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Review

A systematic review on sustainability assessment of internal combustion engines

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ABSTRACT

Internal combustion engines (ICEs) have served as the primary powertrain for mobile sources since the 1890s and also recognized as significant contributors to CO_2 emissions in the transportation sector. In order to achieve "carbon neutrality" for transportation sectors, ICE vehicles (ICEVs) are facing substantial challenges in meeting CO_2 regulations and intense competition from battery electric vehicles and fuel cell vehicles. Consequently, new technologies of ICEs are continually emerging to enhance competitiveness in reducing environmental impacts. However, the limited studies on the life cycle assessment (LCA) of ICEs make it difficult to evaluate the actual contributions of the emerging technologies from a life cycle perspective. Conducting a systematic review of ICEs LCA studies could identify weaknesses and gaps in these studies for new scenarios. Therefore, this article presents the first systematic review of the LCA of ICEs to provide an overview of the current state of knowledge. A total of 87 life cycle assessment studies between 2017 and 2023 using the Scopus database were identified after searching for the keywords "Sustainability assessment" OR "Life cycle assessment" AND "Internal combustion engine*" OR "ICE*" and carefully screening, and then classified and analyzed by six aspects including sustainability indicators, life cycle phases, life cycle inventories, ICE technologies (including alternative fuels), types of mobile sources and powertrain systems. It is concluded that there are quite limited studies solely focusing on LCA of ICEs, and the LCA assessment lacks consideration of: 1. environmental pollution, human health and socio-economic aspects, 2. fuel production process and maintenance & repair phase, 3. small and developing countries, 4. the emerging ICE technologies and zero carbon/carbon-neutral fuels, 5. large and high-power mobile sources and heavy-duty hybrid technologies.

1. Introduction

1.1. Internal combustion engines and the brief introduction of current Statas

Internal combustion engines (ICEs) have been the dominant powertrain for mobile sources since the 1890s due to their high power density, high efficiency, high reliability, and cost-effectiveness. The energy conversion inside ICEs involves the combustion of fossil fuels, leading to the direct release of pollutants and carbon dioxide. Therefore, since 1960s ICE emission regulations have been developed to control the pollutants of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) in major ICE markets, and continued getting tightened until recent years (Winkler et al., 2018). In 2017, 29 countries signed the 'Declaration of the Carbon Neutrality Coalition' at the 'One Planet summit', highlighting the increasing importance of achieving "carbon neutrality" across various sectors (Zhongming et al., 2018). Additionally, many other countries have also implemented measures to control their carbon emissions in recent years. ICEs, primarily powered by fossil fuels currently, have been recognized as significant contributors to CO_2 emissions in the transportation industry. In recent years, regulations have been implemented to restrict CO_2 emissions from ICEs in key markets for ICE (Joshi, 2020). Consequently, ICE vehicles (ICEVs) face substantial challenges in meeting CO_2 regulations and competition from battery electric vehicles (BEVs) and fuel cell vehicles (FCVs).

If solely considering the operating phase (i.e., tank-to-wheel (TTW)), it is evident that ICE vehicles generate much higher carbon emissions

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and environmental pollution compared to BEVs and FCVs. However, including the well-to-tank (WTT) and cradle-to-grave (CTG) processes, it is not immediately clear which of the three have the most significant environmental impacts (Kalghatgi, 2018). Meanwhile, new technologies are continually emerging to enhance ICE's competitiveness in reducing environmental impacts (Fig. 1).

1. The implementation of advanced ICE combustion technologies (He et al., 2021; Novella et al., 2023). The advanced ICE technologies improve the peak effective thermal efficiency (Yang, 2020). Taking Nissan's gasoline engine technology roadmap as an example (Shiraishi and Tsurushima, 2022), the peak gasoline engine efficiency could reach 50% with the application of advanced technologies, the basic thermal efficiency being improved by lengthening the stroke and reducing friction, while further thermal efficiency improvement coming from turbocharging (Uchida, 2006), lean combustion (Dally et al., 2004), waste heat recovery (Valencia et al., 2021), and other new advanced technologies (Fig. 1a). Therefore, it is reasonable to believe that despite the reduction in research and development, ICEs may have efficiency above 50% in mostly conventional configurations, and possibly exceed 60% in novel configurations (Boretti et al., 2011).
2. The substitution of fossil fuels by zero-carbon or carbon-neutral fuels, i.e., hydrogen (Candelaresi et al., 2021), ammonia (Boero et al., 2023), biodiesel (Perčić et al., 2020), bioethanol (Byun et al., 2021), synthetic methanol, synthetic gasoline, and synthetic diesel (Alonso-Villar et al., 2022). As synthetic technology advances, the life cycle CO_2 emissions of the above fuels are expected to be significantly lower than those of fossil gasoline and diesel (Zang et al., 2021) (Fig. 1b). Besides, because the development of energy storage is much more troublesome than the production of irregular electricity by wind and solar, the green hydrogen, as an essential component of a grid renewable energy, may have soon much reduced economic and environmental costs only (Boretti, 2021). Currently, combustion technologies for these alternative fuels are being developed, with some already partially or completely replacing fossil fuels (Qiao et al., 2017). 3. The implementation of hybrid technology. The most common configuration of hybrid technology at present is the powertrain combining ICEs with electric motors. Hybrid technology enables ICEs to operate within the high-efficiency conditions for most of operation time, thereby improving the overall energy conversion efficiency and reducing CO_2 emissions (Xue et al., 2023). In the opinion of the Southwest Research Institute (news: Conference report: SAE WCX 2020 Digital Summit (dieselnet.com)), the market share of conventional ICE-only vehicles will keep decreasing due to the powertrain electrification, but most of the decreased market share will be occupied by hybrid electric vehicles (HEVs) and plug-in electric hybrid vehicles (PHEVs) having an ICE rather than BEVs before 2050 (Fig. 1c). Based on the data of miles per gallon equivalent (MPGe) combined city/hwy provided by the U.S. Environmental Protection Agency (EPA), PHEVs have lower energy consumption than battery electric vehicles thanks to the reduced vehicle weight (Boretti, 2022). Moreover, the efficiency advantage of PHEVs could have been larger if on-board electricity production by a small high efficiency ICE could have been permitted (Boretti, 2019).

1.2. Life cycle assessment studies of internal combustion engines

The life cycle assessment (LCA) method (also known as "sustainability assessment method") serves as a common analysis procedure and decision-making tool for reducing energy consumption and environmental impact throughout a product's entire life cycle (Bergerson et al., 2020). Under the background of carbon neutrality, many studies have been conducted in recent years to examine the potential environmental advantages of BEV or FEV compared to ICEVs using LCA (Onat and Kucukvar, 2022). Verma et al., 2022) reviewed the LCA studies of BEVs in comparison to ICEVs, and concluded that the life cycle GHG emissions level is lower for BEVs. Korol et al. (Burchart-Korol et al., 2018) and Pero et al. (Del Pero et al., 2018) discovered ICEVs would have produced around 60% higher CO_2 emissions compared to BEVs. Bicer et al. (Bicer and Dincer, 2018) announced that compared to BEVs, diesel and gasoline ICEVs could have 44% and 69% higher CO_2 emissions. In these comparison studies, the LCA of ICEs were usually analyzed as the baseline for comparison, and the current advances in ICE technology or alternative fuels were merely mentioned or considered in their LCA models.

Conducting a LCA directly on ICEs or ICEVs can offer more direct insights and serve as a valuable reference for policies and technology roadmaps of ICEs. Liu et al. (Liu and Tang, 2011) conducted a LCA study on diesel engines in light-duty trucks. In the study, the key pollutants and the environmental impacts of four engines were compared, and new configurations and technical improvement suggestions were proposed to reduce pollutant emissions. Li et al. (2013) quantified the energy consumption and environmental emissions in the entire life cycle of a diesel engine, and found the operation phase in the ICE life cycle consumes the most energy, while the indicator of primary energy demand is closely related to the production of the diesel fuel and, the indicators of global warming potential, acidification potential, nutrient enrichment potential are closely related to the engine operation. Saibuatrong et al. (Saibuatrong and Mungcharoen, 2012) applied the Tsinghua-CA3EM model to analyze GHG emissions from vehicles running with various alternative fuel engines. The results indicated that using alternative fuel ICEs can reduce carbon emissions compared to conventional ones. Biofuels, particularly bioethanol derived from molasses, demonstrated the most substantial reductions in CO_2 emissions and energy consumption.

1.3. Motivation

From above, it is evident that the high-efficiency combustion technology, low-carbon/zero-carbon fuel technology, and hybrid technology are consistently decreasing the carbon emissions over the whole life cycle of ICEVs, hence improving the competitiveness of ICEVs in comparison to BEVs and FCVs. Recently, numerous LCA analyses have been carried out to demonstrate the benefits of new powertrain systems over ICEs in terms of the life cycle carbon emissions, with ICEs typically used as a benchmark for comparison (Onat and Kucukvar, 2022), which cannot offer direct insights on environmental impacts of ICEs themselves with LCA methodology. Such phenomena raise certain concerns: How many previous LCA studies have been specifically conducted for ICEs? Have the previous studies effectively taken into account the recent development trend, technological advances and research findings of ICEs in the analysis of the life cycle environmental impact, and what are the research knowledge gaps accordingly? Within the scope of the author's knowledge, review studies on this subject are lacking. The objective of this study is to conduct a systematic review of the LCA studies of ICEs with the following aims.

1) To systematically review LCA studies on ICEs conducted worldwide inrecent years, providing a comprehensive overview of the studies.
2) To classify the reviewed studies based on sustainability indicators, life cycle phase, life cycle inventories, ICE technologies, fuel types, and mobile source and powertrain types, and identify the strength and weakness regarding each indicator.
3) To offer valuable guidance for researchers and LCA practitioners by identifying the knowledge gaps in previous studies considering the recent advances and research findings in ICEs.

In summary, ICEs are facing increasing challenges in meeting CO2 regulations and strong competitions from BEVs and FCVs, new technologies of ICEs are continually emerging to enhance the competitiveness in reducing environmental impacts. However, the limited studies on the LCA of ICEs make it difficult to evaluate the actual contributions

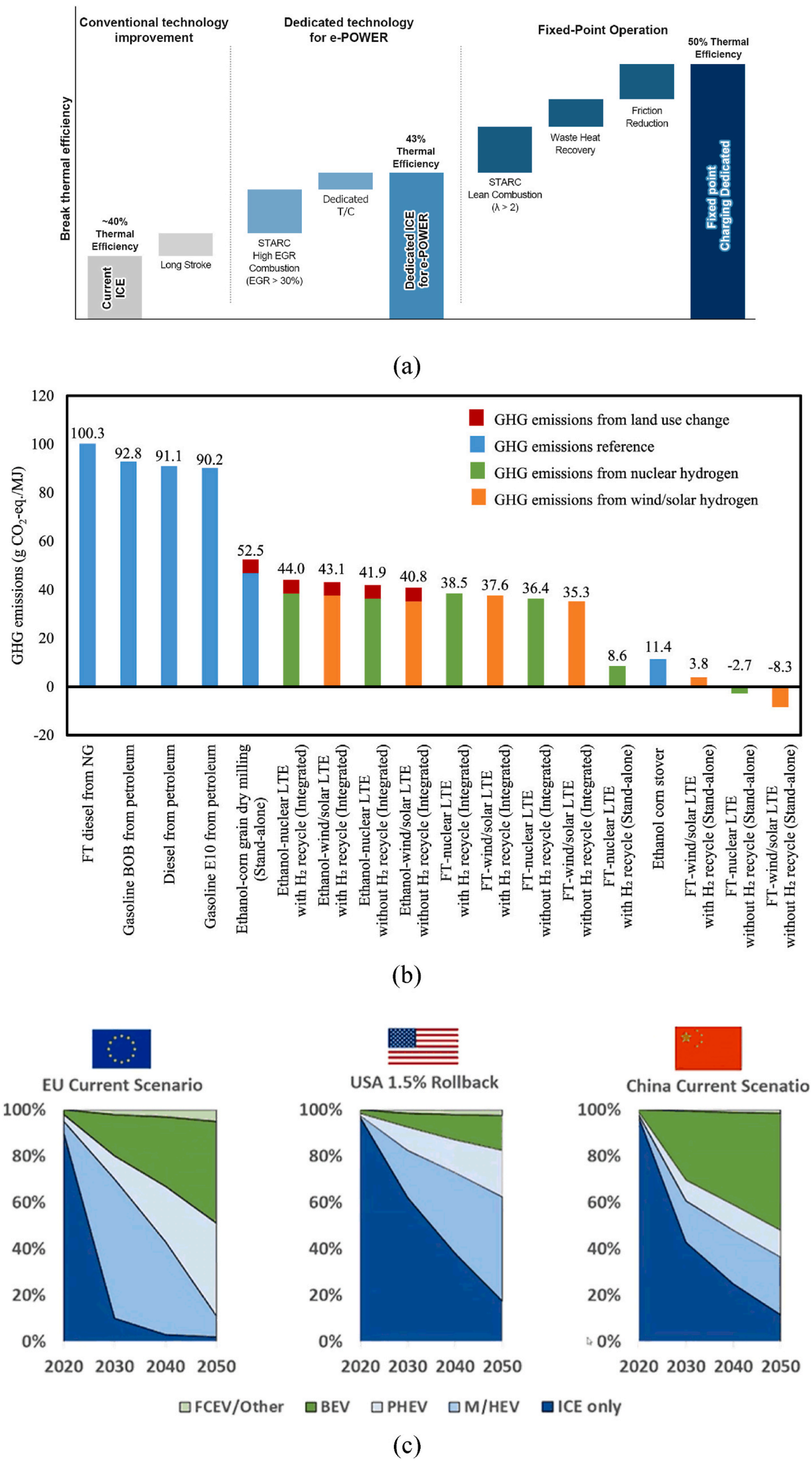

Fig. 1. The development trend of ICE in different aspects:
a) engine efficiency improvement with advanced ICE combustion technologies, b) green house gas emissions of different fuels, c) vehicle market shares of different powertrain configurations in future. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of the emerging technologies from a view of life cycle. There is a lack of comprehensive review articles that provide an overview of the current state of knowledge and an in-depth analysis of the weaknesses and gaps. Accordingly, the main objective of this review is to present the first systematic review in study of the LCA of ICEs. In the first step, the methodology is presented with a brief description of review process and explanation of the article classification aspects. Following that, the results of the reviewed studies are then illustrated and discussed, and finally, prospects for future studies are defined.

2. Literature review process and methodology

The review process consisted of 4 stages to ensure a comprehensive assessment. In Stage 1, the scope of the review was defined, and objectives were established. Questions and motivations were identified, and a database search strategy was developed, including keywords and screening criteria.

In Stage 2, to locate the most pertinent research the article collection was performed through a 3-Step procedure following the systematic search technique developed by Hamidinasab et al. (2023) emphasizing appropriate searching term, trustworthy database, and appropriate criteria of inclusion and exclusion. In Step 1, the Scopus database was utilized for the literature search using the keywords "Sustainability assessment" OR "Life cycle assessment" AND "Internal combustion engine*" OR "ICE*". The search was conducted in the title, abstract, or keywords fields, covering the period from 2017 to 2023, executed on June 20, 2023. The initial search yielded a total of 288 articles, encompassing various types of publications such as original research articles, conference proceedings, review articles, and book chapters. The list of these articles is provided in Table S1 of the excel file “Annex SI1”. In Step 2, the titles of the articles were reviewed to exclude those clearly unrelated to the topic, e.g., studies on "LCA of building construction", "Energy Storage", etc. This screening step resulted in 181 articles, which were listed in Table S2 of the excel file “Annex SI1”. In Step 3, the type and abstract of each article were examined to further refine the selection. Review articles, book chapters, and articles solely concentrating on the LCA of BEV or FEV, as well as those only focusing on engine or vehicle manufacturing, or fuel production were excluded. This process led to the identification of 87 journal articles, which were listed in Table S3 of the excel file “Annex SI1”.

Stage 3 involved a comprehensive review of the screened articles by thoroughly reading their contents. Important aspects were identified and marked for each article, and the articles were subsequently grouped into six categories for analysis purposes, and information was detailed in Table S4 and Table S5 of the excel file “Annex SI2”. The classification output was then analyzed in this manuscript. The articles were classified based on the following aspects.

2.1. Sustainability indicator selection

This classification enables the analysis of whether the study incorporates specific indicator categories representing the environment, society, or economy. Society, ecology, economy and their related indicators are three important aspects of sustainability (Nabavi-Pelesaraei et al., 2021a,b), which are being addressed by various ICE and vehicle related techniques and methods. It facilitates an examination of the extent to which sustainability indicators are emphasized and analyzed in the literature.

2.2. Life cycle phases

This classification is used to evaluate the various stages that a product or system goes through over its entire life span, from raw material extraction to disposal or recycling. (Nabavi-Pelesaraei et al., 2021b; Nabavi-Pelesaraei and Damgaard, 2023). Regarding the research objective of this article, these phases encompass production, operation, maintenance and repair, end-of-life (disposal, recycling, etc.) and energy resource extraction or carrier production of ICEs and ICEVs. For a proper comparison of LCA between the two technologies, it is important to keep the analysis within the same scope (phases). Ideally, a comprehensive and reliable results can be attained through the analysis of all the phases mentioned above. However, due to factors such as the different research objectives, the data accessibility, and the significance of individual phases, some phases may be excluded from the research. Driven by innovations in ICE technologies, policies, and regulations, the impact weights of certain phases may gradually increase, and neglecting the analysis of these phases could become inappropriate.

2.3. Life cycle inventories

Life Cycle Inventories refer to the compilation and quantification of all inputs and outputs associated with a product, process, or system over its entire life cycle (Maklavany et al., 2023). The accuracy of the data provided in the inventory is of significance to ensuring the reliability of LCA results. By statistically examining the origins of data inventories, an overview of the most frequently used data sources or models in ICE LCA studies can be obtained. The overview can assist in comprehensively examining various aspects and features of the life cycle inventory construction, thereby identifying the potential improvement aspects.

2.4. ICE technologies

This classification allows for an overview of the ICE technologies considered in ICE LCA studies. Such analysis aims to examine whether the current LCA studies are alignment with the latest technological advances in ICEs, especially those related to reducing carbon emission and pollution. This is crucial as only by considering the state-of-the-art and potential ICE technologies in the LCA of ICEs can valuable insights be provided for the selection of future technological pathways. The analysis of the alternative ICE fuels in the studies was also conducted individually due to the potential of alternative fuels to fundamentally address carbon emissions from ICEs compared to other engine evolutions.

2.5. Application sectors and powertrain configurations

This classification enables to provide an overview of the ICE application sectors and powertrain configurations in ICE LCA studies. The classification of the type of application sectors is based on the type of mobile sources including sedan, SUV, truck, etc. The power, fuel efficiency, and environmental impacts of ICEs applied to different sectors can vary significantly. With the development of powertrain electrification, the sectors where ICEs are mostly employed are changing gradually. Such classification helps identify whether the current research focuses align with the application scenario of ICEs. The powertrain configurations are classified as ICE-only, hybrid, and plug-in hybrid. Powertrain configurations are classified given the fact that hybrid technology helps ICEs operate in high-efficiency regions.

In Stage 4, the findings from the classification were presented using appropriate expressions, accompanied by an analysis of whether the research status is consistent with the ICE development directions. Additional articles were cited to support the proposed viewpoints. In the end, a final discussion of the results, and the conclusion emphasized the research gaps and recommendations were provided. The literature review process is summarized in Fig. 2. It is important to note that this review has one main limitations: this study is limited to internal combustion engines and does not include other types of thermal engines such as gas turbines, Stirling engines, and so on.

3. Results and discussions

Fig. 3 displays the overall number of ICE LCA studies from 2017 to 2023, and statistics have been made between articles that specifically

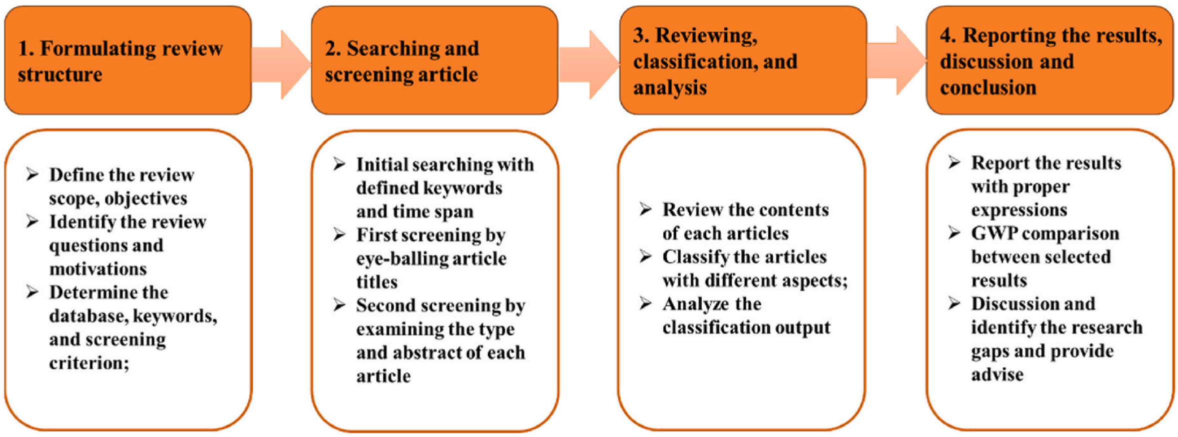

Fig. 2. Literature review process.

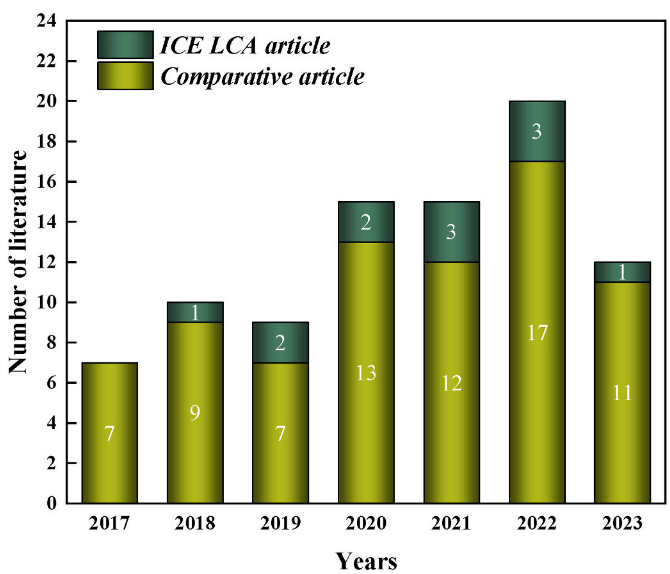

Fig. 3. Number of LCA articles in different years.

focus on LCA of ICEs/ICEVs (named as "ICE LCA article") and articles that involve a comparison between ICEVs, BEVs or FCVs (named as "Comparative article"). Ithas been shown that despite a continuous increase in the number of articles dedicated to ICE LCA research, in most of the studies the LCA of ICEs were usually analyzed as the baseline for comparison. The number of studies focusing solely on the effects of ICE technology advances on the LCA results remains extremely limited.

3.1. Analysis of indicators selection

The section investigated indicators that focusing on environmental and socio-economic implications. The percentages of studies classified by the environmental indicators are shown on the left part in Fig. 4. The majority of studies (89.77%) primarily focused on global warming potential (GWP) as an environmental impact indicator. Other indicators examined in the literature are all lower than 25%, with respiratory effects and surplus ore potential occupying only 1% of the reviewed studies. The majority of studies only examines the environmental impacts, while only a limited number of studies involve the socio-economic impacts. The percentages of studies considering socio-economic impacts are presented on the right part in Fig. 4. The studies involving Life Cycle Cost (LCC), human health and employment only accounts for 10.23%, 10.23% and 1.14% of the reviewed articles, respectively. While ICEs play a crucial role as energy power devices, their environmental indicators are of paramount importance, but their socio-economic impacts should also be emphasized. Merely comparing the impacts of environmental indicators often leads to biased conclusions suggesting that ICEs have inferior impacts. In fact, the extensive use of ICEs provides numerous employment opportunities, and as one of the most mature powertrain devices, they are also more affordable. In terms of socio-economic impacts, the advantages of ICEs are quite evident.

The ICE exhaust emissions include various toxic substances, such as

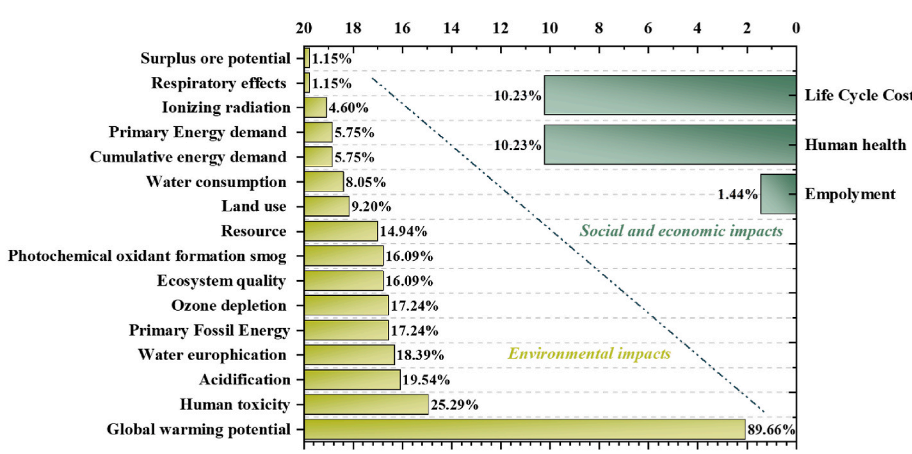

Fig. 4. Percentages of studies categorized by sustainability indicator.

NOx, PM, CO, and volatile organic compounds (VOCs). The impact of these emissions on environmental pollution, and human health is not negligible. Emissions of NOx from ICEs can lead to the formation of acid rain (Chuvashev and Chuprakov, 2019), and the resulting soil degradation, water contamination, etc (Singh and Agrawal, 2007). For human health, inhalation of these substances can lead to respiratory tract and lung damage, resulting in health issues like respiratory inflammation, asthma, and chronic obstructive pulmonary disease (Heberle et al., 2018). Therefore, research and analyzing indicators connected to environmental pollution and human health hold significant importance, and they can provide vital insights for the formulation of emission regulations and the selection of technology pathways for clean combustion and exhaust aftertreatment.

LCC encompasses all expenses associated with a product, project, or system throughout its entire life cycle, thereby facilitating sustainable and cost-effective decision-making. Compared to BEVs and FCVs, one significant advantage of ICEVs lies in the low cost of manufacturing. Gary et al. (Gray et al., 2022) evaluated that the manufacturing costs of electric trucks and fuel cell trucks will remain approximately 2–3 times higher than those of conventional ICE trucks from 2025 to 2040. Moreover, even for a LCC study of ICEs themselves, the adoption of different new technologies and alternative fuels can lead to significant differences in manufacturing and usage costs. Schemme et al. (2020) compared the price of various alternative fuels under the scenarios involving large-scale promotion of green hydrogen and carbon taxation policies. The results show that hydrogen, methanol, and dimethyl ether have relatively lower prices, while butanol and polyoxymethylene dimethyl ether may cost approximately 2–3 times as much as hydrogen.

3.2. Analysis of life cycle phases

Ideally, LCA studies examine the manufacturing, operation, maintenance and repair, end-of-life phases, and the energy resource extraction or carrier production. The manufacturing phase is the production procedure of ICE/ICEV components, starting from raw material extraction to the delivery of ICEs/ICEVs to the end-user. The operation phase is ICE/ICEV operation, involving fuel consumption, power generation, and tailpipe emissions production. The maintenance and repair phase encompass activities contributing to ensuring the reliability and in-use compliance to the regulations of the ICEs/ICEVs. The end-of-life phase involves the disposal and recycling processes of ICEs/ICEVs when they reach the end of their useful life. For ICEs, the energy resource extraction or carrier production is to obtain primary energy resource and converting it into useable fuels. In Fig. 5, the percentage of studies by life cycle phase is presented. Among the life cycle phases, the manufacturing phase was the most studied (94.3%). The operation phase is the second largest life cycle phase considered (88.5%). Energy resource extraction or carrier production and maintenance and repair phase exhibits much lower proportion, accounting for 51.7 %, and 37.9%, respectively.

The process of extracting energy resources, carrier production or the fuel production process could significantly influence the carbon emission results of ICE LCA studies. Novella et al. (2023) obtained GWP results ranging from 0.35 to 0.36 kg CO_2eq/km for conventional gasoline and diesel fuel, based on existing technology status. When e-fuel and green ammonia fuel were utilized, the full life cycle CO_2 emissions of the ICE significantly decreased to 0.066 CO_2eq/km and 0.133 CO_2eq/km, respectively (Elmagdoub et al., 2023; Novella et al., 2023). As the use of zero-carbon or net-zero carbon fuels increases in the future, energy resource extraction or carrier production cannot be neglected in analyzing the environmental impact of ICEs.

For traditional ICEs, it is justifiable to disregard the impact of the maintenance and repair phase, as conventional ICEs exhibit high reliability and typically do not require frequent maintenance or repair. The primary expenses arise from low-price items such as lubricating oil and coolant. In the study by Kosai et al. (2022), it was estimated that the carbon emissions during the maintenance and repair phase of ICEVs accounted for less than 2%, significantly lower than the approximately 15% for BEVs. However, it should be noted that for the methanol ICEs already in use in recent years, as well as for ammonia and hydrogen ICEs that may gradually replace conventional ICEs in the future, the maintenance costs are expected to significantly increase due to the high corrosiveness and poor lubrication properties of the fuels and the resulting of the replacement of high-price fuel injection system (Kumar and Agarwal, 2020). Another factor that could potentially increase the future ICE maintenance impact is the emission control requirement. The proposal of Euro 7 regulations has emphasized the implementation of On-Board Monitoring to record real-time data of various pollutant emissions and exam the compliance throughout the vehicle entire life cycle. Given the efficiency degradation of aftertreatment devices, i.e. selective catalytic reduction, the resources and expenses involved in the maintenance and repair process will continue to rise.

3.3. Analysis of life cycle inventories

Fig. 6a illustrates the percentage of studies by the database sources used when conducting the LCA studies. Most studies utilized prominent databases, including Ecoinvent (33.0%), GREET model (27.3%), and GaBi professional (6.8%), and some even used multiple databases. 5.7% of the studies relied on secondary data derived from previous studies. However, a considerable proportion of studies (26.1%) utilized localized

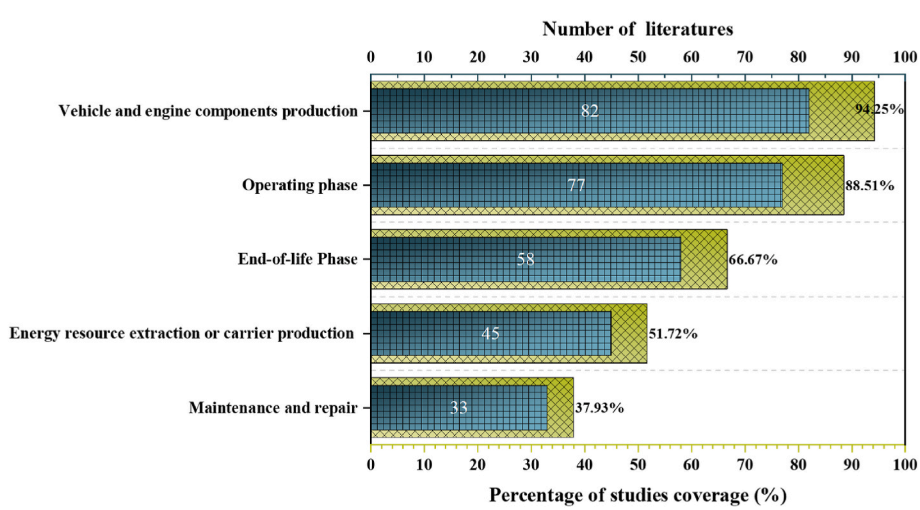

Fig. 5. Percentages of studies categorized by life cycle phase.

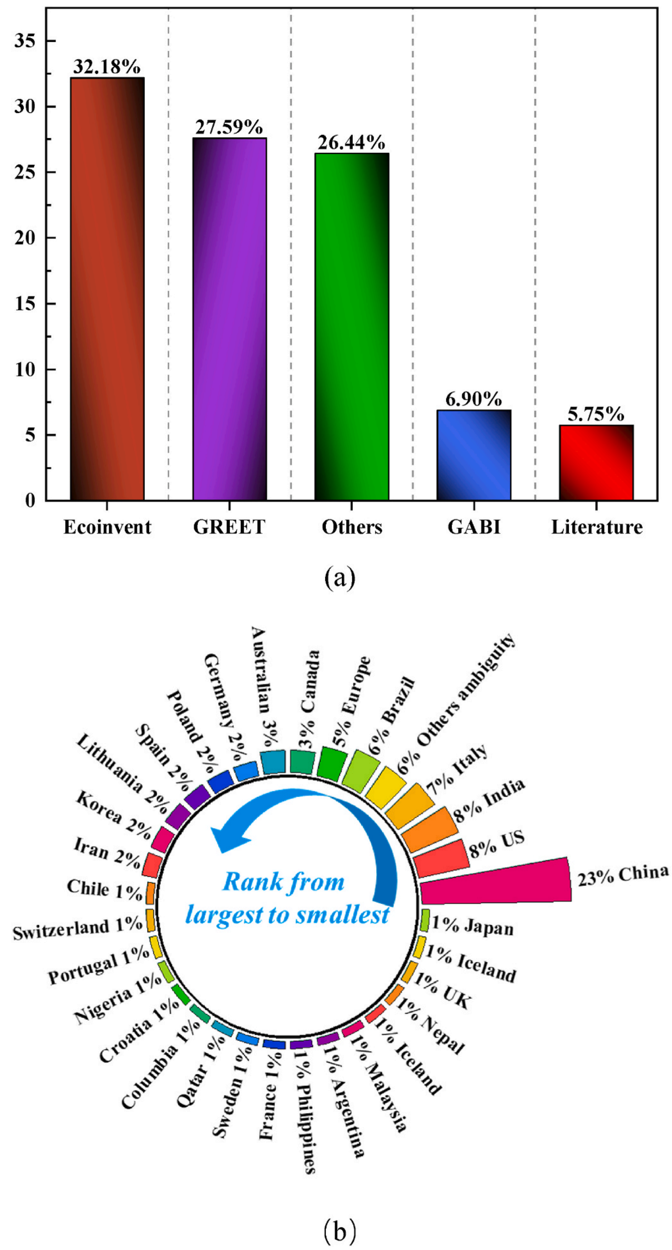

Fig. 6. Percentages of studies categorized by a) database, b) country.

data sources specific to countries or regions rather than prominent databases, such as China (Liu et al., 2021; Xue et al., 2023), India (Peshin et al., 2020), and Japan (Kawamoto et al., 2019). Fig. 6b indicates the percentages of studies by analyzed countries. The most studied country is China (22%), followed by the United States (8%) and India (8%), Italy (7%) and Brazil (6%). While very few studies were made in Poland, Canada, Germany, Korea, France, Iran, Spain, and Australia. It is obvious that ICE LCA studies have significant regionalization characteristics, primarily focusing on major ICE or vehicle markets and developed countries/regions. In comparison, there are very few analyses focused on developing countries/regions, where the raw material sources, industries, and energy structures are very special, and the LCA results could be quite different from those obtained in developed ones. For ICEs with 2L capacity, Novella et al. (2023) obtained the WTW GWP value ranging from 0.35 to 0.36 kg CO_2eq/km based on the Europe and America scenario, while Joshi et al. (2022) calculated the WTW GWP value of 0.5 kg CO_2 eq/km for the scenario of Nepal. Due to the faster development of carbon neutrality in developed countries, developing countries may become the major users of ICEs in the future. Studying the complete life cycle impact of ICEs in developing countries holds a broader and more significant importance.

The accuracy of the data source significantly influences the reliability of the final results. It is noted many studies used the fuel consumption and emission results obtained in the laboratory test of standard vehicle testing cycles such as WLTC or NEDC (Boero et al., 2023; Novella et al., 2023; Seol et al., 2022; Tucki et al., 2020). These data are usually easily collected from public data on government websites. However, recent research with portable emissions measurement systems (PEMS) has revealed significant differences (as high as 30–40%) in fuel consumption and emissions between the values obtained through standard driving cycle tests conducted in laboratories by engine/vehicle manufacturers or authorities, and the results obtained under real-world driving conditions (Fontaras et al., 2017; Zhu et al., 2022).

3.4. Analysis of ICE technologies

This section analyzes the advanced technologies considered in ICE LCA studies. The analysis includes two aspects: 1. Advanced ICE technologies that improve the thermal efficiency of ICEs; 2. Zero-carbon or

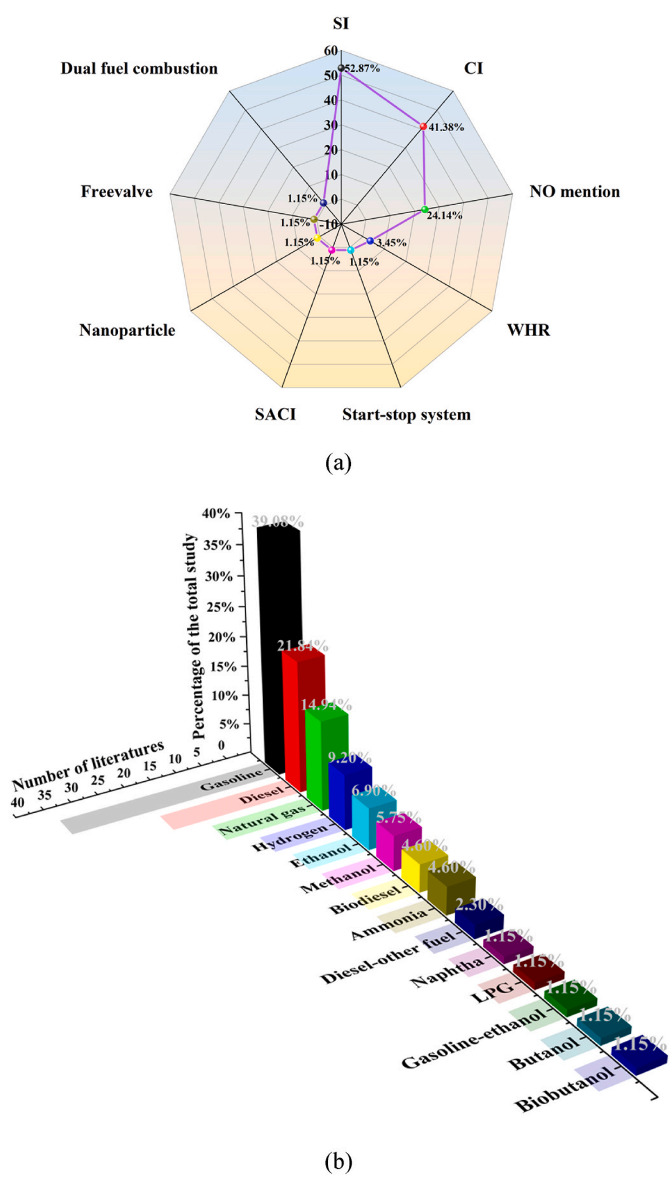

Fig. 7. Percentages of studies categorized by a) powertrain types, b) fuel types.

carbon-neutral fuels which reduce the carbon emissions from the source.

Fig. 7a illustrates the percentage of LCA studies focusing on various ICE technologies. The majority of reviewed studies only considered the basic combustion mode of ICE (spark ignition (SI) combustion (52%) and compression ignition (CI) combustion (41%)) without considering any other engine technologies, while 24% of the studies even have not clearly indicated the combustion mode. Quite limited research has been conducted to analyze the influence of new engine technologies on ICE LCA results, which consist of waste heat recovery (WHR) (3 articles), freevalve (1 article), engine start-stop system (1 article), fuel nanoparticle additive (1 article), dual fuel combustion (1 article), and spark-ignition assisted compression ignition (SACI) (1 article). The introduction of new combustion technologies has a profound impact on the efficiency and emissions of ICEs. For heavy-duty CI engines, WHR proves to be an effective method for enhancing the thermal efficiency, with an average improvement of 3–5% (Di Battista et al., 2022). For light-duty SI engines, lean burn can significantly boost thermal efficiency levels. Nakata (Nakata, 2021) ("The Future of Mobility Towards Carbon Neutrality,",n.d.) found that a super lean burn ($\lambda = 2.5$) light-duty research SI engine achieved the peak brake thermal efficiency of 47%, which is significantly higher than that achieved in conventional spark-ignition engines (35%). Another benefit brought by lean burn is the nearly zero emissions of NOx. Due to the combustion stability issue of lean burn, it is often combined with other advanced combustion technologies such as pre-chamber combustion (Alvarez et al., 2018), high-energy ignition (Ye et al., 2021), and dual-fuel combustion mode (He et al., 2020). A key role of LCA is to predict and evaluate the potential environmental impacts of new technologies during their development and design stages, spanning their entire life cycle. Hence, current research exhibits significant limitations when it comes to assessing the LCA of ICEs with new technologies, especially for light-duty SI engines.

Fig. 7b illustrates the percentage of LCA studies categorized by ICE fuels. Three fossil fuels, gasoline, diesel, and natural gas, represented 39.1%, 21.8%, and 14.9% of the reviewed studies, respectively. Hydrogen studies constitute the largest share among non-fossil fuels, representing 9.2% of the reviewed studies, while studies on ethanol, methanol, and biodiesel account for 6.9%, 5.8%, and 4.6%, respectively. As mentioned above, compared to fossil fuels, ICEs running with non-fossil fuels can achieve reduced life-cycle carbon emissions if the non-fossil fuels are produced from renewable energy sources. Meantime, the low carbon content or high oxygen content features of non-fossil fuels usually result in lower pollutant emissions. It is surprising that LCA studies pay such little attention to non-fossil fuel sources for ICEs. It is known that ICEs are not truly a source of CO2 emissions but the fossil fuels are. Although some technologies regarding using these fuels in ICEs are currently under research, it is crucial to consider the impacts of non-fossil fuels especially those zero carbon/carbon-neutral fuels when conducting LCA studies of ICEs. Without this awareness, it is challenging to demonstrate the advantages of ICEs to policymakers in the current decarbonization context. Therefore, it is necessary and urgent to conduct a significant number of comparative LCA studies between ICEVs using zero carbon/carbon-neutral fuels and BEVs and FCVs.

As carbon-free fuels, hydrogen and ammonia can eliminate emissions such as VOC, HC, and soot particles (Xu et al., 2022). Especially, ammonia, also exhibits significant advantages in terms of high volumetric energy density, safety, and the maturity of storage, transportation, and filling infrastructure (Liu et al., 2022), however, due to the distinctive molecular formula and combustion characteristics, ammonia exhibits unique emission characteristics, including high unburned NH_3 and NOx emissions as well as elevated N_2O emissions (250 times greater greenhouse effect than that of CO_2) (Kurien and Mittal, 2023). These characteristics may lead to unique environmental impacts for ammonia ICEs. Given the above reasons, the LCA research on ICEs using non-fossil fuels is far from sufficient at present.

3.5. Analysis of application sector and powertrain configurations

Fig. 8a illustrates the percentage of studies classified by the ICE application sectors. A small portion of the research has conducted a LCA study of the ICE itself, without specifying a particular application sector (7.95%), while the other research has all specified the application sectors. The majority of the studies (76.14%) examined sedans, followed by SUVs (7.95%). The other sectors include truck, bus, marine, two-wheelers (2Ws) and three-wheelers (3Ws), only accounting for less than 5%. This distribution aligns with the fact that most of the studies are comparative studies between ICEVs and BEVs. The trend of powertrain electrification is anticipated to mostly influence sedans and SUVs rather than the large and high-power mobile sources that are very challenging to transition to massive electrification. Notably, LCA studies on the large and high-power mobile sources, heavy-duty trucks, construction machinery, marine, and civil and general aviation aircraft, etc, are currently insufficient.

Fig. 8b illustrates the analysis of studies categorized by powertrain configurations. It should be mentioned that the LCA studies of the ICE itself were eliminated in this analysis because the powertrain configuration cannot be specified. The results show that 84.1% of the reviewed studies analyzed ICE-only powertrain systems. A considerable

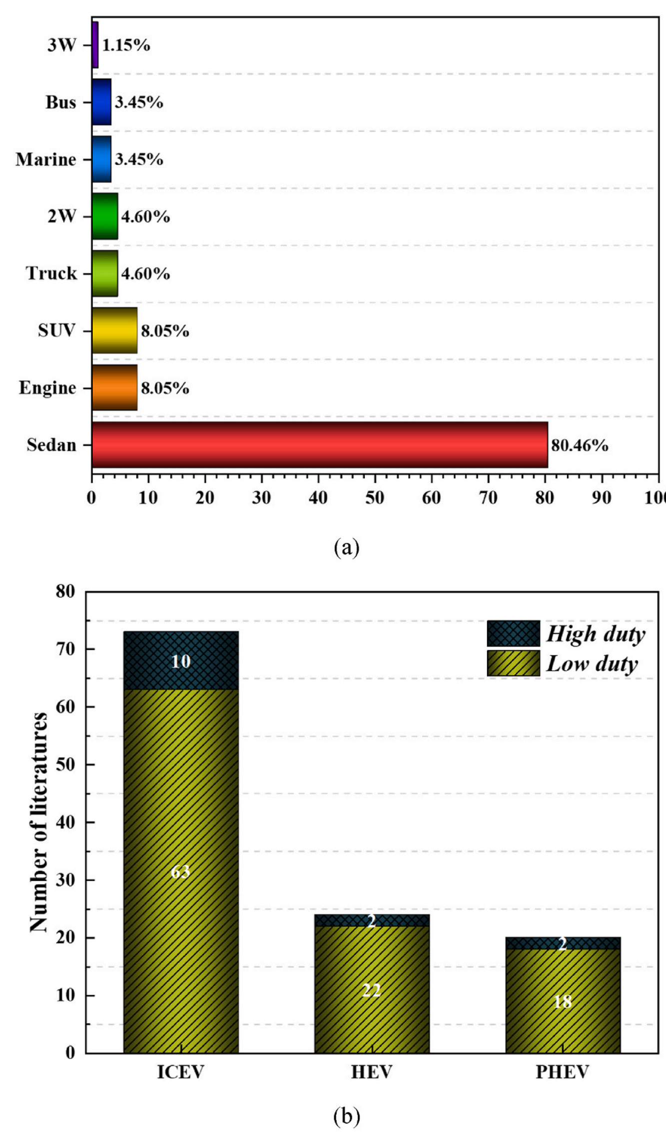

Fig. 8. Percentages of studies categorized by a) application sectors, b) powertrain configurations.

proportion of ICE LCA studies have taken hybrid technology into consideration with the proportions of hybrid and plug-in hybrid technologies reaching 27.3% and 22.7% respectively. However, it's worth noting that these studies primarily focus on applying hybrid technology for light-duty ICEs (40 articles), and there is a noticeable lack of research on applying hybrid technology for heavy-duty ICEs (4 articles). Hybrid technology can effectively tune the operating conditions of the ICE within the high-efficiency range by appropriately allocating the power output between the engine and the electric motor, which is even more important for ICEs adopting new combustion technologies, as these ICEs usually exhibit much higher peak thermal efficiency, but much smaller high-efficient operating regions compared to conventional ICEs. Hybrid light-duty gasoline ICEs can exceed 45% peak BTE when paired with advanced technologies such as pre-chamber combustion, injection system optimization, and cylinder deactivation (Joshi, 2022). Combining hybrid technology with advanced combustion techniques also yields significant energy-saving benefits for heavy-duty ICEs. Depending on various application scenarios, incorporating hybrid technology into heavy-duty ICEs can result in fuel savings of approximately 10%–35% (Buysse et al., 2021; Nieto Prada et al., 2021). Notably, LCA studies on applying hybrid technology for heavy-duty ICEs are far from sufficient.

4. Conclusions

This study intends to thoroughly assess how the LCA technique has been used to examine the actual contributions of the emerging technologies in reducing environmental impacts in the ICE sector given the intense competition from BEVs and FCVs. The systematic review provides an overview of the LCA studies on ICE/ICEV, and the major knowledge gaps are identified and concluded under six main categories and explained as follows.

1) Quite limited studies solely focusing on LCA of ICEs

While the trend towards electrification in automotive powertrains has been evident in recent years, advancements in ICE efficiency, zero-carbon or carbon-neutral fuel technology, and hybrid technology are continually enhancing ICE's competitiveness in reducing environmental impacts. Through literature analysis, it is observed that although LCA studies for powertrains have been growing annually, most LCA studies involving ICEVs are using ICEV as a comparison baseline for BEVs, and the number of studies focusing solely on the effects of ICE technology advances on the LCA results remains extremely limited.

2) Lack of assessment of the impacts on environmental pollution, human health and socio-economic aspects

The majority of studies (89.77%) primarily focused on GWP as an environmental impact indicator. Other environmental indicators, as well as socio-economic indicators human health, and LCC examined in the literature are all lower than 25%. The ICE exhaust emissions on environmental pollution, and human health are not negligible, and the relative research and analysis of such indicators can provide vital insights for the formulation of emission regulations and the selection of technology pathways. LCC is an important aspect because it reflects the advantages of the ICE over other new powertrain types, and at the same time, new ICE combustion and fuel technologies often come with increased overall life cycle costs.

3) Frequent neglection of the fuel production process and maintenance & repair phase

Ideally, ICE LCA studies should examine the manufacturing, operation, maintenance and repair, end-of-life phases and the fuel production process, however, most of the examined paper cannot cover all these phases. The manufacturing phase and the operation phase were the most studied, while the fuel production process and maintenance and repair phase exhibit a much lower proportion, accounting for 51.7 %, and 37.9%, respectively. In recent years, the resource of ICE fuel production has expanded from conventional fossil energy resources to both fossil resources and various renewable energy resources, and the life cycle carbon emission results will differ greatly considering different fuel production resources. With the use of low viscosity and high corrosiveness fuels in the future, as well as the mandatory monitoring of emissions throughout the entire life cycle of vehicles by the upcoming new emission regulations, the expenses involved in the maintenance and repair phase will continue to rise.

4) Limited studies on small and developing countries, and lack of consideration of real-word operations in data collection

Ecoinvent (32.2%) and GREET model (27.6%) were two databases mostly used in the reviewed studies. However, a considerable proportion of articles (26.1%) utilized localized data sources specific to the objective countries or regions. The most studied country is China (22%), The reviewed ICE LCA studies primarily focused on major ICE and vehicle markets or developed regions. In comparison, there were very few analyses focused on developing regions. It is noted that the fuel consumption and emissions data extensively employed in many studies were derived from laboratory tests of standard vehicle test cycles such as WLTC or NEDC, which could significantly differ from the actual fuel consumption and emissions during real-world vehicle operation according to the recent research findings.

5) Lack of consideration of the emerging ICE technologies and zero carbon/carbon-neutral fuels

In terms of ICE technologies, the majority of studies only considered the basic combustion mode, SI combustion (52%) and CI combustion (41%) without involving any other new engine technologies. Previous studies exhibit significant limitations when it comes to assessing the LCA of ICEs with new technologies, especially for light-duty SI engines. In terms of ICE fuels, the majority of research still considered three fossil fuels, gasoline, diesel, and natural gas. The LCA research on ICEs considering non-fossil fuels is far from sufficient. Notably, as a very promising carbon-free fuel with unique combustion and emission characteristics, ammonia was examined in only 1.1% of reviewed studies.

6) Insufficient research on large and high-power mobile sources and heavy-duty hybrid technologies

In terms of ICE application sectors, the majority of the studies (76.14%) examined sedans, followed by SUVs (7.95%), while large and high-power mobile sources that are very challenging to transition to massive electrification have been merely considered in the previous studies. A considerable proportion of ICE LCA studies have taken hybrid technology into consideration. However, it's worth noting that these studies primarily focus on hybrid technology for light-duty ICEs, and there is a noticeable lack of research on hybrid technology for heavy-duty ICEs. Finally, it can be said the findings of this systematic review on the LCA of ICE could have significant implications for various stakeholders, Firstly, researchers and academics in the related field can benefit from the analysis results on the indicators, technologies, fuels that are crucial in ICE LCA studies but have not been adequately assessed. Secondly, Policymakers and government organizations may gain a more comprehensive understanding of the environmental impact of internal combustion engines, potentially leading to relaxation of restrictions on their future use. Finally, professionals and stakeholders in the ICE industry can gain valuable insights, understanding the environmentally friendly potential of different ICE technologies, to make informed decisions regarding the technological roadmap.

CRediT authorship contribution statement

Haoye Liu: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft. **Shiwu Yu:** Data curation, Formal analysis, Investigation, Writing – review & editing. **Tianyou Wang:** Validation, Writing – review & editing. **Ji Li:** Supervision, Writing – review & editing. **Yuanjing Wang:** Writing – review & editing.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141996.

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