Selection of microalgae strains for sustainable production of aviation biofuel

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Abstract

This study develops and applies the PROMETHEE-GAIA method as a new tool to select microalgae strains for aviation fuel production. Assessment involves 19 criteria with equal weighting in three aspects, namely biomass production, lipid quality, and fatty acid methylester properties. Here, the method is demonstrated for evaluating 17 candidate microalgae strains. *Chlorella sp.* NT8a is assessed as the most suitable strain for aviation fuel production. The results also show that unmodified biofuel from the most suitable strain could not meet all jet fuel standards. In particular, microalgae-based fuel could not satisfy the required density, heating value and freezing points of the international jet fuel standards. These results highlight the need for a broad action plan including improvement in the processing or modification of biofuel produced from microalgae and revision of the current jet fuel standards to facilitate the introduction of microalgae-based biofuel for the aviation industry.

Keywords: Carbon emission reduction, fatty acid methylester, fuel properties lipid, microalgae, sustainable aviation fuel.

1. Introduction

Aviation is crucial to globalisation and is a significant aspect of the world economy. Just before the COVID19 pandemic, commercial aviation accounted for over 2% of global carbon emissions. With the return of international and domestic air travel post COVID19, the carbon footprint of the aviation industry is expected to increase even further (IATA, 2021). Moving forward, the aviation industry needs to adopt a comprehensive strategy to attain net-zero emissions by 2050 (Gray et al., 2021). It is particularly difficult to decarbonise the aviation industry due to the lack of low-emission options for long-haul flights. New technologies have been developed to decarbonize the aviation industry. They can be divided into four categories: (1) significant enhancements to aircraft design and flight performance to improve fuel efficiency; (2) changes to airspace management to reduce airborne time and shortening travelled distances; (3) alternative engine technologies such as battery-electric propellers and hydrogen fuel cells; and (4) use of biofuel from renewable biomass (Clouston, 2021).

Improvements in aircraft design and airspace management have been made; however, they cannot fundamentally change the aviation industry's carbon footprint (O'Malley et al., 2021). There are significant technological challenges to realising electric and hydrogen-fuelled aircraft. Batteries have low energy density and are not suitable for long haul flights. Similarly, the energy density of hydrogen is about one-quarter of that of current jet fuel. The large hydrogen fuel tank and safety issues associated with highly flammable and permeable hydrogen gas are major technical challenges making hydrogen aircraft unsuitable for civilian air travel (Henderson, 2021). The aviation industry has, therefore, placed a significant emphasis on the development of carbon-neutral biofuel, known as sustainable aviation fuel (SAF), to displace fossil-based jet fuel (Bwapwa et al., 2017).

SAF production from microalgae is one of the most economically viable options currently in development (Wang & Tao, 2016). During the process of microalgae cultivation, CO_2 is extracted from the atmosphere to produce lipids via photosynthesis. The produced lipids are then converted to fatty acid methyl ester (FAME) to replace conventional jet fuel. In fact, there are instances where the aviation industry has already blended some FAME with conventional jet fuel to lower carbon emissions (Hassan et al., 2021). Microalgae cultivation does not compete against food production for arable land (Vu et al., 2020). Microalgae do not require a large volume of freshwater and they can thrive in both marine and freshwater environments (Wang et al., 2021), grow at a rate much faster than all other energy crops, and obtain nutrients from wastewater (Shuba & Kifle, 2018; Vu et al., 2022).

The quality of the produced biofuel is governed by the quality and content of lipids in the microalgae (Ali et al., 2021). Lipid quality and production using microalgae are dependent on environmental factors, such as growing time, nutrient availability, and exposure to lighting (Siddiki et al., 2022). These environmental factors can be regulated. Thus, the chosen microalgae strain is the most decisive factor governing qualitative fatty acid profiles and lipid production rates. Indeed, previous work has shown considerable variation in the quantities and quality of lipids between different microalgae strains. For example, *Tetraselmis maculata* has a total lipid content of less than 4.5%, while for *Schizochytrium sp.* this is greater than 80% (Huerlimann et al., 2010; Siddiki et al., 2022). Additionally, the amount of lipid present in a given microalgae strain varies depending on its growth phase, with the lowest yields prevalent for logarithmic growing strains in the late logarithmic phase and static or growing strains in the stationary phase (Hu et al., 2008). The production of SAF from microalgae lipids can be performed using the transesterification process. Transesterification is the chemical reaction between fat (lipids) with alcohol to produce alkyl esters or biodiesel (Mofijur et al., 2013). The fuel quality is influenced by the structural features of the individual fatty acids. The quality of SAF to be produced can be controlled by selecting an appropriate microalgae strain with different types of fatty acids, the mixture of the different types of fatty acids through the selection of production organisms, increasing the concentration of desired fatty acids in the lipid, or by the genetic modification (Bwapwa et al., 2017).

Microalgae belong to a very diverse group of fast-growing photosynthesis microorganisms that can produce lipids essential to biofuel production from sunlight (Rastogi et al., 2018; Kumar et al., 2020). As a largely untapped resource, more than one million different microalgae strains are thought to exist in nature. Only a small fraction of these have been fully characterised and industrially cultivated with beneficial use (Nagarajan et al., 2020). Selecting suitable microalgae strains is a major challenge for the commercial realisation of microalgae-based SAF (Lim et al., 2021). Several fundamental qualities are required to inform microalgae, regardless of whether the biomass is used for fuel or other applications. A high “areal” biomass production rate is critical to lower the cost of microalgae-based SAF. It is also essential for the microalgae to have a high lipid content and a constant biochemical composition to meet the stringent jet fuel standards.

The Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE) is a versatile decision support tool to rank a finite set of alternatives from best to worst. In the PROMETHEE method, a pair-wise comparison is made between alternative solutions to determine the best option. PROMETHEE analysis relies on two parameters: criterion weighting and the preference function. The preference function converts the difference between the estimations obtained by two alternatives into a preference level ranging from zero to one based on the difference between the two alternatives (Behzadian et al., 2010). An interactive module known as Graphical Analysis for Interactive Assistance (GAIA) is often included in PROMETHEE for visualisation. With the help of decision vectors that stretch in the direction of the preferred solution, GAIA makes rational decision-making more accessible.

This study develops and applies the PROMETHEE-GAIA method as a new tool to screen and identify suitable microalgae strains for SAF production. The proposed method uses existing data from the literature to assess key parameters for microalgae-based SAF production. It aims to identify microalgae strains that can offer high-quality lipids and high lipid content to meet the stringent aviation fuel standards.

2. Method

2.1 Data collection

In this study, 17 microalgae strains were selected and screened for their growth characteristics, lipid content, and fatty acid methyl ester properties (see Supplementary Materials). The composition data for the growth parameters, lipid content, and fatty acid methyl ester (FAME) of these strains have been reported in previous studies (Duong et al., 2015; Lim et al., 2012).

2.2 Microalgae strain selection

The ranking process was based on three key aspects including microalgae production parameters, lipid quality, and FAME properties. Each of these aspects was analysed using defined criteria. The criteria used to evaluate microalgae production include growth rate, biomass concentration, and lipid productivity. The criteria used to evaluate lipid quality include total FAME, saturated fatty acids (SFA), monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA). The criteria used to evaluate FAME properties using the PROMETHEE method include kinematic viscosity (KV), higher heating value (HHV), long-chain saturated factor (LCSF), degree of unsaturation (DU), cold filter plugging point (CFPP), pour point (PP), oxidation stability (OS), cloud point (CP), cetane number (CN), density (D), iodine value (IV), and saponification value (SV). These criteria have the same weighting in the analysis. Each microalgae strain was first screened based on the individual aspects of biomass production, lipid quality and FAME quality after which all aspects were considered collectively.

2.3 PROMETHEE-GAIA method

PROMETHEE in conjunction with Graphical Analysis for Interactive Assistance (GAIA) is a popular decision analysis process. It has substantial benefits relative to other multicriteria decision analysis (MCDA) methods, because of its decision matrix which leads to the best possible alternatives. It relies on the principle of pairwise comparison of the alternatives. The key steps of the PROMETHEE-GAIA method include selecting preferences, comparing the alternatives, building a criteria matrix, partial ranking, and full ranking. The flow chart of the PROMETHEE-GAIA process used in this study is shown in Figure 1. In this study, the weight of each criterion is considered equal. The preference functions of the criteria were modelled as Min (i.e., lower values are preferred for good fuel) or Max (higher values are preferred for good fuel).

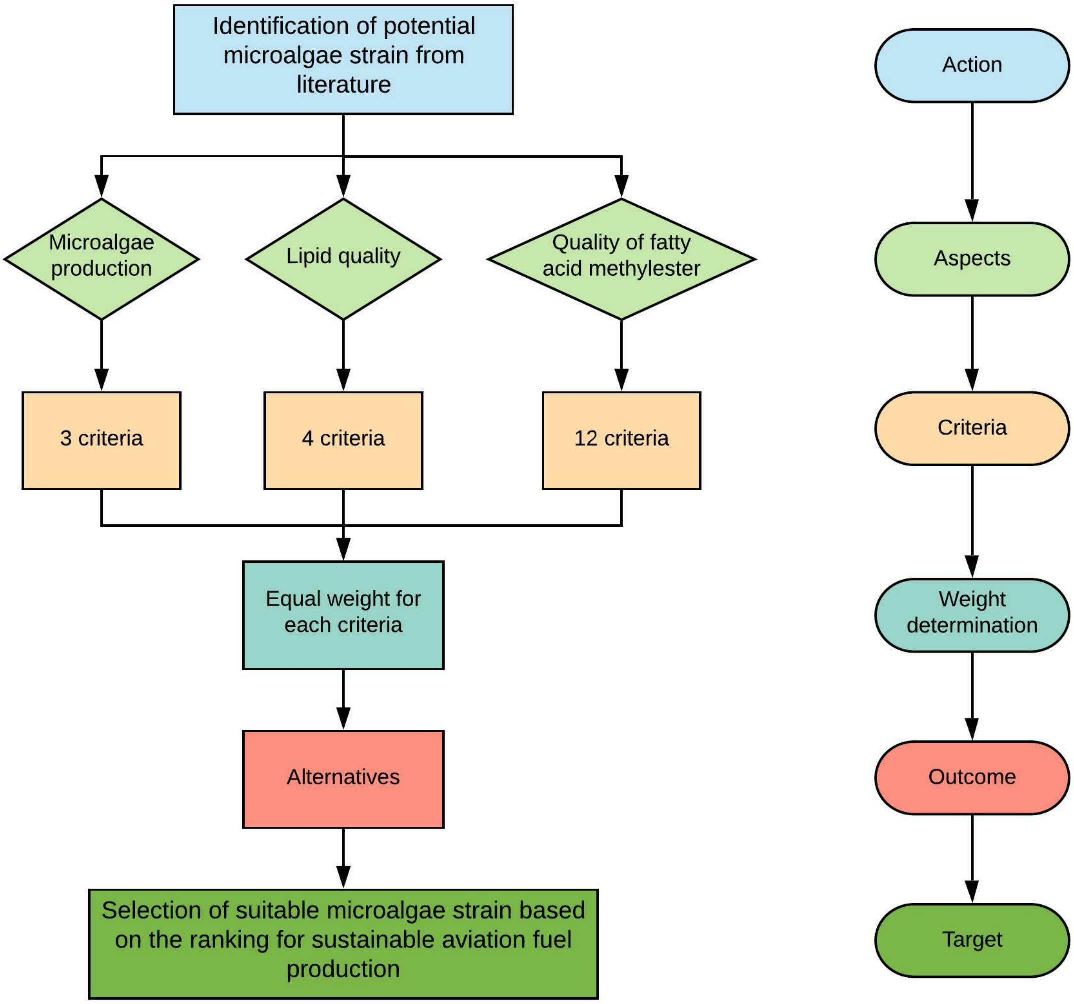

Figure 1: Flow chart of PROMETHEE-GAIA process utilisation in this study.

2.4 Determination of fuel properties based on fatty acids

The quality of the FAME is determined using fatty acid composition data. The fatty acid composition data of high-ranked microalgae six strain (top three for the biomass production and lipid quality aspects) was obtained from Duong et al., (2015) and Lim et al., (2012). The quality of the methylester was determined by the analysis of key FAME properties using empirical formulae from the literature. The physical properties including KV, D, and HHV of each FAME were estimated using equations 1–3 respectively, and a summation of all FAME-derived properties provide the final KV, D, and HHV values of the fuel as published by Ramírez-Verduzco et al., (2012):

$$\ln(KV)_i = -12.503 + 2.496 \times \ln(Molecular\ weight)_i - 0.178 \times C_{DBi} \quad (1)$$

$$D_i = 0.8463 + \frac{4.9}{(Molecular\ weight)_i} + 0.0118 \times C_{DBi} \quad (2)$$

$$HHV_i = 46.19 - \frac{1794}{(Molecular\ weight)_i} - 0.21 \times C_{DBi} \quad (3)$$

where KV_i is kinematics viscosity at 40 ºC (mm^2/s), D_i is the density at 20 °C (kg/m^3), HHV_i is the higher heating value (MJ/kg) of i^{th} FAME. C_{DB} denotes the number of carbon double bonds of the i^{th} FAME.

The cetane number of methyl ester was calculated based on the molecular weight, using the following equation (Krisnangkura, 1986):

$$CN = 46.3 + \frac{5458}{Saponification\ value} - 0.21 \times Iodine\ value \quad (4)$$

where CN is the cetane number. The saponification value (mg KOH/g) and iodine value (g I_2/100g) of fat is predicted by the following equations (Mofijur et al., 2013):

$$SV = \sum_{i=0}^{n} \frac{560 \times FAME_{wt\%}}{Molecular\ weight\ of\ the\ ith\ FAME} \quad (5)$$

$$\mathrm{IV} = \sum_{i=0}^{n} \frac{254 \times FAME_{wt\%} \times C_{DB}}{Molecular\ weight\ of\ the\ ith\ FAME} \quad (6)$$

where SV is the saponification value and IV the iodine value. $FAME_{wt\%}$ is the percentage of each FAME, and C_{DB} is the number of double bonds of the i^{th} FAME.

An equation developed by Ramos et al. (2009) was used to calculate the degree of unsaturation (DU), based on the mass fraction of MUFA and PUFA:

$$DU = \sum MUFA + (2 \times PUFA) \quad (7)$$

Based on Ramos et al., (2009), the long-chain saturation factor (LCSF) is calculated in % and the cold filter plugging point (CFPP) in °C:

$$LCSF = (0.1 \times C16{:}0) + (0.5 \times C18{:}0) + (1 \times C20{:}0) + (2 \times C24{:}0) \quad (8)$$

$$CFPP = (3.1417 \times LCSF) - 16.477 \quad (9)$$

Oxidative stability (OS) is measured in hours and can be estimated by the fatty acid profile with the help of the following formula (Patel et al., 2017):

$$OS = \frac{117.9295}{wt\%\, C18{:}2 + wt\%\, C18{:}3 + 2.5905} \quad (10)$$

Cloud point (°C) and pour point (°C) are estimated using the following equations (Sarin et al., 2009):

$$CP = (0.526 \times C16{:}0) - 4.992 \quad (11)$$

$$PP = (1.1 \times CP) - 5.5 \quad (12)$$

3. Results and discussion

Three key aspects including biomass production, lipid quality and fuel quality are evaluated to select suitable microalgae strains for jet fuel production. The findings are discussed in the following sections.

3.1 Biomass production

The culture condition and biomass production are essential for SAF production. The growth rate, biomass concentration and lipid productivity of 17 microalgae strains are summarised in Table 1. Of these 17 strains, the maximum and minimum growth rate is 0.59 and 0.30 L/day for *Chlorella* sp. NT8a and *Dunaliella salina,* respectively, the biomass concentration is 0.33 and 0.02 g/L/day for *Chlorella* sp. NT8a and *Tetraedron caudatum* NT5, respectively, and the lipid productivity is 14.61 and 1.50 µg/mL/day for *Chlorella* sp. NT8a and *Tetraselmis chui,* respectively. The data in Table 1 demonstrates the need for a systematic multiple criteria analysis to rank suitable microalgae strains for SAF production (Table 2).

3.2 Selection of strain based on the lipid quality aspect

Lipid quality is another crucial parameter for selecting microalgae strains for sustainable fuel production. The fatty acid methyl ester content, saturated fatty acids, monounsaturated fatty acids, and polyunsaturated fatty acids have been selected as key criteria for ranking the 17 microalgae strains based on the lipid quality aspect criteria given in Table 1. Of these 17 strains, the maximum and minimum FAME content is 14 and 1.20 µg/mL dry weight for *Chlorella* sp. NT8a and *Pavlova salina*, respectively, SFA is 53% and 27.04% for *Pavlova salina* and *Graesiella emersonii* NT1e, respectively, MUFA is 37.38% and 5.50% for *Tetraedron caudatum* NT5 and *Pavlova salina*, respectively, and PUFA is 60% and 24.60% for *Dunaliella salina* and *Chaetoceros muelleri*, respectively.

Table 1: The value of the criteria for selecting strain based on biomass production and lipid quality criteria (Duong et al., 2015; Lim et al., 2012).

Microalgae strains	**Criteria for biomass production**			**Criteria for lipid quality**			
	Growth rate (L/day) *	Biomass concentration (g/L/day) *	Lipid productivity (mg/L/day) *	FAME (µg/mL) *	SFA (%) *	MUFA (%) $^{\alpha}$	PUFA (%) $^{\alpha}$
Chaetoceros muelleri	0.35	0.07	3.30	5.90	44.00	31.40	24.60
Chlorella sp. BR2	0.34	0.08	3.90	5.30	43.60	14.40	42.00
Chlorella sp. NT8a	0.59	0.33	14.61	14.00	30.32	15.38	54.30
Dunaliella salina	0.30	0.05	4.80	11.40	31.40	8.60	60.00
Graesiella emersonii NT1e	0.38	0.14	9.99	9.50	27.04	33.14	39.81
Isochrysis galbana	0.35	0.06	2.00	3.90	39.90	29.60	30.50
Nannochloropsis sp. BR2	0.32	0.08	6.20	10.60	40.70	32.80	26.50
Pavlova lutheri	0.48	0.06	2.00	4.00	41.10	20.50	38.30
Pavlova salina	0.45	0.24	2.10	1.20	53.00	5.50	41.40

Scenedesmus dimorphus NT8c	0.52	0.07	9.53	6.95	32.58	35.00	32.42
Scenedesmus dimorphus NT8e	0.41	0.09	12.39	6.50	31.40	37.38	31.22
Scenedesmus sp. NT1d	0.48	0.03	3.17	8.20	29.70	27.33	42.96
Tetraedron caudatum NT5	0.37	0.02	2.71	6.08	28.57	23.28	48.15
Tetraselmis chui	0.35	0.06	1.50	3.20	47.90	18.20	34.00
Tetraselmis sp. M8	0.35	0.11	2.10	2.50	30.40	10.20	59.50
Tetraselmis sp. M8	0.47	0.08	4.80	9.90	38.90	19.50	41.70
Tetraselmis suecica	0.37	0.10	1.50	10.80	45.60	19.70	34.70

*The preference is set to maximum; $^{\alpha}$The preference is set to minimum.

Table 2 shows the overall ranking of the microalgae strain based on biomass production parameters using PROMETHEE MCDA. The φ-score is the net flow score that can be negative or positive depending on the angular distance from the decision vector and the distance from the centre (Anwar et al., 2019). Based on the biomass production aspect *Chlorella sp. NT8a* ranked first (φ-score: 0.31) while *Tetraselmis chui* ranked last (φ-score: -0.11) for the production of sustainable aviation fuel (Table 2). Based on the lipid quality aspect, *Tetraselmis suecica* ranked 1 (φ-score: 0.37) while *Tetraselmis sp.* M8 ranked 17 (φ-score: -0.32) for the production of sustainable aviation fuel.

Table 2: The calculated rank and corresponding φ-score of strains based on biomass production and lipid quality.

Biomass production			**Lipid quality**		
Microalgae strain	Rank	φ-score	Microalgae strain	Rank	φ-score
Chlorella sp. NT8a	1	0.31	*Tetraselmis suecica*	1	0.37
Scenedesmus dimorphus NT8e	2	0.17	*Nannochloropsis sp.* BR2	2	0.20

Scenedesmus dimorphus NT8c	3	0.15	*Pavlova salina*	3	0.20
Graesiella emersonii NT1e	4	0.11	*Tetraselmis chui*	4	0.16
Tetraselmis sp. M8	5	0.01	*Tetraselmis sp.* M8	5	0.15
Nannochloropsis sp. BR2	6	0.00	*Chlorella sp.* BR2	6	0.13
Scenedesmus sp. NT1d	7	-0.02	*Chaetoceros muelleri*	7	0.13
Dunaliella salina	8	-0.04	*Chlorella sp. NT8a*	8	0.03
Chlorella sp. BR2	9	-0.05	*Dunaliella salina*	9	0.01
Pavlova lutheri	10	-0.05	*Pavlova lutheri*	10	0.01
Chaetoceros muelleri	11	-0.06	*Isochrysis galbana*	11	-0.05
Pavlova salina	12	-0.06	*Scenedesmus dimorphus* NT8c	12	-0.15
Tetraedron caudatum NT5	13	-0.07	*Scenedesmus sp.* NT1d	13	-0.18
Tetraselmis sp. M8	14	-0.09	*Scenedesmus dimorphus* NT8e	14	-0.19
Isochrysis galbana	15	-0.09	*Graesiella emersonii* NT1e	15	-0.20
Tetraselmis suecica	16	-0.10	*Tetraedron caudatum* NT5	16	-0.28
Tetraselmis chui	17	-0.11	*Tetraselmis sp.* M8	17	-0.32

3.3 Selection of strain based on the fuel properties derived from fatty acids

The aviation industry has the most stringent fuel standards. Thus, FAME properties are an important consideration to ensure fuel standard compliance. The carbon chain sizes and the number and/or position of double bonds are factors that determine the molecular structure of FAME. Additionally, these molecular characteristics in turn influence the parameters of fuel quality. Table 3 shows the comparative fatty acid composition of the top-ranked strain (top three based on both biomass production and lipid quality). Table 4 shows the FAME's key fuel properties derived from fatty acids of the selected strain.

Table 3: Comparative fatty acid composition of selected strains (Duong et al., 2015; Lim et al., 2012).

Strain Fatty acids	*Chlorella sp. NT8a*	*Scenedesmus dimorphus NT8e*	*Scenedesmus dimorphus NT8c*	*Nannochloropsis sp.*	*Tetraselmis suecica*	*Pavlova salina*
C12:0	0.30	0.26	0.22	0.11	0.01	0.04
C14:0	0.69	0.23	0.18	1.96	0.12	3.69
C15:0	0	0	0	0.22	0.03	0
C16:0	33.43	27.94	22.21	18.51	4.72	4.71
C16:1	2.89	2.13	1.90	15.03	0.31	0.68
C16:2	2.34	1.15	0.71	0.22	0	0
C17:0	0	0	0	0.22	0	0
C18:0	1.03	1.91	1.59	1.68	1.18	1.58
C18:1	15.09	34.49	24.45	3.37	2.05	0.38
C18:2	22.29	9.43	6.29	0.50	2.64	0.21
C18:3	38.85	20.37	17.71	0.22	1.18	0.25
C18:4	0	0	0	0	0	1.16
C20:0	0	0.40	0.31	0.11	0.07	0.08
C20:1	0	0.43	0.33	0	0.28	0
C20:4	0	0	0	3.31	0.44	0
C20:5	0	0	0	10.55	0.39	3.06
C22:0	0	0.39	0.32	0	0	0
C22:5	0	0	0	0	0	1.20
C22:6	0	0	0	0	0	2
Total FAME (µg/mL)	116.91	99.13	76.22	56.04	13.41	19.02
SFA%	30.32	31.4	32.58	40.74	45.65	53.04
MUFA%	15.38	37.38	35	32.83	19.68	5.59
PUFA%	54.30	31.22	32.42	26.43	34.67	41.37

Table 4: Calculated fuel properties based on fatty acid compositions of selected strains.

Criteria	Preferences	*Chlorella sp. NT8a*	*Nannochloropsis sp.*	*P. salina*	*Scenedesmus dimorphus NT8c*	*Scenedesmus dimorphus NT8e*	*T. suecica*
DU	Min	124.0	85.7	88.3	99.8	99.8	89.0
LCSF (%)	Max	3.3	5.0	7.0	5.0	4.8	8.4
IV (g I_2/100 g)	Min	140	134	174	110	107	101
SV (mg KOH/g)	Min	202.6	208.9	206.9	203.9	203.2	205.8
CN	Max	43	42	33	50	51	52
KV (mm^2/s)	Min	3.4	3.3	3.2	3.6	3.7	3.7
D (kg/m^3)	Min	883	883	889	879	880	878
HHV (MJ/kg)	Max	39.2	39.1	39.1	39.3	39.4	39.4
OS (h)	Max	3	4	4	4	4	4
CP (°C)	Min	10	12	8	10	10	14
PP (°C)	Min	6	8	3	6	5	9
CFPP (°C)	Min	-6	-1	6	-1	-1	10

3.4 Selection of suitable microalgae strain

Density is an important characteristic of fuel since it influences engine performance, combustion quality, and other characteristics like the cetane number and viscosity (Mahmudul et al., 2017). Density increases the size of fuel droplets, which impacts combustion quality. On the other hand, reduced density increases the efficiency of atomization and the formation of the air-fuel ratio. Current jet fuel standards specify fuel density in the range of 775 kg/m^3 to 840 kg/m^3. The fuel properties of all selected strains show similar densities which are marginally higher than the jet-fuel standard. However, the density of biofuel derived from these microalgae are compatible with the American (ASTM D6751) and European (EN 14214) fuel standards which are 870-890 kg/m^3 and 860-900 kg/m^3 respectively. Thus, they can be used as drop-in fuel (i.e., to blend with conventional jet fuel).

Fuel viscosity is important for atomization, spray properties, and combustion quality (Mofijur et al., 2013). Inadequate lubrication and increased wear and tear result from lower kinematic viscosity. High fuel viscosity results in large fuel droplets during injection, lowering the combustion quality and increased exhaust emissions. According to the jet fuel standard, the maximum viscosity of fuel can be 8 mm^2/s. *P. salina* produces biofuel with the lowest kinematic viscosity of 3.2 mm^2/s while *T. suecica* results in the highest viscosity fuel of 3.7 mm^2/s. The viscosity of microalgae-based fuel only varies within a narrow range which is mostly consistent with most aviation fuel standards.

The heating value is another crucial parameter. Fuel energy content is defined as the amount of energy generated when a specific volume of fuel is completely combusted (Ashraful et al., 2014). A high heating value will offer improved engine performance. According to the jet fuel standard, the higher heating value of jet fuel must be more than 42.8 MJ/kg. The heating values of biofuel from all strains are marginally below the current jet fuel standards (Table 4).

Results in Table 4 suggest the need for fuel blending to satisfy the heating value in jet fuel standards. The aviation industry can also consider lowering the heating value in fuel standards to accommodate microalgae-based biofuel.

CN is a measurement of ignition timing inside the combustion chamber that determines the ignition quality of fuel (Mofijur et al., 2017). In general, when compared to fossil diesel fuel, FAME has a greater CN (Arbab et al., 2015). A higher CN indicates a shorter ignition delay and early combustion, which aids in the engine's smooth operation. In general, the CN is related to the FAME's saturation levels, with a higher saturation level resulting in a higher CN and a higher unsaturation level resulting in a lower CN (Chacko et al., 2021). A higher cetane number is desirable but no standards have been set for the cetane number. Similar to kinematic viscosity, *P. Salina* exhibited the lowest cetane number and *T. suecica* exhibited the highest cetane number (more than 60% higher than *P. Salina*).

Oxidation stability represents the FAME's ability to maintain the fatty acid composition during extended storage without degradation (Knothe, 2005). Oxidation degradation generates oxidation products that might compromise fuel properties and worsen the fuel quality. The degree of fatty acid unsaturation has an impact on FAME oxidation stability (Wang et al., 2021). Impurities such as metals, FFAs, chemicals, and antioxidants also have a significant impact on stability. Because of corrosive chemicals and deposits, oxidation stability may increase engine wear. Higher oxidation stability is desirable and according to the ASTM D6751 and EN 14214 standards, minimum oxidation should be 3 and 6 hours, respectively. The jet fuel standard has not set a limit.

Cloud point, pour point, and cold filter plugging point/freezing point are commonly utilised criteria to determine the cold flow characteristics of biodiesel (Magalhães et al., 2019). In general, these parameters measure the temperature at which the fuel's liquid phase begins to change and it crystallises, resulting in changes in fluidity and performance (Hazrat et al., 2020). Its cold flow characteristics define the behaviour of the fuel under cold flow conditions. Partial solidification of fuel can cause clogged fuel delivery lines and filters at high altitudes and low temperatures, causing engine ignition problems. The cloud point of a fuel is the lowest temperature at which crystal formation is visible as a cloudy suspension. The CFPP is the lowest temperature at which a given volume of fuel passes through a specified filter in less than 60 seconds (Knothe, 2005). Even though these properties are important, there is no ASTM D6751 or EN14214 standard for them. A standard has only been set for the freezing point of jet fuel. The *Chlorella sp.* NT8a strain has the lowest freezing point at –6 °C but this is still well above the required freezing point required by the current jet fuel standards. The ambient temperature can be as low as –40 °C at the operational altitude of commercial aircraft. Unlike the heating value discussed above, the freezing point is an uncompromisable standard. A suitable fuel additive is required for the adaptation of microalgae-based biofuel in the aviation industry to meet this standard.

The ranking of the following microalgae shortlist for SAF production based on the FAME properties in decreasing order of suitability is *Scenedesmus dimorphus* NT8e (φ-score: 0.09), *Chlorella sp.* NT8a (φ-score: 0.06), *Scenedesmus dimorphus* NT8c (φ-score: 0.06), *Nannochloropsis sp.* BR2 (φ-score: 0.03), *Tetraselmis suecica* (φ-score: -0.11), and *Pavlova salina* (φ-score: -0.13).

Chlorella sp. NT8a and *Tetraselmis suecica* strains are found to be the top-ranked strains based on biomass production and lipid productivity, respectively. Therefore, it is important to rank strains in consideration of all criteria because they are all are important in the selection of suitable strains for the production of sustainable fuel from microalgae. A GAIA plane can analyse the performance evaluation taking into account all 19 criteria examined in this study (Figure 2). The length of the criteria vectors and the direction in which they point demonstrate the impact these criteria have on the decision vector and (red line in Figure 2) the preference for the microalgae strain. The decision vector points toward the top right plane where *Chlorella sp.* NT8a is located. Therefore, *Chlorella sp.* NT8a is identified as a suitable strain for SAF production. The criteria lipid productivity, growth rate, FAME content, LCSF, CFPP and degree of unsaturation are located on the same plane of the decision vector and directed in the same direction of the decision vector. Therefore, it is considered that these criteria have a significant influence on the decision vector. It is preferable to have a decision vector that is long and not orthogonal to the GAIA plane when making a strong decision (Espinasse et al., 1997). The decision vector reveals the most suitable strain, i.e., those aligned with the direction of the decision vector and the outermost criteria in the direction of the decision vector are the most desirable (Brans & Mareschal, 2005). Criteria that are located near (±45°) have a good agreement with the decision vector and those located far apart (135−225°) show different perceptions to the decision vector, and criteria that are nearly in an orthogonal direction have no influence (Espinasse et al., 1997) on the decision vector. For example, lipid productivity, growth rate, FAME content, LCSF, CFPP and degree of unsaturation (in Figure 2) influence decision making whereas OS, SFA, and biomass concentration show different perceptions to the decision vector. The criteria MUFA, CN, IV are independent and have little or no influence on the decision vector. The length of the criteria vectors indicates their influence on the decision vector and therefore the ranking of the strain (Brans & Mareschal, 2005). Although the calculated ranking shows *Chlorella sp.* NT8a to be the most suitable microalgae strain for SAF production, Figure 2 also shows that it is not the most favourable strain for all assessment criteria.

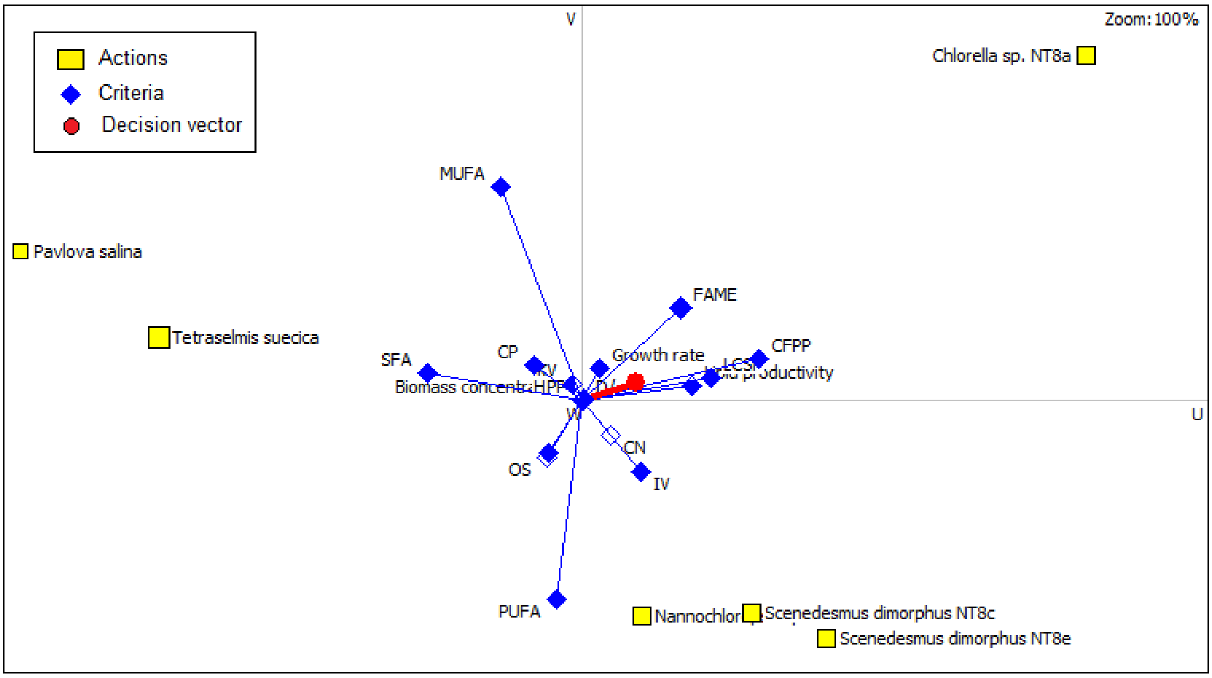

Figure 2: GAIA plane for six microalgae strains against 19 assessment criteria.

By considering all aspects (biomass production, lipid quality and FAME properties), the ranking of the microalgae shortlist for the production of sustainable aviation fuel in decreasing order is *Chlorella sp.* NT8a (φ-score: 0.07), *Nannochloropsis sp.* BR2 (φ-score: 0.03), *Scenedesmus dimorphus* NT8e (φ-score: 0.02), *Scenedesmus dimorphus* NT8c (φ-score: 0.00), *Tetraselmis suecica* (φ-score: -0.03) and *Pavlova salina* (φ-score: -0.08), respectively.

In a summary, among the 17 strains considered in this study, *Chlorella sp. NT8a* is the most suitable strain for SAF production. The findings of the PROMTHEE-GAIA analysis method are compared with two other common MCDA methods including the equal-weighted sum method (WSM) and equal-weighted product method (WPM) summarised in Table 5. In both cases, equal weight for each criterion is considered. WSM selects options based on a weighted sum of particular criteria. The alternative that most closely resembles the criteria is chosen. In WPM, the weights are exponents connected with each criterion value, and their products are compared. The option that best fits all criteria has the highest preference score.

According to WSM, the decreasing order of ranking is *Chlorella sp. NT8a* > *Scenedesmus dimorphus* NT8e > and *Nannochloropsis sp.* BR2; while according to WPM, the ranking order is the same although with different φ-score values (Table 5). It is clear that in both cases *Chlorella sp.* NT8a ranked as the most suitable strain which is aligned with the findings of PROMTHEE-GAIA MCDA.

Table 5: Calculated rank and corresponding φ-score of microalgae strains using WSM and WPM MCDA.

WSM			**WPM**		
Rank	**Strain**	**φ-score**	**Rank**	**Strain**	**φ-score**
1	*Chlorella sp. NT8a*	0.85	1	*Chlorella sp. NT8a*	0.88
2	*Scenedesmus dimorphus NT8e*	0.74	2	*Scenedesmus dimorphus NT8e*	0.85
3	*Nannochloropsis sp. BR2*	0.72	3	*Nannochloropsis sp. BR2*	0.84

Ranked the most suitable strain for sustainable fuel production, the FAME properties of *Chlorella sp.* NT8a were compared with international fuel standards and the FAME of other strains. It can be seen that the viscosity and density of the FAME of all strains meet both ASTM D6751 and EN 14214 standards while oxidation stability results meet only the ASTM D6751 standards. The cetane number of *Scenedesmus dimorphus* NT8e and *T. suecica* FAME meet both standards, *Scenedesmus dimorphus* NT8c FAME meets only ASTM D6751 standards and is marginal to the EN14214 standards. The cetane number of *Chlorella sp.* NT8a, *Nannochloropsis sp.* and *P. salina* FAME are 8.50%, 8.50% and 29.80%, respectively, and lower than the ASTM D6751 standards. Compared to conventional aviation fuel, the kinematic viscosity of all FAME meets the conventional jet fuel standards while density and higher heating value are marginal to the standards. However, no FAME met the freezing point standards of aviation fuel. The fuel properties of SAF can be significantly improved through modification, especially the freezing point.

4. Conclusions

This study evaluated 17 microalgae strains for jet fuel production using a new computer-based PROMTHEE-GAIA MCDA method. *Chlorella sp.* NT8a was assessed as the most suitable. The results show unmodified biofuel from *Chlorella sp.* NT8a can meet some but not all jet fuel standards. In particular, microalgae-based biofuel could not satisfy the required density, heating value and freezing points of the international jet fuel standards. Further work to improve the properties of the obtained biofuel (e.g., using fuel additive) and to relax certain parameters of the current jet fuel standards would be necessary for commercial realisation of microalgae-based aviation fuel.

Supplementary materials

E-supplementary data for this work can be found in e-version of this paper online.

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