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Review Paper

Acetone-Butanol-Ethanol as the Next Green Biofuel – A Review

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Abstract

The development of diesel engines faces challenging targets to satisfy stringent emissions regulation. To address this issue, the use of alcohol biofuels such as methanol and ethanol has attracted numerous attention due to their physicochemical properties and the possibility to be produced from renewable sources and agricultural waste material. Compared to ethanol, longer carbon alcohol such as butanol has higher energy density and lower latent heat, hygroscopicity, aggressivity, and toxicity. It can also be produced from biomass. Yet, despite its noticeable advantages, the use of butanol in the internal combustion engine is hindered by its low production efficiency. If Acetone-Butanol-Ethanol (ABE) is further distilled and purified, pure butanol and ethanol can be acquired, but this involves an energy-intensive process, thus increasing the production cost of butanol. To solve this problem, the direct use of ABE as a biofuel is considered a promising strategy. The idea of using ABE directly in internal combustion engines is then proposed to solve the economic issue of high butanol production costs. A scoping literature review was performed to screen and filter previously published papers on ABE by identifying knowledge gaps instead of discussing what is already known. Therefore, repeated and almost identical studies were eliminated, thus reporting only the most significant and impactful published papers. In terms of the objective, this article aims to review the progress of ABE as a promising biofuel in regard to the engine performance, combustion, and emission characteristics. Focus is also given to ABE's physicochemical properties. Despite their considerable importance, the fuel properties of ABE are rarely discussed. Therefore, this review article intends to analytically discuss the physicochemical properties of ABE in terms of their calorific value, density, kinematic viscosity, and distillation. In general, it is concluded that engine emissions such as NOx and Particulate Matter (PM) could be reduced considerably with the use of ABE. Yet, the BSFC was found to increase due to the relatively lower calorific value and density of ABE blends as opposed to gasoline or diesel fuel, thereby increasing its fuel consumption. In terms of ABE's fuel properties, in general, ABE can be used due to its satisfying physicochemical properties. However, it should be noted that the ABE-gasoline/diesel blends are greatly influenced by each of its component ratios (acetone, butanol, ethanol).

Keywords: Diesel engine; Green biofuel; Physicochemical properties; Acetone, Butanol, Ethanol, Engine performance

1. Introduction

The internal combustion engine was invented in the late nineteenth century when Nicolaus Otto (1876) and Rudolf Diesel (1882) first invented the spark-ignition (SI) and compression-ignition (CI) engine. Today, new technologies such as fuel injection system [1], HCCI engine [2], [3] and electric vehicles [4] continue to develop significantly.

In terms of biofuel utilization, numerous studies have reported that power output of biodiesel was nearly the same with that of petrol diesel. Furthermore, due to its oxygen content, biodiesel and its blends lead to more complete combustion with reduction of soot, carbon monoxide (CO), carbon dioxide (CO_2) and total hydrocarbon (THC) emissions [5]–[9]. Furthermore, biodiesel is also non-toxic, easily degradable, and safer due to its higher flash point, cleaner combustion and lower polycyclic aromatic hydrocarbon (PAH) and nitro PAH compounds emissions [10]. The NOx emission of biodiesel, however, was reported to be higher than diesel fuel in the range between ± 10% depending on engines combustion characteristics. Other drawbacks of using biodiesel are the production cost and the storage issue. Biodiesel is relatively expensive due to less production capacity, and it is difficult to store due to the decline of flow characteristics at low temperatures. Furthermore, the major disadvantage of biodiesel as biofuel is that it can only be used in diesel engines.

A more versatile biofuel that can be used both in gasoline and diesel engine is needed. Biofuels derived from alcohols then arise as a more promising alternative. Alcohols, such as methanol and especially ethanol, have attracted many research groups to implement them in internal combustion engines. Methanol production is very limited, while ethanol, on the other hand, can be produced easily by alcoholic fermentation of sugar from various sources including corn, sugar cane, and agricultural residues. **Table 1** compares the properties of several alcohols with conventional gasoline and diesel fuel.

Unfortunately, recent investigations have revealed that ethanol has some major issue before it can be applied on the engines. It is corrosive and may therefore cause disadvantages to both the existing fuel pipelines distribution and fuel injection system [11]. Ethanol has also far lower flash point and has higher vapor formation compared to diesel fuel, resulting in extra caution for its usage. In addition to these drawbacks, ethanol may worsen local air quality and thus deteriorating human health. Some surfactants or cosolvents must be used to ensure solubility of ethanol and diesel fuel.

A more promising option is offered by butanol [12]. Butanol has a 4-carbon structure and is a more complex higher chain alcohol than ethanol as the carbon atoms in butanol can either form a straight-chain or a branched structure that form different properties. Butanol is also less toxic, less combustible, more energy dense than ethanol. Butanol can also be produced from cellulose waste products of agriculture, or even left-over fibre after sugar crops are harvested. Butanol is also far less corrosive allowing it to be distributed using the existing infrastructure as in used to ship gasoline or diesel fuel. Another advantage of being less corrosive is that butanol can be used without any modification to the vehicle [13].

Table 1. Specification of alcohol fuels and conventional petrol-based fuels [13]

	Methanol	Ethanol	n-Butanol	Gasoline	Diesel
Molecular formula	CH_3OH	C_2H_5OH	C_4H_9OH	C_4-C_{12}	C_{12}-C_{25}
Cetane number	3	8	25	0-10	40-55
Octane number	111	108	96	80-99	20-30
Oxygen content (% weight)	50	34.8	21.6	-	-
Density (g/mL) at 20°C	0.796	0.79	0.808	0.72-0.78	0.82-0.86
Autoignition temperature (°C)	470	434	385	~300	~210
Flash point (°C) at closed cup	12	8	35	-45 to -38	65-88
Lower heating value (MJ/kg)	19.9	26.8	33.1	42.7	42.5
Boiling point (°C)	64.5	78.4	117.7	25-215	180-370
Stoichiometric ratio	6.49	9.02	11.21	14.7	14.3
Latent heating (kJ/kg) at 25°C	1109	904	582	380-500	270
Flammability limits (%vol.)	6.0-36.5	4.3-19	1.4-11.2	0.6-8	1.5-7.6
Saturation pressure (kPa) at 38°C	31.69	13.8	2.27	31.01	1.86
Viscosity (mm^2/s) at 40°C	0.59	1.08	2.63	0.4-0.8 (20°C)	1.9-4.1

It also contains a similar energy content to gasoline and contains 25% more energy density per litre than ethanol [14]. This leads to higher engine performance, allowing the cars to get better mileage on butanol. Improved premixed combustion of butanol was also observed resulted from an effective air-to-fuel mixing process. Despite the advantages, the utilisation of butanol in ICE is hampered by its relatively low production efficiency. Therefore, the direct use of Acetone-Butanol-Ethanol (ABE) is considered more promising approach as it can eliminate the expensive and energy-intensive recovery process. For that reason, this article aims to review recent advancement in the use of ABE as a promising biofuel. Despite their considerable importance, fuel properties of ABE are hardly reviewed. Therefore, emphasis is also put on ABE's physicochemical properties.

2. Methodology

In preparing this review article, we performed a scoping literature review to synthesise findings and evidence from the literature. The aim of this approach is to identify knowledge gaps instead of discussing what is already known. This technique is mainly useful to determine the relevance of inclusion measures and potential research questions. Despite not as comprehensive as systematic reviews, a scoping literature review still involve rigorous methods to ensure the accuracy of the information. This is particularly beneficial in the field of biofuel investigation such as ABE as more studies are nearly similar with comparable methods and outcomes. Therefore, by conducting scoping reviews, we can eliminate repeated and almost identical studies, thus reporting only the most significant and impactful published papers.

3. ABE as the Next Promising Biofuel

One issue that prevents the use of butanol in current internal combustion engine is its high production cost [15]. Pure butanol is produced from Acetone-Butanol-Ethanol (ABE) distillation. Using ABE directly is a more straightforward process as it eliminates the purification process as shown in **Figure 1**. It reduces the cost of fuel recovery for the individual component during fermentation while preserving the advantages of oxygenated fuels. In an internal combustion engine, the use of ABE has been applied both in SI and CI engines in several studies.

In the last five years, there has been a growing interest in the use of Acetone-Butanol-Ethanol (ABE) as a biofuel [16], [17]. ABE (631) and ABE (361) are often selected to understand different ABE's volumetric ratio. A recent development in ABE fermentation technology has allowed the volumetric percentage of each component to be controlled precisely. To improve the combustion phasing of ABE, the acetone content can be increased due to its higher volatility.

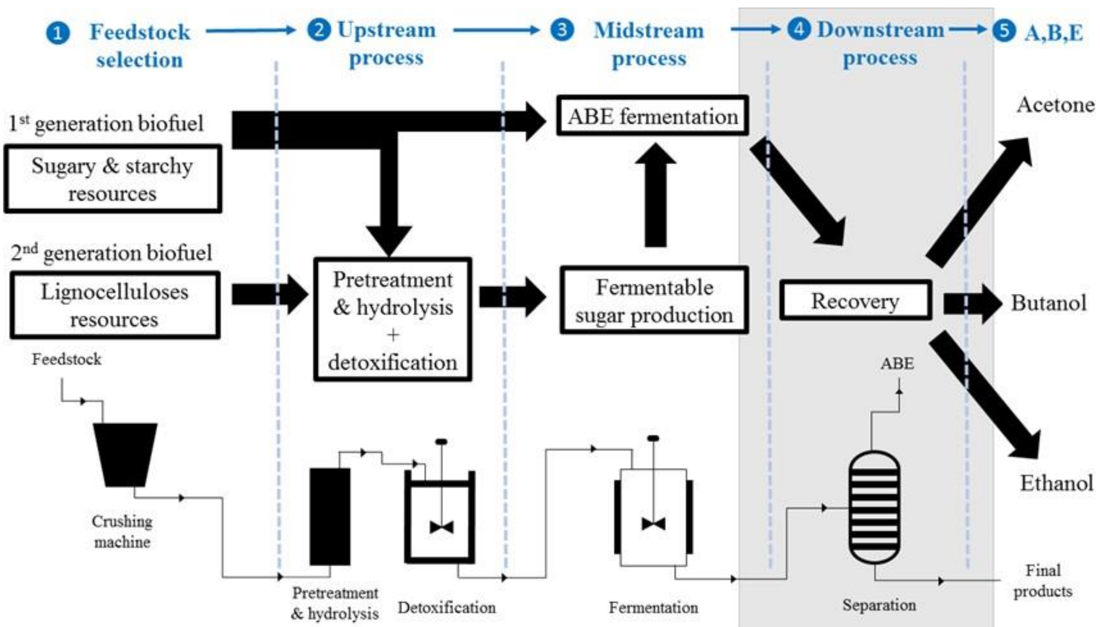

Figure 1. Butanol production from ABE fermentation [13]

This would enhance the vaporization of the fuel mixture and subsequently influence the ignition delay. To achieve the optimized volumetric ratio for ABE-diesel blends, Wu et al. [18] investigated various volumetric ratio of ABE (6:3:1; 3:6:1; 0:10:0, vol. %) in a constant volume chamber. The results showed that an increased acetone percentage would result in a substantial improvement in the combustion phasing.

Soot is an important emission characteristic of diesel exhaust pollutant. The addition of ABE into diesel fuel has been successful to lower soot emissions. Soot emissions of ABE-diesel blends are expected to reduce as a consequence of its extra oxygen content. Lin et al. [19] reported that lower natural flame luminosity was observed due to shorter combustion duration and stronger premixed combustion of ABE blends. As a result, the soot formation was successfully reduced. Wu et al. [18] compared 100% ABE and pure butanol to investigate the spray and combustion characteristics on an optical constant volume chamber. The results showed that ABE and butanol had analogous characteristics on spray and combustion performance, but ABE provided better soot reduction.

Lee et al. [20] also found that ABE-Diesel blends offered lower soot emission with better combustion efficiency compared to diesel at low ambient temperatures and low ambient oxygen concentrations. This study found that the ignition delay of ABE20 was longer than that of D100 (pure diesel) at low ambient temperatures. Another study investigating the soot formation process of ABE was conducted by Fu et al. [21]. They found that ABE had a lower tendency to generating soot than diesel fuel. Initial temperature and oxygen concentration had a negligible impact on their soot due to the fuel composition, molecular structure and fuel physicochemical characteristics. A recent study by Luo et al. [22] has confirmed that the average activation energies of the ABE blends-derived soot are lower than that of diesel. In other words, the soot particles are more prone to oxidise by oxygen content in ABE. Overall, studies on ABE show its potential to reduce one of the most harmful emissions in diesel engine known as soot. **Table 2** summarizes the use of ABE in diesel engine.

Another significant finding on ABE as biofuel was conducted to examine the droplet evaporation of ABE-diesel fuel in a non-combusting droplet chamber [23]. The results showed that adding ABE could increase the evaporation speed of droplet, thus decreasing its lifetime. Moreover, the ABE-diesel blends droplets evaporated faster than diesel. In another study, a semi-detailed chemical mechanism to model ABE-diesel spray combustion in a constant volume chamber was constructed [24]. Results from the literature were used to confirm the mechanism comprising ABE and n-heptane as surrogate fuel species. KIVA-3V programme combined with the validated mechanism were used to simulate the spray dynamic and combustion characteristics inside the chamber. The results of ignition delay, cylinder pressures and heat release rates from both the simulation in a shock tube and constant volume chamber showed reasonable agreements between the experimental and calculated values. The proposed semi-detailed chemical mechanism in this study was able to maintain the kinetic behavior of ABE-diesel blends. It was found that with the increasing of acetone percentage, the combustion phasing advanced significantly, while butanol would offset such advancing effect.

4. Physico-chemical Properties of Acetone-Butanol-Ethanol

Previous studies on ABE as discussed in the introduction have demonstrated the necessity of investigating ABE properties in more detail. Despite their significant importance, fuel properties of ABE are often understudied. It was difficult to obtain the fuel properties of ABE in the literature. Recent developments in ABE have highlighted the need for information on its fuel properties. Therefore, this section aims to critically discuss the physicochemical properties of ABE. Fuel properties of ABE-diesel blends in terms of their calorific value, density, kinematic viscosity, and distillation are discussed.

4.1. Calorific Value

Calorific value is an essential property that represents the energy content and the efficiency of fuel. The gross or higher heating values was used in this study. The lower or net heating value is normally used in European countries, whereas

Table 2. Recent studies on ABE-diesel blends in compression ignition engine

ABE%	Major findings	Ref.
ABE(361)100	• ABE's tendency to generate soot was lower than diesel fuel owing to its physicochemicalproperties.	Fu et al. [21]
ABE(361)100	• ABE retarded combustion phasing similar to butanol • Yet, ABE has a stronger potential to reduce soot formation than butanol in low temperature combustion with high exhaust gas recirculation.	Wu et al. [25]
ABE(631)20 ABE(361)20 ABE(0:10:0)20	• Butanol did not significantly affect the ignition delay and higher acetone ratio of ABE advancedthe combustion phasing.	Lee et al. [26]
ABE(361)10 ABE(361)20 ABE(361)30	• Soot particles were more vulnerable to attack byO_2 as a result of ABE addition	Luo et al. [22]
ABE(361)10 ABE(361)20 ABE(361)30	• ABE's droplet lifetime was shorter than diesel's. • Droplet evaporation of ABE-diesel blends varied with ambient temperature. • ABE-diesel blends evaporated faster than diesel.	Ma et al. [23]
ABE(631)20 ABE(361)20 ABE(0:10:0)20	• Acetone advanced the combustion phasing, while butanol compensated such advancing effect.	Zhang et al. [24]
ABE(361)10 ABE(361)20	• ABE-diesel blends were found to retard the combustion phasing, increase ignition delay and produce higher HC emissions than diesel fuel. • HC emissions could be reduced by advancing injection timing.	Lin et al. [19]
ABE(631)20 ABE(361)20 ABE(0:10:0)20	• Adding extra acetone is effective to improve thecombustion and suppress soot emission.	Wu et al. [18]
ABE(631)20 ABE(361)20 ABE(0:10:0)20	• Lower natural flame luminosity (soot formation)due to shorter combustion duration and strongerpremixed combustion	Wu et al. [27]
ABE(361)20 ABE(361)50 ABE(361)80	• ABE50 can maintain combustion characteristics comparable to diesel fuel. • Ratio of ABE between 20% and 50% showed critical spray behaviour.	Wu et al. [28]
ABE(5:14:1)10 ABE(5:14:1)20 ABE(5:14:1)30 + 0.5% & 1% water	• Water-ABE improved engine efficiency andreduced PM, NOx and PAH significantly	Chang et al. [29]
ABE(361)10 ABE(361)20	• ABE-diesel blends gave longer liquid penetration with brake power being close to pure diesel at 2600 rpm. • At 2000 rpm, maximum in-cylinder pressure was higher for ABE blends compared to diesel fuel. • HC and CO emissions reduced significantly with the addition of ABE, whereas NOx emissionsincreased slightly.	Algayyim et al. [30]
ABE(361)10 ABE(361)20	• Both ABE10 and ABE20 were found to substantially reduce HC emissions compared to diesel fuel	Algayyim and Wandel [31]

the higher or gross heating value is more prevalent in the USA [32]. The only difference is in the measurement of enthalpy change. The lower heating value measures the enthalpy change of combustion without water condensed, while the higher heating value measures it with water condensed.

The reduction of ABE-gasoline/diesel blends' calorific value might be unavoidable, but it may be beneficial to some extent. Despite the reduction in calorific value, brake thermal efficiency (BTE) of an engine fuelled with ABE-gasoline/diesel blends may increase. Theoretically, BTE is inversely proportional to BSFC and calorific value. The overall BTE will increase provided that the reduction in calorific value is not accompanied with significant increase in BSFC. This explains why in some studies, the use of ABE-gasoline/diesel blends could improve engine thermal efficiency despite having higher fuel consumption [29], [33]. Furthermore, the lower calorific value of ABE may reduce combustion temperatures, resulting in lower NOx emission. However, ABE with its extra oxygen content will promote more complete combustion. As a result, combustion temperature will increase and help the formation of higher NOx emission. This is where the higher latent heat vaporisation of alcohols that is known to cause cooling effect may offset such NOx increase, leading to the overall reduction of NOx emissions. Thus, it is important to find the right balance. To confirm these competing factors, further examination with various operating conditions worth investigating.

4.2. Density

Density is a significant physical property of fuel in ICE. Since density affects the mass of the injected fuel, the development of an injection system (pump and injectors) depends heavily on the information of density to adjust fuel volume delivery. However, modern vehicles use a lambda sensor by measuring the oxygen content in the exhaust gas to provide precise feedback to the ECU on how much fuel should be injected. Regardless of the technology, it is important to note that the lower density may result in retarded injection timing. This can worsen engine performance and increase exhaust emissions. One possible solution to address the reduction of the density of ABE blends is by advancing the injection timing in diesel engine. Therefore, the use of ABE in diesel engines may require some adjustment to the engine setting.

In addition to the retarded injection timing, an increase in unburned hydrocarbon (HC) emission may be reported. Lower density fuel produces small droplets that may reach the crevice region, forming unburned hydrocarbons. Also, the leaner mixture resulted from ABE's oxygen content may lead to a quenching effect on the walls that may increase the formation of HC emission even further. However, the lower density of ABE blends will also cause a significant reduction rate in the spray penetration, thus preventing the wall impingement. This is because the mass flow rate decreases with lower density, reducing jet momentum and leading to a weaker force to the surrounding air [34].

4.3. Kinematic viscosity

Kinematic viscosity is a critical biofuel chemical property. To measure the fluidity of biofuel, the kinematic viscosity is generally measured at 40 °C. The viscosity of a biofuel greatly effects engine operating condition. Viscosity may be simply defined as the thickness of a fluid. Therefore, a thick fluid such as biodiesel has higher viscosity compared to a thin liquid like water. In general, the kinematic viscosity is greatly influenced by temperature. It is known that a liquid at a higher temperature will have a reduced kinematic viscosity, whereas gas will show the opposite trend. Therefore, like density, the kinematic viscosity of fuel decreases with increasing temperature.

The viscosity plays an important role in determining engine performance, combustion and emission behaviours. Viscosity affects the atomisation of the injected fuel. Fuels with higher viscosity tend to deteriorate the injection process, resulting in less efficient atomisation. However, lower viscosity fuels can also cause problems such as leakage in pump and injector, thus decreasing maximum fuel delivery and reducing engine power. Since fuel also serves as a lubricant, higher ABE blends may potentially damage the moving parts of the fuel system, owing to its low viscosity. Like low density, low kinematic viscosity could decrease the spray tip penetration since fuel droplets are easily broken and deformed, causing a loss in spray momentum resulting in slow tip penetration [35].

A larger spray cone angle is expected to be observed with the low viscosity of ABE-diesel blends. The increase in spray cone angle may be attributed to the increase in spray instability resulted from ABE's low kinematic viscosity. As a result, better atomisation can be obtained because a larger spray cone angle results in a bigger contact region with the surrounding, thus enhancing the mixing process. This behaviour of low viscosity fuel is similar to that observed by Han et al. [36] and Zigan et al [37]. Note that fuel with lower viscosity can lead to significant energy loss as the fuel pump requires more power to deliver low viscous fuel. Hence, accurate information of ABE's kinematic viscosity is immensely important. Not only does it affect the fuel atomisation, but it also influences the fuel droplets size, the formation of engine deposits and harmful emissions as well as the fuel lubricity. Also, the accurate information of the blends' kinematic viscosity is an important parameter for the electronic control unit.

4.4. Distillation

Another important fuel property is distillation. A distillation curve is normally given as temperature boiling vs the volume of percent distilled. The curve represents the percent of light, medium and heavy component of a fuel's distillation. The temperatures at 10%, 50% and 90% distilled are important values as they are used to calculate cetane index. They are also used to predict engine performance and emission. A fuel with low T10, for example, is known to enhance cold starting, whereas a fuel with high T90 may produce more particulate matter and form deposit in the chamber due to its heavy compounds [38]. Note that ABE blends could successfully reduce PM emission as reported by Chang et al. [33] in **Figure 2**. Like viscosity, characteristics of distillation temperatures may influence fuel atomisation and the evolution of combustion in the internal combustion engine.

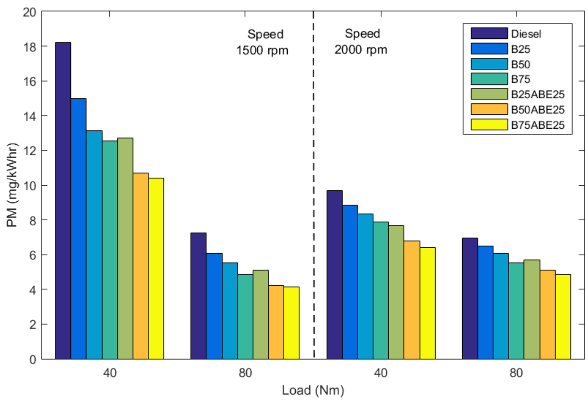

Figure 2. Level of PM emissions from ABE blends [33]

5. Conclusion

The acetone-butanol-ethanol (ABE) fermentation gained its popularity and became the second largest fermentation industry after ethanol in the early 20th century due to demand from car coating industry. Today, interesting in using ABE as a biofuel has emerged. Several preliminary studies have been conducted. Overall, most findings concluded that harmful emissions such as NOx and Particulate Matter (PM) were successfully reduced significantly. However, the BSFC was found to increase. This is because the heating value and energy density of ABE fuel are relatively lower compared to gasoline or diesel fuel, thus increasing its fuel consumption.

Overall, this study has proven that ABE can be used as an additive for diesel fuel due to its satisfying physicochemical properties. However, it should be noted that the ABE-gasoline/diesel blends are greatly influenced by each of its component ratios (acetone, butanol, ethanol). Therefore, different volumetric ratios will give different properties values. However, in general, ABE with 30%, 60% and 10% volumetric ratio show more promising characteristic as it can be used up to higher concentration compared to ratios such as ABE(631) and ABE(136). Also, engine operating condition play a key role in determining the overall performance, combustion and emission characteristics. All in all, the major contribution of the present study is the information herein could be used to give insight into ABE as the next promising biofuel.

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Author's Declaration

Authors' contributions and responsibilities

Wrote the original paper (S.M.N.R., I.V.); Supervision (N.T.); Proofreading and editing (A. S., A.C.O.); Resources (M.B.A., D.W.D.).

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Availability of data and materials

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Competing interests

The authors declare no competing interest.

Additional information

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