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Review

A bibliometric analysis on sustainable aviation fuels: core technologies, challenges and trends

Rafael Belo Duarte[1*], Gabriela de França Lopes[2], João Lourenço Castagnari Willimann Pimenta [1], Luiz Mario de Matos Jorge [1]

[1]Chemical Engineering Department, Chemical Systems and Processes Laboratory, Maringá State University. Colombo Av., 5790, Building D90, Maringá, 87020-900, Paraná, Brazil
[2]Research and Development Department, Geo Biogás & Tech, Juscelino Kubitscheck Av., Londrina, 86020-000, Paraná, Brazil
[*]E-mail: duarterafaelbelo@gmail.com

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Abstract: International initiatives such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) have set goals for the complete de-carbonization of international aviation in this century. It motivated increasing numbers of Sustainable Aviation Fuel (SAF) research projects. The objective of this paper is to provide an overview on SAF research to point one to its foundations and recent advances. Data from the Web of Science database was collected and investigated. Important papers, cooperation networks, textual, productivity and trends analysis is provided. The most productive countries are in the global north, led by the United States and China. Big developing nations such as India and Brazil need to improve. The future of a sustainable aviation sector is heading in the direction of replacement of conventional jet fuel by synthetic hydrocarbon fuels by the end of the century. But there are still doubts about its viability both from the environmental and practical aspects, as there are concerns about feedstock availability and life cycle emissions. Fischer-Tropsch Synthesis, Alcohol-to-Jet and Hydroprocessing of Esters and Fatty Acids appear as the main SAF technologies for drop-in replacements. Longer term prospects are for the development of more efficient aircraft designed for renewables and non-hydrocarbon energy sources.

***Keywords*:** sustainable aviation fuel, bibliometric analysis, Carbon Offsetting and Reduction Scheme for International Aviation, biofuels, biogas, Fischer-Tropsch, alcohol-to-jet, HEFA.

1. Introduction

Fossil fuel sources are finite and impractical to be replaced for alternatives such as batteries or hydrogen in the short term, especially for the aviation sector. Thus, technologies to produce synthetic liquid fuels are required. However far the exhaustion of fossil fuels, it is prudent to have alternatives ready to deploy. For this reason, governments, the private sector, and the scientific community have been investigating this question for the past two decades. The aviation sector is particularly dependent on liquid hydrocarbons. Aircraft are built to last many decades, so there will be a need for drop-in fuels, that is, fuels that burn in current aircraft engines without need of modifications. Furthermore, aircraft must be light, ruling out current battery technology.

Renewable fuels appear as the obvious solution to the problem. But production of synthetic fuels is an energy intensive process. It only makes sense in a mixed or fully renewable grid [1]. Carbon emissions from feedstock

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production, transportation, and processing must be considered in the carbon balance. Another concern is green hydrogen availability, as SAF production routes tend to be intensive H2 consumers. Most current hydrogen is supplied from natural gas reforming. So alternative processes based on biomass gasification and water-gas shift reaction are the most direct replacements [2].

Currently, the most mentioned SAF production processes are: (1) biomass biodigestion to produce biogas (CO_2 + CH_4), which is reformed to syn-gas; or biomass direct gasification (partial combustion) to syn-gas, that is then fed to a Fischer-Tropsch Synthesis reactor (FTS) to produce aliphatic and branched hydrocarbons; (2) alcohol-to-jet (ATJ) is another promising technology, it puts alcohols through an oligomerization process to produce hydrocarbons [3]. The advantage of ATJ is that it can mobilize already developed ethanol production plants, which have successfully operated for many decades in countries such as Brazil; (3) the third main route for hydrocarbon production from biomass is the hydroprocessing of esters and fatty acids (HEFA), which processes animal fats and vegetable oils in high temperature and hydrogen pressure to dehydrate and hydrogenate oils and fats into a deoxygenated mixture similar in nature to crude oil.

SAF production takes on either starchy (including sugars), triglyceride, or lignocellulosic feedstocks into biorefineries, similar in nature to petroleum refineries, where the oxygen content is reduced and carbon chains of a wide range are formed, not always in this order, to produce a crude bio-oil that can be refined into various fractions [2]. It is common the classification of biomass into first generation, sourced from food crops, and second generation, of non-food feedstocks, mostly lignocellulosic [4]. The fuels produced are usually paraffinic, with low sulfur and aromatics content. Lack of aromatics causes fuel seals to shrink [5], so at least 8 vol% aromatics are required on jet fuels [6]. Consequently, SAF must be put through dehydrocyclization to increase aromatic concentration. Even if it is aromatized, current regulations require SAF to be blended up to 50% with conventional jet fuel to ensure proper fuel quality [7].

Hydroprocessing of esters and fatty acids (HEFA) reacts esters and fatty acids with hydrogen to produce hydrocarbons [8]. These reactions include deoxygenation, which increases the energy content; cracking, to break apart excessively long molecules, and isomerization, which reorganizes the carbon chains and improves physical characteristics such as cold flow properties [6], particularly important for aircraft operated at the low temperatures of high altitudes.

Currently, HEFA is the largest industrial source of bio-oil, predominantly biodiesel. Fuels obtained by this route have low sulfur content and generate less soot than fossil counterparts, but the selectivity to aviation kerosene is poor because vegetable oils have carbon chains similar in length to what is encountered in diesel fuel [9].

Fischer-Tropsch synthesis (FTS) is a process for producing hydrocarbons from synthesis gas, a mixture of CO and H2, on catalysts based on cobalt, iron and/or ruthenium [10]. Synthesis gas can be sourced from lignocellulosic biomass via partial combustion (gasification) [2] or from reforming of biogas (CH_4 + CO_2) or methane produced by anaerobic digestion of biomass. Compared to HEFA, FTS is less limited in terms of feedstock and emits less greenhouse gases, however it has higher capital cost [11].

Alcohol-to-jet (ATJ) is a technology of alcohol oligomerization, that is, short alcohol molecules — monomers — grow into long hydrocarbon compounds. Alcohols are dehydrated, oligomerized to long chain olefins and then hydrogenated into a mixture of alkanes. Due to the dehydration step, ATJ catalysts are highly acidic aluminas and zeolites [3].

Another important technologies are Pyrolysis and Hydrothermal Liquefaction (HTL). In which the biomass, often cellulosic, is thermally decomposed into biochar, biogas and bio-oil. The bio-oil is upgraded by hydrotreatment [3] in a manner similar to HEFA process, namely isomerization, cracking, and deoxygenation. Along with gasification plus FTS, pyrolysis and HTL processes can operate on the most highly available and cheap source of renewable carbon: lignocellulosic biomass. Pyrolysis and HTL differ in process conditions. Pyrolysis is a high temperature (400-600ºC), atmospheric pressure treatment for dry biomass; hydrothermal liquefaction is a high pressure, low temperature (7-20 MPa, 280-380ºC) process for wet biomass. HTL biocrude has lower oxygen content, higher energy value, and lower upgrading cost than pyrolysis oil [12].

Although there is an abundance of classical literature reviews on SAF in the literature, to the best of one's knowledge this is the first paper presenting statistical bibliometric analysis of the subject. Bibliometric analysis is a tool for mapping a research field. It can point researchers in the direction of fundamental literature that is not always evident in a classical review, as well as reveal its social structure, most prolific authors, important topics, fundamental documents, and trends. A good methodology is presented by Aria and Cuccurullo [13] along with software to facilitate the workflow. In this context, the paper's objective is to produce a bibliometric review of the available literature, so new SAF researchers can orient themselves. Such analysis is important to avoid already explored paths and hint at promising ones.

2. Methods

This paper is based on the methodology published by Aria and Cuccurullo [13] for the R software environment. R is a computer language for statistical calculations. Data was processed using the "bibliometrix" package. All code was licensed under the GNU General Public License Version 3 and is provided as supplementary material.

2.1. Data collection and research query

The complete dataset regarding Sustainable Aviation Fuels was collected, on april 26, 2023, from the Web of Science platform using the query "sustainable aviation fuel OR aviation biofuel OR aviation bio fuel OR bio-jet fuel OR bio jet fuel OR bio-aviation fuel OR bio aviation fuel (Topic)". To get the whole historical timeline, no time restriction was set.

2.2. Author name disambiguation

R's "refsplitr" [14] was used for author name disambiguation via the script named "AND.R" provided in the supplementary material. It improves author count and collaboration networks by identifying synonyms and homonyms. Name differentiation was based on authors' affiliations, list of coauthors, Orcid IDs, and e-mail addresses.

2.3. Textual analysis

Textual analysis is the study of frequent words and expressions. The objective is to uncover the most relevant terms and how they relate. To improve graphical visualization, lists of irrelevant words and synonyms were created by iteratively visualizing keyword networks, and manually grouping and removing terms at each run. For brevity, the complete lists are not shown. They are provided in the file "bib_analysis.R" of the supplementary material under the variables named "removed_terms" and "synonyms_list".

2.4. Network creation

The networks are created based on each paper's attributes [13]. For example, the country collaboration network was generated based on the authors' addresses. A matrix, counting the numbers of collaborations between each country, is generated and plotted using R's "bibliometrix" package [13]. In other words, if a document has an author from China and another from the USA, one collaboration is added to the network. The higher the count, the thicker the vertices in the network.

3. Results

3.1. Overview

The query returned 1714 documents from 510 different sources on April 26, 2023, of which 1310 are articles and 175 reviews (Table 1). Most of the research is collaborative, only 84 documents have a single author, the average number of authors per document is 4.93, and the most common is 3. There are also a considerable number of international collaborations: 24.39% of total publications.

Table 1. Main information.

Description	Results
MAIN INFORMATION	
Timespan	1995:2023
Sources (Journals, Books, etc)	510
Documents	1714
Annual Growth Rate %	18.32
Document Average Age	4.5
Average citations per doc	20.18
Average citations per year per doc	3.145
References	69562
DOCUMENT TYPES	
Article	1272
Article; data paper	2
Article; early access	38
Article; proceedings paper	35
Correction	4
Editorial material	8
Letter	1
Meeting abstract	8
News item	20
Proceedings paper	151
Review	173
Review; early access	2
DOCUMENT CONTENTS	
Keywords Plus (ID)	3439
Author’s Keywords (DE)	4189
AUTHORS	
Authors	5715
Author Appearances Authors of single-authored docs	8454 84
AUTHORS COLLABORATION	
Single-authored docs	101
Documents per Author	0.3
Co-Authors per Doc	4.93
International co-authorships %	24.39

Regarding the quality of the data, most of the metadata is complete. Notable exceptions are 21.7% of authors' keywords (DE), 13.24% of Web of Science Keywords Plus (ID) and all of Web of Science Categories, not included in the dataset.

SAF research on the Web of Science platform spans from 1995 to current year (2023), as research on sustainable industries increased following a global change in energy policy, discussed in more detail in Section 3.5.2.

Total author count is 5715. Before author name disambiguation this number was 5269. This means that there are more distinct authors that share the same name, or homonyms, than synonyms. During manual author name disambiguation, one noticed that most homonyms are from Chinese researchers. China is the second most productive country in terms of number of published documents and there are many researchers of Chinese origin working in collaboration with the most published country, the United States, which explains the high homonym occurrence.

3.2. Most relevant sources

The journal with the most publications is Elsevier's Fuel (Table 2), followed by Energies (MDPI AG) and Renewable & Sustainable Energy Reviews (Elsevier). From the top ten sources, six are published by Elsevier, and the other four are shared by MDPI AG, Wiley, ACS, and Frontiers Media SA. The source that focus the most on SAF is BioFPR from Wiley, 2.91% of its registered DOIs are on SAF research.

Table 2. Most relevant sources by number of documents.

Sources	Documents	% of total DOIs	Impact factor 2022	ISSN	Publisher
FUEL	125	0.35	8035	0016-2361	Elsevier
ENERGIES	63	0.14	NA	1996-1073	MDPI AG
RENEWABLE & SUSTAINABLE ENERGY REVIEWS	51	0.38	16799	1364-0321	Elsevier
BIOFUELS BIOPRODUCTS & BIOREFINING BIOFPR	47	2.84	5239	1932-104X	Wiley (John Wiley & Sons)
ENERGY & FUELS	44	0.20	4654	0887-0624	American Chemical Society
ENERGY CONVERSION AND MANAGEMENT	41	0.22	11533	0196-8904	Elsevier
APPLIED ENERGY	36	0.17	11446	0306-2619	Elsevier
FRONTIERS IN ENERGY RESEARCH	32	0.67	3858	2296-598X	Frontiers Media SA
JOURNAL OF CLEANER PRODUCTION	32	0.08	11072	0959-6526	Elsevier
ENERGY	31	0.10	8857	0360-5442	Elsevier

3.3. Productivity analysis

The average annual growth rate from 1995 to 2022 is 23.54%, which increases slightly to 25.14%, when one looks only to the last decade — from 2012 to 2022. Until around 2007 there was little interest on the topic (Figure 1). The aviation sector was considered, and still is, one of the most difficult to decarbonize. At the time there was no prospect for SAF implementation in the near future due to high cost and lack of policy. With time, environmental concerns increased, new policies were implemented, and research took off. Most of the difficulty is regulatory and logistical. Technologies for the production of alternative fuels such as Fischer-Tropsch Synthesis and Hydroprocessing of Oils and Fatty Acids were well known at the time. On the regulatory side, the Defense Standard 91-091 of the UK Ministry of Defense [15] was the first to allow, in 1999, the mixing of synthetic hydrocarbons into conventional jet fuel, thanks to the efforts of Sasol.

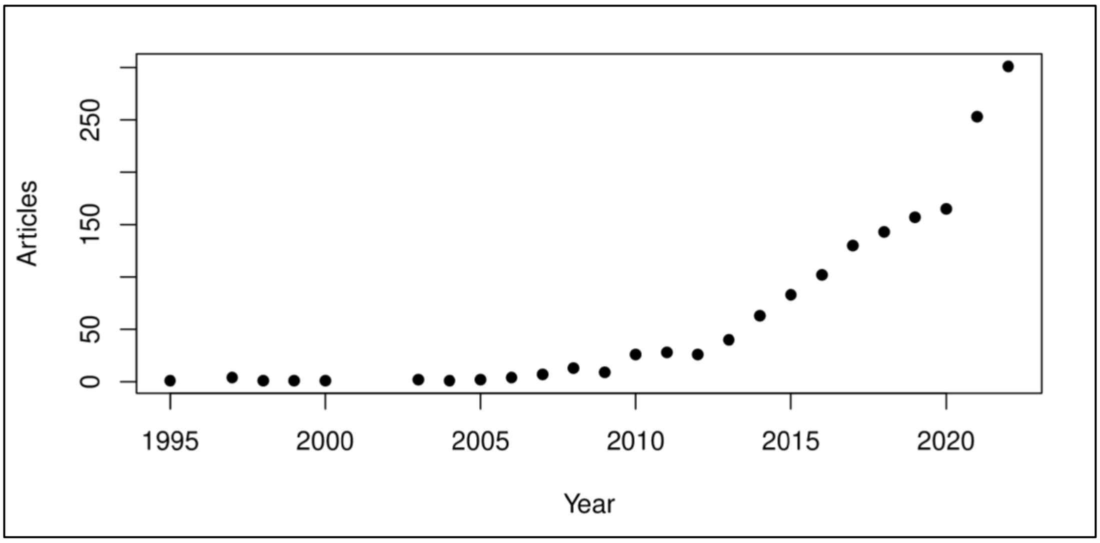

Figure 1. SAF research production numbers from 1995 to 2023.

In the next sections, productivity analysis was split into three levels: national, institutional, and individual. The objective is to get an overview of quantity and quality, by looking at raw publication numbers and metrics such as author h-index. We begin at the national level, move to an overview of the most relevant work by universities and institutes, ending the analysis at the most influential and productive authors.

3.3.1. National productivity

The surge of SAF publications observed in Figure 1 is explained by the international aviation sector's goal of total decarbonization by mid-century. Most of the world's nations have agreed to start reducing emissions by the decade's end [16]. Among these, the most productive in terms of publication numbers are the biggest investors in research and development, the United States and China [17] (Figure 2). The most significant factors on renewable energy development are policy, energy consumption for unit of economic output, and research and development investment (R&D). For high income countries, which already have an established renewable energy sector, the most important effect on renewables adoption comes from policies, while in middle income countries, the most relevant response is from R&D [18].

When one looks at the ratio of multiple country to single country publications in Figure 3, European nations such as the Netherlands and The United Kingdom come ahead, while USA, China and Brazil have room to grow in this aspect. Proportional to economic output and population size, Brazil, and India, in particular, have low productivity and could benefit greatly from more international collaborations.

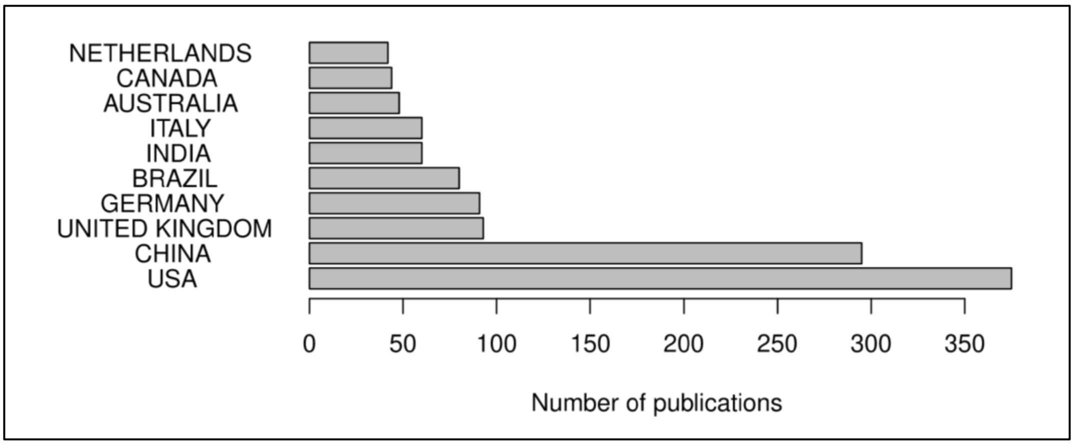

Figure 2. Most productive countries in terms of number of publications.

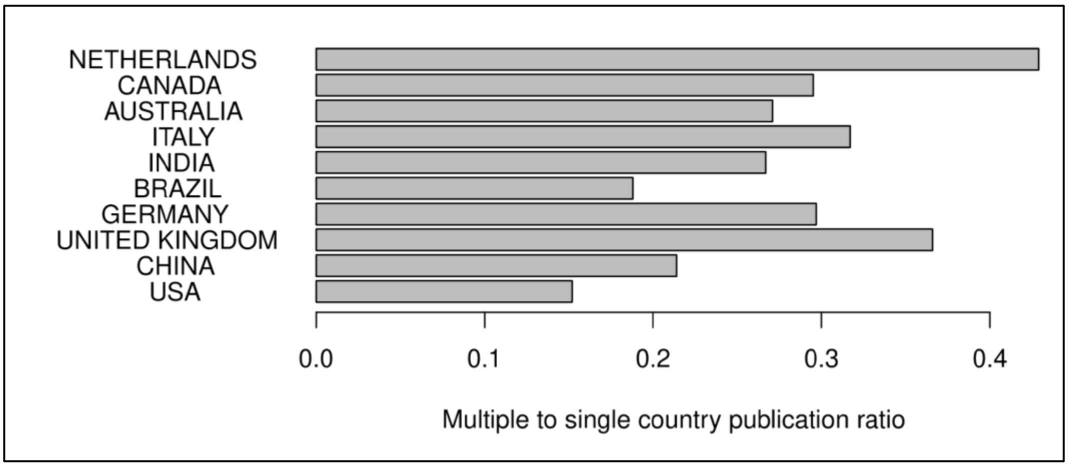

Figure 3. Multiple country to single country publication ratios.

3.3.2. Institutional productivity

The two most productive institutions are Washington State University (WSU) in the USA and Tianjin University in China, with 148 and 91 published documents respectively. Both are well represented by high impact researchers (Table 3).

WSU's most cited papers are on the conversion of lignocellulosic biomass to biofuels [19–21]. Other important work has also been published on techno economic analysis and process design for alternative fuels from Fischer-Tropsch Synthesis, hydrotreatment of pyrolysis oils, and alcohol-to-jet. Along with repurposing studies of current infrastructure for alternative jet fuel production, like ethanol plants [22] and petroleum refineries [23].

Tianjin University's biggest focus is on hydroprocessing, particularly hydrodeoxygenation for the production of high density jet fuel composed of cyclic hydrocarbons [24]. High density fuels are desired for volume limited aircraft, mostly military. Civilian aircraft often take off on a partially filled tank, with just enough fuel for a safe flight to its destination. Thus, it is often not limited by volume and fuels with high volumetric energy density are desired. On the other hand, if an aircraft takes off with a full tank, the optimal fuel would be one with a high energy density per unit mass.

Other relevant work by Tianjin University is on pyrolysis kinetic modelling [25] and production of olefins, aromatics, and hydrocarbons from raw bio-oil and waste cooking oil [26]. Its aromatics content could be an important additive for jet fuel.

3.3.3. Individual productivity

Author research impact was characterized by h-index. It was proposed by Hirsch [27] and is "defined as the number of papers with citation number higher or equal to h" . This means that an author with h-index of 50 has published 50 articles with at least 50 citations each. Five of the top ten authors in order of h-index are from China, two from the United States, two from Europe and another from Mexico (Table 3). The authors' most frequent keywords reveal that the majority work on hydroprocessing and pyrolysis. Most have been publishing since 2015. One notable outlier is Dr. Philippe Dagaut. A research director in the French National Centre for Scientific Research (CRNS), Dr. Dagaut has been publishing papers on reaction kinetics of fuel oxidation since 1986. His work includes kinetic models for the combustion of alternative fuels [28,29]. Such data is essential for combustion and emissions simulations, which can be used in aircraft engine computer models and life cycle assessments.

Table 3. Authors' local impact in order of h-index.

Author	h-index	Total citations	Country	Orcid ID	Most frequent keywords
Zhang Xiangwen	15	557	China	NA	HYDRODEOXYGENATION, BIOFUEL, ALKYLATION, HIGH-DENSITY FUEL, BIO-JET FUEL
Lei Hanwu	14	785	USA	NA	CO-PYROLYSIS, ACTIVATED CARBON, AROMATICS, BIO-JET FUELS, HYDROGENATION
Pan Lun	11	394	China	0000-0002- 3083-4693	ALKYLATION, BIOFUEL, HIGH-DENSITY FUEL, HIGH-DENSITY BIOFUEL, HYDRODEOXYGENATION
Zou Ji-Jun	11	394	China	0000-0002- 9126-1251	BIOFUEL, ALKYLATION, HIGH-DENSITY FUEL, HIGH-DENSITY BIOFUEL, HYDRODEOXYGENATION
Chiaramonti David	10	526	Italy	0000-0002- 1720-7820	BIOFUELS, AVIATION, PYROLYSIS, ADVANCED, ADVANCED BIOFUELS
Wang Wei-Cheng	10	527	Taiwan	0000-0002- 7277-3702	HYDRO-PROCESSING, BIO-JET FUEL, TECHNO-ECONOMIC ANALYSIS, PROCESS SIMULATION, RENEWABLE JET FUEL
Dagaut Philippe	9	288	France	0000-0003- 4825-3288	JET-STIRRED REACTOR, KINETICS, MODELING, OXIDATION, BIOFUELS
Gutierrez- Antonio C.	9	296	Mexico	0000-0002- 7557-2471	BIOJET FUEL, HYDROTREATING PROCESS, RENEWABLE AVIATION FUEL, HYDROPROCESSING, DISTILLATION SEQUENCES
Qian Moriko	9	364	USA	0000-0003- 4492-4961	CO-PYROLYSIS, BIO-JET FUELS, HYDROGENATION, BIOMASS, CYCLOALKANES
Wang Qingfa	9	157	China	NA	HYDROCONVERSION, HYDRODEOXYGENATION, AVIATION FUEL, BIO-JET FUEL, BIO-JET FUELS

A common keyword in Dr. Dagaut's papers that have recently become a trend topic is **jet-stirred reactor**: a tool for conducting fuel oxidation experiments. It is a vessel equipped with nozzles capable of providing turbulent jets of fuel that are used to obtain a thorough mix [30], so that a condition of uniform concentration may be assumed. This, along with conditions of constant residence time, temperature, and pressure, greatly simplifies mass and energy balance equations. Its surfacing as a trend topic indicates that SAF technologies are maturing and moving from fundamental research on fuel production itself, by searching for suitable processes and catalysts, to optimization of fuel composition and emission performance according to current regulations.

The highest h-index author is Dr. Xiangwen Zhang from Tianjin University, which is also the second most productive institution. Dr. Zhang's SAF related papers focus on various topics of chemical reaction engineering and catalyst development, including the production of high-density aviation bio fuel consisting of cyclic hydrocarbons as well as work on hydroprocessing, pyrolysis and alkylation. High density fuels are trending among the most influential authors due to its interesting properties for volume limited aircraft. Dr. Zhang's group includes other top researchers like Dr. Lun Pan and Dr. Ji-Jun Zou, as can be observed in the authors’ collaboration network in Figure 4. The authors' collaboration network also reveals that the top research groups do not collaborate with each other. Fragmentation is certainly an engine for competition between groups, which foments innovation. But in excess it could inhibit sharing of ideas and resources, and limit progress.

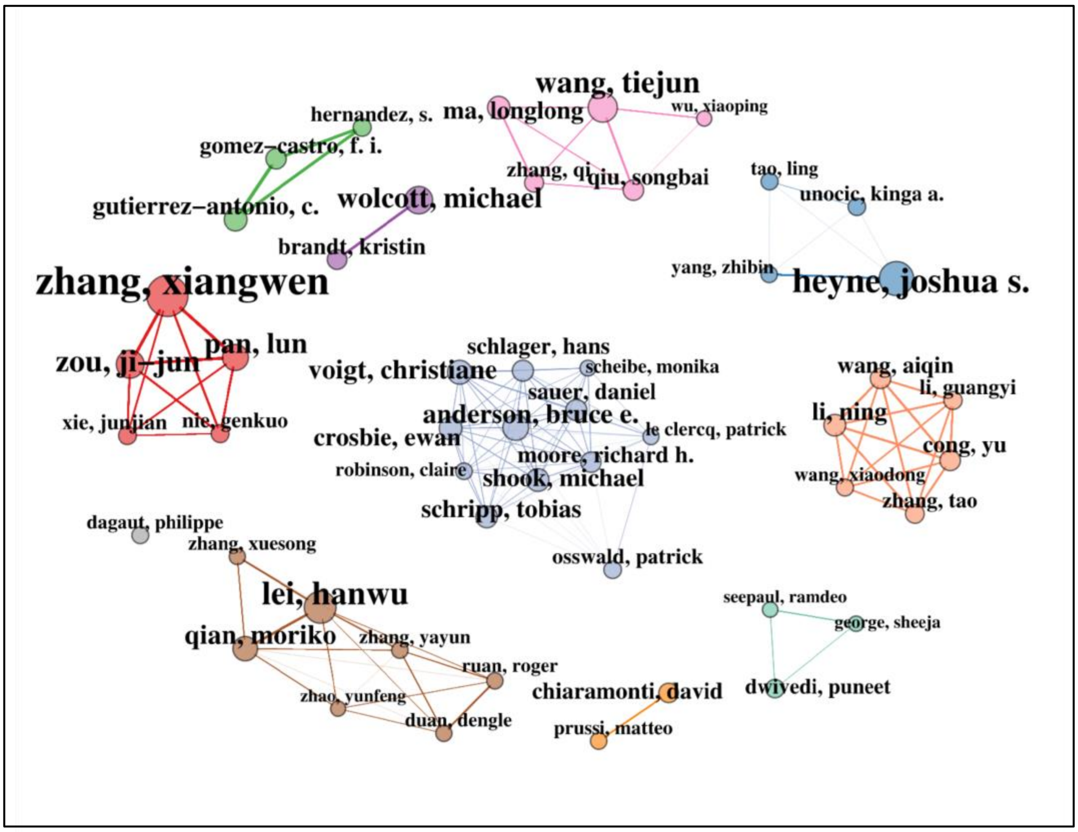

Figure 4. Authors' collaboration network (biggest 50 nodes).

3.4. International collaboration

The two central countries on the global collaboration network (Figure 5), are the United States (193 total connections) and China (188 total connections). Besides centrality, the strongest collaboration link is also between the two nations, with 53 collaborations. All the most connected countries are signatories of CORSIA. In Europe the biggest nodes are The United Kingdom, Germany, and the Netherlands.

The central cluster of countries represents most of the global population, but countries such as India and Brazil have too few connections in proportion to the sizes of their populations and economies. The same is true for overall number and quality[1] of publications. These nations have great growth potential, and with it, the aviation sector's relevance increases. If they are to comply with CORSIA, it is on their interests to develop domestic technologies to be independent of the USA, China, and Europe from the economic and energy security point of view. If SAF research remain at current level, it is likely that soon both nations will be faced with the choice of either fail CORSIA or buy carbon credits and import technology and expertise.

1 Assessed by looking at the country of origin in the rank of authors' h-index.

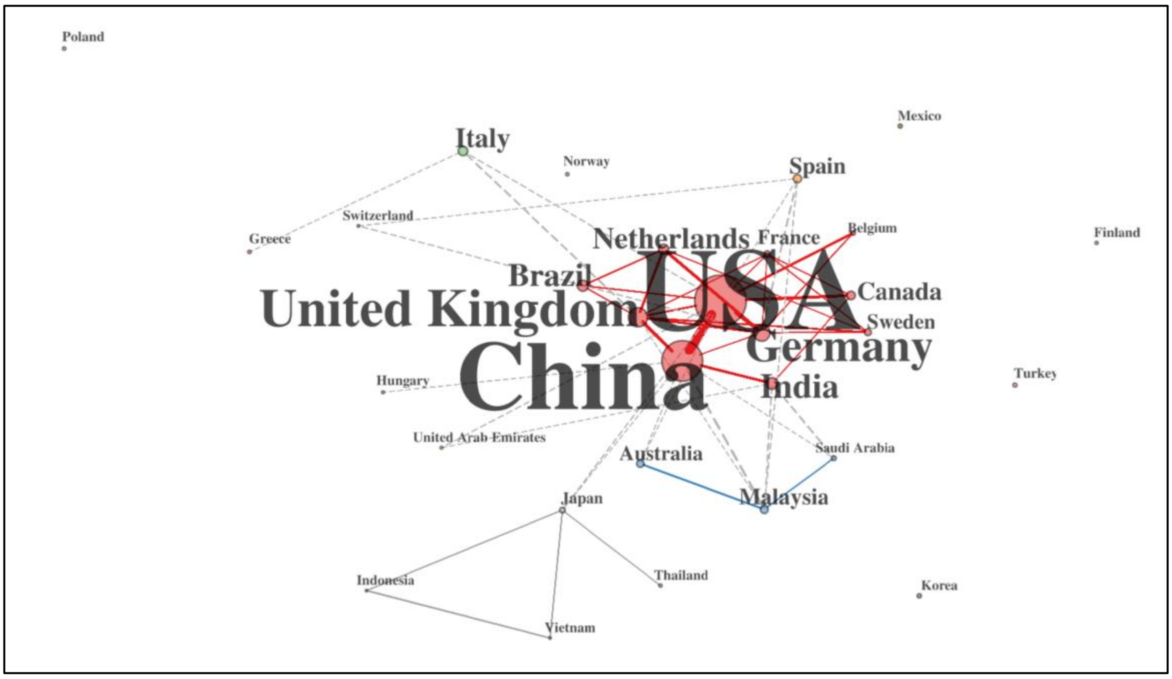

Figure 5. Countries' collaboration network. Node and edge sizes are proportional to the number of connections. The biggest edge, between USA and China, corresponds to 53 connections. The biggest node (USA) has 193 connections.

3.5. Textual analysis

The textual analysis was based on co-occurrence networks built on terms (highlighted in bold) extracted from titles and keywords. Titles are more generalist and provide an overall idea of the most explored topics, while keywords reveal more in-depth information about the technologies under study.

3.5.1. Titles co-occurrence network

Extracted title terms co-occurrence network (Figure 6) reveal the most explored subjects and their relations. The biggest nodes refer to aviation fuel production. The presence of the **review** and **techno-economic analysis** (tec. acon. analysis) nodes reveal a high preponderance of this type of paper. The **life** and **cycle** terms are related to life cycle assessment (LCA), a technique to quantify the environmental impact of a human activity.

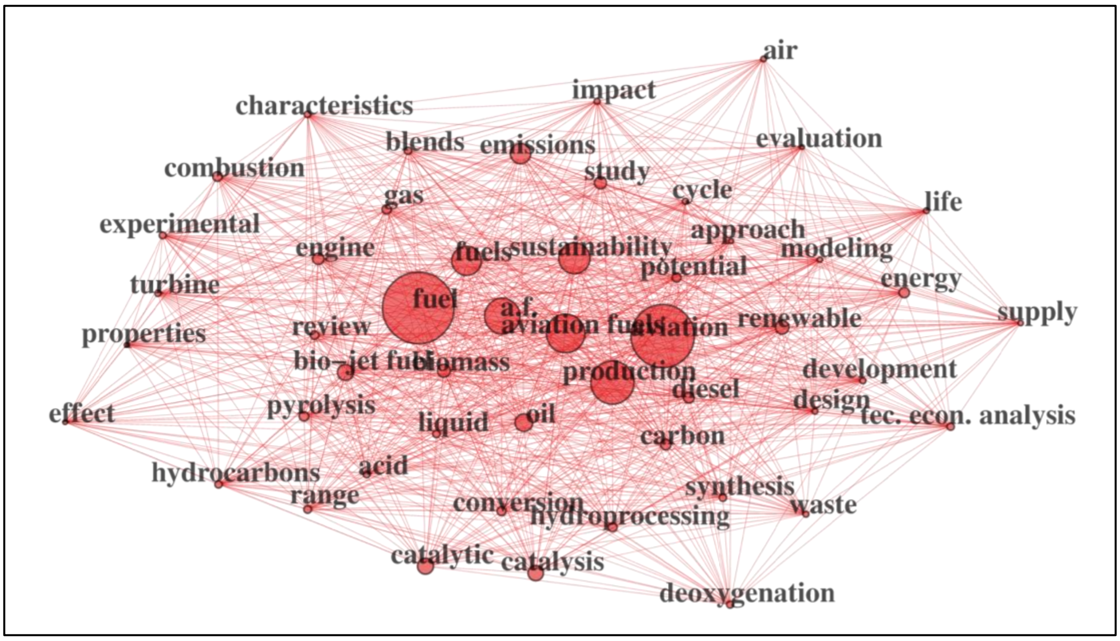

Figure 6. Titles keywords co-occurrence network.

On the experimental side, there is research on the **conversion** of liquid and solid biomass to **hydrocarbons**. It targets hydrolysis, **hydroprocessing**, **deoxygenation** and **pyrolysis** to find catalysts highly active on the conversion of biomass into hydrocarbons of a suitable range to produce synthetic fuels. Another important experimental area is the study of the **characteristics** of fuels, once the best catalysts and operating parameters are found. These papers characterize the properties of SAF, how it behaves when fed into **engines**, appropriate blends with current fossil **fuels**, as well as evaluations of engine **emissions** and **impacts** on **air** quality.

3.5.2. Authors' keywords co-occurrence network

The authors' keywords co-occurrence network (Figure 7) complements the titles' analysis, bringing to the front more useful information. There are three clusters. In the red cluster one term catches the eye: **CORSIA** [31]. It stands for Carbon Offsetting and Reduction Scheme for International Aviation. A measure by the International Civil Aviation Organization (ICAO) adopted in 2016 to reduce CO_2 emissions from international flights. The objective is to cap emissions at 85% of what was emitted in 2019, in the period from 2024 to 2035. Furthermore, there is an ambitious commitment to reach zero emissions by 2050 [16]. Offsetting involves the use of sustainable aviation fuels, deployment of renewable energy sources, reforestation, or any other activity that reduces CO_2 emissions. By 2027, most of the world will be pursuing CORSIA goals [16]. This is a great opportunity for the SAF sector, as airlines will be searching for clean drop-in fuels to grow beyond 2019 levels.

Sustainable Aviation Fuel is a common expression to refer to synthetic aviation fuel sourced from non-fossil carbon. However, even if the feedstock is non-fossil, the resulting product might not be sustainable. A more appropriate term would be "alternative aviation fuel". One approach to assess sustainability is life cycle assessment. Still, the "sustainable aviation fuel" query was kept even if it is sometimes incorrectly used by authors, as the focus of this analysis is on truly sustainable aviation fuels.

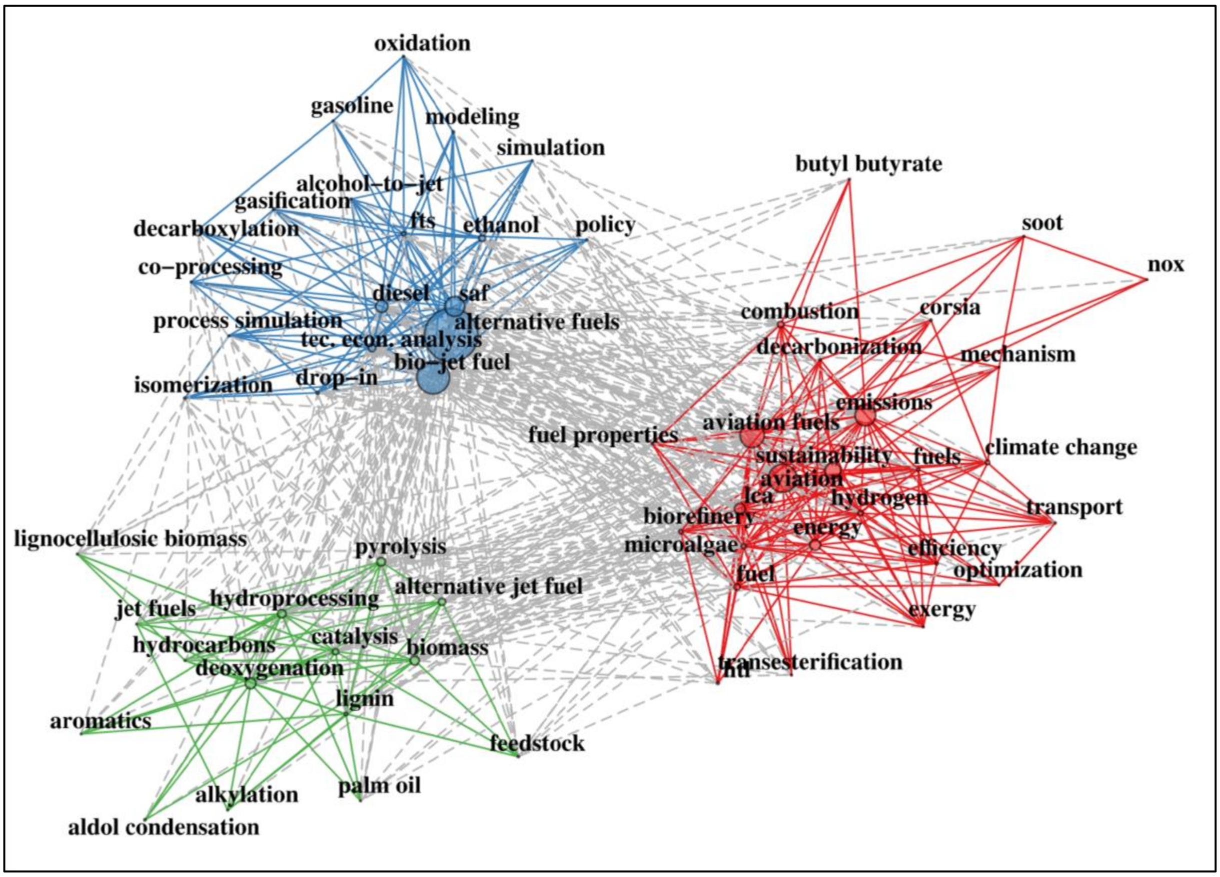

Figure 7. Authors' keywords co-occurrence network.

Still in the red cluster there is a link between **efficiency**, **energy** and **exergy**. Exergy is the maximum amount of useful work that can be extracted from a system when it is brought to thermodynamic equilibrium. In contrast to energy it is not a conservative property. Essentially, exergy is a property that accounts for entropy and allows for the evaluation of system efficiency [32]. Exergy analysis can be applied both to SAF production [33] and aircraft engine performance [34,35].

The blue cluster in Figure 7 refers to three SAF technologies: **Fischer-Tropsch Synthesis** (FTS), **Alcohol-to-Jet** (ATJ) and **deoxygenation** of vegetable oils, which occurs primarily via **decarboxylation** reaction, commonly referred to as DCO_2. In general, crude biomass **feedstocks** cannot be fed to these processes. FTS requires **gasification** into syn-gas; ATJ is mostly fed by fermented ethanol; and deoxygenation by oils extracted from plants. In contrast is **pyrolysis** in the green cluster. Its main advantage is that feedstocks can be introduced into the plant without much treatment. On the other hand, pyrolysis reactor product has lower quality and consequently greater refining cost. For more in-depth information into these technologies, see the three most cited reviews [2,4,19].

As mentioned in Section 3.3.3, one indication of SAF research maturation is the increasing work on fuel properties, by applying tools such as jet-stirred reactors. Such experimental effort provides data on fuel combustion for the development of kinetic models for simulations of aircraft engines prior to flight tests. Furthermore, the carbon mitigation efforts are multidisciplinary. Beyond drop-in fuels, there are other technologies appearing to improve fuel efficiency, like innovative **aircraft designs**. There are nine papers with this keyword. A good way to analyse specific keywords or any other interesting term, is to look only at the subset of the data that mentions it. For the aircraft design term, its keyword network in Figure 8, reveals the most promising aircraft technologies in an early stage of development: hydrogen fuelled aircraft, including new engine and air frame designs for low noise and fuel efficiency.

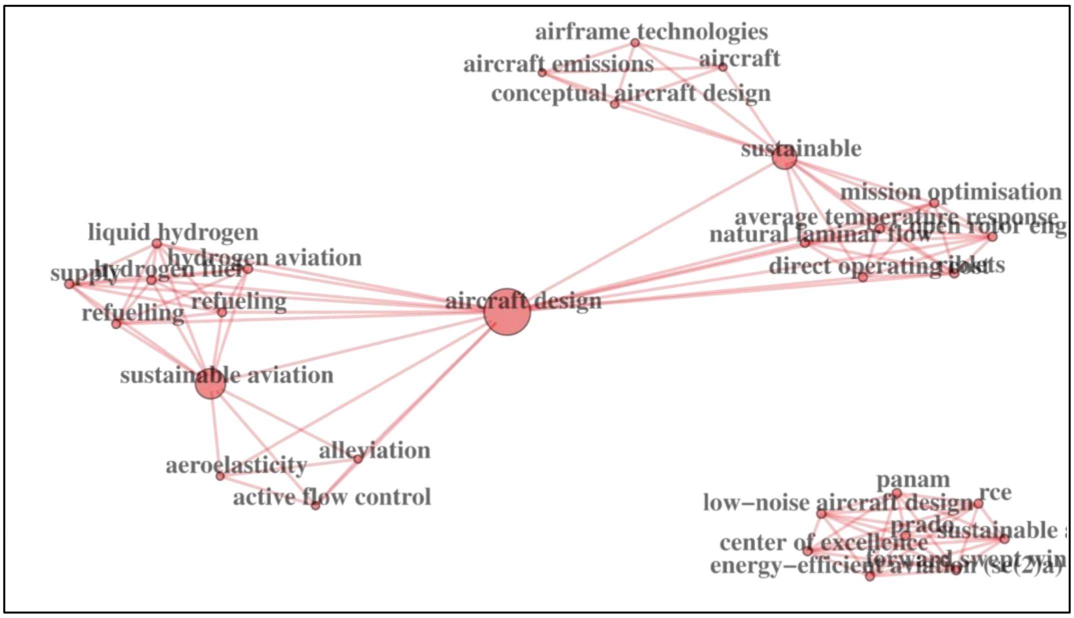

Figure 8. Keyword network of the subset of papers on aircraft design.

3.6. Citation analysis

Important papers were divided in two categories. The most locally cited papers, that is, the ones with most citations within the dataset; and historical papers, which are less cited in recent literature, but contributed greatly to early research. In both cases, the predominant types of papers are reviews and life cycle assessments.

3.6.1. Most locally cited papers

When one begins to work on a new project or research, literature reviews are a great resource to get a quick introduction to a subject. For this reason, the most locally cited papers, listed in Table 4, are reviews published between 2016 and 2020. The period has 40.67% of the total number of documents and 10.9% are reviews. The most recent timespan, from 2021 to 2023, have a similar proportion of reviews (10.68%) but not yet enough time to be read and cited in the same numbers. In general, authors tend to favour recent documents as references, and a document's interval of relevance shifts to the past as new papers are published. Indeed, Figure 9 shows a tendency for recent documents (aged 10 years or less) to reach a maximum rate of citations around age five and then drop in relevance. Few pass the test of time and keep a high citation rate as they age.

Many issues discussed by the papers in Table 4 were already covered above, others are extensions and improvements of previous pioneering work, which will be discussed in the next section. After that, attention is shifted to the future, by looking at recent trends.

Table 4. Most locally cited papers.

Title	Year	Local citations(LC)	Global citations (GC)	LC/ GC ratio	Source
Bio-jet fuel conversion technologies	2016	137	249	0.55	[3]
Aviation biofuel from renewable resources: Routes, opportunities and challenges	2015	121	202	0.6	[36]
A review on the production processes of renewable jet fuel	2017	97	153	0.63	[37]
Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production	2017	82	141	0.58	[38]
An overview on performance characteristics of bio-jet fuels	2019	59	97	0.61	[39]
Sustainable alternative fuels in aviation	2017	53	109	0.49	[40]
Biofuel blending reduces particle emissions from aircraft engines at cruise conditions	2017	49	166	0.3	[41]
Hydrotreatment of vegetable oils: A review of the technologies and its developments for jet biofuel production	2017	49	118	0.42	[42]
Recent development in studies of alternative jet fuel combustion: Progress, challenges, and opportunities	2016	48	120	0.4	[43]
Bio-aviation Fuel: A Comprehensive Review and Analysis of the Supply Chain Components	2020	45	65	0.69	[9]

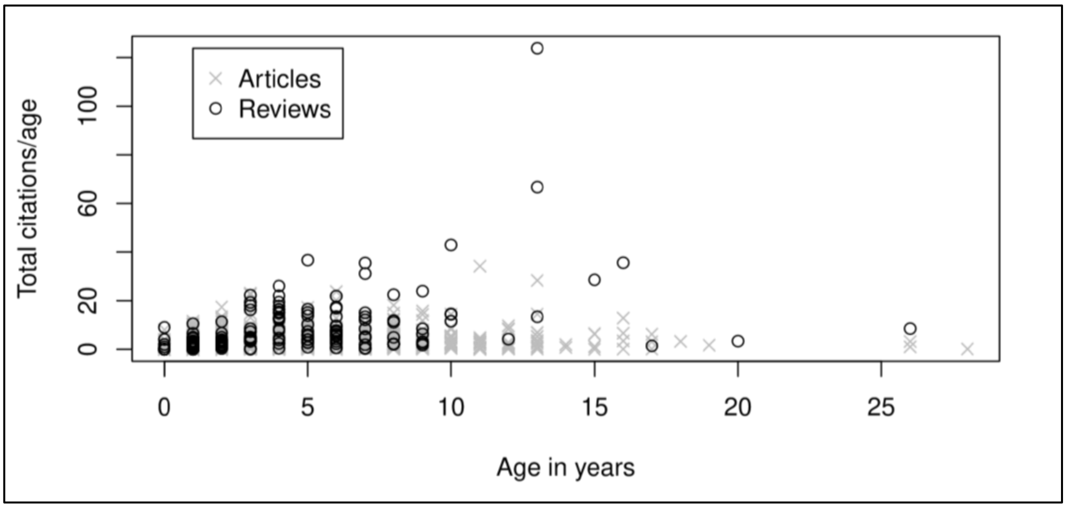

Figure 9. SAF research papers total citations versus age plot, separated by articles and reviews.

3.6.2. Historically influential references: References publication year spectroscopy

It is difficult to identify early influential papers by looking at the number of citations alone. But if one looks at deviations in the number of citations from the five-year median, historical years, and consequently the most cited papers of such years, can be identified. This method is called references publication year spectroscopy [44], or RPYS. The graph that it produces, presented in Figure 10, resembles spectra that would be obtained, for example, from measurements of light absorption. The peaks of the solid line highlight years with an unusually high citation count. The five most historical years for SAF references are, in order of importance, 2010, 2011, 2009, 2008 and 2007. A summary of the most relevant papers for each of these years is presented below, the top cited historical papers are listed in Table 5.

Table 5. Historical papers.

Title	Type	LC	Year	Source
Camelina-derived jet fuel and diesel: Sustainable advanced biofuels	LCA	58	2010	[45]
Transport impacts on atmosphere and climate: Aviation	Climate assessment	42	2010	[46]
Sustainability of supply or the planet: A review of potential drop-in alternative aviation fuels	Review	42	2010	[47]
Aviation gas turbine alternative fuels: A review	Review	111	2011	[48]
Life Cycle Assessment of Potential Biojet Fuel Production in the United States	LCA	60	2011	[49]
Chemical, Thermal Stability, Seal Swell, And Emissions Studies of Alternative Jet Fuels	Experimental	52	2011	[50]
Aviation and global climate change in the 21st century	Climate assessment	65	2009	[51]
Aviation fuel and future oil production scenarios	Feasibility analysis	27	2009	[52]
Catalytic Conversion of Biomass to Monofunctional Hydrocarbons and Targeted Liquid-Fuel Classes	Experimental	26	2008	[53]
Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions From Land-Use Change	LCA	26	2008	[54]
Land Clearing and the Biofuel Carbon Debt	LCA	24	2008	[55]
Historical Developments in Hydroprocessing Bio-oils	Review	34	2007	[56]
Synergies between Bio- and Oil Refineries For the Production of Fuels from Biomass	Review	32	2007	[57]
Processing biomass in conventional oil refineries: Production of high quality diesel by hydrotreating vegetable oils in heavy vacuum oil mixtures	Experimental	28	2007	[58]

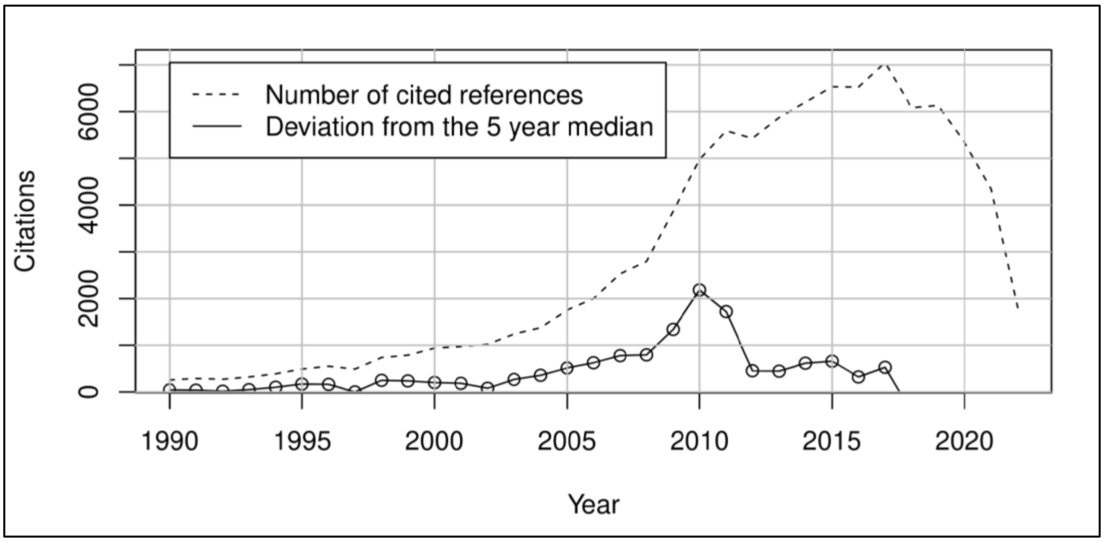

Figure 10. References publication year spectroscopy.

2010

A paper by Shonnard, Williams, and Kalnes [45] (58 LC[2]) on camelina derived jet-fuel and diesel via hydrotreatment (HEFA) presents a life cycle analysis of fuels from camelina cultivated on marginal lands and on lands used for food crops in the periods between harvests. Camelina is a weed native to Europe and well adapted to temperate climates with a short season crop. This route can have greenhouse gas savings of up to 80%. The biggest contributions to emissions are from feedstock production, transportation, and processing. During cultivation, emissions are from farm equipment run on fossil diesel and NO_2 from fertilizer. Hydroprocessing requires large amounts of hydrogen sourced from steam reforming of natural gas and transportation of large volumes of feedstock through great distances is also a problem.

On the topic of climate science, Lee et al. [46] (42 LC) assess that the impact of aviation on the atmosphere is on the direction of warming caused by CO_2, soot, water, and NO_x.

Rye, Blakey, and Wilson [47] (42 LC) present a perspective both from the point of view of sustainability and supply security. Even if a fuel is not sustainable it might still be valuable if it can replace current jet fuel in an oil shortage scenario. Often neglected secondary impacts such as those from land usage and coal or natural gas feedstocks to supplement production must be included in emissions assessment. The two processes evaluated in the review are Fischer-Tropsch Synthesis (FTS) and hydroprocessing. FTS is more suitable for supply diversification, because the syn-gas source does not matter from the production point of view. Hydroprocessing emits less when operated with sustainable feedstock.

2011

Another review by Blakey, Rye, and Wilson [48], now on "Aviation gas turbine alternative fuels" is the most cited of the historical references with 111 local citations. It gives a thorough evaluation of what the authors call aviation alternative fuels. The choice of words is wise, the term "sustainable aviation fuels" is often incorrect. Although alternative aviation fuels combustion is cleaner than conventional jet fuel in almost every case — from HEFA, FTS and ATJ fuels; the whole life cycle of land usage for feedstock production, fuel processing and transportation must be evaluated. It is not yet known if all the proposed alternatives are indeed sustainable. Clearing of natural CO_2 fixing land for fuel production, such as jungles and forests, could have the same if not worse environmental impact than fossil kerosene. Natural forested land has direct impact on CO_2 balance, on other factors such as rain cycles [59], and the availability of land for every other form of life with which we share the planet and may depend on for our survival, even if it is hard to quantify their relationship to mankind. These effects are sometimes referred in the literature as land use change impact, or LUC. In conclusion, as stated by Blakey, Rye, and Wilson [48]: "alternative fuels should only be sourced from marginal land" and, one adds, from industrial and agricultural biomass residues.

Notice that Fatty Acid Methyl Esters (FAME) is seldom mentioned as a possibility for aviation. Their feedstocks have inappropriate chain lengths as mentioned above, but also trace amounts of metals are carried from the feedstock to the final product, which is forbidden by current regulations due to negative effects on engines [48]. Although FAME and HEFA fuels are often sourced from the same feedstocks, they are different. FAME is produced by transesterification of fatty acids from vegetable oils with alcohols using a base as catalyst. HEFA fuels are hydroprocessed vegetable oils, that is, they are reacted with hydrogen in the presence of a catalyst, which removes heteroatoms such as sulfur, nitrogen, oxygen and metals via hydrogenation and hydrogenolysis. More detailed information about hydroprocessing is presented by Ancheyta, Rana, and Furimsky [60], and Sonthalia and Kumar [61].

Still in 2011, an important life cycle assessment by Agusdinata et al. [49] (60 LC) was published. It concluded that the production of bio jet fuel in the United States, at the rate of adoption at the time, would be insufficient to meet the emissions target.

In tandem with life cycle assessments there is another essential line of work on the properties of alternative aviation fuels. Industrial and pilot scale alternative jet fuels (AJF) produced from fossil and bio-sourced carbon produced by Sasol, Shell, Rentech, UOP, and Syntroleum Corporation were studied by Corporan et al. [50] (52 LC). AJFs have better combustion than conventional JP-8 fuel, resulting in less soot and CO in the exhaust. Nevertheless, they need to improve on three essential areas:

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2 Local Citations: citations mentioned within the papers of the dataset. As opposed to global citations, which are all the citations the paper ever received.

1. Lubricity[3] is poor due to the paraffinic nature of the fuels and lack of heteroatoms due to hydrotreatment. Lubricity is improved by double bonds and electronegative atoms, like oxygen, nitrogen, and sulfur [62];

2. Low aromatics content cause insufficient seal swell. In the short term, petroleum aromatics can be added. For the long term, fuel seals can be substituted by materials that perform better with AJFs, like nitrile instead of elastomer seals [50];

3. Density and volumetric energy content must improve.

2009

One of the major concerns of SAF researchers is fuel emissions. For this reason, among historical references are papers on the impact of the aviation sector on climate change [46,51].

2008

Searchinger et al. [54] was one of the first to warn about thinking that a fuel is sustainable because its feedstock captures atmospheric carbon. When biofuel prices increase, farmers clear land to expand crop production, which increases emissions. Crops like corn, for ethanol production, can double emissions. So the feedstock choice must be considered with care.

2007

Utilization of oil refineries for biofuel production was being considered [57,58]. The feedstock that would require minimal modifications for refinery conversion is vegetable oil. Problems with the production of aviation biofuels are the same as others mentioned above: supply scarceness, food security and yield. For lignocellulosic biomass, pyrolysis or hydrolysis are two options to produce bio-oil for hydrotreatment. It is available in greater quantities, but the crude bio-oil is often of poor quality, which increases refining costs.

4. The future

A timeline of recent author's keywords and their time span, in Figure 11, gives hints to what is expected of SAF research in the coming years. Work on lignocellulosic biomass continues, it is the most problematic feedstock but has the greatest potential volume of production. HEFA, FTS, ATJ, pyrolysis and HTL have been established as core technologies for now. Still, there are great challenges ahead. Proofs of concept are plentiful but inefficient for large scale production. There are doubts on the availability of land to produce all the carbon necessary to meet current CORSIA goals. It is estimated that to provide the commercial aviation sector with a 50/50 blend of SAF[4] to conventional jet fuel would require 6% of the world's arable land, just to meet the demands of a sector responsible for 2.6% of CO_2 emissions [47], an unfeasible approach. Therefore, the upstream processes need to improve. The example of land usage given above is based on Jatropa oil alone, but there is more carbon in lignocellulosic biomass. Its supply potential is more than four times larger than oil producing feedstock [49]. Efficiency improvements could involve hybrid processes, combining strengths and weaknesses of the technologies. Surplus hydrogen from gasification plants could be directed to hydroprocessing; the high diesel cut from vegetable oils can be fuelled into the transportation of lignocellulosic biomass; sugar cane bagasse from alcohol-to-jet ethanol can be gasified for FTS. Certainly, the future biorefinery should be as versatile as possible and capable to integrate all above-mentioned technologies to increase efficiency. Several SAF plants have been recently announced worldwide [63]. These will allow collection of data for the next step in the direction of energy security and emission reduction, besides quality-of-life improvements around airports burning cleaner fuels.

3 The capability of a compound to reduce friction and wear.

4 Sourced from Jatropa oil.

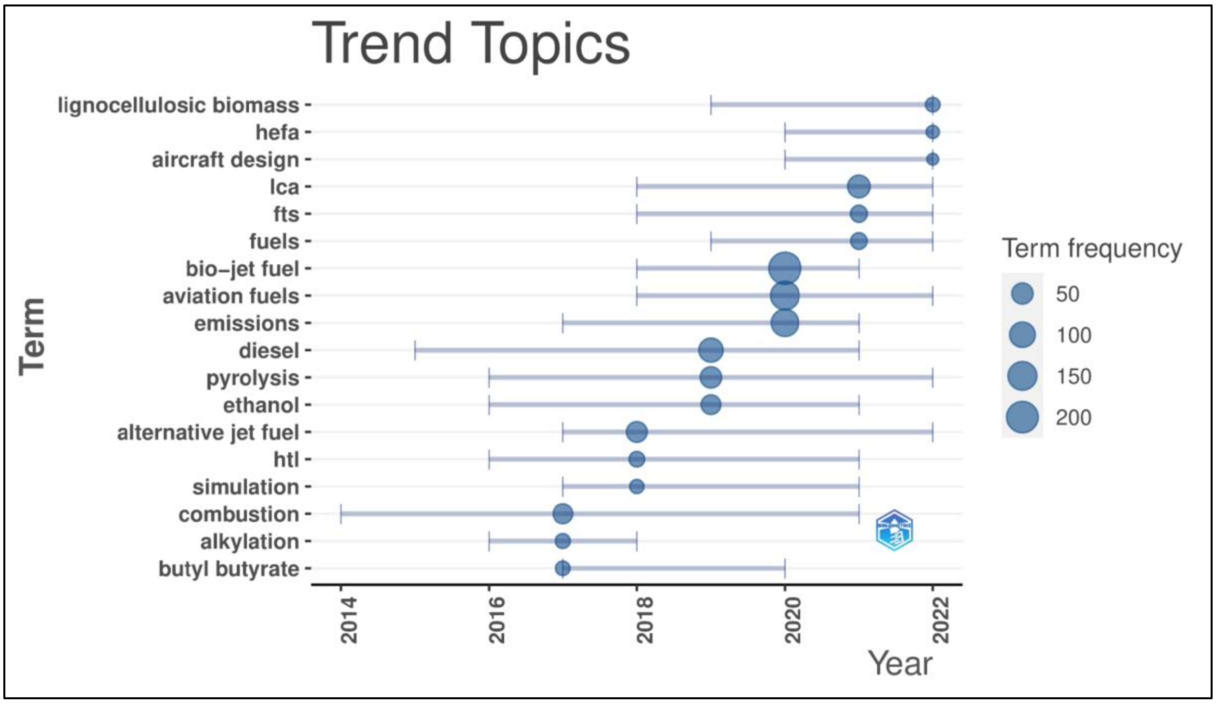

Figure 11. Timeline of most mentioned topics from 2017 to 2022. The bars represent the time span of each term, the location of the circle the year and its size the frequencies.

5. Conclusion

Sustainable aviation fuel research is taking off. In the past decade the average yearly growth rate reached 25.14%. In 2022 alone, 301 documents were published. Recent international policies and agreements provided airline companies with incentives to decarbonization. This paper presented a bibliometric overview of the most relevant SAF research, its benefits and challenges.

Core SAF production technologies in the short-term are Fischer-Tropsch Synthesis (FTS), Alcohol-to-Jet (ATJ), Hydroprocessing of Esters and Fatty Acids (HEFA), and Pyrolysis. FTS is the most versatile in terms of feedstock, it only requires biomass gasification. Its main drawback is high capital cost. HEFA and ATJ are limited in terms of feedstock and tend to produce lower quality fuel, containing low kerosene cuts and high oxygenate content. Pyrolysis could potentially process the largest source of non-fossil carbon, lignocellulosic biomass. However, fuel quality is the worst of all four, which greatly increases refining costs.

In conclusion, these technologies are mature enough to produce synthetic aviation fuels of higher quality than conventional jet fuel, however still at greater cost. The high costs are due to the major challenges faced by SAF researchers: feedstock availability, low aromatics content and high energy consumption. The first step in reducing costs is accumulation of experience and know-how through lab scale research and implementation of regional pilot scale SAF plants. These will help solve most of the engineering and technical problems. However, one issue remains, but its nature is not technical. It is a political-economical one. It is highly unlikely that SAF cost will drop below fossil Jet-A by mid-century. So its adoption will be conditioned to governmental subsidies, regulations on the costs of carbon emissions, and consumer pressure for cleaner fuels.

6. Future Scope

Among above-mentioned technologies, biomass gasification plus Fischer-Tropsch Synthesis is the most versatile and adaptable. In view of this, the future scope of this study is its experimental development from laboratory to pilot scale implementation, to assess technical and economic viability.

Declarations

Authors contributions

Rafael Belo Duarte: Writing - review & editing, Writing - original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Gabriela de França Lopes: Writing - review & editing, Writing - original draft. João Lourenço Castagnari Willimann Pimenta: Writing - review & editing, Writing - original draft, Supervision. Luiz Mario de Matos Jorge: Writing - review & editing, Writing - original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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Competing Interests

The authors are currently involved in a project for the implementation of a pilot scale SAF production plant in the state of Paraná, Brazil

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