Environmental Technology & Innovation 32 (2023) 103343

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

Literature review on life cycle assessment of transportation alternative fuels

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ARTICLE INFO

Article history:
Received 21 July 2023
Received in revised form 17 August 2023
Accepted 17 August 2023
Available online 21 August 2023

Keywords:
Alternative fuel
Life cycle assessment
Life cycle analysis
Transport
Sustainable development
Greenhouse gas emission

ABSTRACT

Environmental concerns, such as global warming and human health damage, are intensifying, and the transportation sector significantly contributes to carbon and harmful emissions. This review examines the life cycle assessment (LCA) of alternative fuels (AF), evaluating current research on fuel types, LCA framework development, life cycle inventory (LCI), and impact selection. The objectives of this paper are: (1) to compare various AF LCA frameworks and develop a comprehensive framework for the transportation sector; (2) to identify emission hotspots of different AFs through simulations and real-world cases; (3) to review AF LCA research; (4) to extract valuable information for potential future research directions. The analysis reveals that all stages, except for hydrogen use, have an environmental impact. LCA boundaries and LCIs vary considerably depending on the raw materials, production processes, and products involved, leading to different emission hotspots. Due to knowledge or data limitations, some stages remain uncalculated in the current study, emphasizing the need for further refinement of the AF LCI. Future research should also explore the various impacts of widespread adoption of alternative fuels in transportation, encompassing social, economic, and environmental aspects. Lastly, the review provides structured recommendations for future research directions.

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https://doi.org/10.1016/j.eti.2023.103343

1. Introduction

As the number of vehicles on the road increases, there is a higher demand for traffic, meaning that more people require transportation services and infrastructure to accommodate their needs. This increased demand leads to higher fuel consumption, as more vehicles are being operated and require energy, typically in the form of fossil fuels, to function. Fossil fuel combustion in transportation generates detrimental greenhouse gases like CO_2, CH_4, and N_2O, which cause heat retention and contribute to global warming and climate shifts (Shafique et al., 2021; Shafique and Luo, 2022). Moreover, vehicles discharge multiple air contaminants, including particulates, NOx, and VOCs, negatively impacting air purity and human well-being.

In summary, the growing number of vehicles on the road leads to increased fuel consumption and contributes to environmental challenges (Shafique et al., 2021, 2022b), including climate change and air pollution, due to the release of greenhouse gases and other harmful pollutants from burning fossil fuels.

In 2021, the transportation sector is estimated to emit approximately 7.6 Gt of greenhouse gases, which accounts for roughly 20.2% of global greenhouse gas (GHG) emissions from end-use sectors (Statista Research Department, 2023). This heightened fuel consumption further intensifies the energy crisis. It is crucial to bolster mitigation measures and implement them effectively to address these environmental and energy-related challenges (Environment, 2022). In fact, numerous cutting-edge technologies and methods have been introduced in the transportation sector to reduce emissions. Examples include improving vehicle performance, altering travel and transportation habits, and adopting low-carbon energy sources as three essential tactics to decrease GHG emissions in the transport field.

1.1. The transportation industry and fuel

Transportation has been closely connected to the worldwide exchange of ideas (Margócsy and Brazelton, 2023), merchandise (Hörcher and Tirachini, 2021), and products, contributing substantially to poverty alleviation (Sanchez, 2008), employment generation, and advancements in agriculture. There exists a direct relationship between economic development and the extent and quality of transportation infrastructure. On a macroeconomic scale, a country's output, employment, and income are connected to the level of internal population movement. At a microeconomic level, transportation expenses affect production, consumer, and distribution costs (The Geography of Transport Systems, 2017).

However, since the 1950s, there has been a growing trend of increased oil consumption for transportation, resulting in substantial global carbon emissions increases. The transportation sector is the most reliant on fossil fuels (Transport,

Nomenclature

2-EH	2-ethylhexanol
AD	Anaerobic digestion
AF	Alternative fuel
AP	Acidification potentials
BEV	Battery electric vehicle
BTL	Biomass to liquid
CCS	Carbon capture and storage
CED	Cumulative energy demand
CM	Cattle manure
CNG	Compresses natural gas
CTL	Coal to liquid
DAC	Direct air capture
DALY	Disability adjusted life years
DME	Dimethyl ether
EA	Emergy accounting
EEA	Embodied energy analysis
FAME	Fatty methyl ester
FCEV	Fuel cell electric vehicle
FCV	Fuel cell vehicle
FFA	Free fatty acid
FT	Fischer Tropsch
FTD	Fischer–Tropsch diesel
GHG	Greenhouse gas
GTL	Gas to liquids
GWP	Global warming potentials
HEFA	Hydro processed esters and fatty acids
HEV	Hybrid electric vehicle
HVO	Hydrotreated vegetable oils
ICEV	Internal combustion engine vehicle
LCA	Life cycle assessment
LCSA	Life cycle sustainability assessment
LDDV	Light-duty diesel vehicle
LNG	Liquified natural gas
LPG	Liquified petroleum gas
LUC	Land use change
MFA	Material flow accounting
MRIO	multi-regional input–output
OTL	Crude oil to liquid
PHEV	Plug-in hybrid electric vehicle
POCP	Photochemical ozone creation potentials
REPA	Resource and environment profile analysis
RM	Raw material
RNG	Renewable natural gas
SMR	Steam methane reforming
SMR	Steam methane reforming
SNG	Synthetic natural gas
STL	Shale to liquid
TEA	Techno-economic analysis
TSD	Transport, Storage, Distribution

2022). Despite being severely affected by the Covid-19 pandemic, emissions continued to rise alongside demand. This growth is most evident in developing countries and emerging economies.

TTW	Tank-to-Wheel
TWS	Thermochemical water splitting
UCO	Used cooking oil
UCOME	Used cooking oil methyl ester
VKT	Vehicle km traveled
VMT	Vehicle mile traveled
WTG	Well-to-Gate
WTT	Well-to-Tank
WTW	Well-to-Wheel

To fulfill the goal of the Paris Agreement, which seeks to limit the rise in global temperatures to 2°C, it is crucial to advocate for a transition to carbon-neutral transportation systems. This involves the adoption of cleaner energy sources (Azam et al., 2022, 2021), innovative technologies (Antonini et al., 2021; d'Amore Domenech and Leo, 2019), and sustainable practices (Dreier et al., 2018) across all modes of transportation, including road, rail, air, and maritime transport. By implementing operational improvements and technological advancements that enhance energy efficiency, we can significantly reduce the carbon intensity of transportation systems worldwide. Such a transition requires collaborative efforts from governments, industries, and individuals to prioritize low-carbon and zero-emission transportation options, such as electric vehicles (Zhao et al., 2020), hydrogen fuel cell technology (Kovač et al., 2021; Miotti et al., 2017), and biofuels (Yan et al., 2010). Additionally, investing in public transportation and infrastructure that supports active transport modes like walking and cycling can further contribute to lowering emissions. Ultimately, the pursuit of a comprehensive, integrated, and sustainable transportation system is essential for addressing climate change and achieving the ambitious goals set by the Paris Agreement (Paris Agreement, 2016).

Fuel plays a critical role in the functioning of transportation systems (Transport, 2022). Currently, gasoline and diesel are the predominant conventional vehicle fuels worldwide (Khalili et al., 2019). Gasoline and diesel, derived from petroleum refining, possess high energy density, low prices, resistance to deterioration, and ease of transportation, making them ideal for spark-ignition and compression-ignition engines (Kumar Singh et al., 2023; Örs et al., 2023). In light of these considerations, alternative fuels (AFs) have started to emerge, offering substantial potential for emissions reduction (Jain, 2009).

In summary, the transportation sector and its fuel usage status hold immense significance. While traditional fuel efficiency has improved over time, the ongoing growth of the transportation sector has led to increased consumption and emissions. The rise of various AFs is an inevitable trend.

Road vehicles can utilize a variety of AFs, such as alternative fossil fuels, biofuels, electricity, and hydrogen.

In order to identify the emission hotspot and other pros/cons offered by these technologies, a thorough analysis, such as a life cycle assessment (LCA), can serve as a useful method. By using LCA, countries can gain a better understanding of the environmental, social and other consequences and advantages associated with the implementation of AFs. This knowledge can then inform decision-making processes and facilitate the development of a more sustainable transportation sector.

Numerous studies have investigated the materials, processes, and outcomes related to these technologies (Bicer and Dincer, 2018; Cai et al., 2022; Carneiro et al., 2017; Cihat Onat, 2022). Despite the wealth of existing research, however, a comprehensive understanding of the trade-offs associated with these technologies remains elusive.

1.2. Life cycle assessment (LCA) definition

LCA is an all-encompassing evaluation method employed to estimate the potential environmental consequences and resource usage linked to a product's complete life cycle. This life cycle encompasses the procurement of raw materials, the manufacturing and processing phases, as well as the product's utilization, and finally, its disposal or recycling. By considering each phase of a product's life, LCA enables a more holistic understanding of its environmental footprint, highlighting areas for potential improvement and promoting sustainable decision-making. In essence, LCA serves as a valuable instrument for businesses, policymakers, and consumers to evaluate and compare the environmental performance of products, fostering the development of eco-friendly alternatives and driving overall sustainability in various industries (Singh et al., 2013).

The development, application, international coordination, standardization, and dissemination of LCA and its methodology have evolved over decades (Bjørn et al., 2018). REPA, the precursor to LCA, focuses on tracking the amount of energy and resources (like crude oil, steel, etc.) used, as well as emissions and solid waste generation. As inventories become more intricate and application scenarios expand, databases adhering to consistent standards and quality, specialized LCA software, and new international standards have been developed successively.

LCA (Hauschild et al., 2018), as defined by the ISO 14040 and 14044 standards, is a systematic process that consists of four main stages:

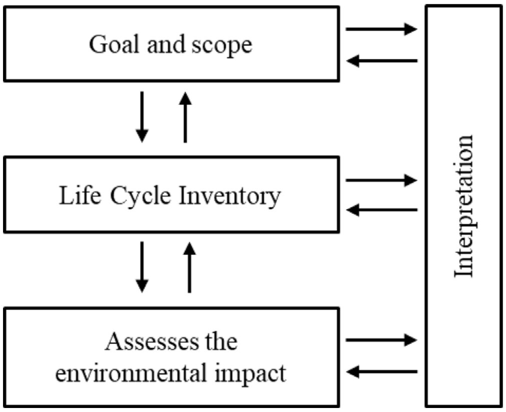


Fig. 1. Framework of Life Cycle Assessment.

(1) Goal and Scope Definition: This initial stage establishes the LCA's purpose and scope, defining the system boundaries and considering potential indirect impacts. It sets the foundation for the assessment by determining the functional unit and identifying the processes involved.

(2) Inventory Analysis: In the subsequent phase, a comprehensive record of data within the specified system scope is assembled. This encompasses input information, like resources, power, and machinery, along with output details, such as main goods, secondary products, contaminants, and waste. Furthermore, indirect effect data, potentially covering environmental and societal consequences or land utilization, is gathered and noted.

(3) Impact Assessment: In the third stage, the environmental impacts are categorized and quantitatively analyzed. This process involves evaluating the potential consequences of the inputs and outputs identified in the inventory analysis by assigning them to specific impact categories, such as climate change, resource depletion, or human health.

(4) Results Interpretation: The final stage involves interpreting the findings, drawing conclusions, and discussing recommendations based on the assessment's results. This step provides valuable insights into the environmental performance of the product or system under study and informs decision-making processes for improvements and sustainable development.

By following these four stages, LCA offers a comprehensive and systematic approach to understanding and evaluating the environmental impacts of products and processes, allowing for informed choices and the promotion of sustainable practices across various industries.

Fig. 1 shows the procedures of LCA according to ISO14040.

In the LCA examination of various complex systems, this paper focuses on the fuel utilized by vehicles in the transportation sector.

1.3. LCA in transportation fuels industry

LCA (Hauschild et al., 2018) is a valuable tool for evaluating the environmental impact and resource usage of products from their creation to end-of-life (EOF). Research has primarily focused on Afs for private cars, which make up a significant portion of travel methods (Liao et al., 2020). In a study conducted in Pakistan, 25 powertrain technologies were analyzed, revealing that natural gas could effectively reduce greenhouse gas emissions, with methane leakage rate being crucial for emission reduction (Khan et al., 2019). Another study in India compared various AFs and determined that electricity, used in battery electric vehicles, resulted in the lowest life cycle emissions across different power grid scenarios (Peshin et al., 2020).

In a Swedish study, Shinde et al. (2021) conducted an LCA analysis on biogas production and power generation for alternative fuels used in bus. Poulikidou et al. (2019) investigated three processes for producing 2-EH as an alternative fuel, comparing their energy demand and global warming potential. Cihat Onat (2022) assessed the sustainability of EVs in Qatar, developing a comprehensive framework for analyzing environmental, social, and economic impacts. The study found that charging performance was poor with a natural gas-generated power grid but improved with a potential solar power grid. Additionally, 14 sustainability indicators were obtained by comparing various types of electric vehicles with traditional internal combustion engine vehicles.

Cai et al. (2022) used LCA to assess the decarbonization potential of new fuel vehicle systems, including various fuel and powertrain technologies for light vehicles in Europe and the US. The study aimed to guide future technology selection and explore short- and medium-term transportation decarbonization through renewable fuels and innovative technologies. A well-to-wheel analysis was conducted using JEC and GREET tools, with JEC contributing a marginal approach for allocating energy consumption and greenhouse gas emissions from conventional fossil fuels.

LCA studies in the transportation sector and alternative fuels should consider socio-economic effects such as accessibility, affordability, equity, travel time, congestion, and noise (Aftabuzzaman, 2007; Choi et al., 2013; Jacyna et al., 2017; Randal et al., 2020; Saif et al., 2019; Serebrisky et al., 2009). Historically, most studies focused on a limited set of environmental impact categories, with sustainability indicators included in only a few investigations (Ahmadi and Kjeang, 2015). Sharma and Strezov (2017) analyzed various alternative and conventional fuels using LCA, considering both environmental and economic impacts. They found that biodiesel and ethanol-based flexible fuel technology had the most significant overall impact on the environment and economy.

Key assessment aspects in alternative fuels research can include environmental, economic, social, and technical impacts, as well as resource material consumption. Environmental impact is the primary focus, as alternative fuels often contribute to emission reduction. However, determining the appropriate weight for evaluation metrics warrants further discussion. In a study evaluating the impact of different hydrogen production routes on public transport, the solar hydrogen production route had the greatest environmental impact due to the toxicity of solar panels (Aydin and Dincer, 2022). Meanwhile, Sharma and Strezov (2017) evaluated multiple environmental consequences, and Bicer and Dincer (2017) conducted a comparison of hydrogen, methanol, and electricity as transport fuels, assessing their respective effects.

Mansour and Haddad (2017) assessed life cycle emissions and economic feasibility of various fuels to provide policy recommendations for developing countries reliant on fuel imports. In the short term, hybrid electric vehicles powered by gasoline, diesel, or biodiesel are most viable. However, biodiesel's limited availability restricts emission reduction potential. In the medium and long term, CNG may be less advantageous in terms of energy consumption, but profitable for high-mileage vehicles. LPG adoption can address infrastructure investment shortages, and EVs remain the preferred choice for lower emissions and greater benefits in the long run. The study presents a framework for alternative fuel strategies considering environmental and cost dimensions and focuses on 7 prevalent air pollutants.

Antonini et al. (2021) also highlighted the importance of diversifying AFs and vehicles to facilitate a transition to low-carbon transportation systems, given the limited availability of biological resources for hydrogen production.

In the LCA of AFs, selecting the appropriate functional unit (FU) is crucial for meaningful comparisons. The FU is typically chosen as either 1 MJ of fuel or 1 km of vehicle distance driven, depending on the scope of assessment. Within the well-to-tank (WTT) scope, which includes farming (if capable), resource materials (RMs) acquisition and transportation, as well as fuel production and storage and transportation, 1 MJ of fuel is often used as the FU. This choice allows for a focused evaluation of the energy content and environmental impacts associated with fuel production and delivery. Conversely, within the tank-to-wheel (TTW) scope, the focus shifts to fuel usage in vehicles, making 1 km of distance driven a more appropriate FU. This choice enables the assessment of the efficiency and environmental impacts of operating vehicles on different fuels. For the comprehensive well-to-wheel (WTW) scope, which combines both WTT and TTW, most studies employ the results from both FU choices to provide a holistic understanding of the entire fuel life cycle. However, a few studies might use only 1 km of distance driven or other FU, depending on their research objectives and methodological approaches.

In Aydin and Dincer (2022), since the primary comparison involves different hydrogen production processes, the FUs are chosen as 1 kg of H2 and 1 vehicle km. A study on bioethanol production from CM in Brazil utilized 1000 kg of CM as the FU (de Azevedo et al., 2017).

Antonini et al. (2021) assessed the life cycle impact of three types of wood-based hydrogen production as an AF. Interestingly, the authors questioned the use of "per kilometer" as a FU, arguing that it might be unfair to AFs with negative carbon emissions in their supply chain. Consequently, they opted for "production of 1 MW of hydrogen, with at least 99.97% purity" as the FU.

Pleanjai et al. (2009) carried out an LCA to evaluate the conversion of waste cooking oil into biodiesel in Thailand, using a 100 km light LDDV as the functional unit (FU). Their findings revealed that biodiesel emissions were 93% lower compared to conventional diesel (Pleanjai et al., 2009). Tessum et al. (2014) utilized 388 billion miles per year as their FU, accounting for 10% of the projected US vehicle mileage in 2020. Carneiro et al. (2017) explored the selection of FUs for fuels derived from biomass, proposing options such as unit input biomass or unit output (e.g., per km traveled). Some research has employed agricultural land area and year as the FU (Esteves et al., 2016; Forte et al., 2017). The majority of studies concur on using a common unit output (1 MJ fuel or 1 km vehicle traveled) as the FU, which can facilitate effective comparisons of various related analysis outcomes in the future (Boero et al., 2023; Zhao et al., 2021).

System boundaries and life cycle inventories in alternative fuel assessments depend on the types of fuels and production technologies being considered. For example, internal combustion engine fuels do not require battery manufacturing accounting in WTW analyses. Poulikidou et al. (2019) conducted LCA analyses for different production routes, resulting in varying inventories. Kannangara et al. (2021) developed an adaptive LCA framework for light vehicles, and the challenges in nationwide assessments stem from rapid technology development, difficult-to-quantify supply chain conditions, regional transportation characteristics, and evolving power grid compositions.

Yeow et al. (2022) compared life cycle GHG emissions of alternative fuels for city delivery trucks in Singapore, finding that both BEVs and FCEVs offer emission reduction potential if upstream fuel production is decarbonized. Battery capacity enhancement is needed for BEVs to meet mileage demands. Zhou et al. (2017) examined WTT impacts of alternative liquid fuels in the Chinese market, with BTL requiring the least energy and emitting the lowest GHGs. Economic benefits of BTL, STL, and CTL are influenced by crude oil prices. Comparing the biofuels and synthetic fuels in China with those fuels in the US, high energy use and GHG emissions for biofuels often stem from fertilizer input and energy requirements during production (Yan et al., 2010). Scacchi et al. (2010) evaluated bioethanol production from wheat, proposing a "seed-to-wheel" research scope.

It is clear that most LCA studies on biomass-derived fuels reach a similar conclusion: the first generation of biofuels involves energy-intensive agricultural activities, leading to increased emissions of particulate matter, NOx, and SOx pollutants during the life cycle. However, Portugal-Pereira et al. (2016) suggested measures to optimize the production process based on a study of biodiesel production from jatropha. These measures include recycling by-products through cogeneration, gasification, or Fischer–Tropsch synthesis routes and improving agricultural and processing practices.

Lyng and Brekke (2019) emphasize the need for sensitivity analysis due to uncertainties in fuel life cycles and recommend maintaining consistent system boundaries for comparative analysis. They suggest using actual measurement data from factories rather than literature and databases to reduce uncertainty. Researchers should consider including multiple types of environmental impacts, as their significance varies across regions and contexts. Advanced fuel production technologies yield more stable LCA results, with sugarcane ethanol production in Brazil being a prime example.

In the TTW phase, factors such as vehicle types, driving cycles, and vehicle cycle modes can lead to emission disparities. Hooftman et al. (2016) examined the influence of vehicle cycles on diesel vehicle emissions and discussed the transition from the New European Driving Cycle (NEDC) to the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) as a new standard. Ribau et al. (2014) argue that optimizing vehicle driving conditions is crucial for reducing GHG emissions but may increase powertrain costs.

1.4. Research aims and research questions definition

The number of LCA studies on fuels discussed in this review shows an overall upward trend on the timeline. Among them, LCA research on electricity as an alternative fuel (AF) has been popular for about a decade, which is closely related to the development history of electric vehicles. Similarly, research on biomass fuels is linked to the advancement of first-generation, second-generation, and third-generation biomass. However, there are very few related studies on the latest fourth-generation biomass fuels. The number of studies on hydrogen is relatively significant, accounting for almost one-third of the reviewed papers. The earliest selected paper on hydrogen dates back to 2014. Overall, it is evident that the types of AFs for LCA are continuously expanding.

Most research on alternative fuels is concentrated around developed countries, possibly because they tend to have more advanced technology and stable data systems. However, developing countries like Brazil and China are also frequently discussed due to their abundant biomass resources. Furthermore, case studies for various cities are available since alternative fuels can also be used in public transport vehicles.

From the perspective of quantity and trend, it is necessary to review past research content to avoid redundant research results in the future (Paul et al., 2021). Moreover, as discussed in the previous section, the AF LCA (alternative fuel life cycle assessment) is impacted by numerous changing factors, such as life cycle scope (WTW, WTT, TTW), scope of influence, selection of functional unit, and allocation procedure. Therefore, an assessment framework is needed to summarize the research conclusions and highlight the emission reduction capabilities, emission hotspots, and other environmental, social, and economic advantages and disadvantages of mainstream alternative fuels.

According to the theme of this paper, and the possible concerns, the following research questions are defined:

RQ1: What are the main alternative fuels being considered and what are the potential alternative fuels for the future according to the LCA results?

RQ2: To address the challenges of comparing different renewable materials, production methods, regions, and powertrain technologies, and to support theoretical and practical emission reduction efforts in the transportation sector, what factors or frameworks should an ideal AF LCA include?

RQ3: Besides achieving existing goals and solving existing problems, what are the potential key subtopics for the future?

1.5. Originality and map of the review

This paper provides a literature review on the LCA method's use in AF transportation research. The application of these AFs can reduce the dependence of future transportation on fossil fuels and further decarbonize the transportation sector. This paper also focuses on the selection of FU and the coverage of environmental impact and other impact indicators in the LCA of AFs. It is expected to analyze the deficiencies of existing research through the review of relevant research, and propose a complete and reliable LCA evaluation framework as far as possible.

The originality of this paper lies in:

(1) Provide theoretical contributions to future research on AF LCA analysis, specifically reflected in the further improvement of the evaluation framework and the provision of evidence for the insufficient scope of life cycle impact, beyond the general statistical analysis of keywords such as author country.

(2) In addition, it provides a more comprehensive review perspective on policy formulation, aiming to call for more practice-friendly extensions of impact analysis through the above evidence.

The rest of this paper is as follows: Section 2, Methodology; Section 3, Fuels used for transportation vehicles; Section 4, LCA Application of Fuels for transportation vehicles; Section 5, Research gap and directions for future research; Section 6, Conclusion and Future outlook.

2. Methodology

The theoretical development of how to write review papers has undergone iterations of various methods or frameworks (Grant and Booth, 2009; Moher et al., 2015, 2009). According to the discussion by Palmatier et al. review papers can be roughly divided into three categories, namely domain-, theory-, and method-based reviews (Palmatier et al., 2018).

Considering that the main subject of this review is LCA research on alternative fuels, this review should belong to domain-based reviews. At the same time, this review followed the rigorous review writing method. In Paul and Criado's subdivision of domain-based reviews and based on the evidences from the about references, this review should further belong to framework-based reviews and narrative reviews (Paul and Criado, 2020).

This paper will follow the SPAR-4-SLR (Scientific procedures and rationales for systematic literature reviews) protocol proposed by Paul et al. aiming to provide effective suggestions for substantial improvement in the development of the field under review (Paul et al., 2021).

The research scope encompasses all articles relevant to the topic. The analysis relies on data and findings derived from all published articles. Subsequent subsections detail the data collection and analysis procedures, the selection and reasoning behind the utilized resources and methods, and the approach to minimize or eliminate research bias.

According to the detailed explanation of the development steps of SLR by Massaro et al. (2016), combined with the characteristics of this paper, the corresponding research steps are arranged as follows:

(1) Define research questions
(2) Develop and write research protocol
(3) Identify study types and keywords, conduct a comprehensive literature search
(4) Define the analytical framework for the literature review
(5) Critical review and discussion through analysis conclusions
(6) Formulate potential topics and paths for future research

2.1. Search strategy

A systematic search was conducted on two leading academic databases, Scopus and Web of Science, for articles published up until June 16, 2023.

The search strategy involved crossmatching selected keywords based on key terms. A search was performed using Boolean logic operators (OR, AND, NOT). Each database's advanced search features were employed to adapt the search syntax. The keywords in Fig. 2's Acquisition section were used as the search terms.

In order to enhance the chances of discovering pertinent primary research, the reference lists of the selected studies and meta-analyses of published articles were carefully scrutinized.

2.2. Inclusion and exclusion criteria

In summary, this study's key focus areas are "AF" (Alternative Fuels) and "LCA" (Life Cycle Assessment), regardless of how the research methodology or life cycle scope of AF evolves. The research mainly examines the LCA of AFs for road transport vehicles, excluding ships and aviation. It specifically concentrates on LCA studies related to AFs, encompassing various raw materials, processes, and products, as long as the primary product involves AFs for road transport.

The review does not prioritize the end-of-life (EOF) of AFs or the consideration of associated storage and infrastructure. Some studies extended LCA methodology to advanced methods like Life Cycle Sustainability Assessment (LCSA) or combined LCA with other techniques (e.g., Monte Carlo Analysis). As long as the research primarily follows LCA principles, it falls within the review's scope. There are no specific requirements for the utilization of different software and databases in this review.

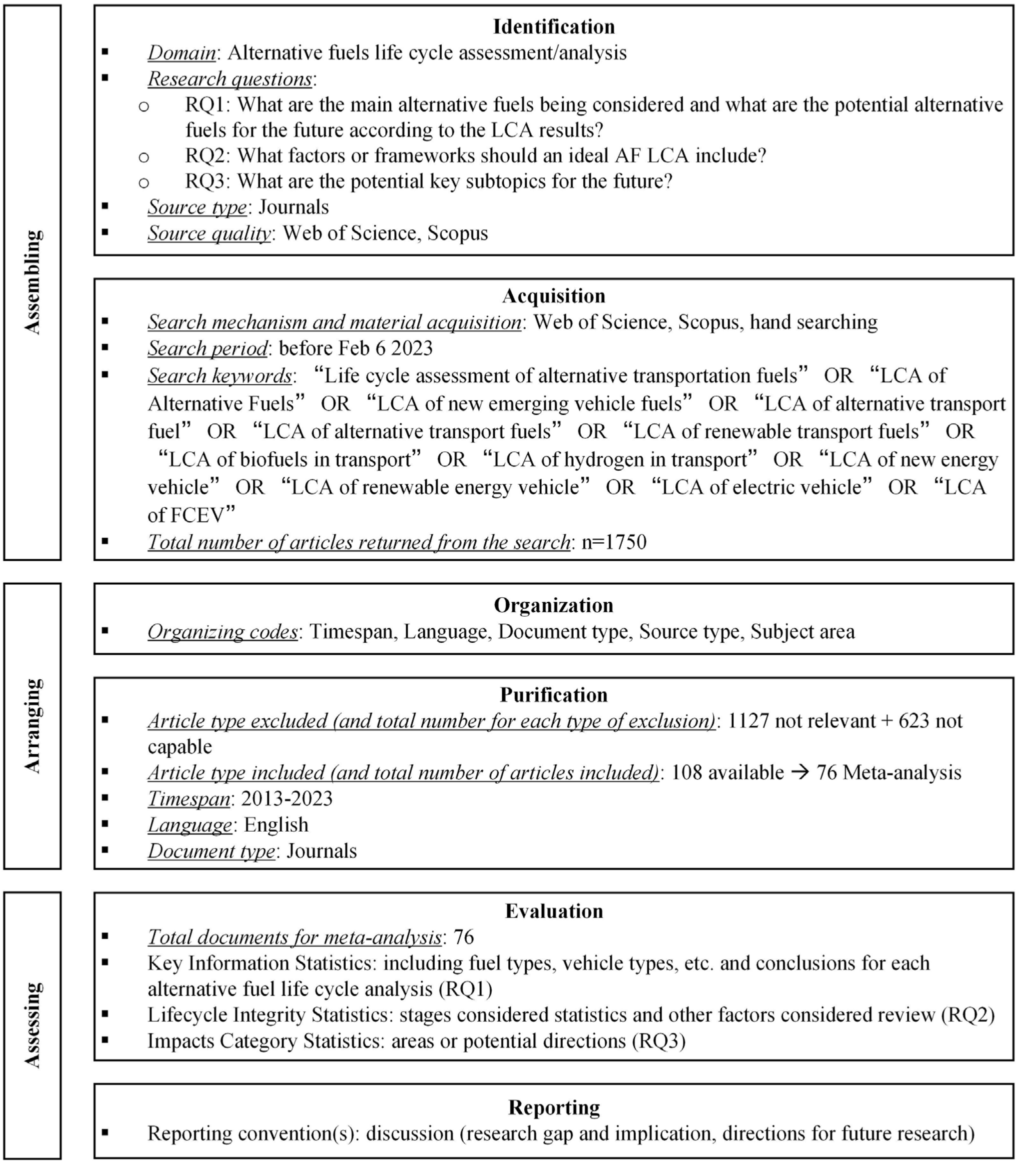
2.3. Study screening and selection outcomes

As depicted in Fig. 2, a total of 76 papers were ultimately selected as the primary review content following literature screening and manual addition. The entire process adhered to the PRISMA method (Moher et al., 2009), encompassing four main stages: identification, screening, eligibility, and inclusion.

2.4. Meta-analysis process

To analyze the 76 selected papers, we used a thorough reading approach to collect important information. First, we carefully examined relevant literature, reclassified fuels based on research needs, and established the baseline system boundary, which we illustrated with two figures.

Next, we extracted and consolidated information from each paper according to the system boundary. We organized this data into three tables that showed basic information, the stages considered, and the impacts assessed. These tables served as the foundation for further analysis.



Identification

- *Domain*: Alternative fuels life cycle assessment/analysis
- *Research questions*:
  - RQ1: What are the main alternative fuels being considered and what are the potential alternative fuels for the future according to the LCA results?
  - RQ2: What factors or frameworks should an ideal AF LCA include?
  - RQ3: What are the potential key subtopics for the future?
- *Source type*: Journals
- *Source quality*: Web of Science, Scopus

Acquisition

- *Search mechanism and material acquisition*: Web of Science, Scopus, hand searching
- *Search period*: before Feb 6 2023
- *Search keywords*: "Life cycle assessment of alternative transportation fuels" OR "LCA of Alternative Fuels" OR "LCA of new emerging vehicle fuels" OR "LCA of alternative transport fuel" OR "LCA of alternative transport fuels" OR "LCA of renewable transport fuels" OR "LCA of biofuels in transport" OR "LCA of hydrogen in transport" OR "LCA of new energy vehicle" OR "LCA of renewable energy vehicle" OR "LCA of electric vehicle" OR "LCA of FCEV"
- *Total number of articles returned from the search*: n=1750

Organization

- *Organizing codes*: Timespan, Language, Document type, Source type, Subject area

Purification

- *Article type excluded (and total number for each type of exclusion)*: 1127 not relevant + 623 not capable
- *Article type included (and total number of articles included)*: 108 available → 76 Meta-analysis
- *Timespan*: 2013-2023
- *Language*: English
- *Document type*: Journals

Evaluation

- *Total documents for meta-analysis*: 76
- Key Information Statistics: including fuel types, vehicle types, etc. and conclusions for each alternative fuel life cycle analysis (RQ1)
- Lifecycle Integrity Statistics: stages considered statistics and other factors considered review (RQ2)
- Impacts Category Statistics: areas or potential directions (RQ3)

Reporting

- Reporting convention(s): discussion (research gap and implication, directions for future research)

Fig. 2. SPAR-4-SLR protocol.
Source: Author's elaboration on Paul and Criado (2020).

In the third stage, we presented research methods and results for each fuel type, based on their classification. We combined this information with the data from the second stage to summarize the current state and research gaps in alternative fuel LCA.

Through this analysis, we addressed the proposed research questions.

Additionally, the data in this review's tables are based on the clear conclusions or data from the published papers. If the information is unclear or incomplete, we have tried to supplement it with additional literature or by comparing it to other studies to establish a unified standard. A blank cell in the table means either a lack of relevant information or the inability to draw reliable conclusions.

All terminology and standards follow international norms, and other data and content are aligned based on this review's requirements. For example, when discussing alternative fuel LCAs, we use terms like Well-to-Wheel (WTW), Well-to-Tank (WTT), and Tank-to-Wheel (TTW) instead of broader phrases like Cradle-to-Grave. This unified language also applies to the considered stages and functional unit selection, among other things. This standardization allows for consistent information presentation across various papers and ensures clarity in the tables.

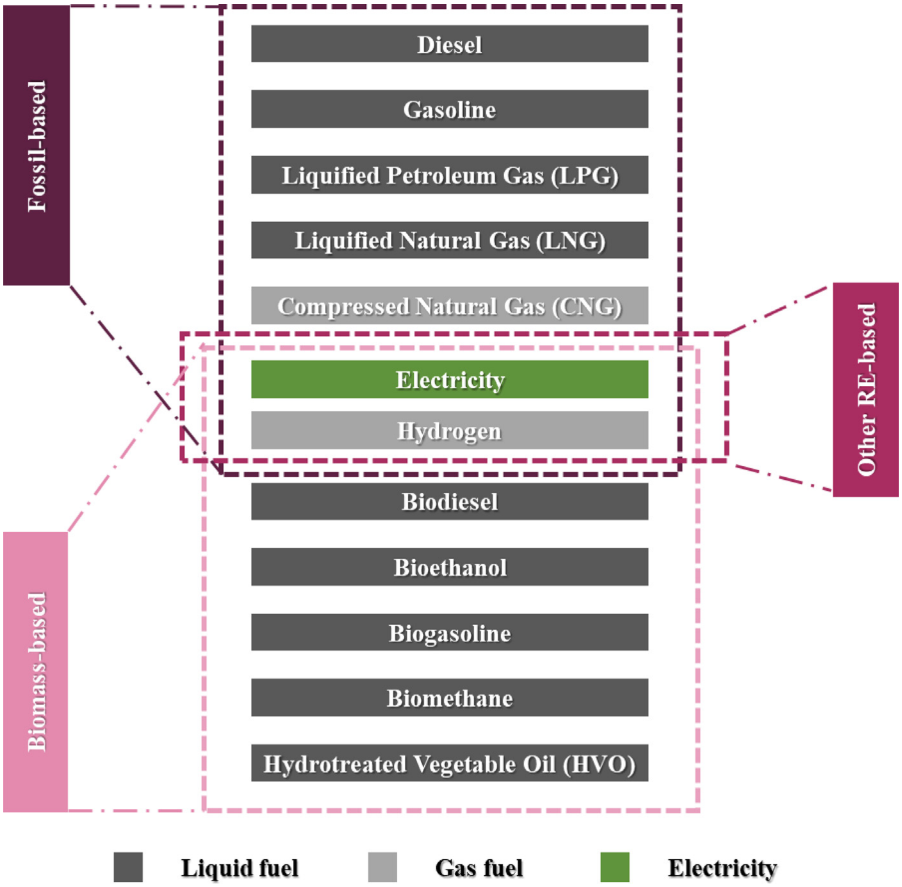


Fig. 3. Fuels classification.

3. Fuels used for transportation vehicles

As the focus of this review is on the transportation domain, the selection of alternative fuels (AF) primarily takes into account those that are currently in use or have potential for application in road traffic. Based on energy sources and utilization methods, these fuels can be broadly categorized into the following two groups.

The rationale behind this classification stems from the traits of the stages that must be considered within the boundary of the AF LCA target system. From the standpoint of fuel energy sources, biomass fuel typically involves farming, while solar power generation may encompass photovoltaic panel manufacturing and other related processes. In terms of fuel usage, different powertrain technologies come into play. For instance, utilizing electricity as an AF often necessitates considering battery manufacturing and recycling.

Based on the aforementioned classification methods, the fuel classification figures are represented in Fig. 3.

Although it is easy to distinguish the differences between their system boundaries based on the above classification, it is not easy to introduce the fuels. Therefore, the following sub-sections will describe fuels as the classification of traditional fuels and alternative advanced fuels.

3.1. Traditional fuels used

Gasoline (Wauquier, 1995) and diesel, traditionally sourced from crude oil, are produced using refining methods like atmospheric distillation, vacuum distillation, and cracking. Gasoline is classified based on its octane number, while diesel is categorized by densities and boiling point ranges. (Abdellatief et al., 2021), Alternative sources for gasoline and diesel include shale oil and coal. The United States leads in global mining output and shale oil production, followed by Russia and China. Shale oil extraction involves processes such as grinding, screening, distillation/retorting, and hydrocracking (Lee, 1990).

China has substantial coal reserves (Zhou et al., 2017), with proven reserves in 2021 reaching 143,197 million tons, approximately 13.3% of global reserves. While the United States, Russia, and Australia possess larger reserves, China

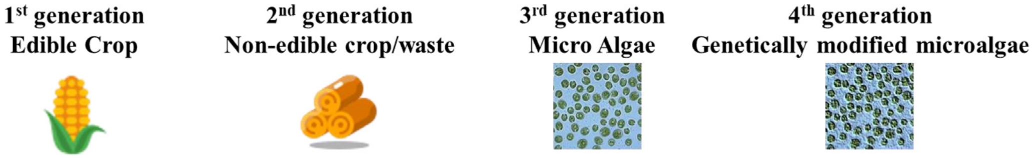


Fig. 4. Classification of biofuel.

has the highest mining volume, responsible for 50.7% of the global mining volume in 2020 (BP p.l.c., 2021). Coal is gasified through the Fischer–Tropsch process to produce syngas, which is then converted into synthetic crude oil. After desulfurization and hydrogenation in the fractionator, gasoline and diesel are refined from it.

3.2. Advance fuel/emerging fuels

In general, AFs either operate using alternative engine technologies or serve as substitutes for conventional fuels. The literature offers a comprehensive overview of the typical RMs and methods for preparing AFs. Both fossil-based and renewable fuels can be classified as AFs, which can further be divided into liquid and gaseous forms.

3.2.1. Electricity

Electricity as an AF is unique, as its use involves the life cycle process of batteries. However, its specific emission reduction capacity depends on the cleanliness of the converted energy source, as electricity must be converted from other sources. Additionally, the emissions and impacts associated with battery production, maintenance, and disposal differ from those of other fuels.

In 2022, global electricity demand grows by 3% (389 TWh), consistent with the growth rate of the past decade. Concurrently, the proportion of renewable energy power generation is gradually increasing, accounting for 28% of the total (3,802 TWh) in the first half of 2022 (Ember, 2022). The cleanliness of the power grid is related to the proportion of renewable energy power generation and directly influences the emission reduction potential of electricity as an AF. The local power generation mix is key to determining whether promoting electric vehicles effectively reduces emissions. When considering electricity as an AF life cycle component, it typically involves the energy source of electricity (or local grid combination) and energy storage, which further includes the battery life cycle (Shafique et al., 2022a).

Electric vehicle (EV) batteries play a critical role in determining the duration and efficiency of electrical energy use. Initially, these batteries went through various developmental phases, including lead–acid and nickel–hydrogen iterations.

In recent times, lithium-ion batteries have emerged as the leading choice for EVs, demonstrating improvements in multiple aspects, such as range, energy density, cost, longevity, performance, fast charging, and safety. Ford's Deng and other experts have highlighted these areas, emphasizing the need for continued advancements to further enhance the capabilities of future EV batteries (Deng et al., 2020).

Undoubtedly, the performance of using electricity as an alternative fuel is influenced by various factors, including charging techniques and powertrain technology, among others. A detailed discussion of the relevant research content and conclusions will be addressed later in this paper.

3.2.2. Biofuel

Biofuel, derived from biomass as a raw material (RM), can be classified based on various features or standards, such as the RM type, conversion process, or application (Parikka, 2004). In 2021, the worldwide demand for biofuels is anticipated to reach 4 exajoules (EJ), with their usage in road transportation constituting 3.6% of the overall fuel demand in the transport sector. As part of the efforts to attain a net-zero emissions target by 2030, biofuels are projected to generate 15 EJ, contributing to 15% of the fuel consumption within the transportation domain (IEA, 2022). Biofuels are typically categorized into four distinct generations, as illustrated in Fig. 4. These classifications, namely "first-generation", "second-generation", "third-generation", and "fourth-generation", represent the advancement and development of biofuel technologies over time, reflecting improvements in feedstock sources, production processes, and environmental impacts (Alalwan et al., 2019).

First-generation biomass fuels use edible crops as RMs, with the United States and Brazil as the main producers due to resource abundance and technological maturity. In 2022, biofuel production in the United States is expected to reach 72 billion liters (including bioethanol and biodiesel), while Brazil will produce 35.6 billion liters, representing approximately 41% and 20% of the total statistics, respectively (IEA, 2021). Concerns such as competition with food resources led to the development of second-generation biomass fuels, which use inedible crops, agricultural waste, or other waste as RMs. However, these fuels are limited by regional resources and technology levels. Third-generation biomass fuels can be grown in artificial environments, overcoming geographical constraints, but their output or energy efficiency is relatively low due to immature technology (Siddiki et al., 2022). Fourth-generation biomass fuels use gene-edited microalgae as RMs, but relevant research and applications are still in the early stages.

Synthetic biofuels, as a substitute for fossil fuels, offer several advantages: (1) minimal engine modification is required; (2) there is no need for additional refueling infrastructure (Rosenfeld et al., 2019). As a result, Europe has established corresponding mandatory blending targets for biofuels.

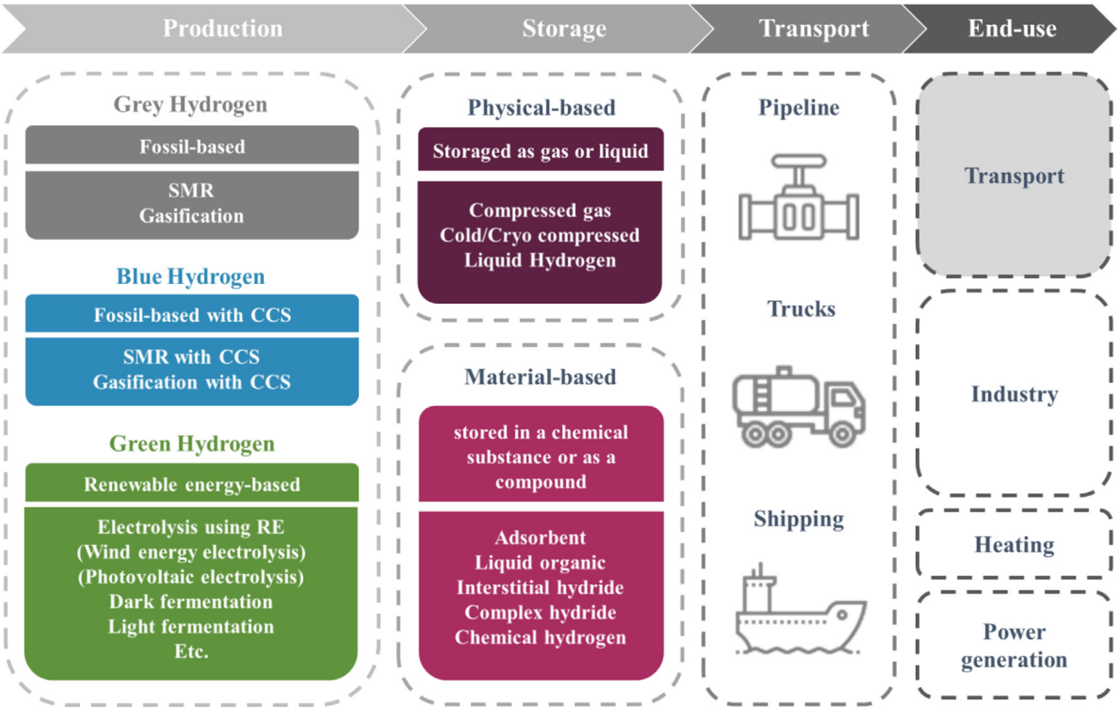


Fig. 5. Hydrogen route map.

3.2.3. Hydrogen

Hydrogen, a promising AF, serves as an energy storage carrier for intermittent solar and wind energy and is discussed separately due to its unique cycle compared to other AFs. There are numerous methods for hydrogen production, including dark fermentation, light fermentation, and their combination, as well as electrolysis methods. Nonetheless, the expenses associated with these eco-friendly techniques are still considerably higher compared to conventional hydrogen production methods using fossil fuels, such as steam methane reforming (SMR), which is currently the most prevalent industrial approach (Kumar et al., 2021).

Depending on the carbon emissions generated during production, hydrogen can be colored gray, blue or green. Gray hydrogen, which is obtained from fossil fuels and has a 95% market share, is represented by SMR and has low production costs but high GHG emissions. Blue hydrogen, also produced from fossil fuels, uses carbon capture and storage (CCS) technology to reduce carbon emissions but is limited by the geological conditions required for CCS technology and the reliable supply of natural gas. Green hydrogen, produced from renewable energy, is the goal and direction for achieving zero emissions in industry and transportation. It involves generating electricity through renewable energy and then producing hydrogen through water electrolysis.

Various hydrogen storage and transportation technologies exist, each with distinct subcategories based on the state and method employed. Storage states include gaseous and liquid forms, while storage methods involve either physical or material-based containment. Hydrogen transportation methods can be classified into three primary approaches: pipeline transportation, cryogenic liquid tanker transportation, and gaseous tube trailer transportation. Each method presents unique advantages and challenges, requiring careful planning for hydrogen infrastructure and distribution networks.

However, the risks associated with hydrogen storage and transportation remain insufficiently addressed (Yang et al., 2021). To effectively utilize hydrogen for carbon emissions reduction in the transportation sector, future efforts must focus on mitigating these concerns (Shen et al., 2019). A detailed hydrogen usage roadmap is provided in Fig. 5.

A more refined classification includes grey, blue, green, brown, and turquoise hydrogen. Grey hydrogen is obtained through steam reforming of methane, brown hydrogen through coal gasification, and turquoise hydrogen via methane pyrolysis (Osman et al., 2022). Some studies suggest classifying hydrogen by the cleanliness index of production rather than the source and method (Han et al., 2021). Although this classification aligns more closely with the original intent, it requires more analytical results to support the classification and will not be introduced here.

4. LCA application of fuels for transportation vehicles

4.1. Review results and system boundaries of AF LCA

Fig. 6 illustrates the fundamental system boundary for the life cycle of AF, based on previously established classification criteria. This framework encompasses a variety of AF types and raw material sources, such as biomass-derived fuels

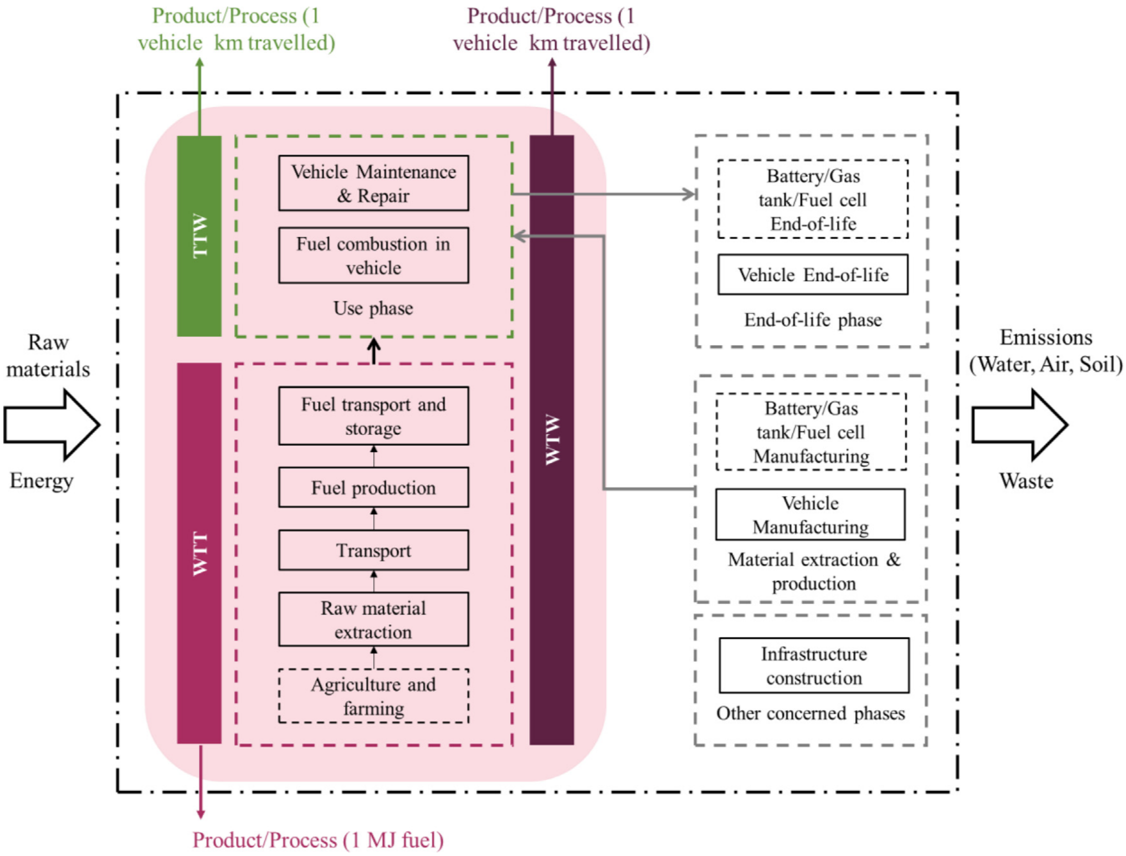


Fig. 6. Comprehensive system boundary.

and electricity as an AF. The figure separately considers the fuel and vehicle life cycles, as well as potential battery and infrastructure life cycles, with possible stages and distinct phases indicated by dotted lines and different colors, respectively. This paper primarily focuses on the AF life cycle within the pink block.

The AF life cycle, or well-to-wheel (WTW), is divided into two stages: well-to-tank (WTT) and tank-to-wheel (TTW). WTT encompasses all upstream stages before fuel delivery to the user, while TTW covers the fuel usage process and any necessary maintenance procedures. Components outside the pink block include vehicle, battery, infrastructure, and other equipment cycles. Though not typically included in the AF LCA, these aspects are incorporated in this discussion due to their significant impact on fuel emissions and application challenges. Comparing AF LCAs without considering external influences would render the analysis inconclusive.

Building upon the previously introduced fuel classification and the life cycle system boundary of AF, we compiled two summary tables from a literature review. Table 1 presents basic information, emphasizing the fuel type (with the raw materials or processes used for a specific fuel identified in brackets), the vehicle type employed, the region, the software or database utilized, whether the LCA method has been expanded, and the life cycle range (WTT, TTW, or WTW) and functional unit (FU) selection. In Table 1, 'N/A' suggests there is no usable/suitable information about this value after reading the full text of the corresponding paper.

The analysis of Table 1 offers several significant insights into the current state of research regarding AFs and the methodologies employed. The breadth of AF types studied is commendable, albeit with an underrepresentation of third and fourth generation biomass fuels, indicating a potential area for future investigation (Curtiss and Kreider, 2010). One clear trend that emerges is the focus on passenger vehicles, both cars and buses, suggesting that these form the primary context for most existing studies. Geographically, it is observed that research is more prevalent and nuanced in regions rich in resources or data, which perhaps offers more opportunities for in-depth studies. As for the research methodologies, there is a clear consensus on the use of standard software and databases. To enhance the reliability of the data, many researchers augment these tools with supplementary sources like government websites and previous literature.

Table 1
Basic information of reviewed papers.

Ref.	Fuel	vehicle type	Software/Database/ Method	Geographical scope	LCA range	LCA type/ Auxiliary tools	Functional unit
(Boero et al., 2023)	Ammonia	car	EcoInvent, OpenLCA	United Kingdom	WTW	LCA	1 VKT
(Jasper et al., 2022)	Electricity, Hydrogen, Diesel	N/A	GaBi, Aspen Plus, GREET	United States	WTW	LCA	1 GJ Fuel
(Aboushaqrah et al., 2022)	CNG, Electricity, Hybrid, Gasoline	taxi	EXIOBASE, GREET	Qatar	WTT, TTW	MRIO-LCSA	1 VKT
(Cihat Onat, 2022)	Electricity, Gasoline	car	EXIOBASE, GREET	Qatar	WTT, TTW	MRIO-LCSA, SFS, AHP	1 VKT
(Cai et al., 2022)	CNG, Renewable Diesel (HVO100), FTD, B7, E10, E85, Electricity, Hydrogen, Diesel	car	GREET, JEC WTW	Europe and United States	WTT, TTW	LCA	1 MJ Fuel, 1 VKT
(Aydin and Dincer, 2022)	Hydrogen	bus	SimaPro, EcoInvent	Ontario, Canada	WTW	LCA	1 kg H_2, 1 VKT
(Yeow et al., 2022)	Electricity, Hydrogen, Diesel	truck	GREET	Singapore	WTT, TTW	process-based LCA	1 VKT
(Medrano-García et al., 2022)	FTD	N/A	Aspen HYSYS, SimaPro, EcoInvent	N/A	WTG	LCA	1 kg Fuel
(Seol et al., 2022)	Electricity, Hydrogen, Diesel, Gasoline	car	GREET	Korea	WTT,TTW	LCA	1 GJ Fuel, 1 VKT
(Puricelli et al., 2022)	Fossil ethyl tert-butyl ether (ETBE), Bio-ETBE, Bionaphtha, Bioethanol, Methanol, Biomethanol, E-methanol, Gasoline	car	EF method, EcoInvent	Europe	WTT,TTW	LCA	1 MJ Fuel, 1 VKT
(Tayarani and Ramji, 2022)	Hydrogen	truck	GREET	Los Angeles&California, United States	WTW	LCA	1 MJ Fuel
(Benavides et al., 2022)	2-Propanol, 2-Methylpropane-1-ol, Furan Mixture, Ethanol, N-Propanol, Prenol/ Isoprenol Mixture, 2-Butanol, Methanol, Diisobulylene	car	GREET	N/A	WTW	LCA, TEA	1 MJ Fuel
(Byun et al., 2022)	Bioethanol (Food waste)	car	Aspen Plus, GREET	Korea	WTT,TTW	LCA, process simulation, supply-chain network (SCN)	1 gal Fuel, year
(Chen et al., 2022)	Hydrogen	car	GaBi	China	WTW	LCA	150,000 km
(Shinde et al., 2021)	Biomethane, Electricity (Biogas)	bus	CML 2001	Västerås, Sweden	WTT, TTW	LCA	1 VKT
(Kannangara et al., 2021)	Electricity, Hydrogen	car	SimaPro, EcoInvent, GHGenius	Canada	WTT, TTW	LCA	1 VKT
(Pacheco-López et al., 2021)	Biodiesel, Bioethanol, plastic waste pyrolysis Oil, plastic waste pyrolysis Ethanol, Diesel, Gasoline	N/A	Aspen Plus, POLYNRTL, EcoInvent, SimaPro	Europe	WTT, TTW	LCA	1 GJ Fuel
(Feinauer et al., 2021)	Butanol (farmed wood) and gasoline blend, gasoline	car	Umberto, EcoInvent	Germany	WTT, TTW	LCA	1 VKT
(Folęga et al., 2022)	Hydrogen	car	Chem CAD process simulator	Poland	WTW	LCA	1 VKT, 1 kg H_2
(Antonini et al., 2021)	Hydrogen	car, truck	Aspen Plus, EcoInvent, Brightway2	Europe	WTG, WTW	LCA	production of 1 MW of hydrogen, with purity of at least 99.97%
(Rodríguez-Vallejo et al., 2021)	Polyoxymethylene dimethyl ethers (OMEn)	car	EcoInvent	Europe	WTW	LCA	1 VKT

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Table 1 (*continued*).

Ref.	Fuel	vehicle type	Software/Database/Method	Geographical scope	LCA range	LCA type/ Auxiliary tools	Functional unit
(Zhao et al., 2021)	Biodiesel (WCO)	truck	EcoInvent	China	WTW	LCA, LCC	1 MJ Fuel
(Delpierre et al., 2021)	Hydrogen	N/A	EcoInvent	Netherlands	WTG	ex-ante LCA	1 kg Fuel
(Phuang et al., 2021)	Biodiesel (Palm)	N/A	Malaysia Palm Oil Board (MPOB), Ecoinvent	Malaysia	WTG	LCA	1 MJ Fuel
(Bello et al., 2020)	Bioethanol (lignocellulosic waste)	car	SimaPro, Ecoinvent	Europe	WTW	LCA	1 VKT
(Okeke et al., 2020)	Biodiesel	truck	SimaPro, TRACI	United States	WTT	LCA	1 gasoline gallon equivalent (GGE) of drop-in diesel
(Foteinis et al., 2020)	Biodiesel (UCO)	N/A	SimaPro	Greece	WTT	LCA	1 tonne Fuel
(Liu et al., 2020)	E10, E85 (corncob)	car	SimaPro	China	WTW	LCA	1 VKT
(Khan et al., 2019)	CNG, Diesel, Gasoline	car	GREET, AVL Cruise	Pakistan	WTT, TTW	LCA	1 MJ Fuel, 1 VKT
(Poulikidou et al., 2019)	2-EH (Biomass)	car	OpenLCA, EcoInvent	Sweden	WTT, TTW	LCA	1 MJ Fuel, 1 VKT
(Chang et al., 2019)	LPG, LNG, Electricity, Hydrogen, Diesel	bus	SimaPro	Taiwan	WTT, TTW	LCA	1 VKT
(Lyng and Brekke, 2019)	NG, Biodiesel, Biogas, Electricity, Diesel	bus	SimaPro	Norway	WTW	LCA	1 VKT
(Rosenfeld et al., 2019)	CNG, Bioethanol (Cellulosic), BTL, SNG (residual biomass), Electricity (EU-28 mix), Hydrogen (SMR), Hydrogen (Renewable Electricity), Gasoline	car	GaBi, EcoInvent, GREET	Europe	WTT, TTW	LCA	1 VKT
(Fernández-Dacosta et al., 2019)	DME (CO2), Methanol (CO2), Hydrogen (SMR), Hydrogen (electrolysis from RE)	N/A	Aspen Plus, EcoInvent	Netherlands	WTW	LCA	1 GJ Fuel
(Winslow et al., 2019)	CNG, Electricity, Diesel	tracktor	GREET	United States	WTT, TTW	LCA	1 MJ Fuel, Year
(Ahmadi, 2019)	Electricity	car	GREET	United States	WTW	LCA	1 VMT
(Chen et al., 2019)	Hydrogen (Supercritical water gasification)	N/A	SimaPro, Ecoinvent	N/A	WTG	LCA	1 kg Fuel
(Bicer and Dincer, 2018)	LPG, CNG, Methanol, Ammonia, Electricity, Hybrid, Hydrogen, Diesel, Gasoline	car	GREET, SimaPro, EcoInvent	Europe	WTT, TTW	LCA	1 VKT

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Table 1 (*continued*).

Ref.	Fuel	vehicle type	Software/Database/ Method	Geographical scope	LCA range	LCA type/ Auxiliary tools	Functional unit
(Sorunmu et al., 2018)	Biogasoline	car	Aspen Plus, PNNL, Chemcad, ArcGIS, SimaPro, EcoInvent, NREL Biofuels Atlas, GREET	United States	WTT, TTW	LCA	1 MJ Fuel, 1 VKT
(Song et al., 2018)	Electricity	bus	Field test and investigation	Macau	TTW	Streamlined LCA	100 VKT
(Yuan et al., 2018)	CNG	taxis, car, bus, truck	Tsinghua-LCA Model (TLCAM)	China	WTW	LCA	1 MJ Fuel, 100 VKT
(Dreier et al., 2018)	B7, B100, Electricity, Diesel	bus	GREET, carbon balance method, ADVISOR	Curitiba, Brazil	WTT, TTW	LCA	1 MJ Fuel
(Gao et al., 2018)	CTL (direct, indirect)	car	N/A	China	WTW	LCA	1 MJ Fuel, 1 tonne Fuel
(Hanbury and Vasquez, 2018)	Electricity (geothermal energy)	car	GREET	Nevada, United States	WTW	LCA	N/A
(Lerner et al., 2018)	Methanol, DME, Diesel, Gasoline	N/A	Aspen Plus	United States	WTT, TTW	LCA	1 GJ Fuel
(Sharma and Strezov, 2017)	LPG,CNG, Biodiesel, Ethanol, Electricity, Hydrogen, Diesel, Gasoline	car	SimaPro, GREET, EcoInvent	Australia	WTT, TTW	LCA	1 MJ Fuel, 1 VKT
(Sen et al., 2017)	CNG, B20, Electricity, Hybrid, Diesel	truck	GREET, AFLEET, online EIO-LCA tool	United States	WTT, TTW	EIO-LCA, process-LCA, Monte Carlo analysis	Total lifetime
(Bicer and Dincer, 2017)	M90, Electricity, Hydrogen	N/A	GREET, SimaPro, EcoInvent	Europe	WTW	process based LCA, Monte Carlo uncertainty analysis	1 VKT
(Mansour and Haddad, 2017)	LPG, CNG, E10, E85, B20, Electricity, Diesel, Gasoline	car	GREET, ADVISOR	Lebanon	WTT, TTW	LCA	100 VKT
(Zhou et al., 2017)	OTL, STL, CTL, BTL	N/A	GREENSCOPE	China	WTG	LCA	1 GJ Fuel
(de Azevedo et al., 2017)	Bioethanol (Cattle Manure)	N/A	SimaPro, EcoInvent	Brazil	WTG	LCA	1000 kg of CM
(Lecksiwilai et al., 2017)	Bioethanol (cassava), Biodiesel (palm oil), Diesel, Gasoline	N/A	N/A	Thailand	WTT,TTW	LCA, Eco Scarcity method	100 MJ Fuel
(Forte et al., 2017)	E10, E85 (lignocellulosic Fiber sorghum (FS))	car	SimaPro, Ecoinvent	Italy	WTG, WTW	LCA	1 kg of harvested dry FS biomass
(Morales et al., 2017)	Bioethanol (Eucalyptus globulus)	car	Aspen Plus, SimaPro	Chile	WTW	LCA	1 VKT
(Esteves et al., 2016)	Biodiesel (Soybean)	N/A	IPCC, SimaPro, QuantumGIS	Brazil	WTG	LCA	1 hectare
(Hooftman et al., 2016)	Electricity, Petrol, Diesel	car	COPERT, PEMS, GIIR, EcoInvent	Belgian	WTT, TTW	LCA	1 VKT

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Table 1 (*continued*).

Ref.	Fuel	vehicle type	Software/Database/Method	Geographical scope	LCA range	LCA type/ Auxiliary tools	Functional unit
(Portugal-Pereira et al., 2016)	Biodiesel (Jatropha)	car	SimaPro, EcoInvent	India	WTT, TTW	LCA	1 MJ Fuel
(Harris et al., 2016)	Biodiesel (sunflower)	N/A	EcoInvent	United States	WTG	LCA	biodiesel production per unit area
(Zucaro et al., 2016)	E10,E85 (perennial Arundo donax L)	car	SimaPro	Italy	WTW	LCA	1 VKT
(Daylan and Ciliz, 2016)	E10, E85 (lignocellulosic)	car	GaBi	Turkey	WTW	LCA	1 VKT
(Ercan and Tatari, 2015)	LNG, CNG, B20, B100, Electricity, Hybrid, Diesel	bus	AFLEET, GREET, MOVES	United States	WTT, TTW	hybrid-LCA, EIO-LCA, Monte Carlo	Total lifetime (12 years with 37,000 miles per year)
(Ashnani et al., 2015)	CNG, Biodiesel, Electricity, Hydrogen, Petrol, Diesel	N/A	N/A	N/A	WTW	streamlined LCA	1 VKT
(Ahmadi and Kjeang, 2015)	Hydrogen (electrolysis), Hydrogen (TWS), Hydrogen (SMR), Gasoline	car	Delucchi	Canadian provinces	WTW	LCA	1 VKT
(Ribau et al., 2014)	Electricity, Hydrogen, Diesel	bus	ADVISOR, PortoDC	Portugal	WTT, TTW	LCA	1 MJ Fuel, 1 VKT
(Messagie et al., 2014)	LPG, CNG, Biodiesel, Bioethanol, Electricity, Hybrid, Hydrogen, Petrol, Diesel	car	SUBAT project, IMPRO-car project, Ecoscore	Europe	WTT, TTW	range-based LCA, Monte Carlo	1 VKT
(Tessum et al., 2014)	CNG, Bioethanol (Corn), Bioethanol (Stover), Electricity, Hybrid, Diesel, Gasoline	car	GREET	United States	WTW	spatially and temporally explicit life cycle inventory model	388 billion miles per year
(Eshton et al., 2013)	Biodiesel (Jatropha)	N/A	EcoInvent	Tanzania	WTT, TTW	LCA	1 tonne (t) Fuel
(Spinelli et al., 2013)	Biodiesel	N/A	EcoInvent, SimaPro, Ecoindicator	Siena, Italy	WTG	LCA, Monte Carlo, MFA, EEA and EA	1 kg Fuel
(Nanaki and Koroneos, 2012)	Biodiesel, Diesel, Gasoline	car	SimaPro	Greek	WTW	LCA	100 VKT
(Bonin and Lal, 2012)	Bioethanol	N/A	N/A	United States	N/A	LCA	per hectare per year
(Varanda et al., 2011)	Biodiesel	N/A	Aspen Plus, EcoInvent, UNIQUAC, IMPACT 2002	N/A	WTG	LCA	N/A
(Hao et al., 2010)	GTL	bus	Tsinghua-CA3EM	Beijing	WTT, TTW	LCA	100 VKT
(Arteconi et al., 2010)	LNG, Diesel	truck	PE International GmbH, GaBi	Europe	WTT, TTW	LCA	1 VKT
(Morais et al., 2010)	Biodiesel	N/A	ASPEN Plus, EcoInvent	Europe	WTG	LCA	1000 kg Fuel

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Table 1 (*continued*).

Ref.	Fuel	vehicle type	Software/Database/Method	Geographical scope	LCA range	LCA type/ Auxiliary tools	Functional unit
(Scacchi et al., 2010)	Bioethanol (Wheat Grain) blends: E0, E5, E10, E85, E100, Gasoline	N/A	SimaPro, EcoInvent	Lombardia of Italy	WTT, TTW	LCA	1 VKT
(Torchio and Santarelli, 2010)	CNG, Biodiesel, Bioethanol, Electricity, Hydrogen, Diesel, Gasoline	car	NEDC	Europe	WTT, TTW	LCA	1 MJ Fuel, 1 VKT

In terms of analytical tools, while the LCA method is predominantly used, some studies integrate LCA with other tools to meet specific research requirements, such as the Monte Carlo analysis when undertaking uncertainty conclusions (Bicer and Dincer, 2017). Most of the research covers the WTW range, with the selection of the FU typically corresponding to the focus of each stage's comparison.

However, it is crucial to scrutinize the stages considered within these studies. Although many claim to account for the complete WTW or WTT range, certain stages are either overlooked or not calculated. This observation is further elaborated in Table 2, which is based on the system boundary highlighted in Fig. 6, underscoring the necessity of a comprehensive approach that considers all stages in future research. Table 1 presents several noteworthy studies that have ventured into areas where established research, as discussed above, has been lacking. These studies diverge from the articles mentioned in the introduction, taking innovative strides in exploring the potential of alternative fuels.

Boero et al. (2023), for instance, ventured into understanding the feasibility of utilizing ammonia as an AF. Their findings revealed that compared to their gasoline-powered equivalents, ICEVs running on ammonia yielded significant reductions in indicators related to global warming potential, acidification, and eutrophication. The decarbonization of the transportation sector is intrinsically tied to the deployment of alternative fuels. In this context, ammonia emerges as a valuable addition to the repertoire of potential fuels, given its compatibility with traditional vehicles. This not only enriches the diversity of fuel options but also promotes industry diversification (Boero et al., 2023).

In a separate study, Seol et al. (2022) incorporated real-world vehicle NOx emission data from South Korea to conduct a life cycle analysis on six base fuels. This approach represents a crucial step towards a more comprehensive understanding of vehicle emissions under real-world conditions. However, despite its strengths, the study faced certain limitations, including a lack of sample data for gasoline vehicles. This shortfall underlines the importance of comprehensive data collection across all vehicle types for a more robust analysis (Seol et al., 2022). Research by Puricelli et al. (2022) examined the environmental impacts of new alternative fuels. Their findings highlight a critical trade-off: while these fuels substantially reduce greenhouse gas emissions compared to traditional fossil fuels, they also result in greater impacts on particulate matter, acidification, and eutrophication, etc. This underscores the importance of a holistic environmental impact assessment when considering alternative fuels. The fuels scrutinized in their study primarily consisted of biofuels or their mixtures (Puricelli et al., 2022).

These studies collectively suggest that while alternative fuels offer promising avenues for reducing greenhouse gas emissions, their adoption is not without challenges. A balanced and comprehensive assessment of their environmental impact, taking into consideration aspects beyond carbon emissions, is essential. Moreover, the studies underscore the value of real-world data in enhancing the accuracy and reliability of such assessments.

Table 2

Stages considered following the definition of the comprehensive system boundaries.

Ref.	Fuel cycle							Battery/Gas Tank/Fuel cell cycle		Vehicle cycle		Infrastructure phase
	WTT					TTW		Production and use	EOF	Vehicle manufacture	Vehicle EOF	
	WTG				GTT							
	Farming	RM extraction/ Pre-treatment	RM TSD	Fuel production	Fuel TSD	Fuel combustion in vehicle	Vehicle maintenance & repair					
(Boero et al., 2023)		√		√	√	√	√			√	√	
(Jasper et al., 2022)		√	√	√	√	√	√					
(Aboushaqrah et al., 2022)		√	√	√	√	√	√	√		√		
(Cihat Onat, 2022)		√	√	√	√	√	√	√	√	√	√	
(Cai et al., 2022)	√	√	√	√	√	√				√	√	
(Aydin and Dincer, 2022)		√	√	√	√	√		√		√		√

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Table 2 (*continued*).

Ref.	Fuel cycle							Battery/Gas Tank/Fuel cell cycle		Vehicle cycle		Infrastructure phase
	WTT					TTW		Production and use	EOF	Vehicle manufacture	Vehicle EOF	
	WTG				GTT							
	Farming	RM extraction/ Pre-treatment	RM TSD	Fuel production	Fuel TSD	Fuel combustion in vehicle	Vehicle maintenance & repair					
(Yeow et al., 2022)		√	√	√	√	√	√	√	√	√	√	
(Medrano-García et al., 2022)		√	√	√								
(Seol et al., 2022)		√	√	√	√	√						
(Puricelli et al., 2022)	√	√	√	√	√	√	√					
(Tayarani and Ramji, 2022)				√	√	√						
(Benavides et al., 2022)		√	√	√	√	√						
(Byun et al., 2022)		√	√	√	√	√				√	√	
(Chen et al., 2022)		√	√	√	√	√	√	√	√	√	√	
(Shinde et al., 2021)	√	√	√	√	√	√						
(Kannangara et al., 2021)		√	√	√	√	√	√	√	√	√	√	√
(Pacheco-López et al., 2021)	√	√	√	√	√	√						
(Feinauer et al., 2021)		√	√	√	√	√						
(Folega et al., 2022)		√	√	√	√	√	√			√		
(Antonini et al., 2021)		√	√	√	√	√						
(Rodríguez-Vallejo et al., 2021)		√	√	√	√	√	√					
(Zhao et al., 2021)		√	√	√	√	√						
(Delpierre et al., 2021)		√	√	√								
(Phuang et al., 2021)	√	√	√	√								
(Bello et al., 2020)		√	√	√	√	√						
(Okeke et al., 2020)	√	√	√	√	√							
(Foteinis et al., 2020)		√	√	√	√							
(Liu et al., 2020)	√	√	√	√	√	√						
(Khan et al., 2019)		√	√	√	√	√				√	√	
(Poulikidou et al., 2019)		√	√	√	√	√						
(Chang et al., 2019)		√	√	√	√	√	√	√		√	√	
(Lyng and Brekke, 2019)		√	√	√	√	√	√			√		
(Rosenfeld et al., 2019)		√	√	√	√	√	√			√	√	
(Fernández-Dacosta et al., 2019)		√	√	√	√	√						
(Winslow et al., 2019)		√	√	√	√	√						
(Ahmadi, 2019)		√	√	√	√	√	√	√		√		
(Chen et al., 2019)			√	√								
(Bicer and Dincer, 2018)		√	√	√	√	√	√	√	√	√	√	
(Sorunmu et al., 2018)		√	√	√	√	√						
(Song et al., 2018)						√						
(Yuan et al., 2018)		√	√	√	√	√						
(Dreier et al., 2018)		√	√	√	√	√						
(Gao et al., 2018)		√	√	√	√	√						
(Hanbury and Vasquez, 2018)		√	√	√	√	√						
(Lerner et al., 2018)		√	√	√	√	√						
(Sharma and Strezov, 2017)		√	√	√	√	√		√				
(Sen et al., 2017)		√	√	√	√	√	√	√		√		√
(Bicer and Dincer, 2017)		√	√	√	√	√	√			√	√	

(*continued on next page*)

Table 2 (*continued*).

Ref.	Fuel cycle							Battery/Gas Tank/Fuel cell cycle		Vehicle cycle		Infrastructure phase
	WTT					TTW		Production and use	EOF	Vehicle manufacture	Vehicle EOF	
	WTG				GTT							
	Farming	RM extraction/ Pre-treatment	RM TSD	Fuel production	Fuel TSD	Fuel combustion in vehicle	Vehicle maintenance & repair					
(Mansour and Haddad, 2017)		√	√	√	√	√						√
(Zhou et al., 2017)	√	√	√	√								
(de Azevedo et al., 2017)		√	√	√								
(Lecksiwilai et al., 2017)		√	√	√	√	√						
(Forte et al., 2017)	√	√	√	√	√	√						
(Morales et al., 2017)	√	√	√	√	√	√						
(Esteves et al., 2016)	√	√	√	√								
(Hooftman et al., 2016)		√	√	√	√	√						
(Portugal-Pereira et al., 2016)	√	√	√	√	√	√						
(Harris et al., 2016)	√	√	√	√								
(Zucaro et al., 2016)	√	√	√	√	√	√						
(Daylan and Ciliz, 2016)		√	√	√	√	√						
(Ercan and Tatari, 2015)		√	√	√	√	√	√	√		√		√
(Ashnani et al., 2015)		√	√	√	√	√	√			√	√	
(Ahmadi and Kjeang, 2015)		√	√	√	√	√				√	√	
(Ribau et al., 2014)		√	√	√	√	√	√			√	√	
(Messagie et al., 2014)		√	√	√	√	√	√			√	√	
(Tessum et al., 2014)				√	√	√						
(Eshton et al., 2013)	√	√	√	√	√	√						
(Spinelli et al., 2013)	√	√	√	√								
(Nanaki and Koroneos, 2012)	√	√	√	√		√						
(Bonin and Lal, 2012)	√	√	√	√	√	√						
(Varanda et al., 2011)				√								
(Hao et al., 2010)		√	√	√	√	√						
(Arteconi et al., 2010)		√	√	√	√	√						
(Morais et al., 2010)		√	√	√								
(Scacchi et al., 2010)	√	√	√	√	√	√						
(Torchio and Santarelli, 2010)		√	√	√	√	√						

In Table 2, most of the papers do a good job of considering the phases that need to be considered for each fuel. However, the cultivation process for biomass fuel, the maintenance issues involved in the use phase of the fuel, and the cycle of battery recycling, car scrapping, fuel tank and infrastructure are missing in different papers.

Tayarani and Ramji (2022), on the other hand, concentrated on the life cycle impact of hydrogen as an alternative fuel transport process. Their research unveiled that within the United States, pipeline transportation exhibited the lowest carbon intensity. However, they also identified a significant hindrance to the sustainable use of hydrogen fuel cell vehicles. The manufacture of on-board hydrogen tanks was found to entail high energy consumption, which poses a challenge to the sustainable implementation of these vehicles (Tayarani and Ramji, 2022).

In an insightful study, Zhao et al. (2021) conducted a comprehensive life cycle analysis of biodiesel production from waste cooking oil (WCO) within a Chinese context. What sets this study apart is its use of data sourced directly from operational WCO biodiesel plants, which lends extensive data support to the entire supply chain, from the collection of WCO to its conversion into biodiesel. This approach underscores the importance of considering all life cycle phases in research, as supported by robust datasets, to ensure a holistic understanding of the subject at hand. The findings from this study suggest that biodiesel derived from WCO can contribute to a reduction in energy consumption. However, it also brings to light the significant challenges hindering large-scale implementation, namely, the high life-cycle cost and low

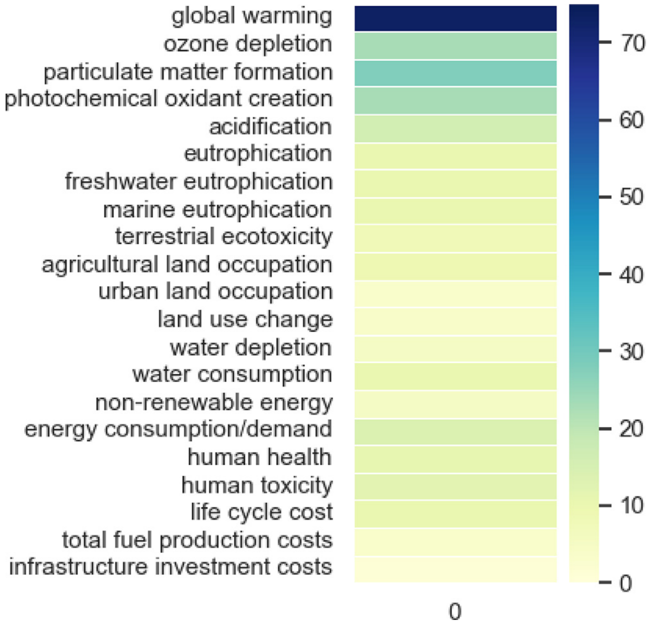

Fig. 7. Heat map for selected impacts: numbers of considered impacts in reviewed papers.

energy conversion rate. These results emphasize that while alternative fuels present promising opportunities for energy sustainability, their economic and efficiency barriers must be addressed to facilitate widespread adoption (Zhao et al., 2021).

In another research effort, Delpierre et al. (2021) introduced a novel hybrid approach in the field of hydrogen production from wind power. This approach combines ex ante LCA, a quantitative tool, with GMA (Global Multidisciplinary Assessment) scenarios, a qualitative tool. The researchers argued that the application of LCA should ideally be supplemented with scenario tools to provide a more comprehensive evaluation. They highlighted the need for in-depth calculations concerning aspects such as water consumption and precious metal consumption during the electrolysis process. This study exemplifies the importance of integrating various analytical tools to address complex environmental and resource implications of alternative energy production processes (Delpierre et al., 2021). During the review process, some papers stated that there was a lack of relevant information. For example, in Cihat Onat (2022), vehicles in Qatar are highly dependent on imports. After the vehicle is scrapped in Qatar, they are directly treated as garbage, and there is no reliable data on recycling. Another part of the papers fails to take these stages and issues into account. At the same time, we also hope to count and discuss various impact indicators. A total of more than 65 impacts were obtained through preliminary statistics, and 51 important indicators were selected through further screening, including environmental impacts, economic impacts, and human health impacts etc. However, due to the excessive content of the table, displaying it in the main text is not conducive to clearly showing the conclusion, so please refer to Appendix in the appendix.

A heatmap, shown as Fig. 7, was created using selected impact indicators related to the research, primarily including those that are more widely considered and those that should be taken into account. Impacts not selected were infrequently considered in the reviewed papers.

The review and organization of literature pertaining to impact indicators yield several salient points. Firstly, a unanimous emphasis on greenhouse gas (GHG) emissions is visible across all papers, underlining the universal recognition of their environmental impact. Secondly, a significant number of papers address not only energy consumption, but also additional environmental and human health impacts, thereby broadening the scope of their investigations.

Conversely, the incorporation of economic indicators is relatively sparse, suggesting an area that potentially warrants further exploration. Moreover, the justification for the selection of specific indicators is largely absent in the majority of papers. Most studies tend to adhere to general standards for calculation without providing a rationale for their indicator selection.

A subset of these studies selects indicators based on their display value or solely for calculation and data presentation purposes. However, only a small fraction of papers venture beyond this to elucidate the impact categories and underlying reasons for concern, thereby providing effective and comprehensive evaluations. This lack of clarity in the rationale for indicator selection suggests a need for greater transparency and explanation in future research.

4.2. Traditional fuels

4.2.1. Diesel

Compared to gasoline and other potential AFs, diesel exhibits the highest GHG emissions during the TTW phase (Sharma and Strezov, 2017). Pollutant emissions (such as CO emissions) from diesel vehicles can be managed by vehicle emission control systems (Mansour and Haddad, 2017). Moreover, utilizing low-sulfur fuel and prohibiting vehicle modifications can help reduce such pollutant emissions (Mansour and Haddad, 2017).

4.2.2. Gasoline

Regarding the emission of toxic substances (Sharma and Strezov, 2017), the gasoline production stage significantly impacts soil quality. According to Zhou et al. (2017), the shale-to-liquids (STL) production process can generate more jobs when crude oil prices are high (assumed to be $100 per barrel) due to the low process life cycle cost of shale oil for manufacturing gasoline and diesel. However, the energy usage and emissions associated with the current STL process life cycle are unsatisfactory. Developing new, high-efficiency, and low-emission retorting technologies is especially promising for countries with substantial shale oil reserves. As the primary research focus of this paper is China, which is rich in coal resources, the author expressed similar expectations and requirements for the coal-to-liquids (CTL) process, which is characterized by high energy consumption and high emissions.

4.3. All fuels type

4.3.1. Liquified Petroleum Gas (LPG)

LPG is generally used for internal combustion engine vehicles. According to a study on the LCA of AFs in Europe, the life cycle emission of LPG is about 0.3 kgCO_2eq/km (Messagie et al., 2014), second to the two petrol technologies. The study also discussed the effects of respiratory effect, acidification and depletion of mineral resources. Since LPG comes from fossil energy, its contribution to the depletion of mineral resources is high, and the respiratory effect and acidification index are at the average level (Messagie et al., 2014) (the highest score of respiratory effect in the study comes from E85, and the highest score of acidification comes from B100).

LPG is also included in the study of AFs in another paper (Mansour and Haddad, 2017). Based on LCA of energy use impact, environmental impact and cost–benefit analysis, LPG has a low price in infrastructure investment. Although it is inferior to traditional gasoline in energy consumption, it can save about 7% (Mansour and Haddad, 2017) of GHG emissions (compared with gasoline). In the short term, the deployment of corresponding AFs has made a certain contribution to the emission reduction target. Chang et al. (2019) studied the carbon footprint of AFs used in Taiwan's bus system. Among them, LPG bus has a carbon footprint of 47.4 gCO_2eq/km (Chang et al., 2019), second to LNG bus and traditional diesel bus. The hot spot of carbon emissions of LPG buses lies in the transportation service stage, accounting for 71.30% (Chang et al., 2019) of the total carbon footprint. Since the carbon footprint of LPG buses is lower than that of traditional diesel buses, the author also estimated that the annual emission reduction potential of a bus can reach 11 tons of CO_2eq after all buses in Tainan are replaced with LPG buses.

4.3.2. Liquified Natural Gas (LNG)

Liquefied natural gas (LNG) is an AF derived from the liquefaction of natural gas. Due to its considerably higher energy density compared to compressed natural gas (CNG), LNG is deemed more suitable for heavy vehicles (Arteconi et al., 2010). In Chang et al.'s (2019) study, the carbon footprint of an LNG bus is 63.14 gCO2eq/km, representing the highest emission. According to the LCA results, the primary emissions of LNG buses occur during the transportation service stage, accounting for 70.30% (Chang et al., 2019) of the total carbon footprint. Similar to LPG buses, increased fuel consumption and emissions result from low energy efficiency during operation. While the bus life cycle is included in this study, the manufacturing and end-of-life (EOF) phases for the vehicle remain essentially the same since all fuels are utilized in the same bus system. The results may reflect the distinct effects of different fuels throughout their life cycles.

Arteconi et al. (2010) investigated the life cycle emissions of large vehicles powered by diesel and LNG within the European market. The outcomes of two distinct LNG procurement strategies vary, with direct procurement from a regasification terminal (LNG TER) reducing GHG emissions by 10% (Arteconi et al., 2010) compared to diesel. In contrast, locally produced LNG using small-scale plants (LNG SSL) exhibits similar emissions to diesel. Yuan et al.'s (2018) research indicates that, compared to conventional fuels, employing natural gas as an AF for automobiles does not result in net energy savings. However, it can lead to significant reductions in both critical air pollutant and GHG emissions.

4.3.3. Compressed Natural Gas (CNG)

Compressed natural gas (CNG) and other gaseous fuels have garnered increasing global interest as prospective alternative fuels. CNG is used in dual-fuel gasoline engines, blended with diesel fuel, and combined with hydrogen to enhance engine performance and reduce emissions. Natural gas is a particularly promising and attractive fuel in China due to its domestic availability, widespread infrastructure, low cost, and clean combustion properties as a transportation fuel. The literature (Union, 2014) indicates that, within the WTW range, CNG's energy efficiency is lower than that of gasoline and diesel. CNG emits fewer greenhouse gases (GHGs) than gasoline but more than diesel.

CNG can be derived from fossil fuels. According to the literature, the production and pipeline transportation of CNG in the United States contribute approximately 11.5 gCO2eq/MJ, while the corresponding process carbon emissions in Europe are estimated to be around 8.8 gCO2eq/MJ (Cai et al., 2022). The waste-to-energy production approach is considered the most promising solution for reducing GHG emissions in the WTW stage in the United States and the European Union. However, the scarcity of raw materials (RMs) and other factors may limit this method's contribution to the transportation sector's decarbonization.

In a study by Mansour and Haddad (2017), CNG was found to be more cost-effective than liquefied petroleum gas (LPG) for internal combustion engine vehicles (ICEVs) with an annual mileage exceeding 30,000 km. This conclusion was derived from a sensitivity analysis of vehicle annual mileage. Clearly, gas-fueled taxis and service vehicles are well-suited for CNG application. In another study (Winslow et al., 2019), the production of CNG from landfill gas (LFG) was investigated. Winslow et al. (2019) noted that many studies have demonstrated the environmental benefits of producing alternative fuels from waste. Thus, they not only assessed the environmental impact of the life cycle but also examined the process's economic aspects in detail.

Through anaerobic digestion (AD), waste RMs (such as animal waste, municipal solid waste, and sewage sludge) can be converted into renewable natural gas (RNG). The potential for reducing emissions by avoiding counterfactual scenarios (e.g., certain established waste management systems) has been demonstrated (Cai et al., 2022).

4.3.4. Biodiesel

The perfect AF for diesel engines is biodiesel, which is primarily constituted of FAME and is made primarily of vegetable oil or animal fat. Biodiesel has a better cetane rating than petroleum-based diesel, around 10% more intramolecular oxygen, and nearly no aromatics or sulfur. There are many ways to obtain biodiesel. For example, it can be produced from vegetable oil and animal fat. There are also several types of related technologies. Kiwjaroun et al. (2009) compared the environmental impact of producing biodiesel using traditional alkali catalytic processes and supercritical methanol processes. For the supercritical methanol process, its advantages (short reaction time, high biodiesel production) and disadvantages (harsh conditions, complex equipment) are obvious. The process has a greater impact on the environment because it requires a much larger methanol flow rate than traditional processes. The various biodiesel production processes in the US and the EU were studied by Cai et al. (2022). In the US, FAME is typically referred to as biodiesel. Vegetable oils like soybean and rapeseed oil, used cooking oil (UCO or yellow oil), and animal fats like tallow are regarded as biodiesel RMs in the United States. In order to generate biodiesel for LCA in Europe, the author chose rapeseed oil, soybean, UCO, and tallow. The market grade for traditional diesel engines in the United States is petroleum diesel (B20) mixed with 20% biodiesel, while petroleum diesel (B7) mixed with 7% biodiesel is the market grade for the European Union. In the way of converting soybeans into biodiesel, the emissions from the production and transportation of soybeans to the processing plant are about 9 gCO_2eq/MJ and 49 gCO_2eq/MJ (Cai et al., 2022), corresponding to the United States and the European Union respectively. The reason for such a big difference is that the soybeans used by the EU to produce biodiesel are basically imported, so the transportation of RMs will obviously become one of the emission hotspots.

Due to the large amount of by-products in the process of biodiesel production from soybeans, different distribution methods (by-product treatment methods) have a great impact on the carbon emission intensity of the conversion process (or the whole WTT process) and combustion process (Cai et al., 2022).

Rapeseed oil can also be used to produce biodiesel. The GREET results show that the GHG emission intensity of its WTT stage and combustion is 34 gCO_2eq/MJ (Cai et al., 2022) in the United States, and 48 gCO_2eq/MJ (Cai et al., 2022) in Europe. The reason for the discrepancy in the results is the same as for the analysis of soybean-derived biodiesel described above. For vegetable oils such as rapeseed oil, the HVO route has gradually become the focus of attention in Europe and the United States. In addition, inedible tallow, and biomass (through rapid pyrolysis) can also be used as RMs. In Mansour and Haddad (2017), it is found that HEV using B20 is more energy-saving than using E10, because the diesel engine is more efficient. Lyng and Brekke's paper (2019) mentioned that if the RM of biodiesel (such as palm oil) requires too much land use, the corresponding life cycle emissions will also be large. In this study (Lyng and Brekke, 2019), POCP and AP were strongly influenced by the operation of palm oil mills, and the same happened during the production of biodiesel from rapeseed.

In Brazil, a study calculated the life cycle impact of soybean biodiesel considering LUC analysis. The author proposed a reasonable calculation method for GHG emissions caused by LUC. The conclusion indicates that 97.1% (Esteves et al., 2016) of the increase in GHG emissions comes from LUC (based on annual emissions per hectare). Therefore, effective use of land and avoidance of deforestation will also become an important aspect of the sustainability potential of biodiesel. In Prasad's book (2020), a second generation biodiesel production method for Vanua Levu Island was also studied. The RM selected for this process is from Pongamia, a plant that can survive on various types of soil and effectively utilize the land resources on the island. Compared to traditional diesel production, the proposed method has a carbon dioxide emission index that is five times lower (Prasad, 2020). Moreover, the contribution of Pongamia-derived biodiesel to air acidification potential and eutrophication potential is relatively low. It is foreseeable that AF LCA for certain special geographical environments can provide more adaptive emission reduction recommendations.

The research focus of Morais et al. (2010) is on three different production routes for biodiesel, so the scope of the study is WTG. The conventional alkali catalytic process for FFA pretreatment, the acid catalytic process, and the supercritical methanol process using propane as a cosolvent are these three procedures. Depletion of abiotic resources and marine aquatic ecotoxicity are two significant effect categories when examining probable environmental impacts. The outcomes demonstrate that the minimal steam consumption of the supercritical methanol process with propane as a cosolvent makes it the most environmentally friendly of the three routes (Morais et al., 2010).

4.3.5. Biogasoline

Like biodiesel, LCA research often focuses on different technologies for producing biogasoline.

Sorunmu et al. (2018) evaluated a subsequent upgrading technology applied in biomass pyrolysis to bio-oil (in order to obtain deoxidized stable bio-oil), namely electrochemical deoxygenation (EDOx). Three scenarios are compared: (a) small-scale EDOx; (b) Traditional hydrodeoxygenation (HDO); (c) Partial EDOx with HBO combination (due to incomplete deoxidation of EDOx, under existing technology). The main product is biodiesel. Based on the actual situation, the biomass supply logistics in the United States is analyzed. In the section of sensitivity analysis, since electrochemical deoxidation requires electricity, the GHG intensity of nine power grids is compared; The sensitivity of different methods of hydrogen production was also analyzed. The study pointed out the emission reduction potential of EDOx, and suggested that pyrolysis facilities should be set up in areas with insufficient hydrogen supply and relatively clean power grid in the United States.

4.3.6. Biomethane

Biomethane can be obtained through upgrading from biogas (Lyng and Brekke, 2019), the production of anaerobic fermentation. Biomethane can be used for many purposes, such as transportation fuel and heating fuel. Since digestate, another product of AD, is useful as biological fertilizer, some studies also explore the life cycle emissions under different distribution conditions. Lyng and Brekke (2019) carried out LCA of upgraded biogas, that is, biomethane, as an AF for buses. The AFs for comparison include natural gas, electricity, biodiesel, and fossil diesel. Under the fictitious settings, the results indicate that biomethane has the lowest life cycle environmental impact; however this finding also heavily depends on the system boundaries, travel time, and methane leakage assumptions.

As the main component of natural gas is also methane, another study (Khan et al., 2019) on natural gas also pointed out that methane leakage rate should be an important emission hot spot using natural gas as an AF for transportation. It can be said that the leakage rate is an important emission link for both biomethane and methane in natural gas.

4.3.7. Biomethanol

Methanol (CH-3-OH) (Verhelst et al., 2019), one of the AFs for gasoline, is regarded as one of the best fuels for internal combustion engines (IC) because of its high octane number and high molecular oxygen content. Methanol is an ideal AF for transportation (Bicer and Dincer, 2017), with the advantages of high combustion efficiency, low cost, significant reduction of nitrogen oxide emissions, and almost no combustion of solid particles.

4.3.8. Bioethanol

Both ethanol and methanol are regarded to be environmentally acceptable fuels to replace fossil fuels because of their similar physical and chemical characteristics. It can be blended in various ratios with other fuels to enhance engine emissions. According to the different proportion of ethanol mixed with gasoline; the common names of bioethanol mixed fuel in the market are generally E10, E85, etc. (representing 10% and 85% of ethanol respectively).

In Cai et al. (2022), the LCA of bioethanol production using different RMs in the US and the European Union is compared. The selection of this RMs is based on the mainstream production methods in the corresponding markets of the US and the European Union. For the United States, this RMs is: corn, corn stalk and sorghum; For the EU, these RMs are wheat and sugar beet. JEC (used for the European Union) and GREET (used for the United States) are two assessment methodologies for biofuels that make the assumption that the carbon cycle of biochar generated during biomass growth and fuel combustion is carbon neutral. The essay also takes into account various climatic conditions and farming methods. Although maize ethanol produced in the United States and the European Union have similar WTTs and burning carbon intensities (using 1 MJ as FU), the two regions' production processes differ because of different distribution rules for various by-products and assumptions about energy input. In order to further reduce GHG emissions, CCS is also thought to be suitable to maize ethanol fermentation plants.

Due to high fuel consumption per kilometer and various driving cycle assumptions, the United States' emissions per kilometer in the WTW stage—using the medium-sized E10 gasoline ICEV as an example—are greater than those in the European Union (Cai et al., 2022). It is important to note that ethanol made from agricultural residues such as maize straw in the United States and wheat straw in the European Union can dramatically lower emissions by roughly 68% and 79%, respectively, when compared to petroleum gasoline (E10) (SI, ICEV) (Cai et al., 2022). In a study of biofuels in China (Ou et al., 2009), corn ethanol, cassava ethanol, and sweet sorghum derived ethanol were included in the comparison range. The results show that among the three bioethanol fuels, only cassava ethanol exhibits significant energy-saving advantages, and as cassava is not a food RM, it is sustainable in terms of emission reduction. According to de Azevedo et al.'s (2017) a analysis of the life cycle effects of manufacturing bioethanol by CM, which took into account 18 environmental effects, only climate change, human toxicity, particulate matter generation, and the depletion of fossil fuel resources have major effects. The scientists also noted that within the life cycle, energy consumption, drying emissions, sulfuric acid in pretreatment, buffer solution in enzymatic hydrolysis, and sodium phosphate in fermentation are the drivers of environmental effect variations. Several improvement measures can be implemented in response to these factors to lessen the impact of the related emissions.

4.3.9. Dimethyl ether (DME)

The simplest ether molecule, DME fuel has the chemical formula CH-3-OCH-3 (Fleisch et al., 1997). Because to its exceptional self-ignition properties and lack of a carbon–carbon bond compared to other fuels, the use of DME as an AF in diesel engines has drawn the attention of numerous studies. In contrast, DME fuel has a substantially higher cetane rating than regular diesel fuel. DME is supposed as a direct and clean substitute for diesel (Olah et al., 2009). The preparation methods of DME are also different. The earliest industrial method is to recover from the by-product of synthetic methanol. DME can also be produced from synthesis gas or obtained by dehydration of methanol (Asthana et al., 2016).

In the study by Fernández-Dacosta et al. (2019), a LCA of the WTW process of DME produced from CO_2 was carried out, and DME was considered to be an economically worthy alternative to diesel, but it was still affected by the price of CO_2 feedstock and emission taxes. In terms of emissions, DME has a net GWP similar to that of fossil fuels.

4.3.10. Bio butanol

Butanol has been found as an AF with multiple advantages over ethanol, such as its higher energy content, being able to be mixed with gasoline in any proportion, and requiring no engine modifications (Szulczyk, 2010). Some studies have confirmed that butanol mixed with gasoline at a ratio of 30% (Hergueta et al., 2017; Pregger et al., 2020) can effectively reduce emissions of pollutants such as carbon monoxide, hydrocarbons, and nitrogen oxides during vehicle operation. Due to regional resource differences, most LCA studies in the United States (Väisänen et al., 2016) and Brazil (Pereira et al., 2015) use corn or sugarcane as the RM for butanol production, while European studies (Niemisto et al., 2013) focus on LCA for butanol production based on waste and lignocellulose. Although the potential of butanol as an AF is gradually being emphasized, most studies focus more on the production stage or the pure fuel utility stage. Hergueta et al. (2017) evaluated the life cycle impact of butanol gasoline mixtures over the entire WTW range. The RM for butanol production in their study comes from lignocellulose in pine wood.

The research results of Feinauer et al. (2021) show that although the mixture of biological butanol and gasoline is superior to pure gasoline in performance, bio-butanol has a higher lifetime GHG emissions impact than pure gasoline, and is significantly higher in terms of land use, ozone layer depletion, and ionizing radiation. The environmental impact is caused by three factors, namely, the production of electricity, steam, and sawdust from upstream chain. Feinauer et al. (2021) also points out that butanol's emission in the TTW range is less than that of pure gasoline, which should be the research impetus for its potential as an AF.

4.3.11. Electric vehicle

When electricity is used as an AF (the corresponding vehicle is called electric vehicle), due to the high energy consumption and emissions in the battery manufacturing phase (10%–75% of the total energy consumption in the manufacturing process, 10%–70% of the GHG emissions in the manufacturing process), the WTT phase is the hot spot of electric-based vehicles emissions (Sharma and Strezov, 2017). It is precisely because the emission hot spot of electric vehicles exists in the WTT stage, so the cleanliness of the power grid (reflected in some studies as regional sensitivity studies, or for different power grid generation combinations in a single region) is the focus of the research on electricity as an AF (Sharma and Strezov, 2017).

For example, in Cihat Onat (2022), the power generation in Qatar at the time of the publication of the literature was 100% dependent on natural gas, and various motives (including the construction of a large solar photovoltaic power station in Qatar in 2022) led to the LCA of electric vehicles for solar power generation. This paper also introduces the integrated SFS-AHP and CODAS methods (CODAS is a new MCDM method) to assess the environmental, economic and social impacts (also known as triple bottom line). It is worth mentioning that in this paper, because Qatar's vehicles are all imported, domestic supply chain and global supply chain are considered, and MRIO method is used in this part. Due to the lack of detailed life cycle list, although the study considers the WTW analysis, it only carries out quantitative analysis on the impact of the operation phase. The author believes that the dynamic relationship of environmental, economic and social indicators should be further considered in the future.

According to Cai et al. (2022)'s research on the decarbonization potential of European and American transport sectors,at present, the emission intensity of the US grid is higher than that of the European grid, and the BEV of the US is larger. Therefore, for the use of BEV, the GHG emissions of the US in the WTW phase are about twice that of Europe (considering similar products). When the power grid gradually transits to a clean power grid, without considering the impact of batteries, the BEV emissions will be close to zero. However, it is clear that battery is the emission hotspot of BEV's life cycle. In the United States, 29% (Cai et al., 2022) of GHG emissions in the cradle to grave of BEV come from automobile manufacturing (including battery manufacturing). Electric buses are also a type of interesting scenario where electricity is used as an AF. Song et al. (2018) calculated the life cycle emissions of diesel buses and electric buses based on real urban bus test data in Macao. The emissions of electric buses based on the pre-publication power mix exceed those of traditional diesel buses (taking into account charging and distribution losses). Further, the author believes that the growing number of electric buses in Macao can have the potential to significantly reduce carbon emissions by cleaning the power mix, testing and selecting the best charging and discharging efficiency, and appropriate comprehensive traffic management.

Using electricity as an AF, it is inevitable to discuss the production and manufacture of electric vehicles and batteries. Compared with traditional vehicles, electric vehicles need less steel because they do not need internal combustion engines. The production process of electric power and battery has certain negative impact on the environment, taking into account human toxicity, stratospheric ozone depletion and GHG emissions (Bicer and Dincer, 2017).

Different battery types have different processes from production and manufacturing to scrap and recycling, and the purpose of recycling is also different. Generally, the purpose of recycling is to recycle valuable materials and comply with ecological laws (Bicer and Dincer, 2017). Some researchers have studied different recovery methods. Mechanical, pyrometallurgical and hydrometallurgical processes are the main three types of recovery technologies. Hydrometallurgy requires much less energy than pyrometallurgy.

It is worth mentioning that in different studies, the assumptions and comparisons of battery cycle are different, and the conclusions about the advantages and disadvantages of different batteries or technologies are also varied (Shafique et al., 2023a,b). With the gradual and extensive application of batteries and electricity in the transportation sector, Kannangara et al. (2021) points out that a comprehensive evaluation of multiple types of batteries should be carried out. At the same time, the author believes that in addition to the comparative analysis of the different emission intensity of the power grid, the impact of the life-cycle mileage, battery replacement and battery size of electric vehicles should also be included in the LCA. The relevant sensitivity analysis results show that the BEV will reduce its GHG emission reduction capacity in the case of high EI power grid or using larger batteries.

4.3.12. Hydrogen

Hydrogen may be created from any energy source, making it a sustainable energy carrier. Hydrogen can subsidize and extend the supply of fuel for automobiles and may offer long-term choices based on renewable resources. In addition, it can be employed as a medium for intermittent renewable energy storage (such as solar energy and wind energy). Due to its high fuel cycle efficiency, FCV can reduce energy usage by about 20% when compared to CV, according to a study by Ashnani et al. (2015).

The method of hydrogen production has a significant impact on the energy requirements and emissions of hydrogen fuel cell vehicles during their entire life cycle (Simons and Bauer, 2015). Just 4% (Osman et al., 2020) of hydrogen is currently produced by electrolysis, and the majority of the RMs for commercial hydrogen production are still fossil fuels. For the transportation industry to implement hydrogen decarbonization, the promotion of clean hydrogen generating techniques is essential.

Hydrogen production through NG SMR is a common way to obtain hydrogen. Further, carbon capture technology can be applied in this process to obtain greater emission reduction potential, but at the same time, energy efficiency will be reduced. The literature points out that the GHG emissions of the US in this process are slightly lower than those of the European Union, which is due to the relatively long transportation distance of the relevant natural gas RM sources in Europe. Besides, the energy efficiency of hydrogen production in the US and the European Union is 71.9% and 76% respectively (Cai et al., 2022). It has been pointed out in the literatures (Baral et al., 2021; Yeow et al., 2022) that even if hydrogen based on fossil production (such as steam methane reforming) is applied to fuel cell trucks, the GHG emissions of WTW are still lower than that of conventional diesel. However, it is worth mentioning that since the compression and liquefaction of hydrogen involves the use of electricity, the carbon intensity of the electricity production process will affect the carbon emission intensity of the hydrogen cycle.

Bicer and Dincer (2017) conducted a LCA of hydrogen produced by underground coal gasification (UCG) as an AF. UCG is considered as a clean way of coal utilization. The results in another paper show that the GWP value of conventional hydrogen production is 7.9 $kgCO_2eq/kg\ H_2$, which is 6.8, 1.9, 2.1, 0.5, and 0.2 $kgCO_2eq/kg\ H_2$ for PV electrolysis, wind electrolysis, high temperature electrolysis, dark fermentation, photo fermentation, conventional hydrogen, respectively. The global warming potentials of the WTW phase using this hydrogen as AFs are 0.060, 0.016, 0.018, 0.007, 0.006 and 0.053 $kgCO_2eq/km$ (Same as the corresponding order above). By comparison, the global warming potentials of CNG buses and diesel buses are 0.082 and 0.125 $kgCO_2eq/km$ respectively (Aydin and Dincer, 2022). This study also shows that the high ecotoxicological indicators (land, sea, fresh water) in various processes of hydrogen production are caused by chemicals used in the manufacturing process of photovoltaic panels and wind turbines.

Dark fermentation is a hydrogen production technology that does not require light sources. It uses facultative and specialized anaerobic bacteria to ferment the substrate. Some studies have pointed out that it can be applied to wastewater with high organic load, such as municipal waste, food waste, etc., because the use of commercial substrates will increase costs (Aydin and Dincer, 2022). In addition, the neutral scale application of this technology has been studied (Balachandar et al., 2020).

Photo fermentation is a technology that converts biomass into hydrogen through photosynthetic bacteria. Light fermentation bacteria grow slowly, so the efficiency of hydrogen production is lower than dark fermentation. The effluent (mainly organic acid) from the dark fermentation process can be used as the substrate of the light fermentation process. Therefore, some papers (Meky et al., 2021; Zhang et al., 2020) have studied the combination of these two technologies. The experiment shows that this new technology has suppressed some risks in the fermentation process, and has improved the hydrogen production efficiency and other indicators.

Hydrogen production from electrolytic water is a potentially sustainable and clean method for hydrogen production. Since the RM comes from water and the product of hydrogen combustion is also water, this technology is considered sustainable. However, in the process of electrolysis, whether the power grid combination is clean is the factor that determines whether the water decomposition is clean. At present, the most mature electrolysis technology is the alkaline electrolysis process using alkaline electrolyte (Abuşoğlu et al., 2017). And such emerging technologies as polymer electrolyte membrane (PEM) electrolysis have also received more and more attention (Aydin and Dincer, 2022; Hu et al., 2022). The PEM process uses pure water instead of alkaline electrolyte. Hydrogen can be used in fuel cell electric bus (FCEB). Downstream emissions from this application are considered zero. In Aydin and Dincer (2022), the fuel consumption of FCEB is assumed to be 0.15 kg H_2/km. In addition, in this paper, the author did not consider the impact of parameters such as stop, traffic and slope on fuel consumption. The energy efficiency of electrolytic hydrogen production is basically the same in the United States (67%) and the European Union (65%) (Cai et al., 2022).

In the short term, due to cost reasons, gasoline and diesel hybrid vehicles (Mansour and Haddad, 2017) are more suitable for developing countries like Lebanon that rely on fuel imports. In a study (Ribau et al., 2014) of FC-HEV and FC-PHEV, it was shown that higher capacity batteries can reduce fuel consumption, but their costs will increase. The purpose of the study is to apply multi-objective optimization algorithms to determine appropriate powertrain solutions to balance the conflict between fuel cell vehicle costs and fuel consumption.

In addition to traditional and currently popular hydrogen production methods, a study from Poland showed that hydrogen in coke oven gas can be separated by the PSA process to obtain a hydrogen product with a purity of 99.999% (Folęga et al., 2022). The path of hydrogen synthesis from coke oven gas (with CCS) has lowered GHG emissions by 30.71% and 54.88% (Folęga et al., 2022) in comparison to conventional processes like steam methane reforming and coal gasification. Folęga et al. (2022) also mentioned that hydrogen fuel cell technology itself is no longer a bottleneck for hydrogen as an AF. The real difficulties come from the low availability of hydrogen refueling stations and the harsh conditions required to install hydrogen tanks in vehicles in Poland.

4.3.13. Ammonia

Ammonia, like hydrogen, is a potential fuel source for ICEVs. However, each has its own set of advantages and disadvantages. Ammonia boasts a higher density than hydrogen, making it easier to compress and store. However, it also has drawbacks such as being corrosive and toxic. Additionally, the combustion of ammonia releases nitrous oxide and contributes to greenhouse gas emissions. Although ammonia is used in the transportation industry, its consumption is much lower than that of hydrogen, and its application is still in the early stages. Therefore, it will not be discussed in detail in the previous chapter, and this section will only cover the latest research related to it.

Boero et al. performed a life cycle analysis of ICEVs fueled with ammonia, considering nine different configurations (operating modes and emission control strategies). On average, the GWP100 emissions of ICEVs are 0.098 $kgCO_2eq$/km, although this value is not the level of fuel life cycle emissions (Boero et al., 2023).

5. Discussion

The level of global GHG emissions continues to rise, and the need to decarbonize the transport sector is receiving increasing attention. Carbon emissions in the transportation sector mainly come from the life cycle of vehicles, fuels and infrastructure.

Regarding that the goal is to make a certain contribution to mitigating global warming and improving the sustainable performance of fuel through such research, the expected research should be complete, accurate (including sensitivity analysis), and practical (as much as possible), possibly combined with local resource information and instructional implications.

To structure our discussion, we have divided it into two aspects: “research gap and implication” and “future research directions”. Our goal is to provide valuable information that can help stakeholders (including researchers and policy-makers, etc.) reduce emissions in the transportation sector by addressing their concerns.

5.1. Research gap and implications

There are several points for improving theory- and policy-oriented research in the future:

(1) Complete Life Cycle Analysis and Life Cycle Inventory is important. Insufficient consideration of stages within the framework of the system leads to incomplete life cycle inventory analysis. For different RMs, production processes, and fuel products, some studies have not considered all aspects comprehensively. For instance, almost half of the studies on biomass fuels neglect farming, while more advanced AFs such as hydrogen often overlook the corresponding infrastructure and the life cycle of storage and transportation tanks.

(2) Underestimation of Life Cycle Impacts should attract more attentions. The number of life cycle impacts is frequently underestimated. Most studies focus on GHG emissions and energy consumption, which is insufficient even when other

environmental impacts are considered. In addition, research on economic impacts beyond environmental impacts remains limited. For a region or a country, the development of sustainable transportation technology involves different impacts that various stakeholders pay attention to over different timeframes. Comprehensively considering potential development routes will be crucial to future life cycle impact analysis of AFs.

(3) Inconsistencies in FUs selection pose challenges for fair comparison. Although most studies have reached a consensus on selecting FUs, inconsistencies still persist. Most studies choose 1MJ Fuel in the WTT stage, 1 VKT or 1 VMT in the WTW stage, and a small number of studies on a single product or technology select the quality of fuel as FU. For fuels with negative carbon emissions, the selection of FUs remains open to debate and may lead to counterintuitive results.

(4) Transparency of allocation procedure should be noticeable. The allocation procedure should be as transparent as possible. It is recommended to follow international standards where data conditions permit, avoiding allocations and expanding system boundaries to account for the benefits of by-product processing. Inaccessibility and insufficiency of data in some countries and regions hinder research in this area.

(5) Data and calculation still have limitations. Even when system boundaries and stages are adequately considered, the calculation of corresponding stage impacts may be abandoned due to lack of data or low local technical level. Some studies provide detailed explanations for uncalculated parts, while others focus on specific life cycle impact stages. Authentic, reliable, and detailed data are crucial for future detailed analyses across various regions, vehicles, fuels, and production methods.

(6) Comprehensiveness and fairness in stage and impact consideration are necessary. It is challenging to comprehensively and fairly consider stages and impacts due to uneven technological development of various AFs and varying stakeholder focuses. Balancing the weight of each impact category at each stage is difficult (Ekener et al., 2018).

(7) Complex real-world situations need to be properly discussed. Real complex situations are hard to predict, as software or database calculations are idealized and may not accurately reflect actual conditions. Case analyses based on real situations are still time-consuming and labor-intensive. When stages and impacts are fully considered, quantifying the gap between existing technologies and scenarios to replace traditional fuels and technologies requires careful weighting among the main pillars, such as environment, economy, and society.

5.2. Directions for future research

If future research on AF LCA wants to serve the progress of theory or policy, a fair and transparent research framework, data sources and distribution methods are the primary basis. In addition to the key content that can be improved discussed in the previous section, there are three directions that can further promote the development of this field in the future.

(1) Including more powertrain and road situation in AF LCA:

  (a) Fuel Consumption: The choice of powertrain and road situation affects the fuel consumption of the vehicle, which in turn impacts the overall environmental impact of the fuel. For example, a vehicle with a more efficient powertrain, such as an electric or hybrid vehicle, will consume less fuel per unit of distance traveled compared to a traditional gasoline or diesel vehicle. This means that alternative fuels that are used in more efficient powertrains will have a lower overall environmental impact than those used in less efficient powertrains (Antonini et al., 2021).

  (b) Energy Efficiency: The energy efficiency of a vehicle is also affected by the powertrain and road situation. For example, an electric vehicle is more energy-efficient than a traditional gasoline or diesel vehicle because it converts a higher percentage of the energy stored in the battery to power the wheels. Similarly, driving on a highway at a constant speed is more energy-efficient than driving in stop-and-go traffic in a city. This means that alternative fuels used in more energy-efficient vehicles and driving situations will have a lower overall environmental impact than those used in less energy-efficient vehicles and driving situations. In the Global Conference on Energy Efficiency of this year, IEA also emphasize the importance of improving energy efficiency for 2050 zero-emission goals (IEA, 2023).

(2) Quantifying gaps in contributors to emissions hotspots during AF LCA:

  (a) Conducting sensitivity analysis on the LCA results helps identify the most significant contributors to emissions hotspots. This allows stakeholders to focus on improving those areas to reduce the overall environmental impact of the alternative fuel. By quantifying the gaps in contributors to emissions hotspots, we can identify the areas where improvements will have the greatest impact (Khan et al., 2019).

  (b) Quantifying the gaps in contributors to emissions hotspots also increases accountability for stakeholders in the alternative fuel supply chain. By identifying the areas where emissions are most significant, stakeholders can work together to reduce those emissions and ensure that the alternative fuel is produced and used in a sustainable manner (Lecksiwilai et al., 2017).

(3) Integrating other methods/technologies into AF LCA:

   (a) There are several methods that can be combined with LCA to enhance its effectiveness and accuracy. These methods include Multi-Criteria Decision Analysis (MCDA) (Cai et al., 2017; Dias et al., 2022; Domingues et al., 2015; Haase et al., 2022), machine learning (Ahmadi et al., 2022), and others. While these combined methods are still in the early stages of exploration, they hold great potential for improving the future LCA of alternative fuels in the transport sector.
   (b) By integrating these methods into LCA, we can make more informed decisions about the use of alternative fuels in the transport sector. However, further research is needed to fully understand the potential of these methods and to ensure that they are used appropriately and effectively in LCA.

6. Conclusions

Life cycle assessment (LCA) is a tool of global recognition and credibility due to its adherence to international standards. This makes it particularly useful for assessing alternative fuels (AFs) in the transportation sector. The LCA methodology can take various forms such as life cycle impact assessment (LCIA), economic input–output LCA (EIO-LCA), and process-LCA, each tailored to specific purposes and requirements. Furthermore, LCA can be synergistically used with other tools and methods like the Monte Carlo algorithm, providing an enhanced understanding of the subject matter.

This paper provides a comprehensive review of the research conducted over the past decades on the themes of AF LCA. Through a rigorous screening process, we distill the key findings and insights from mainstream AF life cycle analyses. These insights span various dimensions including the emission reduction capabilities of AFs, identification of emission hotspots, and other environmental, social, and economic pros and cons associated with AFs. Moreover, we delve into critical definitions within the LCA framework such as functional units (FUs) and system boundaries, and subsequently propose an optimal evaluation framework. This framework is based on the LCA of AFs for diverse transport systems and aims to tackle challenges presented by raw materials, production modes, regional differences, and powertrain technologies.

Yet, there is a noticeable lack of research focusing on public transport and developing countries. Given that public transport systems can significantly diminish private car travel demand, they represent a promising avenue for future AF research. Similarly, developing countries, constrained by technology and raw material availability, could benefit from identifying and addressing development bottlenecks via AF LCA. Existing research, while adept at addressing specific concerns, is often limited by data scarcity, instability, and inadequate consideration of various stages. Consequently, future research should focus on acquiring reliable and valid data, establishing comprehensive LCA frameworks for different AFs, and conducting extensive discussions and analyses of emission hotspots and other impacts. Furthermore, regions with potential for AF development should be given greater attention. Lastly, future research could explore quantifying emission hotspot contributors, integrating new methods, and considering the implications of energy powertrain and road conditions.

CRediT authorship contribution statement

Fangjie Liu: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. **Muhammad Shafique:** Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization, Validation, Writing – review & editing, Supervision. **Xiaowei Luo:** Conceptualization, Methodology, Resource, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix

See Table A.1.

Table A.1

Impact considered.

Ref. Impact Category	(Sharma and Strezov, 2017)	(Khan et al., 2019)	(Shinde et al., 2021)	(Ercan and Tatari, 2015)	(Poulikidou et al., 2019)	(Peshin et al., 2020)	(Hao et al., 2010)	(Bicer and Dincer, 2018)	(Nanaki and Koroneos, 2012)	(Chang et al., 2019)	(Jasper et al., 2022)	(Aboushaqrah et al., 2022)	(Elagouz et al., 2021)	(Sen et al., 2017)	(Sorunmu et al., 2018)	(Cihat Onat, 2022)	(Cai et al., 2022)	(Bicer and Dincer, 2017)	(Aydin and Dincer, 2022)	(Kannangara et al., 2021)	(Yeow et al., 2022)	(Pacheco-López et al., 2021)	(Mansour and Haddad, 2017)	(Lyng and Brekke, 2019)	(Rosenfeld et al., 2019)	(Zhou et al., 2017)
Global warming	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Ozone depletion								√										√	√			√		√		
Ionizing radiation																						√				
Particulate matter formation	√			√					√			√		√		√			√			√	√			
Photochemical oxidant creation	√		√									√				√			√			√		√		
Acidification			√					√	√		√													√		
Terrestrial acidification																						√				
Tropospheric acidification																			√							
Air acidification																										
Freshwater acidification																										
Eutrophication			√					√	√															√		
Aquatic eutrophication																										
Freshwater eutrophication	√																					√				
Marine eutrophication	√																					√				
Terrestrial eutrophication																										
Human toxicity: cancer									√													√				
Human toxicity: non-cancer																						√				
ecotoxicity									√		√															
Terrestrial ecotoxicity								√											√			√				
Aquatic ecotoxicity																										
Freshwater ecotoxicity potential	√																		√			√				
Marine ecotoxicity potential	√																		√			√				
Agricultural land occupation	√											√				√						√				
Urban land occupation	√																									
Land use change																										
Water consumption	√											√				√						√				
Mineral resource scarcity																						√				
Fossil resource scarcity	√								√																	
Energy resource depletion																										
Water withdrawal				√								√				√										

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Table A.1 (*continued*).

Ref. Impact Category	(Sharma and Strezov, 2017)	(Khan et al., 2019)	(Shinde et al., 2021)	(Ercan and Tatari, 2015)	(Poulikidou et al., 2019)	(Peshin et al., 2020)	(Hao et al., 2010)	(Bicer and Dincer, 2018)	(Nanaki and Koroneos, 2012)	(Chang et al., 2019)	(Jasper et al., 2022)	(Aboushaqrah et al., 2022)	(Elagouz et al., 2021)	(Sen et al., 2017)	(Sorunmu et al., 2018)	(Cihat Onat, 2022)	(Cai et al., 2022)	(Bicer and Dincer, 2017)	(Aydin and Dincer, 2022)	(Kannangara et al., 2021)	(Yeow et al., 2022)	(Pacheco-López et al., 2021)	(Mansour and Haddad, 2017)	(Lyng and Brekke, 2019)	(Rosenfeld et al., 2019)	(Zhou et al., 2017)
Non-renewable energy																										
Energy consumption/demand		√		√	√		√		√			√				√							√		√	√
Abiotic resources depletion								√																		
Human health	√							√				√	√			√						√				
Human toxicity								√			√							√								
Employment												√				√										√
Sustainability index																										
Life cycle cost	√										√		√	√		√										
Capital cost	√										√															
Operating costs	√																									
Total fuel production costs											√															
Emission costs																										
Maintenance cost																										
Infrastructure investment costs																							√			
DALY																										
Powertrain cost																										
Net energy																										
Net present cost of fuel																										
Economic cost-benefit																							√			
GDP																√										
Air pollution externalities														√												

Ref. Impact Category	(Ashnani et al., 2015)	(Fernández-Dacosta et al., 2019)	(Esteves et al., 2016)	(Prasad, 2020)	(Arteconi et al., 2010)	(Song et al., 2018)	(Hooftman et al., 2016)	(Ribau et al., 2014)	(Ahmadi and Kjeang, 2015)	(Yuan et al., 2018)	(Eshton et al., 2013)	(Feinauer et al., 2021)	(Messagie et al., 2014)	(Folęga et al., 2022)	(Morais et al., 2010)	(Portugal-Pereira et al., 2016)	(Tessum et al., 2014)	(Winslow et al., 2019)	(Medrano-García et al. 2022)	(de Azevedo et al., 2017)	(Scacchi et al., 2010)	(Antonini et al., 2021)	(Spinelli et al., 2013)	(Varanda et al., 2011)	(Ahmadi, 2019)	(Dreier et al., 2018)
Global warming	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Ozone depletion												√			√					√				√		
Ionizing radiation												√								√						
Particulate matter formation	√					√			√	√		√	√			√	√	√		√				√	√	
Photochemical oxidant creation							√					√								√		√		√		
Acidification				√																						
Terrestrial acidification												√				√				√				√		
Tropospheric acidification																										
Air acidification															√											
Freshwater acidification												√			√											
Eutrophication				√																						
Aquatic eutrophication															√					√						
Freshwater eutrophication												√														
Marine eutrophication												√														

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Table A.1 (*continued*).

Ref. Impact Category	(Ashnani et al., 2015)	(Fernández-Dacosta et al., 2019)	(Esteves et al., 2016)	(Prasad, 2020)	(Arteconi et al., 2010)	(Song et al., 2018)	(Hooftman et al., 2016)	(Ribau et al., 2014)	(Ahmadi and Kjeang, 2015)	(Yuan et al., 2018)	(Eshton et al., 2013)	(Feinauer et al., 2021)	(Messagie et al., 2014)	(Folega et al., 2022)	(Morais et al., 2010)	(Portugal-Pereira et al., 2016)	(Tessum et al., 2014)	(Winslow et al., 2019)	(Medrano-García et al. 2022)	(de Azevedo et al., 2017)	(Scacchi et al., 2010)	(Antonini et al., 2021)	(Spinelli et al., 2013)	(Varanda et al., 2011)	(Ahmadi, 2019)	(Dreier et al., 2018)
Terrestrial eutrophication												√			√											
Human toxicity: cancer												√														
Human toxicity: non-cancer												√														
ecotoxicity																										
Terrestrial ecotoxicity															√					√				√		
Aquatic ecotoxicity															√					√		√		√		
Freshwater ecotoxicity potential												√														
Marine ecotoxicity potential																										
Agricultural land occupation												√								√		√		√		
Urban land occupation																				√						
Land use change			√																							
Water consumption												√								√						
Mineral resource scarcity												√								√				√		
Fossil resource scarcity						√						√								√						
Energy resource depletion	√												√													
Water withdrawal																										
Non-renewable energy		√														√						√	√	√		
Energy consumption/demand																					√	√				√
Abiotic resources depletion															√											
Human health																						√	√			
Human toxicity							√								√					√				√		
Employment																										
Sustainability index									√																	
Life cycle cost																									√	
Capital cost																										
Operating costs																										
Total fuel production costs		√							√																	
Emission costs																									√	
Maintenance cost																									√	
Infrastructure investment costs																										
DALY							√												√							
Powertrain cost								√																		

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Table A.1 (*continued*).

Ref. Impact Category	(Ashnani et al., 2015)	(Fernández-Dacosta et al., 2019)	(Esteves et al., 2016)	(Prasad, 2020)	(Arteconi et al., 2010)	(Song et al., 2018)	(Hooftman et al., 2016)	(Ribau et al., 2014)	(Ahmadi and Kjeang, 2015)	(Yuan et al., 2018)	(Eshton et al., 2013)	(Feinauer et al., 2021)	(Messagie et al., 2014)	(Folega et al., 2022)	(Morais et al., 2010)	(Portugal-Pereira et al., 2016)	(Tessum et al., 2014)	(Winslow et al., 2019)	(Medrano-García et al. 2022)	(de Azevedo et al., 2017)	(Scacchi et al., 2010)	(Antonini et al., 2021)	(Spinelli et al., 2013)	(Varanda et al., 2011)	(Ahmadi, 2019)	(Dreier et al., 2018)
Net energy											√															
Net present cost of fuel																		√								
Economic cost-benefit																										
GDP																										
Air pollution externalities																										

Ref. Impact Category	(Boero et al., 2023)	(Puricelli et al., 2022)	(Tayarani and Ramji, 2022)	(Benavides et al., 2022)	(Byun et al., 2022)	(Chen et al., 2022)	(Rodríguez-Vallejo et al., 2021)	(Zhao et al., 2021)	(Delpierre et al., 2021)	(Phuang et al., 2021)	(Bello et al., 2020)	(Okeke et al., 2020)	(Foteinis et al., 2020)	(Liu et al., 2020)	(Chen et al., 2019)	(Gao et al., 2018)	(Hanbury and Vasquez, 2018)	(Lerner et al., 2018)	(Lecksiwilai et al., 2017)	(Forte et al., 2017)	(Morales et al., 2017)	(Harris et al., 2016)	(Zucaro et al., 2016)	(Daylan and Ciliz, 2016)
Global warming	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Ozone depletion	√							√	√	√	√	√	√	√	√					√	√	√	√	√
Ionizing radiation								√		√			√											
Particulate matter formation		√						√				√	√							√		√	√	
Photochemical oxidant creation	√	√						√	√		√		√		√					√	√		√	√
Acidification		√				√			√	√		√		√	√		√					√	√	√
Terrestrial acidification	√										√		√							√	√			
Tropospheric acidification																								
Air acidification																								
Freshwater acidification																								
Eutrophication	√									√		√		√	√							√		
Aquatic eutrophication																								
Freshwater eutrophication	√	√									√		√							√	√		√	
Marine eutrophication		√							√		√		√							√	√		√	
Terrestrial eutrophication		√							√															√
ecotoxicity										√		√					√					√		
Terrestrial ecotoxicity													√								√			
Aquatic ecotoxicity																								
Freshwater ecotoxicity potential		√									√		√								√			
Marine ecotoxicity potential											√		√								√			
Agricultural land occupation													√											
Urban land occupation													√											
Land use change		√							√		√													
water depletion									√				√						√		√		√	
Water consumption		√		√							√						√							
Mineral resource scarcity		√					√	√	√	√			√											
Fossil resource scarcity	√			√			√	√	√	√	√	√	√	√			√			√	√	√	√	

(continued on next page)

Table A.1 (*continued*).

Ref. Impact Category	(Boero et al., 2023)	(Puricelli et al., 2022)	(Tayarani and Ramji, 2022)	(Benavides et al., 2022)	(Byun et al., 2022)	(Chen et al., 2022)	(Rodríguez-Vallejo et al., 2021)	(Zhao et al., 2021)	(Delpierre et al., 2021)	(Phuang et al., 2021)	(Bello et al., 2020)	(Okeke et al., 2020)	(Foteinis et al., 2020)	(Liu et al., 2020)	(Chen et al., 2019)	(Gao et al., 2018)	(Hanbury and Vasquez, 2018)	(Lerner et al., 2018)	(Lecksiwilai et al., 2017)	(Forte et al., 2017)	(Morales et al., 2017)	(Harris et al., 2016)	(Zucaro et al., 2016)	(Daylan and Ciliz, 2016)
Energy resource depletion		√					√		√	√									√					
Water withdrawal																								
Non-renewable energy																								
Energy consumption/demand																√								
Abiotic resources depletion						√									√									
Human health		√					√			√							√							
Human toxicity								√			√		√	√							√			
Human toxicity: cancer										√		√										√		
Human toxicity: non-cancer		√										√										√		
Employment																								
Sustainability index																								
Life cycle cost				√				√								√		√						√
Capital cost																								
Operating costs							√																	
Total fuel production costs																								
Emission costs																								
Maintenance cost																								
Infrastructure investment costs																								
DALY																								
Powertrain cost																								
Net energy																								
Net present cost of fuel																								
Economic cost-benefit																								
GDP																								
Air pollution externalities																								

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