Low-Carbon Alcohol Fuels for Decarbonizing the Road Transportation Industry: A Bibliometric Analysis 2000-2021

Chao Jin
Tianjin University
Jeffrey Dankwa Ampah (jeffampah@live.com)
Tianjin University https://orcid.org/0000-0002-0985-151X
Sandylove Afrane
Tianjin University
Zenghui Yin
Automotive Technology and Research Center, China
Xin Liu
Tianjin University
Tianyun Sun
Tianjin University
Zhenlong Geng
Tianjin University
Mubasher Ikram
Tianjin University
Haifeng Liu
Tianjin University

Research Article

Keywords: Methanol, Ethanol, Gasoline, Diesel, Internal combustion engine, Bibliometric analysis

Posted Date: April 30th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-409872/v1

Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on August 23rd, 2021. See the published version at https://doi.org/10.1007/s11356-021-15539-

1.

Abstract

Environmental pollution and depletion of resources from the combustion of fossil fuels have necessitated the need for biofuels in recent years. Oxygenated fuels such as low carbon alcohols have received significant attention from the scientific community in the last two decades as a strategy to decarbonize the transport sector. However, a documentation of the progress, paradigm, and trend of this research area on a global scale is currently limited. In the current study, the bibliometric analysis is adopted to analyze the global transition of automotive fuels from conventional oils to low carbon alcohols in the 21st century. A dataset of 2250 publications was extracted from the Web of Science Core database and analyzed with CiteSpace, Biblioshiny, and Bibexcel. Interest in methanol and ethanol combustion research as transportation fuels is increasing, with a 70% estimated growth by the end of the next decade compared to current levels. China, India, and USA have been the major players in the research field, with Tianjin University being the most influential institution. Research has primarily centered on the combustion, performance, and emission characteristics of ethanol fuel. Alternative fuels to compete actively with low carbon fuel in the near foreseeable future are green hydrogen and biodiesel. Advanced combustion technologies and artificial intelligence are sure to increase in this research area in the coming decades.

Highlights

- Bibliometric analysis on low carbon alcohol combustion in an internal combustion engine.
- Web of Science Core Collection database, from 2000 to 2021, was used.
- Growing research field with an average annual growth rate of 12%.
- Critical research hotspots of future studies on alternative fuels for internal combustion engine have been identified.

1. Introduction

The rapid depletion of fossil fuel reserves and its related-environmental pollution has accelerated the search for clean alternative fuels worldwide (Chen et al., 2013; Huang et al., 2016). The use of alcohol as alternative renewable fuels for internal combustion engines (ICEs) has been reported to minimize these problems (Zhu et al., 2021). An internal combustion engine (ICE) is a heat engine where the combustion of a fuel occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit (Mayank et al., 2016). Low or short-chain carbon alcohols viz methanol and ethanol have been identified as two of the most promising oxygenated fuels (Han et al., 2020; Zhu et al., 2021) to decarbonize the transportation sector. They have a wider range of feedstock and relatively simpler production routes. Compared to traditional oils, i.e., diesel and gasoline, the C1-C2 alcohols have excellent fuel properties such as high latent heat of vaporization, lower adiabatic flame temperature, oxygenated molecule, absence of C-C bonds, high oxygen content, lower viscosity, high H/C ratio, low sulfur content, and high evaporative cooling (Kim et al., 2020; Zhu et al., 2021). These collective attributes work together to reduce post-combustion emissions in neat or blended methanol/ethanol fuels.

Accelerated patronage for alcohol combustion as alternate fuels in ICE was recorded in the middle of the 1970s and reached its peak by the middle of 1980 (Solomon et al., 2007). These oxygenated fuels were thought to be attractive due to their production from natural products or waste materials, whereas traditional oils, which are non-renewable resource cannot be manufactured (Canakci et al., 2013; Chen et al., 2005). In addition, these oxygenated fuels could be used without significant modifications to the existing engine structure. Amongst various alcohols, ethanol and methanol are considered the most suitable fuels for ICEs. They are characterized by relatively higher flash point and autoignition temperature compared to that of pure diesel and gasoline, making them safer for storage and transportation. The latent heat of methanol (110 KJ/kg) and ethanol (846 KJ/kg) is relatively higher than diesel's (243 KJ/kg) and gasoline's (180–350 KJ/kg); thus, there is an increase in the volumetric efficiency for alcohols due to the reduction in the intake manifold's temperature (Iliev, 2019). The stoichiometric air-fuel ratio of the short-chain alcohols is relatively smaller than the pure petroleum fuels; hence methanol and ethanol would require a smaller amount of air to complete combustion (Pikonas et al., 2003). Ethanol and methanol have better anti-knock characteristics, and their higher-octane number enables higher compression ratios of engines, thus increasing thermal efficiency (Bata et al., 1989; Dasilva et al., 2005).

There are several strategies to apply these low carbon alcohols in internal combustion engines; the three most common types (Alptekin, 2017; Rakopoulos et al., 2008) are as follows: (1) fumigation into the intake air charge (Abu-Qudais et al., 2000; Surawski et al., 2010). A fumigation system injects a gaseous or liquid fuel into the intake air stream of compression ignited engine. This fuel burns and becomes a part-contributor to the power-producing fuel. NO_x and particulate matter reduction increase with increasing levels of fumigation. However, in general, fumigation fuels increase HC, CO, and NO_2 emissions (Cooke et al., 1971; Li et al., 2020; Zhang et al., 2011).

The second strategy is a complete substitution of commercial gasoline or diesel with methanol or ethanol via port or direct injection. The high-octane number of oxygenated alcohols enables them to be used directly in engines with flexible injections such as alcohol single fuel mode (Gong et al., 2019). It has several advantages such as: controlling the amount of alcohol injected in each engine; incomplete combustion at low load and roar combustion at high load could be avoided; simultaneously reduce THC, CO, NO_x, and soot emissions effectively; could achieve an ultra-high proportion of alcohol instead of traditional oil (Li et al., 2019). However, there are certain drawbacks to this type of strategy: direct use of primary alcohols in ICEs without assistance is difficult due to their lower cetane numbers and viscosities (Ning et al., 2020) compared to gasoline and diesel; moreover, this strategy requires significant modification of engine hardware and injection system to nullify the effect of alcohols' autoignition resistance and low lubricity, respectively (Haupt et al., 2004).

The third strategy is achieved through blending methanol or ethanol in diesel or gasoline. By far, this is the most common strategy employed by researchers (Kim et al., 2020) since little or no modification is required of the engine itself. Significant emission reduction has been achieved when blended fuels of oxygenated alcohols-diesel/gasoline are used (Labeckas et al., 2014; Tse et al., 2015). However, these fuel systems are characterized by phase separation limitations. The polarity difference existing between the alcohols and oils prevents the formation of a single-phase uniform mixture between their blends (Jin et al., 2019a; Jin et al., 2019b; Jin et al., 2020). The alcohols are relatively hygroscopic and miscible with water, thus lowers the upper blending limit with diesel or gasoline (Jin et al., 2019a). All automotive fuels must be homogenous to prevent severe consequences such as blockages and pumping difficulties during storage and transport (Oasmaa et al., 2015). The situation warrants the use of either an emulsifier to suspend small droplets of ethanol within the gasoline/diesel or a co-solvent with the ability to promote molecular compatibility and bonding to yield a homogenous mixture (Shahir et al., 2014; Wu et al., 2020). In addition, the lower cetane number, calorific value, and viscosity of low carbon alcohols have also been described as a limitation to its blends with traditional oils (Ileri, 2016). Low cetane number and viscosity (extreme cases) leads to poor ignition (prolonged ignition delay) and atomization, respectively, which leads to the formation of more incomplete combustion products detrimental to the environment, whereas lower calorific value increases fuel consumption.

Several researchers have reviewed the growing literature in this field of research. To mention a few, Kumar et al. (2013) reviewed the advances made in diesel-alcohol blends and their effects on the performance and emissions of diesel engines. A similar study was conducted by Prakash et al. (2018) on the recent advancements in biofuels and bioenergy utilization. Niculescu et al. (2019) also analyzed the literature concerning diesel-biodiesel-alcohol blends in compression ignition engines. Finally, Kumar and Chauraria (2019) reviewed the performance and emissions of a compression ignition engine fueled with alcohol-diesel blend. The reviews as mentioned earlier mainly: (1) compared the physicochemical properties between alcohols and their conventional oil counterparts; (2) report on the progress of alcohol production from different sources; and (3) analyze the effect of alcohol/conventional oil type and blending ratio on performance, combustion, and emission characteristics. However, these traditional reviews have certain limitations. Increasing research interest in ethanol/methanol application has resulted in many publications over the past decade compared to the previous decades. Minimal attempts have been made to map the global research in this area. More knowledge could be gained by qualitatively and quantitatively analyzing the existing literature and exploring and tracking the evolution of a large number of published works.

A typical non-traditional review methodology is the bibliometric analysis. It is a set of mathematical and statistical methods to display up-to-date and on-going knowledge that has been applied in many disciplines of science and engineering. The tool could be employed to ascertain the research trends by the publication outputs of countries, characteristics of authors, and research institutes to make an overall researching perspective of a topic of interest. Also, the distribution of words in the article title, author keywords can be used to evaluate research trends of different researching periods or countries. Meyer (2020) employed bibliometric and network analysis to analyze the research trend in the decarbonization of road freight transportation. The network and content analysis revealed that decarbonization of road freight transportation is approached from three directions; (1) technological innovations such as alternative fuels and electrification. (2) operation measures to make use of last-mile solution, routing, consolidation, and vehicle fill. (3) economic measures such as the influence economic activities and development have on road freight transport, energy efficiency, and carbon emissions. The research trend and characteristics of carbon emissions from the transport sector was also investigated by Tian et al. (2018) This analysis revealed that within the transportation sector, road transport is the most researched area, with electric vehicle being the most common topic. Emissions, specifically CO_2 was the second most frequent topic category. Natural gas and alternative fuels dominated fuel related keywords. Great interest was given to vehicle design, carbon capture and storage, and torque control strategy as technological-related topics. Zhang et al. (2018) used the technique of bibliometric analysis to investigate the research trend of biodiesel between 1991–2015. Their study revealed that microalgae, Jatropha curcas, vegetable oil, and waste cooking oil were the most general raw materials for biodiesel production in that period.

Surprisingly, to the best of the authors' knowledge, the use of bibliometrics analysis for methanol and ethanol in ICEs is very limited (no direct publication exists so far) despite the growing research interest in this topic. Thus, the current study seeks to use bibliometric analysis to answer at least one of the following research gaps: (1) how long has the landscape of low carbon alcohol utilization in ICEs research evolved? (2) how are the scientific studies on low carbon alcohol utilization in ICEs distributed among the core and other scientific journals in this research? (3) what are the most relevant publications on this research topic? (4) what are the most productive and influential funding agencies, countries, organizations, and authors that have contributed to the application of low carbon alcohol in ICEs? (5) what are the recent research hotspots in methanol/ethanol combustion for the transport sector? The current bibliometric review seeks to bridge these research gaps and provide researchers with a better understanding of the development of ethanol and methanol combustion in ICEs as a basis for future research directions.

1.2 Retrospection; Low carbon alcohol combustion in ICEs

1.2.1 Ethanol

A long history of ethanol and gasoline-ethanol blends as automotive fuels exists (Solomon et al., 2007). In the mid-1800s, Samuel Morey developed an engine that ran on ethanol and turpentine. In 1860, German engine inventor, Nicholas Otto, known for his development of a modern internal combustion engine (Otto cycle) used ethanol as fuel for one of his engines (HVA, 2011). By 1862, ethanol's cost had increased significantly as a result of its imposed tax of $2 per gallon to help pay for the civil war (Mimi, 2008). Around the 1890s, Henry Ford built his first automobile, 'the quadricycle,' to run on pure ethanol. After 50 years of tax imposition, congress removed the tax to make ethanol more competitive to gasoline as a motor fuel. In 1908, the model T was developed by Henry Ford that could run on pure ethanol, gasoline or a blend of the two. Demand for ethanol grew from 50–60 million gallons per year during the world war I (1917-18). By the 1920s, the octane property of ethanol made it as an attractive fuel to reduce engine knocking of gasoline fueled engines. In the 1930s, 6–12% ethanol blended in gasoline were sold over 2,000 gasoline stations in the mid-west. The start of World War II increased demand and production of ethanol; however, the rise in ethanol’s demand was for non-fuel wartime purposes. After the war, interest in ethanol reduced as leaded gasoline proved easier and cheaper to produce, while the discovery of new oil reserves reduced the search for alternative fuels (Solomon et al., 2007). In 1975, interest in ethanol was revived once more as the US-Environmental Protection Agency instituted regulations to phase out leaded gasoline. The US Energy Tax Act of 1978 introduced the term gasohol, which refers to gasoline with at least 10% alcohol content by volume, excluding alcohols produced from petroleum, natural gas, or coal (Mimi, 2008; Solomon et al., 2007). 40 cent per gallon as subsidy was realized for every gallon of ethanol blended into gasoline after this law came into effect.

Between 1980-1990s, the phasing out of leaded gasoline made methyl tertiary butyl ether (MTBE) the most dominating oxygenated fuel in the gasoline market. After this period, MTBE dominance was curtailed due to its toxicity, especially in ground drinking water, making ethyl tertiary butyl ether (ETBE) take over throughout the 1990s (Solomon et al., 2007). The Energy Policy Act of 1992 provided regulations for at least 85% ethanol as an alternative transport fuel. By 1997, major US manufacturers began mass production of E-85 powered FFV. The Energy Policy Act of 2005 was instituted to ensure gasoline sold in the US contained a minimum volume of renewable energy, mainly ethanol made from corn. On April 21, 2009, 55 ethanol-producing companies led by Growth Energy submitted partial waivers to increase the ethanol blend limit from 10 to 15%. Eighteen months later, the EPA approved the partial waiver request to pass out E15 as automotive fuel (HVA, 2011).

1.2.2 Methanol

Boyd, in the 1920s, raised early concerns that conventional oil would run out, and efforts were to be put in place to increase engine efficiency to reduce fuel consumption via improved knock resistance of refined fuels (Boyd, 1950). His exact words were, “butyl alcohol (butanol) did not knock in any of the engines they had then,” referring to engines available during the 1920s, proving that the attractiveness of alcohols in engines was apparent early on. In the 1940s, during the Second World War, there was a limited supply of petroleum fuels, especially in Europe, forcing vehicles to be run on the fumes from wood burners which comprised methanol, CO, and hydrogen (Hagen, 1977). Huge discussions on alternate synthetic fuels, especially alcohol, went on due to the imminent shortage of petroleum resources. However, the discovery of large petroleum resources reduced the search for these alternative fuels until 1974 during the acute awareness of the oil embargo's fuel shortage (Hagen, 1977). By 1975, several studies on methanol and its use in gasoline considered the difficulties and problems, and advantages had been reported. The American Chemical Society and the Society of Automotive Engineers had held meetings to emphasize the urgent need for alternative fuels, especially methanol (Most and Longwell, 1975). Lawrence Livermore Labs continued their studies of methanol in engines. The US Energy Research and Development Administration and other institutions such as the University of Santa Clara collaborated to characterize the detailed performance of methanol and gasoline-methanol blends in IC engines. In 1976, the first international conference on methanol combustion in ICE was held, sponsored by the Swedish Methanol Development Co. (Hagen, 1977).

By the mid-1970s, small vehicle fleet trials were conducted in Germany (Bertau et al., 2014). Larger fleets were brought on board in the late 1970s and early 1980s by Germany, Sweden, New Zealand, and China. In the same period, Ford and Volkswagen developed the first flexible fuel vehicles (FFV) and participated with other 100 vehicles in the test program in the 1990s in California. Over 21,000 methanol M85 flexible FFV fueled with methanol-gasoline blend were used in the US by the mid-1990s (Bromberg and Cheng, 2010). The FFV program's interest took a hit as methanol prices increased, whereas gasoline’s diminished in the mid-to-late – 1990s. Ethanol went on to receive methanol’s attention as the methanol program in California ended in 2005. However, methanol is highly used in racing vehicles such as Grand Prix cars as of today. Low levels of methanol (M3) in gasoline exist currently in Great Britain. At present, the use of methanol is more dominant in the shipping sector (e.g., Stena Line, Methanex vessel). However, at present, Chinese road transport is rolling out M15, M30, M85, and M100 for commercial application (Andersson and Salazar, 2015; Zhao, 2019).

Table 1 compares the key fuel properties between the alcohols and conventional oils. The decline of conventional oil is inevitable unless more reserves are discovered coupled with energy-efficient systems and proper policing; this infinite resource behavior of conventional oils is emphasized in Fig. 1, bolstering the increasing need for alternative fuels such as methanol and ethanol.

Table 1

Fuel properties of fuels under review (Agarwal, 2007; Harari et al., 2020; Ickes et al., 2014; Jamrozik et al., 2019; Waluyo et al., 2021).

Property (unit)	Methanol	Ethanol	Diesel	Gasoline
Molecular formula	CH_3OH	C_2H_5OH	$C_{14}H_{30}$	C_7H_{16}
Molecular weight (g/mol)	32.04	46.06	198.40	100.20
Cetane number	3	8	51	-
Research octane number	136	129	15–25	97
Lower heating value (MJ/kg)	19.5	26.9	42.5	42.9
Heat of evaporation (MJ/kg)	1100	840	243	180–350
Auto-ignition temperature (K)	503	698	503	192–470
Stoichiometric air fuel ratio	6.45	9.06	14.60	14.70
Viscosity (40 °C)	0.65	1.52	4.59	0.67
Carbon content (%)	37.5	52.2	85.0	86.0
Hydrogen content (%)	12.5	13	15	14
Oxygen (%)	50	34.8	0	0

1.3 Review of performance and emission characteristics of methanol and ethanol combustion in ICEs

In this section, the previous results of other researchers on the combustion of methanol and ethanol in both compression and spark ignition engine is reported as an overview on the performance and emission characteristics of an alcohol-fueled ICE.

1.3.1 Ethanol combustion in a spark-ignition engine

Table 2

Performance and emission characteristics of ethanol in a spark-ignition engine.

Ethanol blend	Engine type	Performance	Emission	Baseline Fuel	Ref.
1. E10W*, E20W*	Naturally-aspirated, port injection	+Brake power, +torque, +BSFC, +BTE	-CO, -HC, +NO$_x$	Gasoline	(Deng et al., 2018)
2. E10, E30, E60	Single cylinder, four stroke spark ignition	-BTE, +BSFC	+CO, -UHC, -NO$_x$	Gasoline	(Li et al., 2017)
3. E100	Low power gasoline engine	-BMEP, +BTE, +BSFC	-UHC, -CO, NO$_x$, ~CO$_2$	Unleaded gasoline	(Koç et al., 2009)
4. E50, E85	Hydra, overhead cam shaft, with fuel injection	+Brake power, +torque, +BSFC	-CO, -HC, -NO$_x$	Unleaded gasoline	(Balki and Sayin, 2014)
5. PE10, PE15, PE20, PE25	Four stroke, single cylinder, spark ignition, multifuel, VCR with open ECU	+BTE, +BSFC, +brake power	-HC, -CO, +NO$_x$, ~CO$_2$	Gasoline	(Dhande et al., 2021)

*hydrous ethanol; +: increase; −: decrease; ~: varies

1.3.2 Methanol combustion in a spark-ignition engine

Table 3

Performance and emission characteristics of methanol in a spark-ignition engine.

Methanol blend	Engine type	Performance	Emission	Baseline Fuel	Ref.
1. M10, M20	Single cylinder four stroke spark ignition	-BSEC, -EGT, +BSFC, +BTE	-HC, -CO, -NO, -smoke opacity	Gasoline	(Agarwal et al., 2014)
2. M10, M20	3-cylinder, port fuel injection, four stroke	-BTE	-CO, = NO_x	Gasoline	(Yanju et al., 2008)
3. M5, M10, M15, M20	Single cylinder, variable compression four-stroke	+BMEP, BTE	-	Gasoline	(Bilgin and Sezer, 2008)
4. Me10, Me15, Me20, Me25	3-cylinder, 4 stroke, spark ignition	+BTE, -brake power	-CO, -HC	Gasoline	(Liu et al., 2007)
5. Me10, Me25	Single-cylinder, 4 stroke, spark ignition	-Brake torque, -brake power	-NO, +HC	Gasoline	(Qi et al., 2005)
+: increase; −: decrease; =: slightly higher or equal					

1.3.3 Ethanol combustion in compression ignition engine

Table 4

Performance and emission characteristics of ethanol in compression ignition engine.

Ethanol blend	Engine type	Performance	Emission	Baseline Fuel	Ref.
1. e1, e2, e3, e4, e5	Single cylinder, water-cooled, four-stroke stationary diesel engine	-BTE, -exergy efficiency, -EGT	-NO_x, -CO_2, -smoke opacity, +HC, +CO	Diesel	(Jamuwa et al., 2016)
2. 5% Ethanol, 10% Ethanol	Six cylinder, in-line, four stroke compression ignition, direct injection, water-cooled, turbocharged, after-cooled	+BSFC, =BTE	-Soot density, =NO_x, -CO, +THC	Diesel	(Rakopoulos et al., 2008)
3. E10, E15, E20, E30	Direct injection, turbocharged	-BSFC	+HC, ~CO, ~NO_x, -smoke	Diesel	(Lei et al., 2011)
4. RE10, RE30	6 cylinders, 4 valves, water-cooled, turbocharger wit air intercooler	+BSFC, -BTE, -excess co-efficient	+NO_x, -soot, -CO, +HC	Diesel	(Wu et al., 2020)
5. E5, E10, E15	Four-cylinder, 4 stroke naturally aspirated	+BSFC, BTE	+CO, -NO, ~HC	Diesel	(Labeckas et al., 2013)
+: increase; −: decrease; =: slightly higher or equal; ~: varies					

1.3.4 Methanol combustion in compression ignition engine

Table 5

Performance and emission characteristics of methanol in compression ignition engine.

Methanol blend	Engine type	Performance	Emission	Baseline Fuel	Ref.
1. M5, M10, M15	Direct injection, naturally aspirated, and four stroke	+BSFC, +BSEC, -BTE	-CO, -THC, -smoke opacity, +NO_x	Diesel	(Sayin et al., 2010)
2. DM10, DM15, DM20, DM25, DM35, DM40	Four stroke compression ignition	-EGT	+NO_x, ~THC, -CO, ~CO_2	Diesel	(Jamrozik, 2017)
3. Ratio of methanol by mass (0–70%)	Direct injection, 4 stroke, single-cylinder	-BSFC	-NO_x, +HC, +CO	Diesel	(Song et al., 2008)
4. Methanol mass fraction (0–85%)	Single cylinder direct injection diesel engine	-BSFC	-NO_x, -smoke, +HC, +CO	Diesel	(Liu et al., 2010)
5. Me10, Me20, Me30	Four-cylinder four-stroke	+BTE, -brake power, -brake torque	-	Diesel	(Najafi and Yusaf, 2009)

+: increase; −: decrease; ~: varies

To summarize, ethanol/methanol combustion has its own merits and demerits compared to pure diesel and gasoline. Results may differ from one researcher to another due to differences in test procedures, emission control equipment, engine operating parameters such as load, speed, compression ratio, equivalence ratio, etc.; thus, a more general observation can only be stated. Overall, alcohol-diesel/gasoline blends in a lower alcohol concentration showed improvement in engine torque and brake power. For higher ratios of alcohol, additives such as cetane improvers could improve the brake torque and power. Similarly, at high concentrations of alcohol, BSFC increases compared to that of the neat oils; researchers explain that the relatively lower energy content of alcohols may be responsible for the observation. BTE on average has been reported to increase with an increase in alcohol fraction as a results of alcohols’ lower viscosity which improves fuel atomization. Generally speaking, HC and CO emissions are increased and lowered, respectively for alcohol blends in compression ignition engines. Typically, percentage differences in NO_x and HC emissions for alcohol blends and neat conventional oils were relatively modest. However, for spark-ignition engines, HC, NO_x, CO, and CO_2 are relatively higher in pure traditional oils than alcohol blends, which could be attributed to alcohols' high oxygen content.

The literature available so far shows excellent fuel characteristics in the combustion of alcohols. However, more effort could be put in place to address the alcohol-oil solubility problem, cetane, and lower heating value reduction to help realize the maximum characteristics of alcohol fuels.

2. Methodology

Bibliometric analysis is the application of quantitative tools to study science (Pritchard, 1969). Thus, researchers have a powerful technique to investigate larger datasets at their disposal than a traditional review while maintaining a high level of rigor, scientific soundness, transparency, and replicability (Dada, 2018; Rey-Martí et al., 2016). The current study aimed to identify what is known and unknown in fuel combustion from the start of the present century, focusing on low carbon alcohols, diesel, and gasoline. Hence, a quantitative analysis was conducted, applying performance analysis and science mapping using three bibliometric software; CiteSpace, RStudio biblioshiny package, and BibExcel. The conceptual design of the current study is highlighted in Fig. 2.

CiteSpace is one of the most sought-after bibliometric tools for investigating the evolution of a topic. It is developed to ascertain the structure and distribution, and distribution of scientific knowledge in the context of scientific meteorology, data analysis, and information visualizations, allowing the easy trace and understanding of the research paradigm of the interested literature landscape (Chen, 2006). The 5.7.R2 (64 bit) version of CiteSpace with Java was used. Social Network Analysis (SNA) is a quantitative method of analyzing and visualizing the relationship among research entities (Mao et al., 2015). In this study, SNA was adopted with CiteSpace's aid to visualize and analyze the various research entities' academic collaboration. SNA (authors, countries, institutions), co-citation network analysis (cited journals, local references of documents), and keyword analysis (keywords; title, abstract, author keywords, and keyword Plus) were evaluated with CiteSpace to map out the past, current, and future research trend of low carbon alcohol application in ICEs. The parameters in CiteSpace were set at: (1) Time slicing = 2000–2021, years per slice = 1; (2) Node type = author, institution, country, keyword, cited journal, cited reference; (3) Network selection criteria was based on Top N = 50; (4) link strength and scope = cosine and within slices, respectively; (5) Pruning = pathfinder and sliced network.

The bibliometrix package of RStudio is a handy scientific mapping tool, especially for non-coders (Aria and Cuccurullo, 2017). It comprises five analysis levels; dataset, authors, document, conceptual, intellectual and social. Each level includes different indicators, statistical measures, and visual representations. Three field plots, wordcloud and theme evolution were performed with this software. Persson's BibExcel was minorly used in the current study; its main function was to identify the co-occurring frequencies of the network between authors, institutions, countries, documents, and keywords.

The Web of Science Core Collection (WoS) with sub-field databases including Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI), Conference Proceedings Citation Index—Science (CPCI-S), Conference Proceedings Citation Index-Science (CPCI-S), Emerging Sources Citation Index (ESCI), Current Chemical Reactions (CCR-EXPANDED), Index Chemicus (IC) were selected for the current study. The WoS is a widely accepted database for different scientific fields that employ bibliometric analysis (Chen et al., 2014; van Leeuwen, 2006). It has over 100 subjects, making the database reliable for providing more consistent and standardized records than other databases such as Scopus (Bettencourt and Kaur, 2011; Hou et al., 2015).

The search term for applying low carbon alcohol in ICEs, “TOPIC: (Methanol combust* or ethanol combust* or low* carbon alcohol* combust* or primary alcohol* combust* or short chain alcohol* combust* or 'methyl alcohol* combust*' or 'ethyl alcohol* combust*' or 'c1 alcohol* combust*' or 'c2 alcohol* combust*') AND TOPIC: (Internal combust* engine * or 'compress* ignit* engine* or spark ignit* engine* or 'IC engine*' or 'CI engine*' or 'SI engine*') was entered on the database on the 30th January 2021 with a timespan of publications within 2000–2021. The inclusion of asterisk (*) at the end of words ensures that all the words with the same root are included in the search result. “TOPIC” also involves a simultaneous across title, abstract, author keywords, and Keywords Plus. The initial search yielded 2,458 publications.

The obtained literature contained publications (< 3%) with titles such as “Fuel processing for low-temperature and high-temperature fuel cells - Challenges, and opportunities for sustainable development in the 21st century (Song, 2002)” which may seem unrelated to the aim of the current study. However, a critical look at these papers reveal that they make reference to the improvement of some of the limitations identified in low carbon alcohol combustion in ICE which could serve as a reference point for future direction. Thus, these very less fraction of publications with such ‘unrelated’ titles were all considered for the current study. The h-index is a good measure of a research entities’ impact on a subject and has the advantage of being objective (Kinney, 2007). A scientist has index h if h of his/her N papers have at least h citations each, and the other (N-h) papers have fewer than h citations each (Braun et al., 2006). The impact factor of top-performing journals was obtained from the Journal Citation Reports (JCR) 2019 edition. It is a standardized indicator popularly adopted to measure the quality of journals, research papers, as well as researchers (Mao et al., 2015). The higher the impact factor, the higher the quality of the research. Other performance indicators included total local and total global citation scores (TLCS and TGCS), number of publications, collaborative index. TLCS refers to citations of a publication by the publications extracted for current study whereas TGCS refers to citation by any publication either within or not within the extracted documents. In addition, the attractive and active indexes of the countries have been employed from previous studies (Chen and Guan, 2011; Shen et al., 2018). The methodology of these two indexes expressed in Eq. 1 and Eq. 2 was adopted from Huang et al. (2020);

$$AI_t^i = \frac{(P_t^i)/(\Sigma P)}{(TP^t/\Sigma TP)} \qquad \text{Eq. 1}$$

$$AAI_t^i = \frac{(C_t^i)/(\Sigma C)}{(TC^t/\Sigma TC)} \qquad \text{Eq. 2}$$

Where, AI_t^i and AAI_t^i represent the activity index and the attractive index of country *i* in the year *t* respectively. P_t^i and C_t^i are the number of publications and citations of publications on low carbon alcohol combustion in ICEs of country *i* in the year *t*; ΣP and ΣC are the total number of publications and the sum of citations about the topic under review in country *i* during a given period. Similarly, TP^t and TC^t represent the global number of publications and citations of publications in the year *t*; ΣTP and ΣTC

represent the total number of articles and the sum of citations during the same period as that of *ΣP* and *ΣC*, respectively.

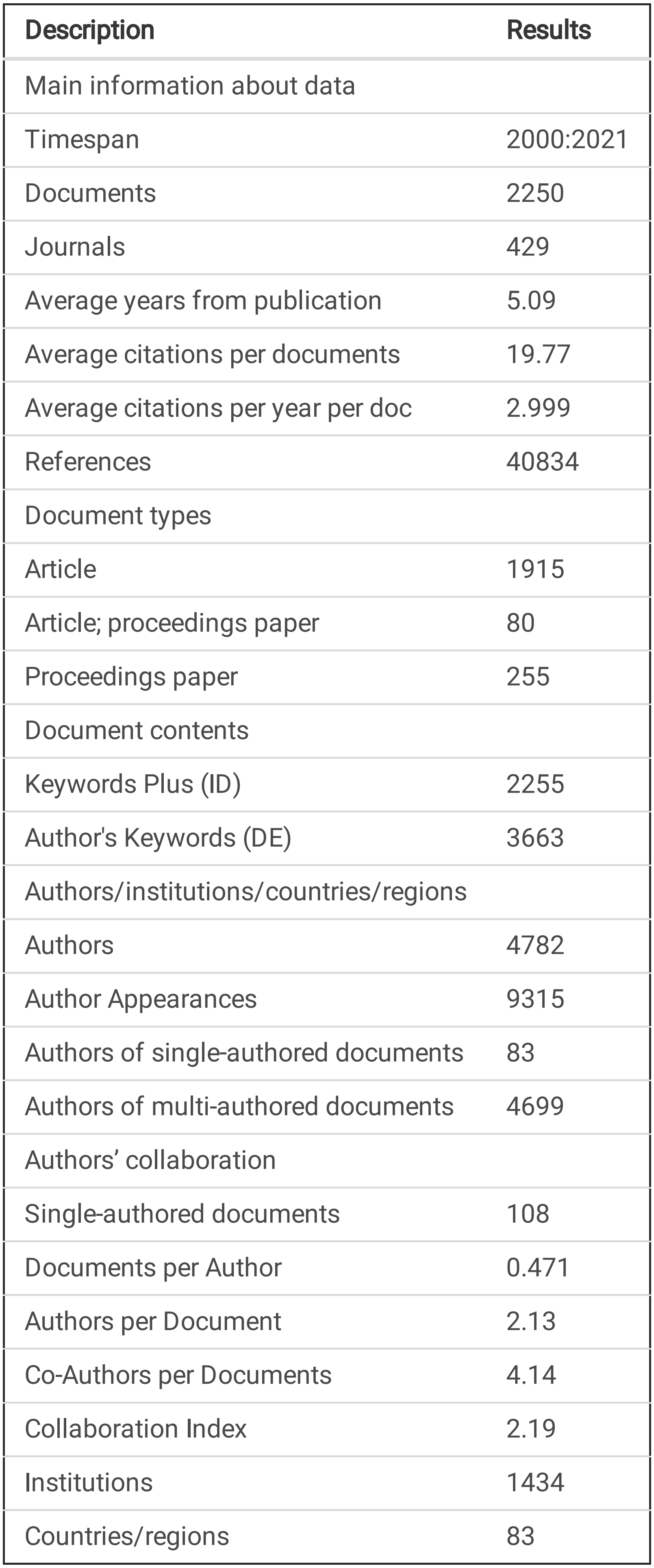
When the value of *AI* > 1, the productivity of the country is greater than the global average; *AI* < 1, the productivity of the country is less than global average; *AI* = 1, productivity of country is same as global average. The same rule applies to *AAI* but in this case describes the degree to which studies of a country attracts other researchers either local or international.

3. Results And Discussion

Article and *proceedings paper* types of publications accounted for 84% and 14% of the initial search results. The remaining 2% of documents were classified *as reviews, letters, meeting abstracts, editorial materials*, etc. Thus, only *articles* and *proceeding papers* were used for the current study as previously done by Mao et al. (Mao et al., 2015) because these types of documents provide more original research findings and include more information on authors and their affiliations. 99% of the refined documents were published in the *English* language. The other 1% included publications written in major languages such as *Czech* (0.308%), *Polish* (0.220%), *Turkish* (0.176%), etc. Hence, the search results were further refined to only include publications written in English as it is the most universal and commonly used academic language worldwide (Chen et al., 2017). After this further screening, the remaining publications extracted for the current study were 2,250. The main information about the obtained documents has been displayed in Table 6.

Table 6

Main description of extracted documents.



Description	Results
Main information about data	
Timespan	2000:2021
Documents	2250
Journals	429
Average years from publication	5.09
Average citations per documents	19.77
Average citations per year per doc	2.999
References	40834
Document types	
Article	1915
Article; proceedings paper	80
Proceedings paper	255
Document contents	
Keywords Plus (ID)	2255
Author's Keywords (DE)	3663
Authors/institutions/countries/regions	
Authors	4782
Author Appearances	9315
Authors of single-authored documents	83
Authors of multi-authored documents	4699
Authors’ collaboration	
Single-authored documents	108
Documents per Author	0.471
Authors per Document	2.13
Co-Authors per Documents	4.14
Collaboration Index	2.19
Institutions	1434
Countries/regions	83

3.1 Publications’ evolution over time.

Figure 3 presents the primary performance of alcohol-combusted-related literature published in the 21st century so far. Results show that interest in the subject has grown significantly in the last decade compared to the previous decade. The publications between *2011* to *2021* were at least eight times that of *2000* to *2010*. The number of citations, however, followed a different trend as that of the number of publications. The peak of citations for both local and global was realized in *2016.* This observation may be explained by the fact that the studies during this period have significantly impacted global fuel combustion research and thus aroused interest from scientists. This explanation is further bolstered by the peak h-index occurring at the same period. The publications in the slow development period have relatively the most influence on the subject compared to the initial and rapid developmental stages with regards to citations and h-index. Interestingly, at the time of reporting these findings, the number of publications on the combustion of low carbon alcohol in ICEs for *2021* was 53, which is just two publications short of those produced from *2000* to *2004* combined. Referring to previous studies (Andreo-Martínez et al., 2020; Zheng et al., 2015), polynomial, linear and exponential regression could be employed in making future growth estimations of a given dataset. From *2000–2007*, *2008–2015*, and *2016–2020*, the publications could be fitted with a 2nd order polynomial function y=-0.0179x2 + 1.8036x + 7.625 (R^2 = 0.7899),y = 2.1012x2-30.435x + 144.46(R^2 = 0.9903), and y = 0.2143x2 + 16.386x-80.6 (R^2 = 0.9996), respectively, where X is the number of years since the start of the period and Y is the number of publications accumulated each year. The R^2 value of the rapid development period is the closest to 1 and could be used to fairly estimate the number of publications to be expected in the next seven-year period. By the end of *2021* to *2027*, the number of publications on the current subject is expected to increase to 358 to 567, respectively, an increase of 7.5–70.3% relative to *2020’s*. These figures signify that more communication, interest, and co-operation among researchers is expected by the end of the next decade.

3.2 Distribution of output in journals.

In the current research, there were 2,250 publications across 429 related journals; the top 20 productive journals as well as the h-index, impact factor, and cited times of journals are listed in Table 7. The two major study themes consistent in the top 20 journals were ‘energy’ and ‘environment’. These 20 journals constitute approximately 63% of the total number of publications used in the current review. The top 3 most publishing journals were *Fuel, Energy*, and *Energy and Fuels*. The top three journals' trend does remain the same except for Energy and Fuels in terms of h-index. *Energy and Fuels* lost their spot to *Applied Energy*. This observation could be attributed to the influence of the journals in terms of their citations. Higher number of publications with lower citation reduces the h-index of the journal. For example, the total citation of *Applied Energy*, and *Energy* was 3,985 and 3,538, respectively, compared to their 111 and 124 publication records. Simultaneously, the trend is entirely different for impact factor. The top three high-quality research journals were *Applied Energy*, *Energy Conversion and Management*, and *Environmental Science and Technology.* The dynamics of the top 5 publishing journals in Table 7 with respect to time is shown in Fig. 4. For the first ten years, the difference in publication output of these five journals was less spontaneous. However, by the end of 2020, *Fuel's* dominance in the subject area became apparent. In addition, *Fuel's* productivity has been on the rise since the start of the century, but that of the other four journals has stabilized within the last four years.

Co-citation of journals is described in Fig. 5. Two journals are cited in the same publication if a line known as edge connects the two journals. The bigger the node, the stronger the co-citation of the journal. From Fig. 2, it can be seen that *Fuel* is the most frequently co-cited journal per the size of its node (1,776 co-citations), followed by *Energy Conversion and Management* (1,310 co-citations), and *Applied Energy* (1,260 co-citations).

Table 7

Journals' performance from 2000 to 2021.

Journal	NP	TC	h-index	Impact factor	PY start
1. Fuel	417	9909	51	5.578	2006
2. Energy	124	3538	36	6.082	2000
3. Energy & Fuels	121	2359	28	3.421	2005
4. Applied Energy	111	3985	40	8.848	2009
5. Energy Conversion and Management	110	3726	36	8.208	2000
6. Applied Thermal Engineering	77	2262	27	4.725	2007
7. Renewable Energy	61	2008	25	6.274	2003
8. International Journal of Hydrogen Energy	60	2221	22	4.939	2002
9. Combustion and Flame	45	1281	21	4.570	2006
10. Energies	43	177	9	2.702	2016
11. International Journal of Engine Research	37	300	10	2.382	2007
12. Proceedings of The Institution of Mechanical Engineers Part D-Journal of Automobile Engineering	35	387	10	1.384	2003
13. SAE International Journal of Engines	27	169	7	-	2015
14. Fuel Processing Technology	26	570	13	4.982	2009
15. Proceedings of The Combustion Institute	26	591	14	5.627	2002
16. Environmental Science and Pollution Research	23	308	10	3.056	2017
17. Journal of Engineering for Gas Turbines and Power-Transactions of the ASME	23	454	9	1.804	2003
18. Journal of Energy Resources Technology-Transactions of the ASME	22	250	10	3.183	2007
19. Thermal Science	19	104	6	1.574	2011
20. Combustion Science and Technology	17	115	6	1.730	2002

NP, TC, PY represents the number of publications, total citations, and publication year, respectively.

3.3 Funding Agencies

The growth of research often greatly depends on support from funding agencies. These agencies play a significant role in pushing forward frontiers of scientific research per national, regional, or international policy on a specific agenda. Table 8 displays the top 10 funding agencies driving the studies of methanol/ethanol utilization in ICEs. According to Table 8, funding agencies from Asia, Europe, and North America are the main contributors to research into the current study's subject in the 21st century. For the first quarter of the study period, no research support from these top funding agencies was given to the researchers, thus explain the low productivity of publications in that period, as seen in Fig. 3. In the last two quarters, these agencies made significant research support to research institutions which should explain the increase in productivity from 2011–2020 of Fig. 3. For funding agencies that have supported at least ten publications, 1,051 funds have been provided so far, and 70% of these supports are from the top 10 funding agencies listed in Table 8, signifying their enormous contribution towards clean combustion. *The National Natural Science Foundation of China (NSFC)* alone has supported 337 publications which far exceeds the second and third funding agencies, namely, *United States Department of Energy* (76) and *National Council for Scientific and Technological Development* (47). This observation implies that the *NSFC* is the major player in the global utilization of low carbon alcohol in ICEs research as far as funding agencies are concerned.

Table 8

Most funding agencies from 2000–2021.

Funding Agencies	Country	NSP	2000–2005	2006–2010	2011–2015	2016–2021
National Natural Science Foundation of China NSFC	China	337	0	10	63	264
United States Department of Energy DOE	USA	76	0	2	26	48
National Council for Scientific and Technological Development CNPQ	Brazil	47	0	2	14	31
CAPES	Brazil	43	0	0	7	36
Fundamental Research Funds for The Central Universities	China	42	0	0	3	39
China Scholarship Council	CHINA	41	0	0	8	33
Engineering Physical Sciences Research Council EPSRC	UK	38	0	2	19	17
UK Research Innovation UKRI	UK	37	0	1	18	18
National Science Foundation NSF	China	36	0	1	12	23
European Commission	-	33	0	0	6	27

NSP refers to the number of supported publications.

3.4 Authors’ performance

In this section, the performance of the top 20 authors leading the research in the subject of the current study is discussed. This group of authors listed in Table 9 constitute 0.42% of the total authors involved in the current study; however, their publications make up 20.8% of the total publications extracted. Criteria for assessing these authors' performance were limited to the number of publications, h-index, and total citations. According to the number of publications, *Gong CM, Mamat R, Liu FH, Zhao H*, and *Lu XC* were the top 5 publishing authors. *Ji CW, Wang SF*, and *Agarwal AK* replaced *Mamat R, Liu FH*, and *Lu XC* to complete the top 5 authors according to the h-index. The latter group of authors' losses of spot could be attributed to their relatively low total global citation scores. Highly cited publications of authors usually increase the h-index and vice versa. *Xu HM* and *Gong CM* are the most TGCS- and TLCS-rated authors in Table 9, respectively. *Liu FH* and *Qian Y* have the most recent publications (2015), whereas *Li J* has the oldest publication (2002). In addition, the academic co-authorship amongst influential authors was analyzed and displayed in Fig. 6. The most partnership existed between *Gong CM* and *Liu FH* (28 Collaborations), followed by *Qian Y* and *Lu XC* (18 collaborations), and *Ji CW* and *Wang SF* (17 collaborations). In Fig. 7, the annual scientific production of these 20 authors is shown. The most active years of these authors can typically be found in the current study's rapid developmental stage. *Gong CM, Mamat R, Liu FH, Zhao H*, and *Lu XC* had their most publishing year in 2020, 2017, 2020, 2016, and 2019, respectively. The author with the most different publication and citation years is *Huang Z*, publishing and being cited in seventeen different years out of a possible twenty-one.

Table 9

Top 20 performing authors.

Author	NP	h-index	TLCS	TGCS	PY start
Gong CM	40	18	458	804	2008
Mamat R	29	11	91	413	2014
Liu FH	28	12	251	471	2015
Zhao H	28	13	186	507	2010
Lu XC	27	11	135	486	2005
Agarwal AK	26	13	261	817	2003
Liu JP	26	13	136	438	2013
Yao CD	25	11	192	597	2008
Ji CW	24	17	188	636	2010
Huang Z	23	12	286	473	2005
Xu HM	23	13	294	952	2011
Wang Y	22	10	163	336	2013
Sarathy SM	21	10	85	344	2012
Wang Z	21	11	176	502	2010
Wang SF	19	15	138	503	2010
Qian Y	18	8	68	209	2015
Wang CM	18	7	129	388	2012
Irimescu A	17	10	100	291	2011
Maurya RK	17	11	186	582	2009
Li J	16	10	165	380	2002

NP, TGCS, TLCS, PY represents number of publications, total global citation scores, total local citation scores and publication year, respectively.

3.5 Institutions’ performance

The 20 most active institutions leading the research of low carbon alcohol combustion in ICEs are listed in Table 10. Their NP accounts for 33% of the total publications. *Tianjin University* tops the chart with 91 publications, followed by *Jilin University* (64 publications) and *Tsinghua University* (52 publications). Half of the institutions mentioned in Table 10 are located in mainland China with 58% of the total publications of the twenty institutions. These figures demonstrate the global dominance of Chinese universities on the current subject. Other notable institutions outside China were *Indian Institutes of Technology*, and *University Illinois*. *Tianjin University* maintained its first position in TLCS and TGCS; the *University of Birmingham* and *Tsinghua University* ranked second and third/fourth, respectively for both TLCS and TGCS. In terms of h-index, *Tianjin University, Tsinghua University*, and *University of Birmingham* ranked first, second, and third, respectively, which could be attributed to their relatively superior NP, TLCS, and TGCS.

Represented in Fig. 8 is the academic partnership amongst the most productive institutions across the globe. The most institution collaboration existed between *Dalian Minzu University* and *Jilin University* (21 collaborated-publications), followed by *Tsinghua University* and *University of Birmingham* (16 collaborated-publications), and *Beijing Institute of Technology* and *University Illinois* (16 collaborated-publications).

Table 10

Performance of top 20 institutions.

Institutions	Country	NP	h-index	TLCS	TGCS
Tianjin University	China	91	27	647	2222
Jilin University	China	64	20	384	944
Tsinghua University	China	52	22	371	1418
Shanghai Jiao Tong University	China	51	15	168	732
Anna University	India	46	14	167	969
University of Birmingham	UK	41	21	402	1580
Hunan University	China	35	17	153	659
Indian Institutes of Technology	India	35	20	292	1366
Universiti Malaysia Pahang	Malaysia	35	11	94	400
Xi'an Jiaotong University	China	34	16	328	972
Consiglio Nazionale delle Ricerche (CNR)	Italy	31	14	155	509
National Institute of Technology	India	29	14	148	680
Beijing Institute of Technology	China	27	13	178	558
University Illinois	USA	26	13	263	768
Beijing University of Technology	China	25	18	208	669
University of California, Berkeley	USA	25	12	131	459
Dalian Minzu University	China	24	11	103	400
Lund University	Sweden	23	9	38	211
Vellore Institute of Technology (VIT)	India	23	13	64	520
Wuhan University of Technology	China	23	11	78	293

NP, TGCS, TLCS represents number of publications, total global citation scores and total local citation scores, respectively.

3.6 Countries’ performance

China, India, and *USA* have been the three most performing countries/regions on the current study subject. As seen in Table 11, these three countries have alone contributed to approximately 60% of the total studies published in this field between 2000–2021. *Brazil* ranks 7th with 111 publications so far. It can also be seen *China* ranks 1st in both single and multiple country publications and also had the most total citations. The results of the countries’ total citations are consistent with their h-index. The top 3 most cited countries maintained their position with regards to the h-index, which implies that the studies of the *Chinese*, *Indians*, *Americans (USA)*, were highly influential to the studies of other researchers. According to the attractive index in Fig. 9a, only *China's* AAI for four different periods was almost equal or greater than that of the global average. *India's* AAI was less than the global average except during the last quarter; however, it was the only country whose attractiveness increased with time. The highest AAI was recorded by *USA* during the third quarter, whereas the lowest AAI so far has been recorded by *Italy, Malaysia, Iran*, and *Saudi Arabia* in the 2000–2005 period. On average, the most attractive studies originate from *China*. On the other hand, as seen in Fig. 9b, the research activity of *US* (AI) was the highest, having AI greater than global average except for 2016 to 2021. Though *China* has the most publications, its active publication period has only been relatively recent, thus explaining its lower AI compared to that of *US* and *UK* in the earlier periods. The activeness of *Malaysia, Iran*, and *Saudi Arabia* has only been from the start of the third quarter.

The academic partnership amongst the various countries is reported in Fig. 10. The most collaboration existed between *China* and *USA* (79), *China* and *UK* (46), and *Iran* and *Malaysia* (15).

The dominance of these countries correlates with their biofuel production, government subsidies, and programs. *Brazil* is one of the pioneer countries to implement programs for the production of ethanol fuel from sugarcane. Since 1977, *Brazil's* ethanol-use mandate has been mandatory, with a state-legislated 4.5% blend of anhydrous ethanol to gasoline (Barros, 2020). The legislation allows ethanol to be blended in gasoline within the range of 18-27.5%, and it is currently set at 27%. In addition, the tax for gasoline rose from R$0.38/liter to R$0.79/liter in 2017. Ethanol's tax increase was relatively lower than gasoline's (from R$0.12 /liteR$0.13/liter, while for ethanol distributors, it increased from zeroR$0.11liter), which favored ethanol's competitiveness compared to gasoline (Barros, 2020). About 40% of fuel used in *Brazilian* road transport vehicles is ethanol (Anderson, 2009). In the *US*, an astonishing 16.1 billion gallons of clean, renewable ethanol was produced in 2018 (RFA, 2019). Between 2017–2018, ethanol consumption grew by 300 million gallons, driven largely by record exports of over 1.6 billion gallons as the demand for octane increases globally. Domestic demand was also on course to record levels as January 2018's blend rates topped a record 10.75%, despite the existence of the so-called 'blend wall.' *China's* increased productivity in this field of study could be attributed to its growing effort to increase the biofuel fraction of its current energy mix, as 30% of the total global primary energy demand in the next two decades will be from Asia, mainly from *China* and *India* (IEA, 2010). *China* ranked 3rd in the 2012 global rankings of ethanol fuel production (Sarathy et al., 2014). The E10 target of *China* was planned to follow an incremental expansion through a few selected provinces and cities (Kim, 2018). As of 2017, 11 provinces and cities were enrolled on the mandatory E10 blend as ethanol pilot zones. In the case of methanol, there are 50 methanol gasoline blending terminal centers either completed or under construction in 15 *Chinese* provinces, and there is more than 1.2 million metric tons (or 400 million gallons) of annual methanol blending capacity (Klein, 2020). Subsidies have been made available to increase ethanol fuel uptake; advanced cellulosic ethanol production subsidy is currently $0.007 per liter (600 RMB per ton) (Kim, 2018). The government of *India* has made plans to provide financial incentives, including subsidies, grants, tax credits, accelerated depreciation on plant expenditures, differential pricing vis-à-vis – 1G Ethanol, Viability Gap Funding (VGF of INR 5000 crore, or $735 million), all within 6 years

(Aradhey, 2019). These provisions have boosted ethanol production and consumption in *India* in recent years, and efforts are being made to make second-generation ethanol a more attractive fuel than gasoline and first-generation ethanol. Finally, the *European Union* adopted the new Renewable Energy Directive for 2021–2030 (RED II). The energy directive seeks to achieve a renewable energy target of at least 32% by 2030, with a 14% target allocated for the transport sector (Bob et al., 2019).

In Fig. 11, the relative trend in the five continents' research output in four different timelines is depicted. *Europe* and *America’s* dominance were apparent in the first quarter. However, from the second to the final quarter, *Asia* has been at the forefront of the research on the current subject, with most of its contributions from *China* and *India*. Figure 12 is a geographical representation of past studies on the combustion of low carbon alcohol in ICE from 2000 to 2021. Despite being the third-largest continent according to the number of countries, *Europe* had the most country-diversified publications, followed by *Asia, America, Africa*, and *Oceania* in that order.

Table 11

Research output of countries from 2000 to 2021.

Country	NP1	NP2	SCP	MCP	h-index	TC	Top 3 collaborations*
China	562	513	407	106	48	9931	USA, UK, Australia
India	425	397	370	27	43	6735	Vietnam, USA, Canada
USA	348	243	182	61	46	6601	Saudi Arabia, Germany, UK
United Kingdom	153	104	59	45	35	2869	Spain, Germany, Thailand
Turkey	131	120	112	8	34	4130	Sweden, Denmark, Netherlands
Brazil	111	102	82	20	17	1051	Spain, UK, France
Italy	75	66	61	5	20	1248	Sweden, Belgium, Canada
Malaysia	75	55	35	20	22	1111	Iran, Australia, Iraq
Iran	65	53	39	14	16	771	Australia, Canada, Indonesia
Saudi Arabia	64	35	24	11	22	699	Egypt, Canada, Ireland
Australia	61	36	18	18	26	853	Iraq, Germany, Spain
Spain	56	36	22	14	16	720	Mexico, Belgium, Colombia
Germany	54	39	31	8	17	737	Netherlands, Sweden, Ireland
France	50	25	17	8	18	685	Spain, Algeria, Belgium
Korea	49	46	34	12	17	776	Japan, Indonesia, Saudi Arabia
Canada	45	32	21	11	16	542	Belgium, Israel, Netherlands
Sweden	38	25	16	9	13	363	Belgium, Denmark, Netherlands
Poland	36	35	33	2	12	538	Hungary, Slovakia
Japan	33	20	19	1	13	294	Egypt, Thailand, Belgium
Greece	23	21	18	3	10	397	Belgium, UAE

NP1, NP2, SCP, MCP, TC, refer to number of publications (overall), number of publications (according to corresponding author's country), single country publication, multiple country publication, and total citations, respectively. *collaborations from countries in column 1 to countries in column 8. Note–United Kingdom consists of records from England, Scotland, Wales, and Northern Ireland.

3.7 Research hotspots and trends

The current subject's research trend is evaluated based on the frequency of keywords from titles, abstracts, author keywords, and keyword-plus. The most frequent keywords are shown in Fig. 13. It can be seen that the top 3 keywords (per minimum count) were *ethanol* (864), *combustion* (826), and *performance* (821). The use of 'minimum' is to imply that other root forms of the word had appeared in relatively lower positions. The top three keywords reveal to the current study that the main research hotspot of the subject at hand centers around the *combustion*, *performance*, and *emission* characteristics of alcohol-fueled engines. With *ethanol* ranking first, its *methanol* counterpart ranked 8th with a minimum count of 354, which is less than *ethanol's* by 244%. The figures suggest that in the 21st century, the combustion of *ethanol* in ICEs seems more preferable to *methanol*. The relatively better fuel properties of *ethanol* over *methanol's* make the former attain more complete combustion and efficiency with relatively lesser pollution. Varol et al. (2014) compared the blends of different alcohols in unleaded gasoline for the mixtures' emission and performance characteristics. Their study revealed that CO_2 and HC emissions were higher in the *methanol* blends compared to *ethanol's*. Moreover, the BSFC and BTE were higher and lower in the *methanol* blends than *ethanol's*, respectively. Corrosivity in *methanol* has been reported to be affected by the alcohol's high polarity. *Methanol*-fueled engines require modifications to engine fuel systems as methanol tends to cause issues of material compatibility and both metals and elastomers (soft components used for seals and fuel lines) can be attacked by *methanol* if not chosen properly (Klein, 2020). The electrical conductivity could be a measure of a fuel's corrosivity; compared to *ethanol*, *methanol's* electrical conductivity is at least four times higher (Klein, 2020). Also, the solubility of *methanol* in oil is relatively poorer than that of ethanol (Jin et al., 2019b; Jin et al., 2020), hence, more co-solvent is needed in the *methanol*-oil blends. Interestingly, *biodiesel* ranked 4th as the most co-cited keyword with a minimum citation count of 684. Several authors have reported that *biodiesel's* addition to diesel/gasoline-alcohol blends has several added benefits such as cetane enhancement and promotion of miscibility (Alam et al., 2006; Subbaiah et al., 2010). Emissions have also been reported to reduce in oil-alcohol blends with the addition of *biodiesel* (Subbaiah et al., 2010). Between the two conventional oils, *gasoline* aroused more interest from researchers than *diesel*, with a minimum count of 357 and 158, respectively. The primary reason could be due to cost; *gasoline* prices have been lower than *diesel* almost continuously since September 2004 (EIA, 2021). As of January 2021, *gasoline's* price was $2.33/gallon compared to $2.68/gallon of *diesel* (EIA, 2021). According to the International Council on Clean Transportation, combustion of 1L of *diesel* fuel produces 11% more CO_2 than the same amount of *gasoline* fuel (ICCT, 2019). Consequently, the *spark-ignition engine* appeared in many studies than *compression ignition engine* (225 and 173 minimum citation counts, respectively). *Spark ignition engines* based on the Otto cycle are the most popular internal combustion engines, as they can burn a wide range of fuels including gasoline, natural gas, propane, biogas and landfill gas (Breeze, 2018). *Diesel (compression ignition) engines* are more expensive to manufacture and require intensive NO_x abatement technologies. The main drawback to *gasoline engines (spark ignition)* compared to *diesel engine* for years has been lower efficiency; however, with the introduction of efficiency technologies, such as direct injection, turbocharging and downsizing, cooled EGR, and variable valve timing and compression-ratio engines, the efficiency advantages of *diesel engines* are further eroded (ICCT, 2018). Moreover, solubility of *ethanol* in *gasoline* can be achieved without co-solvent whereas that of *diesel* is impossible (Lapuerta et al., 2007; Rakopoulos et al., 2011; Rakopoulos et al., 2014). These factors could explain for the higher interest in *gasoline and spark ignition engine* by the researchers investigated in the current study. Furthermore, the most appearing advanced combustion technique was *low temperature combustion* (minimum count of 73) with *Homogeneous charge compression ignition (HCCI)* being the most common type (63 minimum counts). For author keyword co-occurrence analysis, the most co-occuring pairs were *combustion-emission* (144 times), *performance-emission* (131 times), *ethanol-emissions* (78 times), *performance-combustion* (60 times), *ethanol-combustion* (51 times), *ethanol-gasoline* (46 times).

The emergence of broad and core themes is captured using three field plots, as seen in Fig. 14. The figure aims to highlight how the combustion of low carbon alcohols in ICE has changed over the last two decades. Two cutting points of timelines were set, i.e., 2005 and 2010, producing three different periods; 2000–2005, 2006 to 2010, and 2011 to 2021. The stream of lines connecting one theme to another describes how a theme's research focus has evolved with time. The bigger the size of the node and stream, the bigger the themes' influence in that particular period. The research started with eight major themes: *alternative fuel, ethanol, engine performance, methanol*, and *internal combustion engine*. As a theme, *alternative fuel* has evolved into three different themes; *ethanol, combustion*, and *engine performance*. The theme evolved from 2000–2005 into *ethanol* in 2006–2021 and ended in 2011–2021 as *combustion and engine performance*. It could be suggested from this observation that, amongst the several *alternative fuel* options available for combustion in ICE, the relative attention of researchers on solely *ethanol combustion* and *performance* became great, which is in line with the observation in Fig. 13. *Ethanol* as a theme has remained unevolved for the entire duration of the century so far. However, the same cannot be said for its *methanol* counterpart. As one of the major themes at the start of the century, *methanol* has evolved into *ethanol* with more focus on the C2 alcohol due to its extra advantages than the C1 alcohol, and the evolution follows the same pattern as in *alternative fuels*. *Combustion* and *engine performance* have all not evolved, implying a sustained interest of these themes by researchers. However, just like *methanol*, the *diesel engine* has undergone three evolutions. The diesel engine's focus as a whole topic was narrowed down to *combustion* and *exhaust emissions* from the first period to the end of the second. The *combustion* theme from this stream has remained as it is but that of *exhaust emissions* evolved after 2010 into *engine performance* and *ethanol* in 2011–2021. Interest in *advanced combustion technology (HCCI)* became more spontaneous in 2006–2010 with three main current research focus; *engine performance, ethanol*, and *hydrogen*. The focus on *hydrogen* as combustion fuel became less apparent after 2000–2005. However, in the 2011–2021 period, interest in this fuel as an alternative to *methanol, ethanol* or *diesel, gasoline* has emerged but a slower rate per its node size. The results of Fig. 14 are very consistent with Fig. 13, further re-emphasizing the growing communication of combustion, performance, and emission characteristics of ethanol.

The main research direction of the three most influential continents, *America, Asia*, and *Europe*, is highlighted in Fig. 15 according to the frequently occurring author keywords. From the figure, it can be concluded that these three continents' research focus has fairly been the same. In no particular order, *ethanol, combustion, performance*, and *emissions* have been the top 4 author keywords across all research studies coming from these three continents. However, it is worth mentioning that there were some differences in the research trends but had very minimal influence compared to the bigger picture. For instance, *artificial neural network (ANN)* became a popular topic in *America's* research field, making its way to the 50 most occurring author keywords. *ANN* was relatively not prominent in the studies originating from *Asia* and *Europe*. The machine learning term failed to make it to the top 50 author keywords in these two continents.

The section is concluded with the main research direction of the most productive countries and journals. A three-field plot is generated, as shown in Fig. 16, with top 10 countries on the left, top 10 journals on the right, and top 10 keywords in the middle. From the figure, it can be seen that the top 5 keywords from these ten countries are the same as that of global as shown in Fig. 13, except for *biodiesel* (global) and *blend* (top 10 countries). This demonstrates that the research direction of the current study's subject is mostly driven by these ten countries, especially *China, India*, and *USA*. On the other hand, *methanol* is not a top 10 highly occurring word of these ten influential countries. This implies that the top 10 ranking of *methanol* on a global scale could have been influenced mainly by countries outside the those mentioned in Fig. 15; thus, *methanol* can be said to have been a favorite fuel option in those countries. These ten countries also found *Fuel* as the most attractive journal for their publications. Apart from *Renewable Energy*, and *Combustion of Flame*, the main publications by these journals originated from *China. Combustion of Flame* was mainly supplied with studies from *USA*, whereas *India* was the main publication country of *Renewable Energy*. The top 10 keywords were mainly influenced by publications from *Fuel*.

4. Most Influential Literature

The most influential literatures of the 2250 documents are listed in Tables 12 and 13. Two groups of literature are discussed; most cited local documents, and most cited local references. The former refers to documents within the 2250 dataset with the highest citation from documents within the same dataset. The latter also identifies the most cited articles in the reference list of all the 2250 documents combined. *J. Haywood's* 1988 book titled *"Internal Combustion Engine Fundamentals"* (J.B, 1988) is the most locally cited reference which a complete guide to working principle and characteristics of all internal combustion engines. However, for the purpose of the current study, emphasis is placed on the second-ranked document. In 2007, *Agarwal* published an article titled *"Biofuels (alcohols and biodiesel)* applications as fuels for internal combustion engines" (Agarwal, 2007) which has been the most locally cited reference in the citations of the 2250 documents. The article provides an overview of three main liquid biofuels, i.e., alcohols, biodiesel, and vegetable oils. For alcohols, attention was focused on their properties, engine modification requirement, regulated and unregulated emissions from ethanol-operated engines, and the engine performance of diesohol and gasohol blends. Their study revealed that ethanol as a fuel additive in unleaded gasoline results in improved performance and exhaust emissions characteristics. Generally, brake power, brake thermal efficiency, volumetric efficiency, and fuel consumption improves, whereas a negative trend is observed in brake specific fuel consumption and equivalence air-fuel ratio. With emission characteristics, ethanol-unleaded gasoline blends lead to a significant reduction in exhaust emissions for CO and HC for all engine speeds, but CO_2 increases marginally. Dieseohol up to 20% ethanol content could directly be used in a CI engine without any modification to the engine's hardware. The most co-cited local references were *Al-Hassan A, 2003-Hsieh WD, 2002* (55 co-citations) (Al-Hasan, 2003; Hsieh et al., 2002), *Gu XL, 2012*-Szwaja S, 2010 (49 co-citations) (Gu et al., 2012; Szwaja and Naber, 2010*), and Jin C, 2011*-Szwaja S, 2010 (47 co-citations) (Jin et al., 2011; Szwaja and Naber, 2010). Figure 17 depicts the most cited local references with a minimum of fifty citation counts.

On the other hand, *Hsieh's* 2002 study titled *"Engine performance and pollutant emission of an SI engine using ethanol-gasoline blended fuels"* (Hsieh et al., 2002) has been the most locally cited document. In this paper, the researchers have experimentally blended ethanol in gasoline at 0, 5, 10, 20, and 30 vol% ethanol content. The study revealed that higher ratios of ethanol decrease the heating value of the blended fuels, whereas octane number increases. The maximum Reid vapor pressure of the blends initially increases to a maximum at 10% ethanol content and then decreases. Blends increased the torque and fuel consumption of the engine slightly and significantly reduced CO and HC emissions; CO_2 increases and NOx emissions varied depending on the engine's operating condition.

In summary, the following conclusions can be drawn from these twenty literatures; 40% of these publications were solely dedicated for reporting the combustion of ethanol fuel in ICEs in contrast to 5% of methanol. A large portion of the remaining 55% documented results from both ethanol and methanol, with a less significant portion for either engine characteristics or higher alcohols. Also, 15% of the publications originated from the American continent compared to 45% and 40% of Asia and Europe, respectively. None of the documents were published during the rapid development period (2016–2021). 40% were published prior to the start of the slow development period. Thus, it can be observed that, the documents that have really had an impact in this research field were mostly published during the slow development period (60%). Majority of the publications were more focused on the performance and emission characteristics of the fuels than their combustion characteristics. Thus, more studies are required to evaluate the combustion characteristics such as ignition delay, in-cylinder pressure, heat release rate, etc. of low carbon alcohol-fueled ICEs.

Table 12

Most locally cited references.

Paper title	Total citations	First author	Country/region	Ref.
1. Internal combustion engine fundamentals	498	John B. Heywood	USA	(J.B, 1988)
2. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines	185	Avinash Kumar Agarwal	India	(Agarwal, 2007)
3. Progress in the production and application of n-butanol as a biofuel	118	Chao Jin	China	(Jin et al., 2011)
4. Engine performance and pollutant emission of an SI engine using ethanol–gasoline blended fuels	116	Wei-Dong Hsieh	Taiwan	(Hsieh et al., 2002)
5. Ethanol–diesel fuel blends––a review	110	Alan C. Hansen	USA	(Hansen et al., 2005)
6. Effect of ethanol–unleaded gasoline blends on engine performance and exhaust emission	105	M. Al-Hasan	Jordan	(Al-Hasan, 2003)
7. Combustion of n-butanol in a spark-ignition IC engine	95	S. Szwaja	USA/Poland	(Szwaja and Naber, 2010)
8. Emission characteristics of a spark-ignition engine fuelled with gasoline-n-butanol blends in combination with EGR	92	Xiaolei Gu	China	(Gu et al., 2012)
9. Alcohol combustion chemistry	92	S. Mani Sarathy	Saudi Arabia	(Sarathy et al., 2014)
10. The effects of ethanol–unleaded gasoline blends on engine performance and exhaust emissions in a spark-ignition engine	90	Mustafa Koç	Turkey	(Koç et al., 2009)

Table 13

Most locally cited documents.

Paper title	Local Citations	Global Citations	First author	Country	Ref.
1. Engine performance and pollutant emission of an SI engine using ethanol–gasoline blended fuels	116	350	Wei-Dong Hsieh	Taiwan	(Hsieh et al., 2002)
2. Emission characteristics of a spark-ignition engine fuelled with gasoline-n-butanol blends in combination with EGR	92	213	Xiaolei Gu	China	(Gu et al., 2012)
3. Combustion performance of bio-ethanol at various blend ratios in a gasoline direct injection engine	68	150	Turner Dale	UK	(Turner et al., 2011)
4. A comparison of performance of higher alcohols/diesel fuel blends in a diesel engine	65	198	JavierCampos-Fernández	Spain	(Campos-Fernández et al., 2012)
5. Study of spark ignition engine fueled with methanol/gasoline fuel blends	64	139	Liu Shenghua	China	(Liu et al., 2007)
6. The effect of compression ratio on the performance, emissions and combustion of an SI (spark ignition) engine fueled with pure ethanol, methanol and unleaded gasoline	62	103	Mustafa Kemal Balki	Turkey	(Balki and Sayin, 2014)
7. Effects of ethanol addition on performance and emissions of a turbocharged indirect injection Diesel engine running at different injection pressures	61	209	Özer Can	Turkey	(Can et al., 2004)
8. Hydrous ethanol vs. gasoline-ethanol blend: Engine performance and emissions	61	163	Rodrigo C.Costa	Brazil	(Costa and Sodré, 2010)
9. Evaluation of Butanol–Gasoline Blends in a Port Fuel-injection, Spark-Ignition Engine	60	145	Jeremie Dernotte	France	(Dernotte et al., 2010)
10. Combustion efficiency and engine out emissions of a S.I. engine fueled with alcohol/gasoline blends	56	106	M.A. Costagliola	Italy	(Costagliola et al., 2013)

5. Limitation & Future Perspective

Similar to any bibliometric study, the current study is not spared from limitations. First of all, restriction of data collection to WoS database may have introduced research bias. The use of other popular databases such as Scopus may have resulted in different results and conclusions. In addition, per the authors' discretion, the search terms were chosen to reduce high pollution in the dataset as much as possible. However, different results may have been reached if other relatable search terms were added. Finally, the consideration of only the 21st-century publications may have told a different story compared to that of all possible publication years from WoS. Future studies can address these limitations by extending the coverage to include more databases, increased timeline, and relevant search terms.

Regardless, based on our review and findings in the current study, prospective opportunities for future research could be suggested; (1) compared to the collaborative index from different research fields (Fusco et al., 2020; Kawuki et al., 2020; Secinaro et al., 2020), there is room for improvement in more collaborative studies across multi-national/institution/author levels. (2) current empirical studies on low carbon alcohol combustion are limited, which calls for more future studies with different research focus such as future alternatives to low carbon alcohols or the advancement in technology for the combustion of methanol and ethanol in ICE. A disparity exists in the geographical distribution of research output. Most influential authors and institutions are centralized in developed countries except for the case of China and India. Research from Africa and South America (except Brazil) is heavily underrepresented despite the abundant variety of alcohol feedstocks in these regions. The current study recommends more investment and studies in these resource-rich continents to drive the globe's effort to achieve a sustainable low carbon society and meet most of the climate goals such as the Kyoto Protocol, The Paris Agreement, Sustainable Development Goals (goal 7 and 13), etc. Low carbon fuel in the near foreseeable future will face stern competition from other alternative fuel sources, especially with the growing research trend in green hydrogen and green electricity in the 21st century (Yun, 2020). In all scenarios, alcohol fuels will occupy an important fraction of the future transportation fuel regardless of the numerous alternatives that may emerge (Rosillo-Calle and Walter, 2006).

6. Conclusion

The current study aimed to map the scientific output of low carbon alcohol combustion in internal combustion engines in the 21st century with 2,250 documents from Web of Science Core Collection, analyzed with CiteSpace, biblioshiny app, and Bibexcel. The main conclusions from the empirical review are summarized below:

1. The research and communication of low carbon alcohol combustion in ICEs are growing rapidly, with an average annual growth rate of 12%. By the end of the next decade, productivity could increase by up to 70% compared to the current state.
2. The National Natural Science Foundation of China and Chinese institutions led by Tianjin University were the most influential funding agency and research institution globally in this line of research, making China the most productive country, followed USA and India.

3. Asia has been the most productive continent, followed by Europe, America, Africa, and Oceania. However, Europe has had the most diversified country publications in this research line from 2000–2021.
4. The keyword analysis revealed that ethanol, gasoline, and spark-ignition engine were more researched than their counterparts, methanol, diesel, and compression ignition engine, respectively. The main research theme has so far centralized around the alcohols' performance, combustion, and emission characteristics, especially ethanol. The alternative fuels to emerge as competition for methanol and ethanol were biodiesel and hydrogen.
5. The application of artificial intelligence is growing remarkably in different research fields; however, the same degree of patronage for the advanced technology cannot be said for the combustion of alcohol fuels in internal combustion engine judging from the results obtained for the most frequently used keywords. Research in this direction can further increase the comprehensiveness and productivity in this area of research.

7. Declarations

Ethics approval and consent to participate;

Not applicable

Consent for publication;

Not applicable

Competing interests;

The authors declare that they have no competing interests

Author’s contribution

Chao Jin: Conceptualization, Methodology. Jeffrey Dankwa Ampah: Investigation, Writing-Original draft preparation. Sandylove Afrane: Software. Zenghui Yin: Data curation. Xin Liu: Visualization. Tianyun Sun: Validation. Zhenlong Geng: Validation. Mubasher Ikram: Validation. Haifeng Liu: Writing-Reviewing and Editing, Supervision.

Availability of data and materials;

Not applicable

Acknowledgement

The authors would like to acknowledge the financial supports provided by the National Natural Science Foundation of China (Grant No. 51922076, 91941102).

8. References

1. Abu-Qudais M, Haddad O, Qudaisat M (2000) The effect of alcohol fumigation on diesel engine performance and emissions. Energy Convers Manag 41(4):389–399. https://doi.org/10.1016/S0196-8904(99)00099-0
2. Agarwal AK (2007) Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Prog Energy Combust Sci 33(3):233–271. https://doi.org/10.1016/j.pecs.2006.08.003
3. Agarwal AK, Karare H, Dhar A (2014) Combustion, performance, emissions and particulate characterization of a methanol–gasoline blend (gasohol) fuelled medium duty spark ignition transportation engine. *Fuel Processing Technology* 121, 16–24. https://doi.org/10.1016/j.fuproc.2013.12.014
4. Al-Hasan M (2003) Effect of ethanol–unleaded gasoline blends on engine performance and exhaust emission. Energy Convers Manag 44(9):1547–1561. https://doi.org/10.1016/S0196-8904(02)00166-8
5. Alam M, Song J, Zello V, Boehman A (2006) Spray and combustion visualization of a direct-injection diesel engine operated with oxygenated fuel blends. International Journal of Engine Research 7(6):503–521. https://doi.org/10.1243/14680874jer01506
6. Alptekin E (2017) Evaluation of ethanol and isopropanol as additives with diesel fuel in a CRDI diesel engine. Fuel 205:161. . 10.1016/j.fuel.2017.05.076
7. Anderson LG (2009) Ethanol fuel use in Brazil: air quality impacts. Energy Environ Sci 2(10). https://doi.org/10.1039/b906057j
8. Andersson K, Salazar CM (2015) Methanol as a marine fuel report. Energy, F
9. Andreo-Martínez P, Ortiz-Martínez VM, García-Martínez N, de los Ríos AP, Hernández-Fernández FJ, Quesada-Medina J (2020) Production of biodiesel under supercritical conditions: State of the art and bibliometric analysis. Appl Energy 264. https://doi.org/10.1016/j.apenergy.2020.114753
10. Aradhey A (2019) India Biofuels Annual 2019
11. Aria M, Cuccurullo C (2017) bibliometrix: An R-tool for comprehensive science mapping analysis. Journal of informetrics 11(4):959–975. https://doi.org/10.1016/j.joi.2017.08.007
12. Balki MK, Sayin C (2014) The effect of compression ratio on the performance, emissions and combustion of an SI (spark ignition) engine fueled with pure ethanol, methanol and unleaded gasoline. Energy 71:194–201. https://doi.org/10.1016/j.energy.2014.04.074
13. Barros S (2020) Biofuels Annual
14. Bata RM, Elrod AC, Rice RW (1989) Emissions From IC Engines Fueled With Alcohol–Gasoline Blends: A Literature Review. J Eng Gas Turbines Power 111(3):424–431. https://doi.org/10.1115/1.3240271
15. Bertau M, Offermanns H, Plass L, Schmidt F, Wernicke H-J (2014) *Methanol: The Basic Chemical and Energy Feedstock of the Future*. Springer

16. Bettencourt LMA, Kaur J (2011) Evolution and structure of sustainability science. *Proceedings of the National Academy of Sciences* 108(49), 19540. https://doi.org/10.1073/pnas.1102712108
17. Bilgin A, Sezer İ (2008) Effects of Methanol Addition to Gasoline on the Performance and Fuel Cost of a Spark Ignition Engine. Energy Fuels 22(4):2782–2788. https://doi.org/10.1021/ef8001026
18. Bob F, Sabine L, Sophie B (2019) EU Biofuels Annual 2019
19. Boyd TA (1950) Pathfinding in fuels and engines. SAE International. https://doi.org/10.4271/500175
20. Braun T, Glänzel W, Schubert A (2006) A Hirsch-type index for journals. Scientometrics 69(1):169–173. https://doi.org/10.1007/s11192-006-0147-4
21. Breeze P (2018) Chapter 4 - Spark Ignition Engines, In: Breeze, P. (Ed.), *Piston Engine-Based Power Plants*. Academic Press, pp. 35–45. https://doi.org/10.1016/B978-0-12-812904-3.00004-5
22. Bromberg L, Cheng WK (2010) Methanol as an alternative transportation fuel in the US: Options for sustainable and/or energy-secure transportation
23. Campos-Fernández J, Arnal JM, Gómez J, Dorado MP (2012) A comparison of performance of higher alcohols/diesel fuel blends in a diesel engine. Appl Energy 95:267–275. https://doi.org/10.1016/j.apenergy.2012.02.051
24. Can Ö, Çelikten İ, Usta N (2004) Effects of ethanol addition on performance and emissions of a turbocharged indirect injection Diesel engine running at different injection pressures. Energy Convers Manag 45(15):2429–2440. https://doi.org/10.1016/j.enconman.2003.11.024
25. Canakci M, Ozsezen AN, Alptekin E, Eyidogan M (2013) Impact of alcohol–gasoline fuel blends on the exhaust emission of an SI engine. Renewable Energy 52:111–117. https://doi.org/10.1016/j.renene.2012.09.062
26. Chen C (2006) CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. J Am Soc Inform Sci Technol 57(3):359–377. https://doi.org/10.1002/asi.20317
27. Chen CS, Rao PSC, J, D.J (2005) Oxygenated fuel induced cosolvent effects on the dissolution of polynuclear aromatic hydrocarbons from contaminated soil. Chemosphere 60:1572–1582. https://doi.org/10.1016/j.chemosphere.2005.02.039
28. Chen H, Yang Y, Yang Y, Jiang W, Zhou J (2014) A bibliometric investigation of life cycle assessment research in the web of science databases. The International Journal of Life Cycle Assessment 19(10):1674–1685. https://doi.org/10.1007/s11367-014-0777-3
29. Chen K, Guan J (2011) A bibliometric investigation of research performance in emerging nanobiopharmaceuticals. Journal of Informetrics 5(2):233–247. https://doi.org/10.1016/j.joi.2010.10.007
30. Chen W, Liu W, Geng Y, Brown MT, Gao C, Wu R (2017) Recent progress on emergy research: A bibliometric analysis. Renew Sustain Energy Rev 73:1051–1060. https://doi.org/10.1016/j.rser.2017.02.041
31. Chen Z, Liu J, Han Z, Du B, Liu Y, Lee C (2013) Study on performance and emissions of a passenger-car diesel engine fueled with butanol–diesel blends. Energy 55:638–646.

https://doi.org/10.1016/j.energy.2013.03.054

32. Cooke DF, Dodson MG, Williams A (1971) A shock-tube study of the ignition of methanol and ethanol with oxygen. Combust Flame 16(3):233–236. https://doi.org/10.1016/S0010-2180(71)80093-7
33. Costa RC, Sodré JR (2010) Hydrous ethanol vs. gasoline-ethanol blend: Engine performance and emissions. Fuel 89(2):287–293. https://doi.org/10.1016/j.fuel.2009.06.017
34. Costagliola MA, De Simio L, Iannaccone S, Prati MV (2013) Combustion efficiency and engine out emissions of a S.I. engine fueled with alcohol/gasoline blends. Appl Energy 111:1162–1171. https://doi.org/10.1016/j.apenergy.2012.09.042
35. Dada OL (2018) A Model of Entrepreneurial Autonomy in Franchised Outlets: A Systematic Review of the Empirical Evidence. International Journal of Management Reviews 20(2):206–226. https://doi.org/10.1111/ijmr.12123
36. Dasilva R, Cataluna R, Menezes E, Samios D, Piatnicki C (2005) Effect of additives on the antiknock properties and Reid vapor pressure of gasoline. Fuel 84(7–8):951–959. https://doi.org/10.1016/j.fuel.2005.01.008
37. Deng X, Chen Z, Wang X, Zhen H, Xie R (2018) Exhaust noise, performance and emission characteristics of spark ignition engine fuelled with pure gasoline and hydrous ethanol gasoline blends. Case Studies in Thermal Engineering 12:55–63. https://doi.org/10.1016/j.csite.2018.02.004
38. Dernotte J, Mounaim-Rousselle C, Halter F, Seers P (2010) Evaluation of Butanol–Gasoline Blends in a Port Fuel-injection, Spark-Ignition Engine. Oil Gas Science Technology – Rev IFP 65(2):345–351. https://doi.org/doi.org/10.2516/ogst/2009034
39. Dhande DY, Sinaga N, Dahe KB (2021) Study on combustion, performance and exhaust emissions of bioethanol-gasoline blended spark ignition engine. Heliyon 7(3):e06380. https://doi.org/10.1016/j.heliyon.2021.e06380
40. EIA (2021) Petroleum & Other Liquids. https://www.eia.gov/petroleum/gasdiesel/ (Date accessed: 17th March, 2021)
41. Fusco F, Marsilio M, Guglielmetti C (2020) Co-production in health policy and management: a comprehensive bibliometric review. BMC Health Serv Res 20(1):504. https://doi.org/10.1186/s12913-020-05241-2
42. Gong C, Li Z, Yi L, Liu F (2019) Comparative study on combustion and emissions between methanol port-injection engine and methanol direct-injection engine with H2-enriched port-injection under lean-burn conditions. Energy Convers Manag 200:112096. https://doi.org/10.1016/j.enconman.2019.112096
43. Gu X, Huang Z, Cai J, Gong J, Wu X, Lee C-f (2012) Emission characteristics of a spark-ignition engine fuelled with gasoline-n-butanol blends in combination with EGR. Fuel 93:611–617. https://doi.org/10.1016/j.fuel.2011.11.040
44. Hagen DL (1977) Methanol as a Fuel: A Review with Bibliography. *Society ofAutomotive Engineers, Inc.*

45. Han J, Somers LMT, Cracknell R, Joedicke A, Wardle R, Mohan VRR (2020) Experimental investigation of ethanol/diesel dual-fuel combustion in a heavy-duty diesel engine. Fuel 275. https://doi.org/10.1016/j.fuel.2020.117867
46. Hansen AC, Zhang Q, Lyne PW (2005) Ethanol-diesel fuel blends – a review. Bioresour Technol 96(3):277–285. https://doi.org/10.1016/j.biortech.2004.04.007
47. Harari PA, Banapurmath NR, Yaliwal VS, Khan TMY, Soudagar MEM, Sajjan AM (2020) Experimental studies on performance and emission characteristics of reactivity controlled compression ignition (RCCI) engine operated with gasoline and Thevetia Peruviana biodiesel. Renewable Energy 160:865–875. https://doi.org/10.1016/j.renene.2020.07.009
48. Haupt D, Nord K, Tingvall B, Ahlvik P, Egebäck K-E, Andersson S, Blomquist M (2004) Investigating the Potential to Obtain Low Emissions from a Diesel Engine Running on Ethanol and Equipped With EGR, Catalyst and DPF. *Sae Technical Paper Series*
49. Höök M, Söderbergh B, Jakobsson K, Aleklett K (2009) The Evolution of Giant Oil Field Production Behavior. Nat Resour Res 18(1):39–56. https://doi.org/doi:10.1007/s11053-009-9087-z
50. Hou Q, Mao G, Zhao L, Du H, Zuo J (2015) Mapping the scientific research on life cycle assessment: a bibliometric analysis. The International Journal of Life Cycle Assessment 20(4):541–555. https://doi.org/10.1007/s11367-015-0846-2
51. Hsieh W-D, Chen R-H, Wu T-L, Lin T-H (2002) Engine performance and pollutant emission of an SI engine using ethanol–gasoline blended fuels. Atmos Environ 36(3):403–410. https://doi.org/10.1016/S1352-2310(01)00508-8
52. Huang H, Teng W, Liu Q, Zhou C, Wang Q, Wang X (2016) Combustion performance and emission characteristics of a diesel engine under low-temperature combustion of pine oil–diesel blends. Energy Convers Manag 128:317–326. https://doi.org/10.1016/j.enconman.2016.09.090
53. Huang L, Zhou M, Lv J, Chen K (2020) Trends in global research in forest carbon sequestration: A bibliometric analysis. J Clean Prod 252:119908. https://doi.org/10.1016/j.jclepro.2019.119908
54. HVA (2011) Ethanol Timeline. https://www.historicvehicle.org/ethanol-timeline/ (Date accessed: 15th March, 2020)
55. ICCT (2018) Diesel car sales decline will have negligible impact on attainment of European CO2 emission standards
56. ICCT (2019) Gasoline vs. Diesel; comparing co2 emission levels of a modern medium size car model under laboratory and on-road testing conditions
57. Ickes A, Wallner T, Zhang Y, De Ojeda W (2014) Impact of Cetane Number on Combustion of a Gasoline-Diesel Dual-Fuel Heavy-Duty Multi-Cylinder Engine. SAE Int J Engines 7(2):860–872. https://doi.org/10.4271/2014-01-1309
58. IEA (2010) World Energy Outlook
59. Ileri E (2016) Experimental study of 2-ethylhexyl nitrate effects on engine performance and exhaust emissions of a diesel engine fueled with n-butanol or 1-pentanol diesel–sunflower oil blends. Energy Convers Manag 118:320–330. https://doi.org/10.1016/j.enconman.2016.04.015

60. Iliev S (2019) Comparison of Ethanol and Methanol Blending with Gasoline Using Engine Simulation, *Biofuels - Challenges and opportunities*. https://doi.org/10.5772/intechopen.81776
61. Heywood JB (1988) Internal Combustion Engine Fundamentals. McGraw-Hill Ed., New York
62. Jamrozik A (2017) The effect of the alcohol content in the fuel mixture on the performance and emissions of a direct injection diesel engine fueled with diesel-methanol and diesel-ethanol blends. Energy Convers Manag 148:461–476. https://doi.org/10.1016/j.enconman.2017.06.030
63. Jamrozik A, Tutak W, Gnatowska R, Nowak Ł (2019) Comparative Analysis of the Combustion Stability of Diesel-Methanol and Diesel-Ethanol in a Dual Fuel Engine. *Energies* 12(6). https://doi.org/10.3390/en12060971
64. Jamuwa DK, Sharma D, Soni SL (2016) Experimental investigation of performance, exhaust emission and combustion parameters of stationary compression ignition engine using ethanol fumigation in dual fuel mode. Energy Convers Manag 115:221–231. https://doi.org/10.1016/j.enconman.2016.02.055
65. Jin C, Pang X, Zhang X, Wu S, Ma M, Xiang Y, Ma J, Ji J, Wang G, Liu H (2019a) Effects of C3–C5 alcohols on solubility of alcohols/diesel blends. Fuel 236:65–74. https://doi.org/10.1016/j.fuel.2018.08.129
66. Jin C, Yao M, Liu H, Lee C-fF, Ji J (2011) Progress in the production and application of n-butanol as a biofuel. Renew Sustain Energy Rev 15(8):4080–4106. https://doi.org/10.1016/j.rser.2011.06.001
67. Jin C, Zhang X, Geng Z, Pang X, Wang X, Ji J, Wang G, Liu H (2019b) Effects of various co-solvents on the solubility between blends of soybean oil with either methanol or ethanol. Fuel 244:461–471. https://doi.org/10.1016/j.fuel.2019.01.187
68. Jin C, Zhang X, Han W, Geng Z, Tessa Margaret Thomas M, Dankwa Jeffrey A, Wang G, Ji J, Liu H (2020) Macro and micro solubility between low-carbon alcohols and rapeseed oil using different co-solvents. Fuel 270. https://doi.org/10.1016/j.fuel.2020.117511
69. Kawuki J, Yu X, Musa TH (2020) Bibliometric Analysis of Ebola Research Indexed in Web of Science and Scopus (2010–2020). *Biomed Res Int* 2020, 5476567. https://doi.org/10.1155/2020/5476567
70. Kim G (2018) China Biofuels Annual 2018
71. Kim HY, Ge JC, Choi NJ (2020) Effects of Ethanol–Diesel on the Combustion and Emissions from a Diesel Engine at a Low Idle Speed. Applied Sciences 10(12). https://doi.org/10.3390/app10124153
72. Kinney AL (2007) National scientific facilities and their science impact on nonbiomedical research. Proc Natl Acad Sci U S A 104(46):17943–17947. https://doi.org/10.1073/pnas.0704416104
73. Klein T, 2020. Methanol: A Future-Proof Fuel A Primer Prepared for the Methanol Institute
74. Koç M, Sekmen Y, Topgül T, Yücesu HS (2009) The effects of ethanol–unleaded gasoline blends on engine performance and exhaust emissions in a spark-ignition engine. Renewable Energy 34(10):2101–2106. https://doi.org/10.1016/j.renene.2009.01.018
75. Kumar R, Chaurasia O (2019) A Review on Performance and Emissions of Compression Ignition Engine Fueled with Ethanol-diesel Blend. Journal Européen des Systèmes Automatisés 52(2):205–

214. https://doi.org/10.18280/jesa.520214

76. Kumar S, Cho JH, Park J, Moon I (2013) Advances in diesel–alcohol blends and their effects on the performance and emissions of diesel engines. Renew Sustain Energy Rev 22:46–72. https://doi.org/10.1016/j.rser.2013.01.017
77. Labeckas G, Slavinskas S, Lus T, Klyus O (2013) Combustion and performance parameters of a Diesel engine operating on ethanol-Diesel fuel blends
78. Labeckas G, Slavinskas S, Mažeika M (2014) The effect of ethanol–diesel–biodiesel blends on combustion, performance and emissions of a direct injection diesel engine. Energy Convers Manag 79:698–720. https://doi.org/10.1016/j.enconman.2013.12.064
79. Lapuerta M, Armas O, García-Contreras R (2007) Stability of diesel–bioethanol blends for use in diesel engines. Fuel 86(10–11):1351–1357. https://doi.org/10.1016/j.fuel.2006.11.042
80. Lei J, Bi Y, Shen L (2011) Performance and Emission Characteristics of Diesel Engine Fueled with Ethanol-Diesel Blends in Different Altitude Regions. *Journal of Biomedicine and Biotechnology* 2011, 417421. https://doi.org/10.1155/2011/417421
81. Li Y, Gong J, Deng Y, Yuan W, Fu J, Zhang B (2017) Experimental comparative study on combustion, performance and emissions characteristics of methanol, ethanol and butanol in a spark ignition engine. Appl Therm Eng 115:53–63. https://doi.org/10.1016/j.applthermaleng.2016.12.037
82. Li Y, Jia M, Xu L, Bai X-S (2020) Multiple-objective optimization of methanol/diesel dual-fuel engine at low loads: A comparison of reactivity controlled compression ignition (RCCI) and direct dual fuel stratification (DDFS) strategies. Fuel 262:116673. https://doi.org/10.1016/j.fuel.2019.116673
83. Li Z, Wang Y, Geng H, Zhen X, Liu M, Xu S, Li C (2019) Effects of diesel and methanol injection timing on combustion, performance, and emissions of a diesel engine fueled with directly injected methanol and pilot diesel. Appl Therm Eng 163. https://doi.org/10.1016/j.applthermaleng.2019.114234
84. Liu J, Li Y, Li G, Zhu Z, He H, Liu S (2010) Effect of Pilot Diesel Quantity and Fuel Delivery Advance Angle on the Performance and Emission Characteristics of a Methanol-Fueled Diesel Engine. Energy Fuels 24(3):1611–1616. https://doi.org/10.1021/ef901281m
85. Liu S, Clemente C, Hu ER, Wei T, Y (2007) Study of spark ignition engine fueled with methanol/gasoline fuel blends. Appl Therm Eng 27(11):1904–1910. https://doi.org/10.1016/j.applthermaleng.2006.12.024
86. Mao G, Liu X, Du H, Zuo J, Wang L (2015) Way forward for alternative energy research: A bibliometric analysis during 1994–2013. Renew Sustain Energy Rev 48:276–286. https://doi.org/10.1016/j.rser.2015.03.094
87. Mayank CJ, Mayank J, Sumit S, Anurag B (2016) Alcohol as an Alternative Fuel in I.C. Engine: A Review. International Journal of Engineering Technical Research (IJETR) 4(2):2454–4698
88. Meyer T (2020) Decarbonizing road freight transportation – A bibliometric and network analysis. Transportation Research Part D: Transport Environment 89:102619. https://doi.org/10.1016/j.trd.2020.102619
89. Mimi A (2008) History of Ethanol. *Journalism & Mass Communications: Student Media. 6*

90. Most WJ, Longwell JP (1975) Single-Cylinder Engine Evaluation of Methanol - Improved Energy Economy and Reduced NOx. SAE International. https://doi.org/10.4271/750119
91. Najafi G, Yusaf TF (2009) Experimental investigation of using methanol-diesel blended fuels in diesel engine, *Proceedings of the Fourth International Conference on Thermal Engineering: Theory and Applications*, Abu Dhabi, UAE
92. Niculescu R, Clenci A, Iorga-Siman V (2019) Review on the Use of Diesel–Biodiesel–Alcohol Blends in Compression Ignition Engines. *Energies* 12(7). https://doi.org/10.3390/en12071194
93. Ning L, Duan Q, Chen Z, Kou H, Liu B, Yang B, Zeng K (2020) A comparative study on the combustion and emissions of a non-road common rail diesel engine fueled with primary alcohol fuels (methanol, ethanol, and n-butanol)/diesel dual fuel. Fuel 266. https://doi.org/10.1016/j.fuel.2020.117034
94. Oasmaa A, Sundqvist T, Kuoppala E, Garcia-Perez M, Solantausta Y, Lindfors C, Paasikallio V (2015) Controlling the Phase Stability of Biomass Fast Pyrolysis Bio-oils. Energy Fuels 29(7):4373–4381. https://doi.org/10.1021/acs.energyfuels.5b00607
95. Pikonas A, Pukalskas S, Grabys J (2003) Influence of composition of gasoline - ethanol blends on parameters of internal combustion engines. Journal of KONES Internal Combustion Engines 10:205–211
96. Prakash KS, Sonil N, Pravakar M (2018) Recent advancements in biofuels and bioenergy utilization. Recent Advancements in Biofuels Bioenergy Utilization, 1–402. https://doi.org/10.1016/j.renene.2018.01.070
97. Pritchard A (1969) Statistical bibliography or bibliometrics. Journal of documentation 25(4):348–349
98. Qi DH, Liu SQ, Zhang CH, Bian YZ (2005) Properties, performance, and emissions of methanol-gasoline blends in a spark ignition engine. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 219(3), 405–412. https://doi.org/10.1243/095440705x6659
99. Rakopoulos CD, Rakopoulos DC, Giakoumis EG, Kyritsis DC (2011) The combustion of n-butanol/diesel fuel blends and its cyclic variability in a direct injection diesel engine. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 225(3), 289–308. https://doi.org/10.1177/2041296710394256
100. Rakopoulos DC, Rakopoulos CD, Giakoumis EG, Papagiannakis RG, Kyritsis DC (2014) Influence of properties of various common bio-fuels on the combustion and emission characteristics of high-speed DI (direct injection) diesel engine: Vegetable oil, bio-diesel, ethanol, n-butanol, diethyl ether. Energy 73:354–366. https://doi.org/10.1016/j.energy.2014.06.032
101. Rakopoulos DC, Rakopoulos CD, Kakaras EC, Giakoumis EG (2008) Effects of ethanol–diesel fuel blends on the performance and exhaust emissions of heavy duty DI diesel engine. Energy Convers Manag 49(11):3155–3162. https://doi.org/10.1016/j.enconman.2008.05.023
102. Rey-Martí A, Ribeiro-Soriano D, Palacios-Marqués D (2016) A bibliometric analysis of social entrepreneurship. J Bus Res 69(5):1651–1655. https://doi.org/10.1016/j.jbusres.2015.10.033

103. RFA (2019) 2019 ethanol industry outlook
104. Rosillo-Calle F, Walter A (2006) Global market for bioethanol: historical trends and future prospects. Energy Sustain Dev 10(1):20–32. https://doi.org/10.1016/S0973-0826(08)60504-9
105. Sarathy SM, Oßwald P, Hansen N, Kohse-Höinghaus K (2014) Alcohol combustion chemistry. Prog Energy Combust Sci 44:40–102. https://doi.org/10.1016/j.pecs.2014.04.003
106. Sayin C, Ozsezen AN, Canakci M (2010) The influence of operating parameters on the performance and emissions of a DI diesel engine using methanol-blended-diesel fuel. Fuel 89(7):1407–1414. https://doi.org/10.1016/j.fuel.2009.10.035
107. Secinaro S, Brescia V, Calandra D, Biancone P (2020) Employing bibliometric analysis to identify suitable business models for electric cars. J Clean Prod 264. https://doi.org/10.1016/j.jclepro.2020.121503
108. Shahir SA, Masjuki HH, Kalam MA, Imran A, Fattah IMR, Sanjid A (2014) Feasibility of diesel–biodiesel–ethanol/bioethanol blend as existing CI engine fuel: An assessment of properties, material compatibility, safety and combustion. Renew Sustain Energy Rev 32:379–395. https://doi.org/10.1016/j.rser.2014.01.029
109. Shen S, Cheng C, Yang J, Yang S (2018) Visualized analysis of developing trends and hot topics in natural disaster research. PLoS One 13(1):e0191250. https://doi.org/10.1371/journal.pone.0191250
110. Solomon BD, Barnes JR, Halvorsen KE (2007) Grain and cellulosic ethanol: History, economics, and energy policy. Biomass Bioenerg 31(6):416–425. https://doi.org/10.1016/j.biombioe.2007.01.023
111. Song C (2002) Fuel processing for low-temperature and high-temperature fuel cells: Challenges, and opportunities for sustainable development in the 21st century. Catal Today 77(1):17–49. https://doi.org/10.1016/S0920-5861(02)00231-6
112. Song R, Liu J, Wang L, Liu S (2008) Performance and Emissions of a Diesel Engine Fuelled with Methanol. Energy Fuels 22:3883–3888. https://doi.org/10.1021/ef800492r
113. Subbaiah GV, Gopal KR, Hussain SA, Prasad BD, Reddy KT (2010) Rice bran oil biodiesel as an additive in diesel-ethanol blends for diesel engines. *International Journal of Recent Research and Applied Studies* 3(3)
114. Surawski NC, Miljevic B, Roberts BA, Modini RL, Situ R, Brown RJ, Bottle SE, Ristovski ZD (2010) Particle Emissions, Volatility, and Toxicity from an Ethanol Fumigated Compression Ignition Engine. Environmental Science Technology 44(1):229–235. https://doi.org/10.1021/es9021377
115. Szwaja S, Naber JD (2010) Combustion of n-butanol in a spark-ignition IC engine. Fuel 89(7):1573–1582. https://doi.org/10.1016/j.fuel.2009.08.043
116. Tian X, Geng Y, Zhong S, Wilson J, Gao C, Chen W, Yu Z, Hao H (2018) A bibliometric analysis on trends and characters of carbon emissions from transport sector. Transportation Research Part D: Transport Environment 59:1–10. https://doi.org/10.1016/j.trd.2017.12.009
117. Tse H, Leung CW, Cheung CS (2015) Investigation on the combustion characteristics and particulate emissions from a diesel engine fueled with diesel-biodiesel-ethanol blends. Energy 83:343–350. https://doi.org/10.1016/j.energy.2015.02.030

118. Turner D, Xu H, Cracknell RF, Natarajan V, Chen X (2011) Combustion performance of bio-ethanol at various blend ratios in a gasoline direct injection engine. Fuel 90(5):1999–2006. https://doi.org/10.1016/j.fuel.2010.12.025
119. van Leeuwen T (2006) The application of bibliometric analyses in the evaluation of social science research. Who benefits from it, and why it is still feasible. Scientometrics 66(1):133–154. https://doi.org/10.1007/s11192-006-0010-7
120. Varol Y, Öner C, Öztop HF, Altun Ş (2014) Comparison of Methanol, Ethanol, orn-Butanol Blending with Unleaded Gasoline on Exhaust Emissions of an SI Engine. Energy Sour Part A Recover Utilization Environ Eff 36(9):938–948. https://doi.org/10.1080/15567036.2011.572141
121. Waluyo B, Setiyo M, Saifudin, Wardana ING (2021) Fuel performance for stable homogeneous gasoline-methanol-ethanol blends. Fuel 294. https://doi.org/10.1016/j.fuel.2021.120565
122. Wu Y, Zhang X, Zhang Z, Wang X, Geng Z, Jin C, Liu H, Yao M (2020) Effects of diesel-ethanol-THF blend fuel on the performance and exhaust emissions on a heavy-duty diesel engine. Fuel 271. https://doi.org/10.1016/j.fuel.2020.117633
123. Yanju W, Shenghua L, Hongsong L, Rui Y, Jie L, Ying W (2008) Effects of Methanol/Gasoline Blends on a Spark Ignition Engine Performance and Emissions. Energy Fuels 22(2):1254–1259. https://doi.org/10.1021/ef7003706
124. Yun Y (2020) *Alcohol Fuels: Current Status and Future Direction*. https://doi.org/10.5772/intechopen.89788
125. Zhang M, Gao Z, Zheng T, Ma Y, Wang Q, Gao M, Sun, XJJ.o.MC, Management W (2018) A bibliometric analysis of biodiesel research during 1991–2015. 20(1), 10–18
126. Zhang ZH, Tsang KS, Cheung CS, Chan TL, Yao CD (2011) Effect of fumigation methanol and ethanol on the gaseous and particulate emissions of a direct-injection diesel engine. Atmos Environ 45(11):2001–2008. https://doi.org/10.1016/j.atmosenv.2010.12.019
127. Zhao K (2019) A Brief Review of China's Methanol Vehicle Pilot and Policy
128. Zheng T, Wang J, Wang Q, Nie C, Smale N, Shi Z, Wang X (2015) A bibliometric analysis of industrial wastewater research: current trends and future prospects. Scientometrics 105(2):863–882. https://doi.org/10.1007/s11192-015-1736-x
129. Zhu J, Wang S, Raza M, Feng Y, Li J, Mao Y, Yu L, Qian Y, Lu X (2021) Autoignition behavior of methanol/diesel mixtures: Experiments and kinetic modeling. Combust Flame 228:1–12. https://doi.org/10.1016/j.combustflame.2021.01.026

Figures

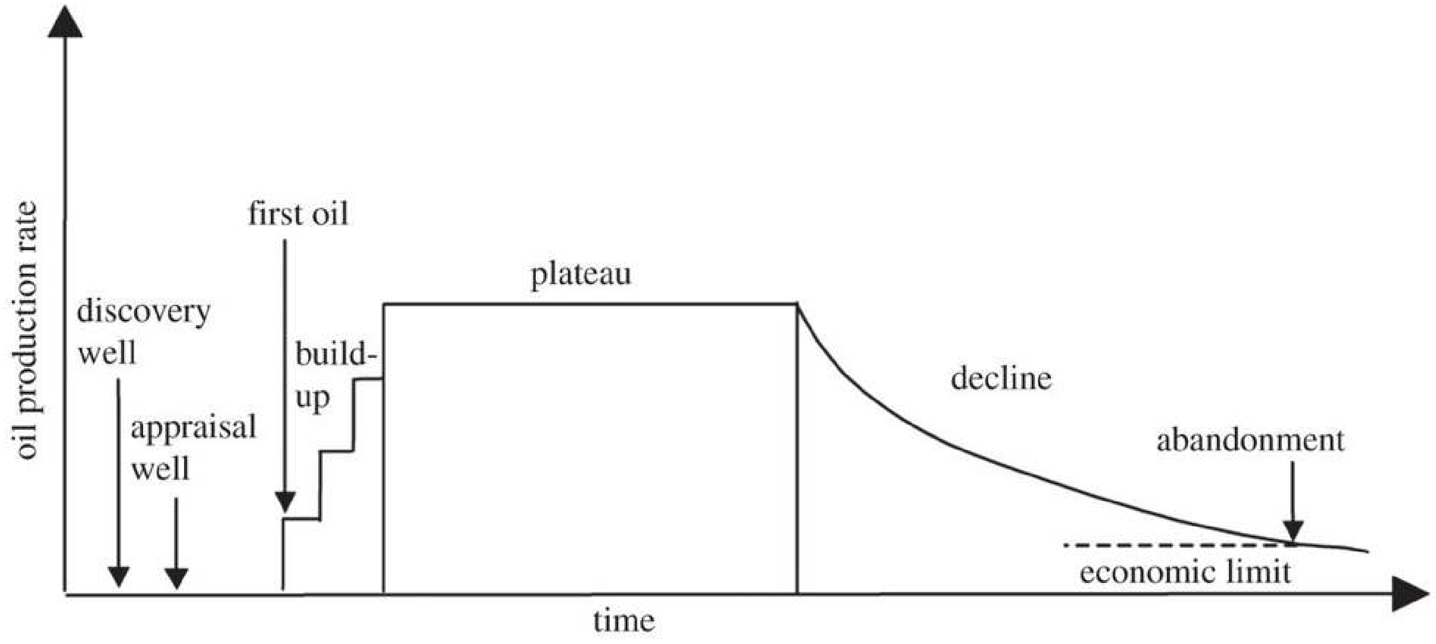
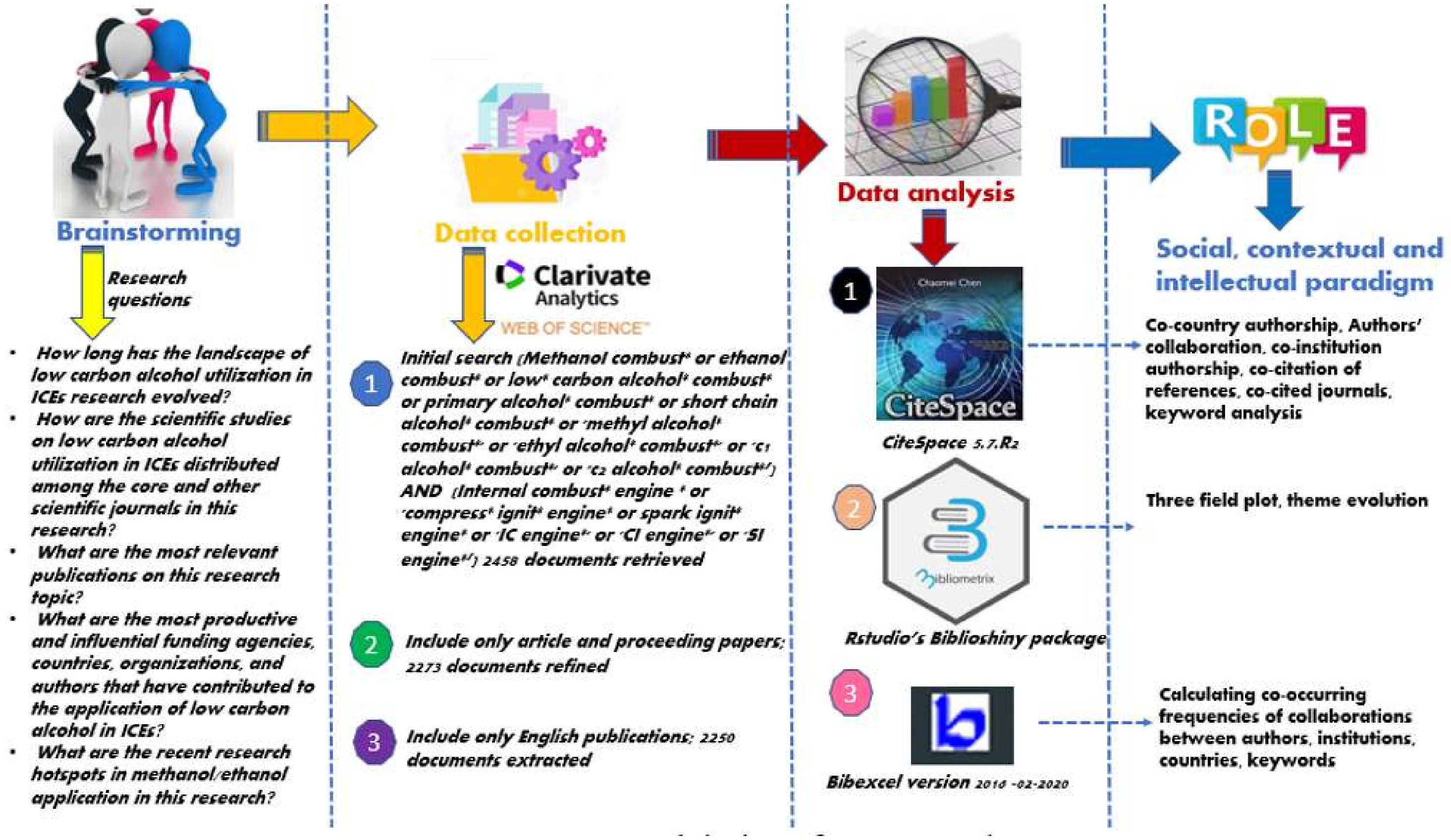


Figure 1

Idealized production behavior of an oil resource. Source: Höök et al. (2009).



- How long has the landscape of low carbon alcohol utilization in ICEs research evolved?
- How are the scientific studies on low carbon alcohol utilization in ICEs distributed among the core and other scientific journals in this research?
- What are the most relevant publications on this research topic?
- What are the most productive and influential funding agencies, countries, organizations, and authors that have contributed to the application of low carbon alcohol in ICEs?
- What are the recent research hotspots in methanol/ethanol application in this research?

1 Initial search (Methanol combust* or ethanol combust* or low* carbon alcohol* combust* or primary alcohol* combust* or short chain alcohol* combust* or 'methyl alcohol* combust*' or 'ethyl alcohol* combust*' or 'c1 alcohol* combust*' or 'c2 alcohol* combust*') AND (Internal combust* engine * or 'compress* ignit* engine* or spark ignit* engine* or 'IC engine*' or 'CI engine*' or 'SI engine*') 2458 documents retrieved

2 Include only article and proceeding papers; 2273 documents refined

3 Include only English publications; 2250 documents extracted

Co-country authorship, Authors' collaboration, co-institution authorship, co-citation of references, co-cited journals, keyword analysis

Three field plot, theme evolution

Calculating co-occurring frequencies of collaborations between authors, institutions, countries, keywords

Figure 2

Conceptual design of current study.

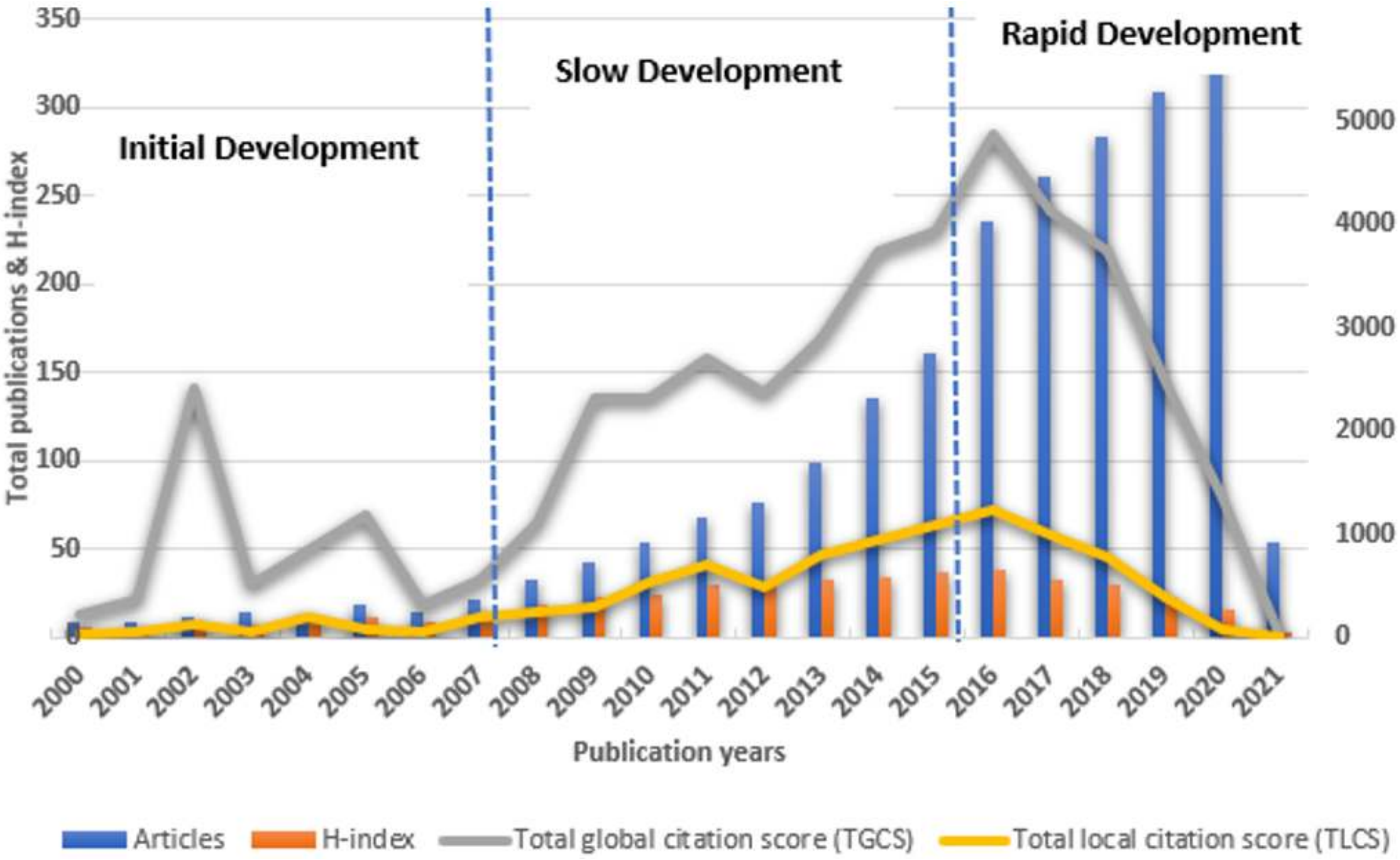


Figure 3

Research output on low carbon alcohol combustion in ICEs from 2000-2021.

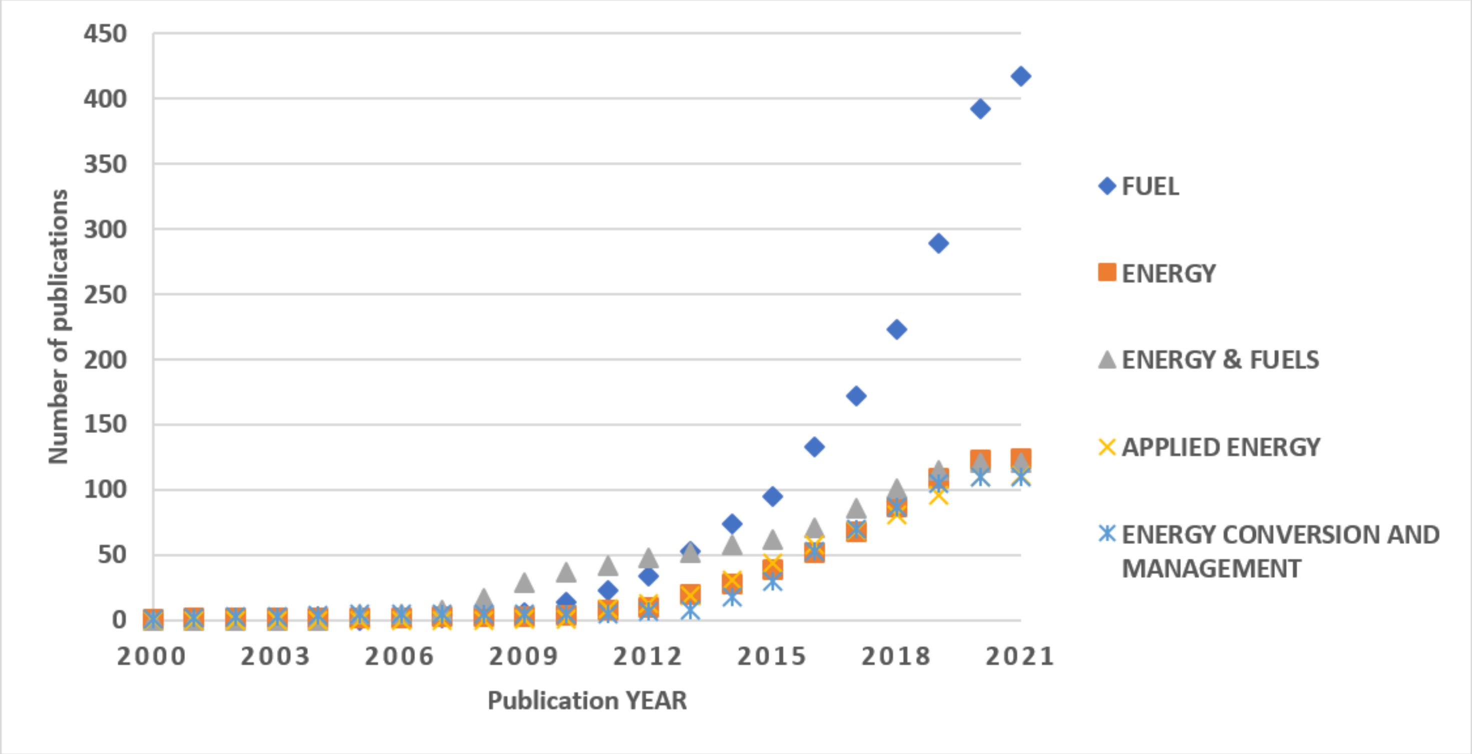


Figure 4

Top 5 journals' dynamics with respect to time.

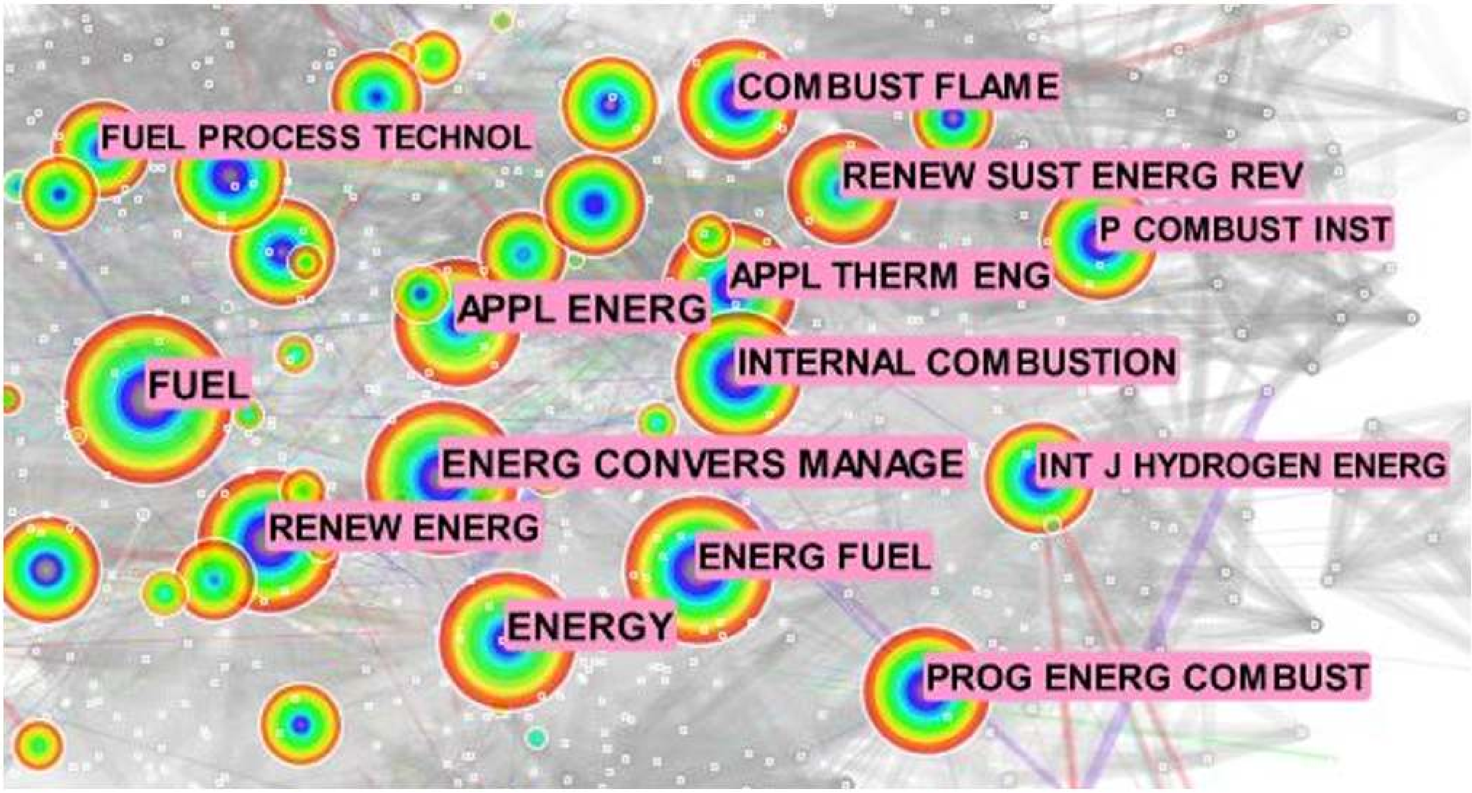


Figure 5

Journal co-citation analysis (Node type=citation; Threshold set at ≥500 citations; colors closer to the middle of the node represent older publication years whereas outer colors are more recent publication years)

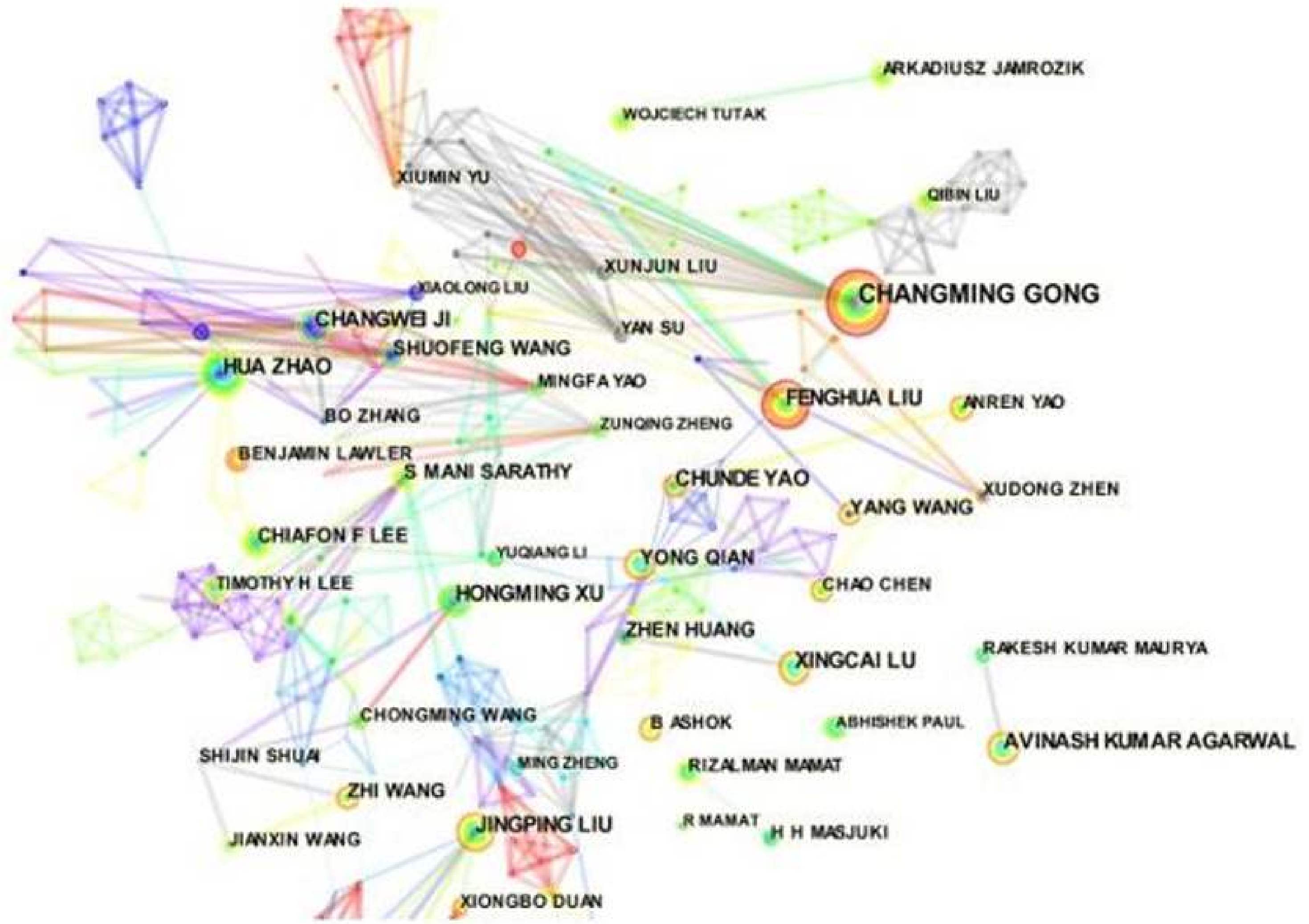


Figure 6

Academic partnership amongst top authors (Node type=citations; Threshold set at ≥10; colors closer to the middle of the node represent older publication years whereas outer colors are more recent publication years).

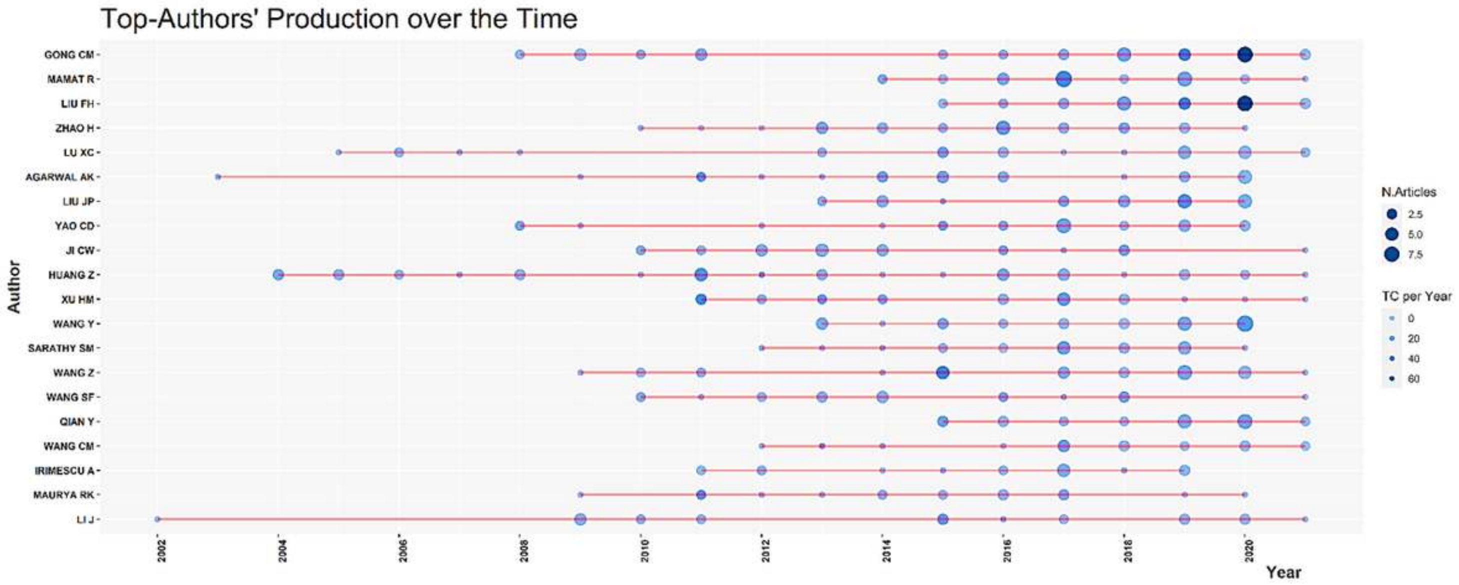


Figure 7

Annual scientific production of top 20 authors from 2000 to 2021.

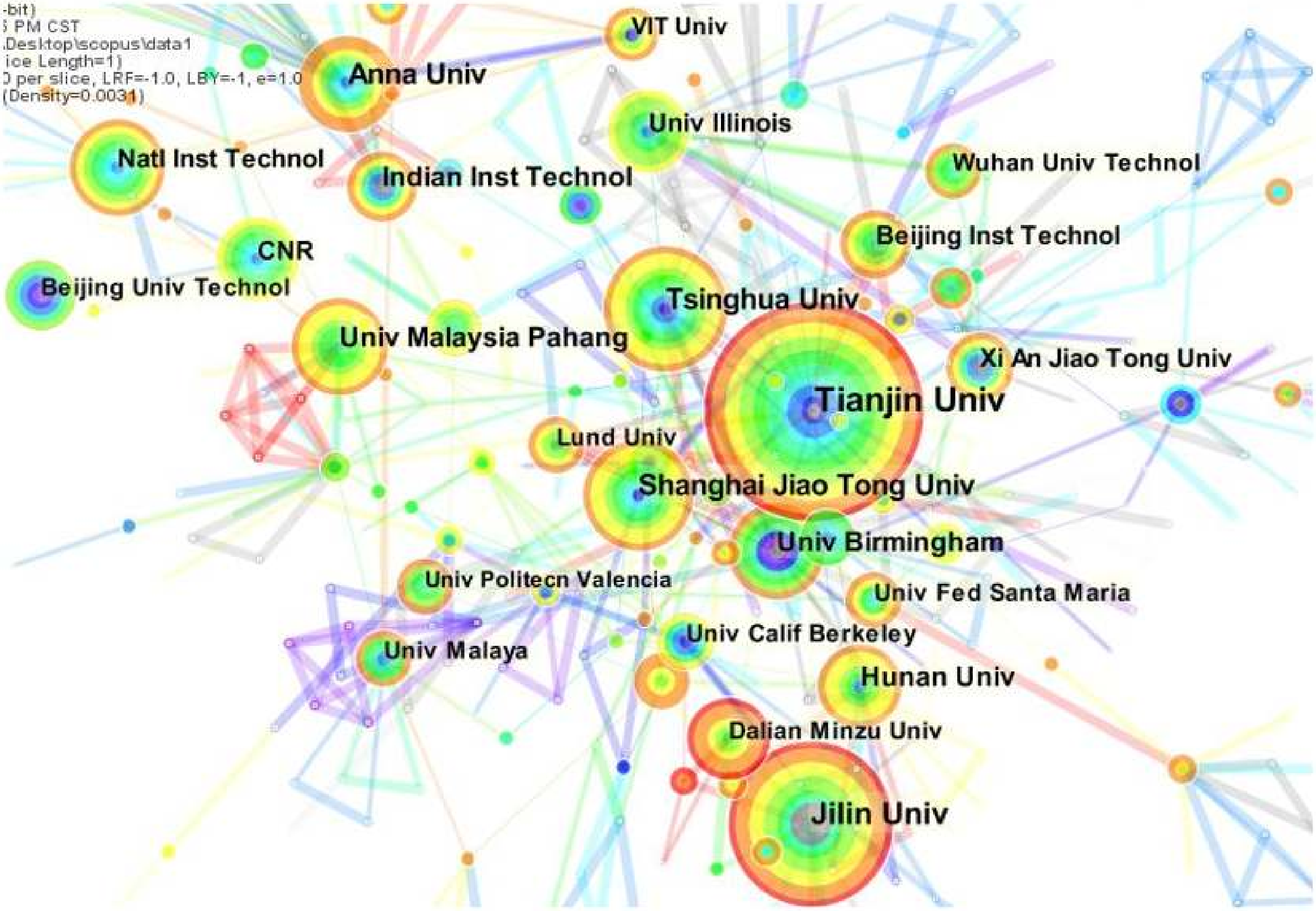
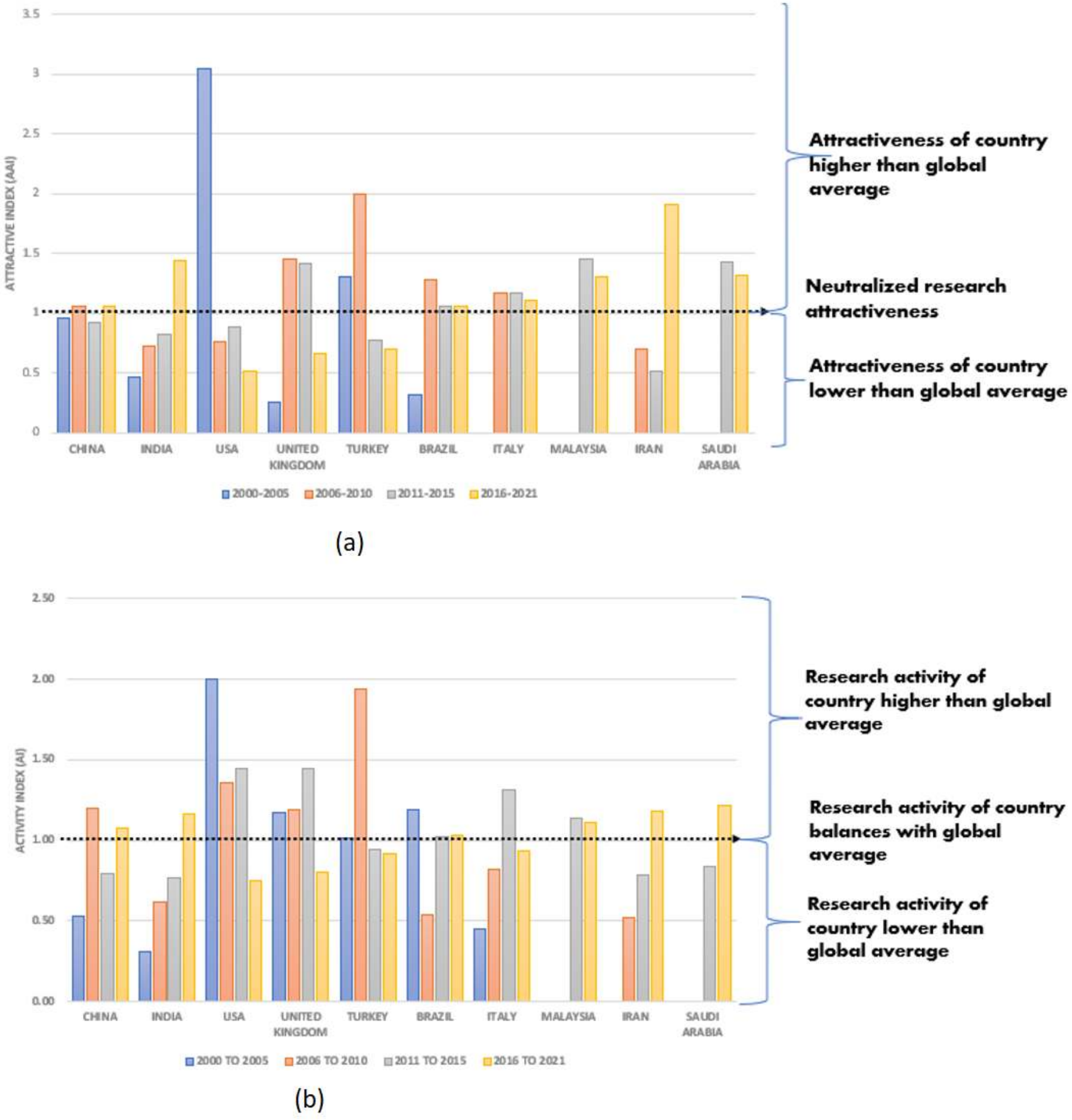


Figure 8

Academic partnership amongst top institution (Node type=citations; Threshold set at ≥20; colors closer to the middle of the node represent older publication years whereas outer colors are more recent publication years).



(a)

(b)

Figure 9

(a) Attractive Index (AAI) of ten major countries. (b) Activity Index (AI) of ten major countries.

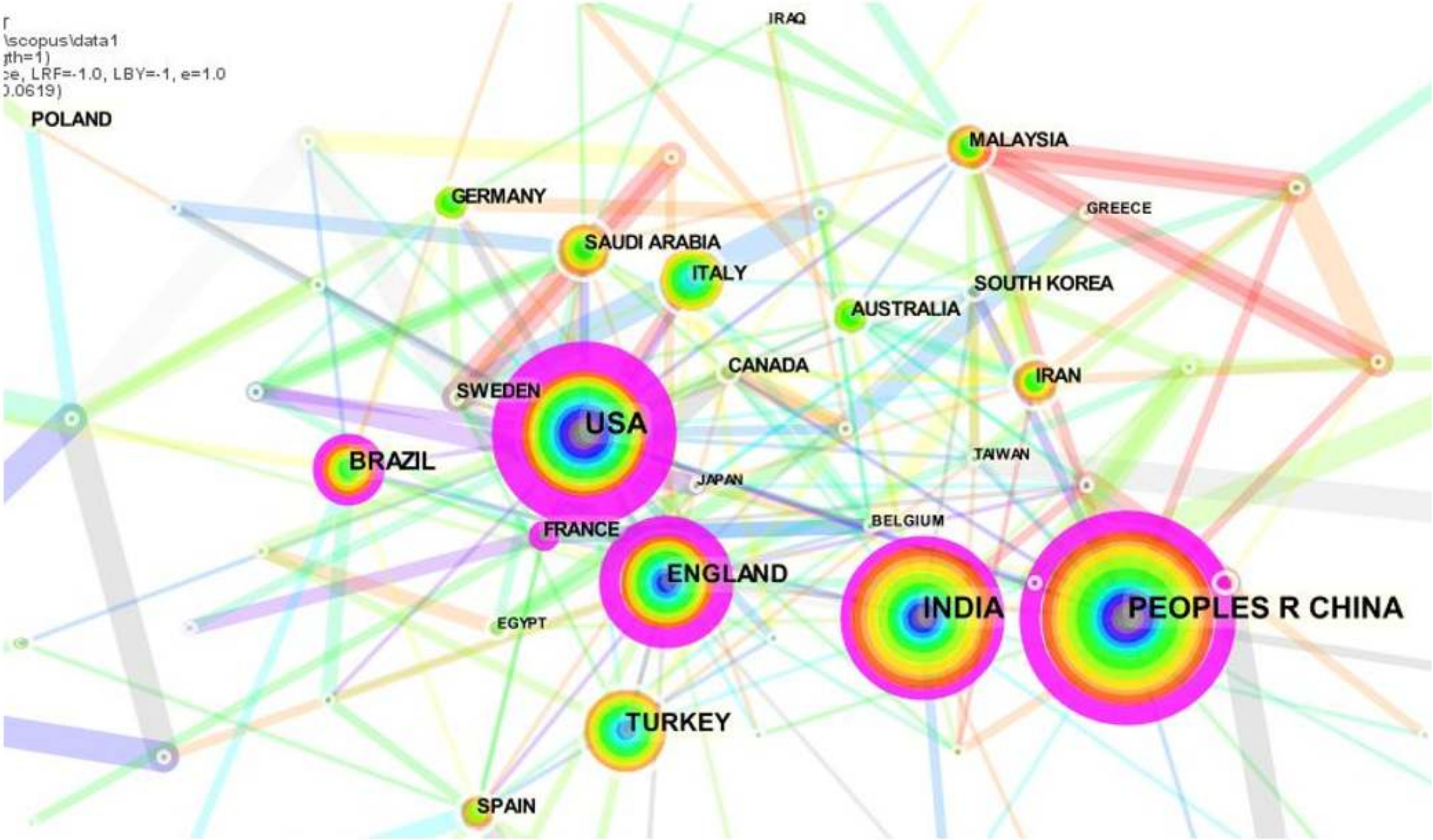


Figure 10

Academic partnership amongst top countries (Node type=citations; Threshold set at ≥20; colors closer to the middle of the node represent older publication years whereas outer colors are more recent publication years).

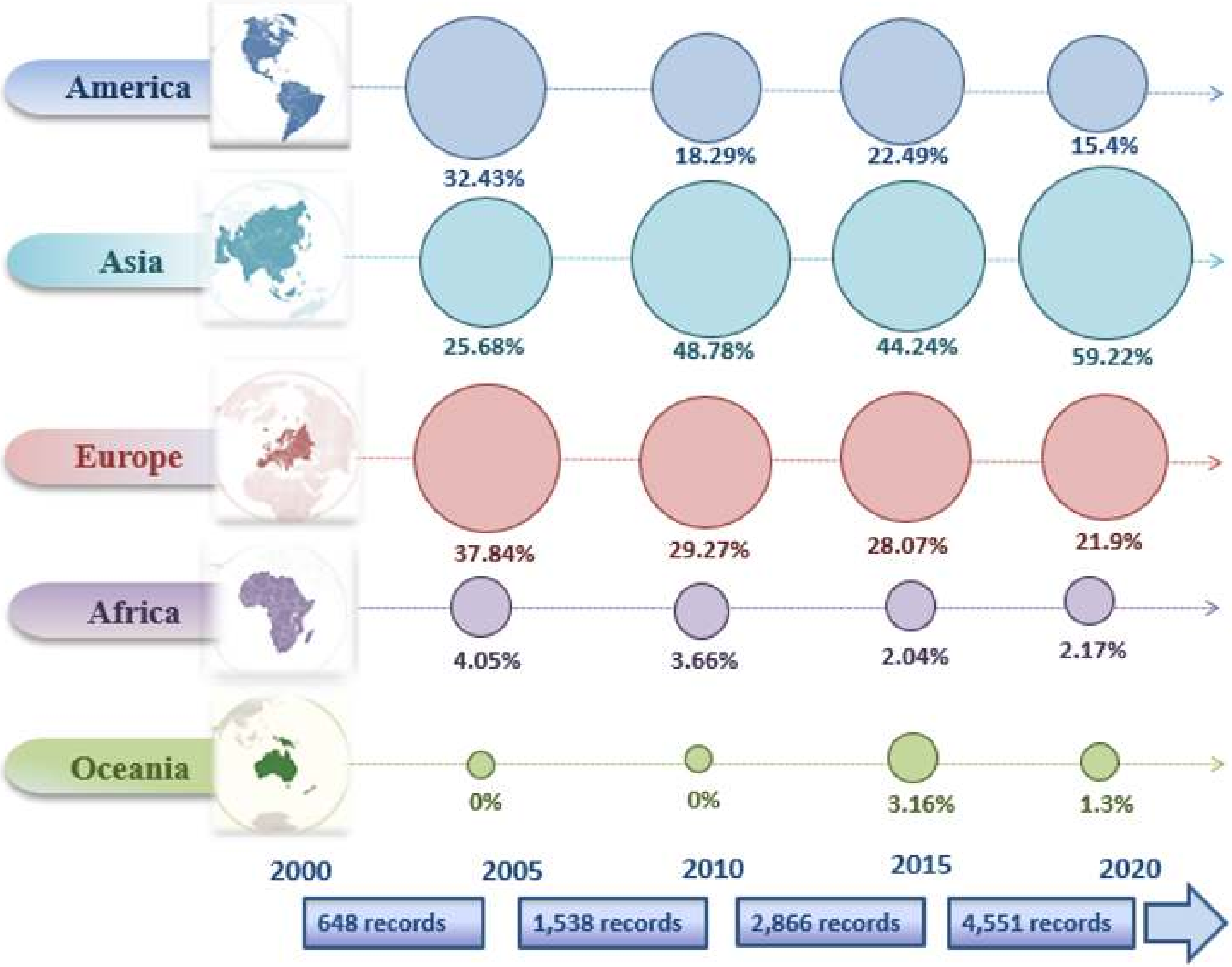


Figure 11

Research trend dynamics of the five continents in four different timelines. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 12

Geographical distribution of all countries/regions that have conducted studies on low carbon alcohol combustion in ICE between 2000-2021. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

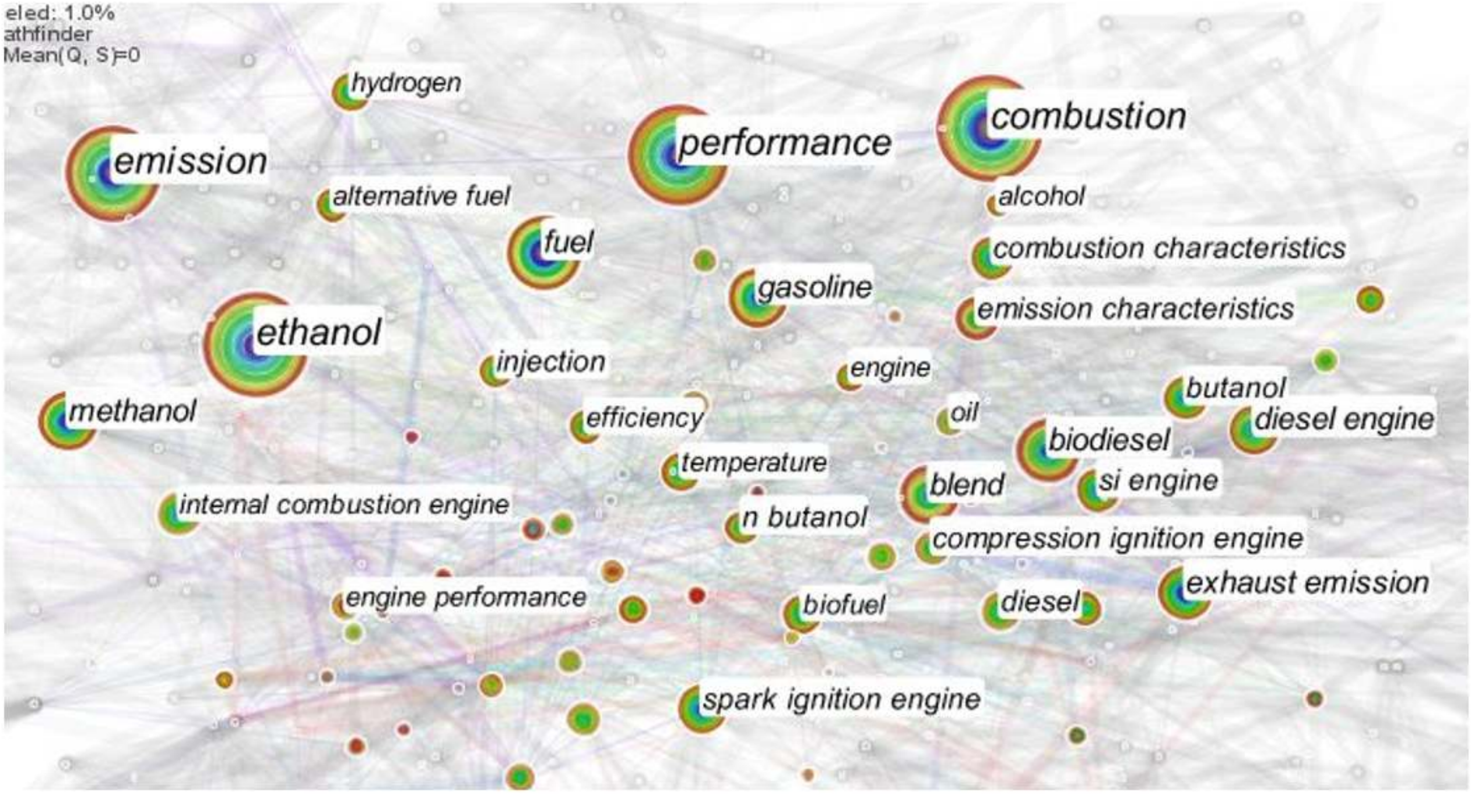


Figure 13

Keyword co-citation analysis (Node type=frequency; Threshold set at ≥100; colors closer to middle of node represent older publication years whereas outer colors are more recent publication years).

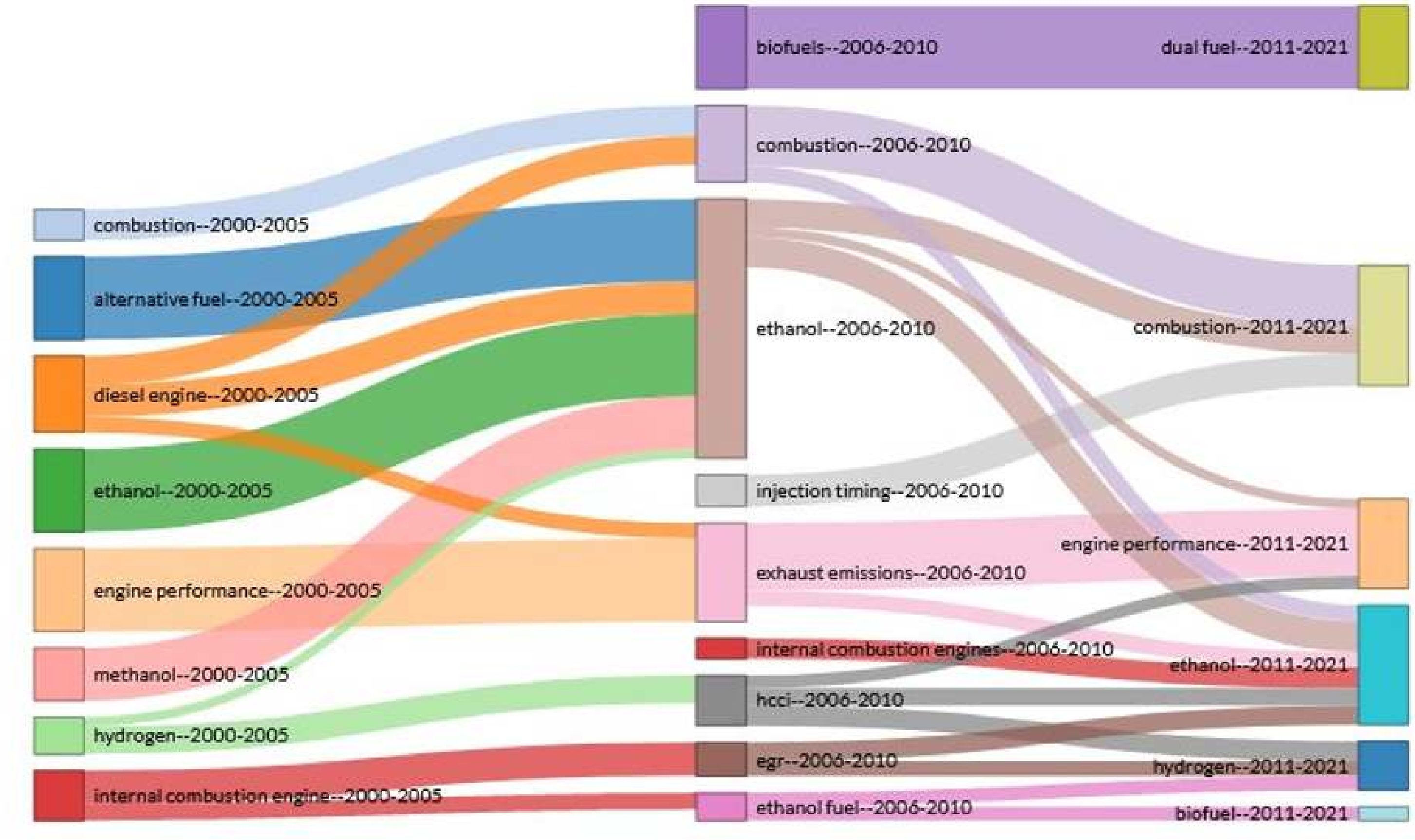
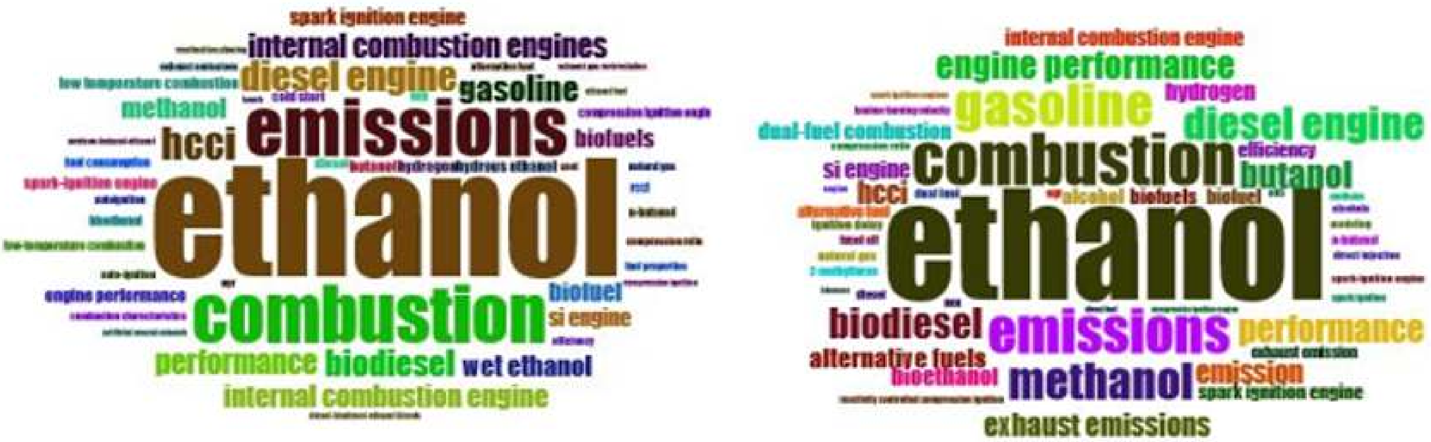


Figure 14

Thematic evolution of low carbon alcohol combustion in ICE research.

ASIA



AMERICA

EUROPE

Figure 15

Main research direction of most influential continents from 2000 to 2021.

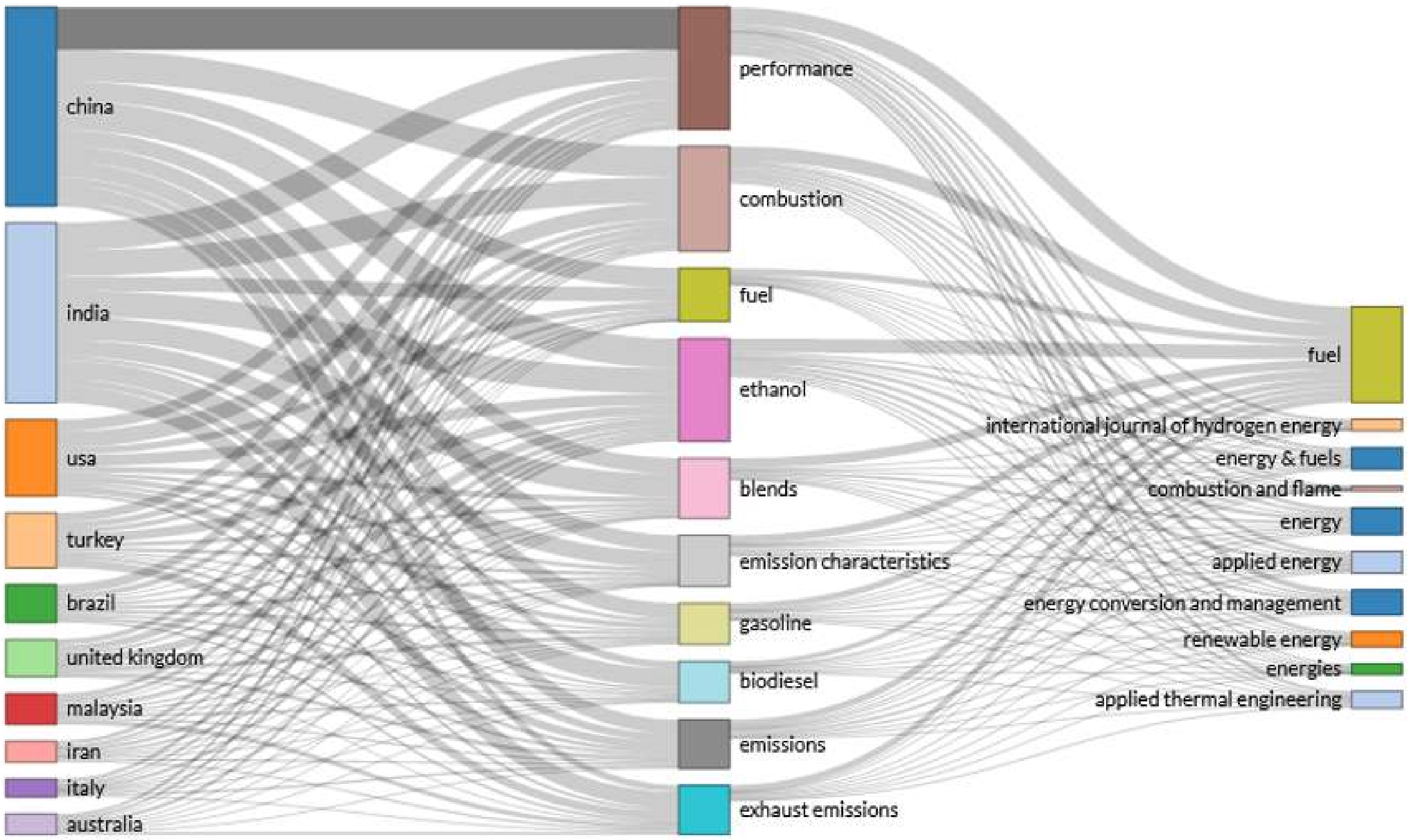


Figure 16

Main research direction of top 10 countries and journals.

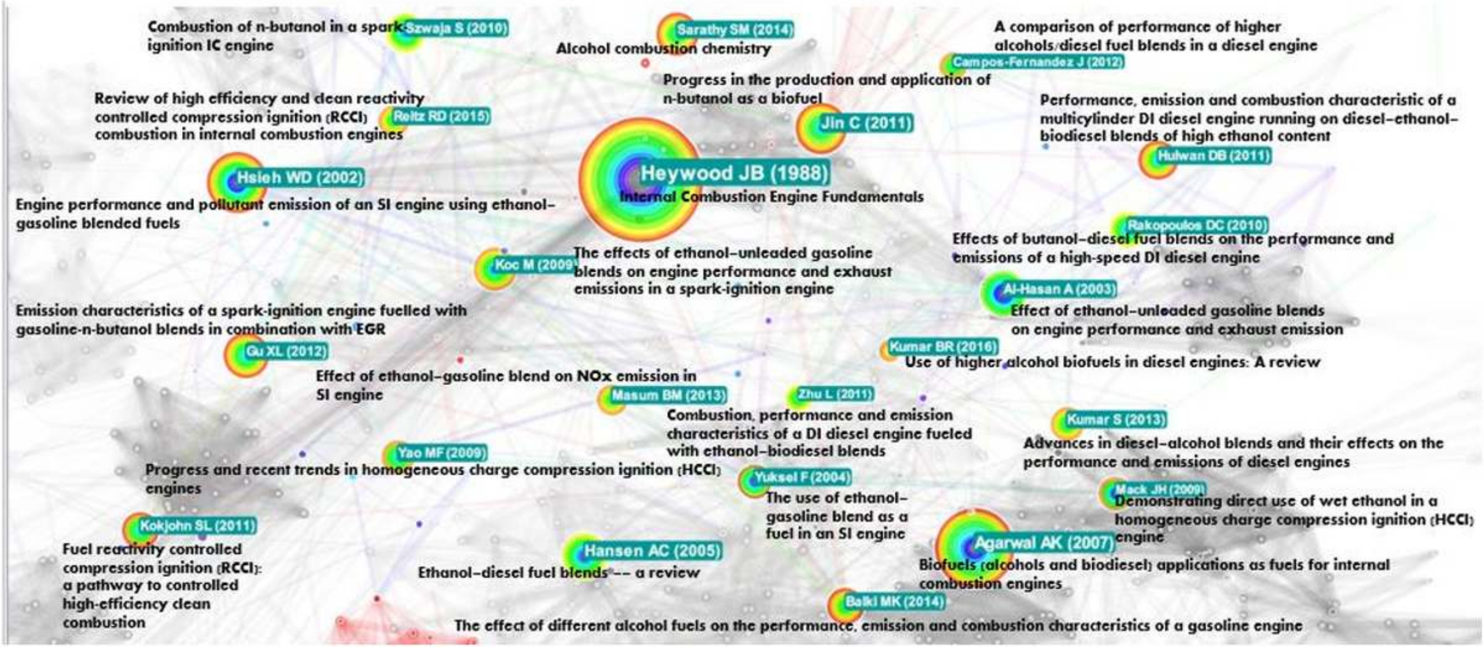


Figure 17

Most co-cited local references (Node type=citations; Threshold set at ≥50; colors closer to middle of node represent older publication years whereas outer colors are more recent publication years).