is still stable until 737 ms, after which it starts to extinguish after 938 ms shown in Figure 2(a). In jatropha oil, the flame was more stable and started to extinguish after 1340 ms shown in Figure 2(b). This is due to large unsaturated fatty acids content of oleic acid and its low flashpoint. A low flash point indicates the time required to burn faster. Second, the flame on the ceiba pentandra oil burns at 67 ms, whereas the jatropha oil is 134 ms burns quickly. Increasing length of carbon chain and degree of saturation both increase viscosity and reduce ignition delay [12]. Vegetable oils burn on three stages: unsaturated fatty acid begin to burn in first stage, saturated fatty acid begins to burn in stage two, and glycerol begins to burn in the third stage. When saturated fatty acids start to exhaust, while glycerol begins to evaporate, saturated fatty acids begin to penetrate and become trapped on glycerols. Trapping saturated fatty acids in glycerol causes the pressure of increased evaporation and, finally, pressure bubbles burst in micro-explosions. These micro-explosions cause the flames to become more stable.

The combustion of vegetable oils with higher content on unsaturated fatty acid results on longest and most stable flames life because oleic and linoleic acid carbon atoms leaving the droplet area react with the air so that they burn actively and energetically. This area is good sourcess of radiant heating energy to maintain flames stability. This is caused by the unsaturated fatty acid composition being more dominant and highly reactive to produce a stable flame.

3.2. Temperature and time of evolution for various vegetable oils

Figure 3 shows that the highest temperature reached 780 °C in jatropha oil at 871 ms, whereas ceiba pentandra oil it was 671.75 °C at 737 ms. Jatropha oil absorbs the most energy at the beginning of combustion, whereas ceiba pentandra oil absorbs the most energy on the end of combustion. Temperature of jatropha oil at beginning on combustion was highers than that of ceiba pentandra oil; however, on the end combustion, temperature of ceiba pentandra oil was higher. Ceiba pentandra oil requires a longer heating time than jatropha oil. Because ceiba pentandra oil has the highest viscosity and saturated fatty acids, it is mostly composed of short and stiff molecules. The highest temperatures of jatropha oil and ceiba pentandra oil show the end of combustion process until droplets run out, the flame extinguishes, and then the temperature decreases. There is an increase in temperature due to the increased rate of evaporation and surface area; there is a change in the behavior of molecules as the rates of evaporation increased and the droplet diameter decreased.

Flame temperatures of vegetable oils are influenced by length of carbon chains and the number of double bonds [17]. Besides that, the higher the degree of unsaturation, the higher the temperature produced. This is similar to research conducted by Benjumea *et al.* [24], who found that temperature increases along with the increasing degree of unsaturation. The increases in heat of burning unsaturated fatty acids indicated an increase number of carbon atoms. Combustion characteristics are affected by many physicochemical properties, which significantly impact ignition delays [25]. Unsaturated fatty acids contain two bonds. Double and triple bonds cause molecules to become weak, making them less stable, more energetic, and more easily oxidized, causing them to burn faster. This is because unsaturated fatty acids have lower flash points. The rate of energy release is influenced by three factors: the flashpoint, caloric value, and duration of burning as shown in Figure 2. Jatropha oil has a lower flash point and higher calorific value than other oils. Therefore, jatropha oil has a higher temperature than ceiba pentandra oil. The high temperature of flame resulting from the combustion of oil indicates the amount of power generated to combustion of oil. Higher temperature of the flame, the greater power generated by oil combustion process.



(a)

(b)

Figure 2. Stability and shape of flames at evolution time of various vegetable oils: (a) ceiba pentandra oil and (b) jatropha curcas oil

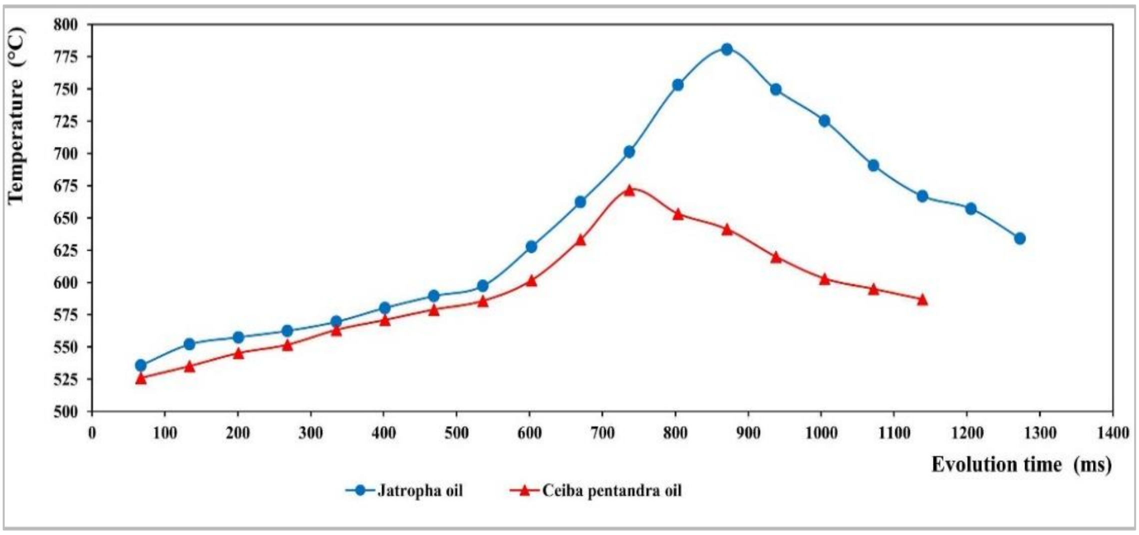


Figure 3. Evolution time versus flame temperature of various vegetable oils

3.3. Burning rate and evolution time for various vegetable oils

The burning rate against the evolution time of ceiba pentandra and jatropha oil is shown in Figure 4. Trends of the burning rate are increasing with increasing evolution time. Ceiba pentandra oil has a higher burning rate of 0.185 mm/s at an evolution time of 1139 ms, compared to jatropha oil at 0.155 mm/s at an evolution time of 1273 ms. Ceiba pentandra oil started burning at 67 ms with a burning speed of 0.018 mm/s until the fire began to extinguish after 1139 ms. While jatropha oil started burning at 67 ms with a burning speed of 0.01 mm/s, after passing an evolution time of 1273 ms, the flame began to extinguish. This shows that the chain content of unsaturated fatty acid on form of linoleic and palmitic acids, flash point, kinematic viscosity, length of carbon chain, and double bond in ceiba pentandra oil are greater than those in jatropha oil [23], [26].

Thus, the van der Waals deployment force that binds to the carbon chains of ceiba pentandra oil is weaker than that of jatropha oil. This causes ceiba pentandra oil droplets to respond differently to jatropha oil. The polyunsaturated fatty acid chain content had a significant effect on burning rate. This result is similar to that of Ibadurrohman *et al.* [17], founds that increasing the degree of unsaturation leads to higher combustion rates. Increasing trend of burning rate in jatropha oil has increased steadily compared to ceiba pentandra oil, which has experienced an extreme increase (Figure 4). This shows that the response of unsaturated fatty acid content to heat absorbed in ceiba pentandra oil is more active and less stiff than that of jatropha oil.

3.4. Flame height and evolution time in various vegetable oils

The characteristics of flame height during the combustion of various single-droplet pure vegetable oils are shown in Figure 5. The flame height of ceiba pentandra has an increasing trend since the droplet burning from the beginning until 871 ms with a height of 55.03 mm then drops until it extinguishes, while the jatropha oil is 46.82 mm at a time of 938 ms then drops to 26.44 mm before the flame extinguished. That is because long-chains unsaturated fatty acid and glycerols cause microexplosions. This micro explosion causes the shape of the flame to split and expand, such that evaporation occurs faster, thus increasing the size of the flame. Ceiba pentandra oil has a higher glycerol content than jatropha oil, which causes it to take more time and energy to carry out the combustion process. The longer combustion resulted in the highest combustion temperature, so that the flame became higher. Jatropha oil has a high oleic acid content and a low flash point value; therefore, evaporation occurs faster. Figure 2 shows that jatropha oil produced more time for the flame to extinguish than ceiba pentandra oil did. The flame of jatropha oil is less stable than that of ceiba pentandra because higher flame indicated that flames tend to be less stable because they have a longer stretch.

The height of a flame depends mainly on the chemical properties and characteristics of the combustion process. Chemical properties were closely related to oxygen supply of fuel. The change in flame height occurs because the air binds more fuel molecules, such that the fuel fraction at the surface of the flame increases. This increase in fuel fraction results in more fuel that has not yet been completely burned, which causes the flame level to be lower.

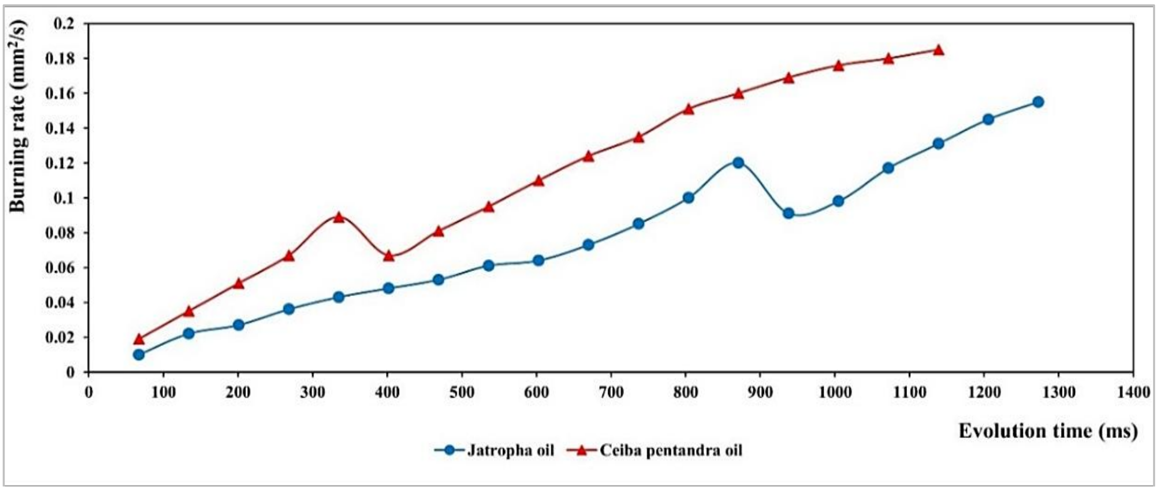


Figure 4. Evolution time versus the burning rate of various vegetable oils

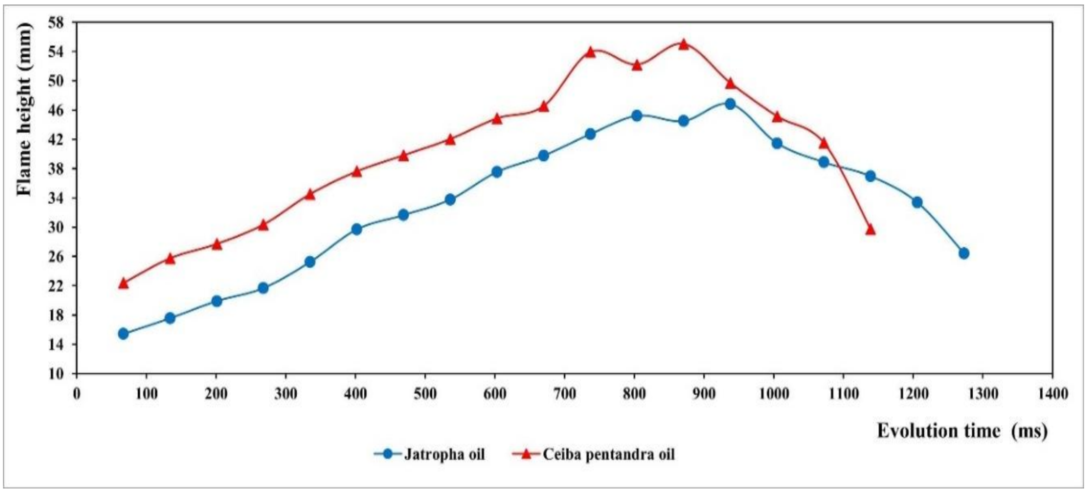


Figure 5. Evolution time versus flame height of various vegetable oils

4. CONCLUSION

High contents of oleic and stearic acids and the high flash point of jatropha oil cause delays in combustion and flame instability. Unsaturated fatty acids with large content cause burning and flame spread faster, while saturated fatty acids react more slowly and cause the flame to propagate slower-moving backward. Linoleic fatty acids dominate Ceiba pentandra oil because they are composed of long-chain fatty acids and double bonds, which produce a fast-burning rate, whereas jatropha oil is dominated by mono-unsaturated fatty acids, so that burning rates are longer. Energy absorption is more reactive in jatropha oil at the beginning of combustion, whereas Ceiba pentandra oil is more energetic on the end of combustion because of influence fatty acids and double bonds that form vegetable oil. As the next step in this study, a wide variety of vegetable oils is further expanded, and the experimental equipment is intended to be analyzed to understand the combustion characteristics and exhaust gas emissions. However, this studies still has shortcomings related to number of vegetable oils, catalyst addition, and magnetic fields. Further research is needed to develop and apply it to the internal and external combustion engines, to obtain data for advancements in industry and transportation.

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AUTHOR CONTRIBUTIONS STATEMENT

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Muhamad Nur Rohman		✓	✓	✓		✓		✓	✓	✓	✓	✓		
Mochamad Choifin	✓			✓	✓	✓	✓		✓	✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interests regarding the publication of this paper.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [DP]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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