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Review of life cycle assessment for automobiles: A meta-analysis-based approach

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ABSTRACT

The key considerations for advanced life cycle assessment (LCA) of automobiles leading to a low carbon economy are globalization in automobile life cycle, social expansion in new automobile technology, country diversity in automobile usage, and country factor in battery degradation of electric vehicle. This study was aimed at comprehensively reviewing automobile LCA studies using a meta-analysis-based approach. This approach was applied to 332 peer-reviewed papers from the comprehensive and specific perspectives. The specific perspective focuses on the above-mentioned globalization, social expansion, and country diversity aspects. The study findings revealed the progress and the limitations in automobile LCA studies. These progresses and limitations highlighted the urgency to expand the automobile LCA studies from technology assessment to system design, including policy making and decision-making related to governments and drivers. In addition, this review identified the upcoming challenges for advancing automobile LCA from the aspects of globalization, social expansion, country diversity, and battery degradation. These challenges could be overcome by considering global reuse across countries, the balance of in-use automobile demand and the infrastructure supply, and the International Vehicle Emission (IVE) model within a fleet-based LCA as the core of the LCA methodology.

1. Introduction

As a part of the global movement for building a low carbon economy, the European Union (EU) plans to implement a new regulation towards the reduction of CO_2 emissions in new automobiles from a life cycle perspective [1]. This EU regulation that expands the regulatory coverage from direct emissions in the use stage to total emissions in the entire life stage increases the significance of life cycle assessment (LCA) in automobiles [2,3].

The life cycle of an automobile that requires various materials, parts, and fuels is rarely completed within a single country. It is known that the automotive industry drives the international specialization based on the global supply chain structure [4–6], which implies globalization at the production stage, which is part of the earlier life cycle of automobiles before the use stage. As for globalization in the latter life cycle of automobiles, that is, after the use stage, the international trade of used automobiles including electric vehicles (EVs) from developed countries to developing countries has been reported by the United Nations Environment Program (UNEP) and Fuse et al. [7,8]. The second life cycle of conventional vehicles and EVs imported by developing countries poses a potential environmental threat due to poor waste management in the importing countries that lack appropriate technologies to recycle end-of-life vehicles and lithium-ion batteries [9–14]. Thus, the aspect of "globalization in automobile life cycle" is a key consideration in advanced LCA targeting automobiles.

Automobile LCA functions as a communication tool supporting the social expansion of related low-carbon technologies such as EVs [15–19]. Fleet-based LCA studies for EV and fuel cell vehicle (FCV) have directly investigated the degree of their social expansion in national or regional scale fleets over time [20]. The social expansion of such new

Abbreviations: ASEAN, Association of Southeast Asian Nations; Ave, average; CNG, Compressed natural gas; EoL, end-of-life stage; EU, European Union; EV, Electric vehicle; F and E, fuel and electricity stage; FCV, Fuel cell vehicle; HV, Hybrid vehicle; ICDV, Internal combustion diesel engine vehicle; ICGV, Internal combustion gasoline engine vehicle; ICV, Internal combustion engine vehicle; Inf, infrastructure stage; IVE, International Vehicle Emissions; km, kilometers; LCA, Life cycle assessment; Mai, maintenance stage; PHV, Plug-in hybrid vehicle; PO, powertrain type; Pro, production stage; PU, purpose type; PY, published year; QM, quality of methods; SB, system boundary; SD, Standard deviation; t, tonnes; TTW, Tank to wheel; Use, use stage; UNEP, United Nations Environment Programme; VLC, Vehicle life cycle; VT, vehicle type; WTT, Well to tank; WTW, Well to wheel.

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auto technologies (e.g., EV and FCV) relies on the fuel supply infrastructure (e.g., electric charging station and hydrogen refueling station) [21,22]. Certain studies have addressed the significance of including the road and fuel supply infrastructure supporting the automobile's functioning in automobile LCA [23–25]. Hence, advancing LCA for new auto technologies necessitates consideration of the aspect of "social expansion in new automobile technology" especially focusing on the related infrastructure.

The use stage of the internal combustion engine vehicle (ICV), which will potentially be replaced in the future by the EV and/or FCV, given their social expansion, is well known as a major source of air pollutant emissions in the transportation sector [26,27]. Upon focusing on the use stage of ICV in automobile LCA, air pollutant emissions are considered to vary with country, due to the diversity in vehicles, emission control, and driving factors (e.g., vehicle type and age, emission standards, and traffic congestion) [28–31]. Especially in developing countries, motorcycles are reported to be a major emission source because they cause traffic congestion through mixed traffic phenomenon and transport modes of different speeds [32–35]. Hence, the aspect of "country diversity in automobile usage" is a key consideration in advanced LCA targeting conventional automobiles.

EV and its lithium-ion battery have been positioned as important targets in automobile LCA studies [15–18]. The life cycle environmental impact of EV depends on the lifetime of the lithium-ion battery, owing to the high environmental impact of battery production [14]. Battery lifetime is determined by battery degradation, which in turn depends on the charging cycle of the EV user and the ambient temperature in the EV driving environment [36,37]. Electric vehicles are sold and used worldwide, especially in China and the United States [38]. The degree of battery degradation is expected to vary in countries with different ambient temperatures [39]. Thus, advanced LCA of EV necessitates consideration of the aspect of "country factor in battery degradation of electric vehicle" especially focusing on the ambient temperature.

As mentioned above, advanced LCA leading to a low carbon economy has four aspects, "globalization in automobile life cycle," "social expansion in new automobile technology," "country diversity in automobile usage," and "country factor in battery degradation of electric vehicle," as the key considerations. These four aspects are hereafter abbreviated as globalization aspect, social expansion aspect, country diversity aspect, and battery degradation aspect.

Many reviews on automobile LCA have been published, as this is an established research area [3,18,20,25,40–44]. We focused on previous reviews that included the above-mentioned aspects in their review scope. The present study also focused on the method used to review automobile LCA studies. A description-based method and a meta-analysis-based approach have been employed to quantitively assess the reviewed target publications and their contents. The meta-analysis-based approach provides a more quantitively aggregated review than the description-based approach. By combining the above-mentioned four aspects in the advanced LCA and the meta-analysis-based approach, previous review studies can be categorized into three types, as follows.

The first type of review studies have considered the aspects using a description-based approach or a weak meta-analysis-based approach [18,20,40]. Hawkins et al. referred to the social expansion and the country diversity aspects using a description-based approach in hybrid vehicles (HVs) and EVs [40]. Based on the study by Hawkins et al. Nordelof et al. increased the number of publications and used a simple counting method, which was a weak meta-analysis approach [18]. Garcia et al. reviewed publications that used fleet-based LCA, which reflects the direct social expansion of the target automobiles in their fleet over time, using a description-based approach [20]. Hence, these studies satisfied only part of the four aspects and did not utilize a complete meta-analysis-based approach.

The second type of studies have not considered the aspects using a meta-analysis-based approach [41–44]. Aichberger et al. adopted a complete meta-analysis-based approach for EVs that consisted of aggregate analysis and inventory meta-analysis [41]. Aggregate analysis-specific review studies were conducted by Dilman et al. and by Gompf et al. [42,43]. Inventory meta-analysis was improved through a statistical model for publications on biofuel [44]. Although the second type of studies advanced the meta-analysis-based approach over the first type, these studies did not include all the four aspects in their review scope.

The third type of studies have incorporated the aspects using a meta-analysis-based approach [3,25]. The company FVV Prime Movers reviewed publications on only passenger cars using a meta-analysis-based approach and mainly focusing on the infrastructure related to the social expansion aspect [25]. Furthermore, Ricardo Energy & Environment provided a comprehensive review of publications on passenger cars, trucks, and buses using detailed aggregate analysis [3]. However, the review scope of Ricardo Energy & Environment was limited to only country diversity and battery degradation aspects [3].

Our literature review revealed that there exists no automobile LCA review study, which has targeted all vehicle types including motorcycles, with all the aspects of globalization, social expansion, country diversity, and country factors in battery degradation as the review scope using a meta-analysis-based approach. Hence, this study is the first attempt to apply a meta-analysis-based approach in automobile LCA review studies from a comprehensive and a specific perspective, respectively focusing on all vehicle types and all the four aspects. This study contributes to an update of the knowledge about the current location and the future direction of automobile LCA studies and contributes to automobile LCA research progress. Therefore, the aim of this study was to comprehensively review automobile LCA studies using the meta-analysis-based approach.

The structure of this paper is as follows: In Section 1, the background and the aim of this study are described. Section 2 focuses on the target studies on automobile LCA and the meta-analysis-based approach used in this study. The results of this meta-analysis-based approach are summarized in Section 3. Based on the results obtained in Section 3, Section 4 explores the upcoming challenges in automotive LCA research. Finally, the findings of this study are summarized in Section 5.

2. Method

2.1. Target studies

Automobile LCA includes the target vehicle type, target powertrain type, target purpose type, and target system boundary. In terms of the powertrain type, this study covered the internal combustion engine vehicle (ICV), Hybrid vehicles (HV), Electric vehicles (EV), and Fuel cell vehicles (FCV). The system boundary includes life stages, such as production, use, and end-of-life stages. The vehicle type, purpose type, and system boundary covered in this study are shown in Figs. 1 and 2.

As shown in Fig. 1, passenger cars, trucks, buses, and motorcycles were selected as the vehicle type in this study. The purpose of the study was grouped into four categories: 1) comparison of technology (e.g., ICV versus EV), 2) evaluation of specific technology (e.g., light-weighted ICV), 3) fleet-based LCA (e.g., social expansion of EV), and 4) others. The additional vehicle and purpose type in this study that were compared with Ricardo Energy & Environment [3] study, which is the most comprehensive review, are motorcycle -and fleet-based LCA, respectively.

As shown in Fig. 2, the system boundary of this study incorporated all life stages such as production, use, end-of-life, fuel and electricity production, maintenance, and infrastructure. The system boundary in this study included the infrastructure stage, which was unavailable in Ricardo Energy & Environment [3] and the maintenance stage, which was unavailable in FVV Prime Movers [25]. The target vehicle type, powertrain type, and system boundary in this study represent the refocus of the publications reviewed in Ricardo Energy & Environment

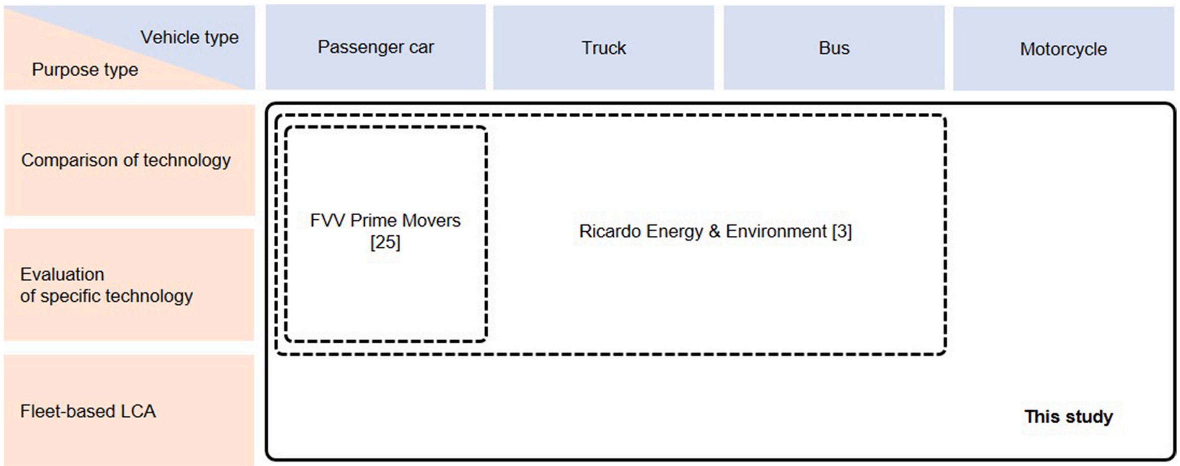

Fig. 1. Vehicle types and purpose types covered in this study.

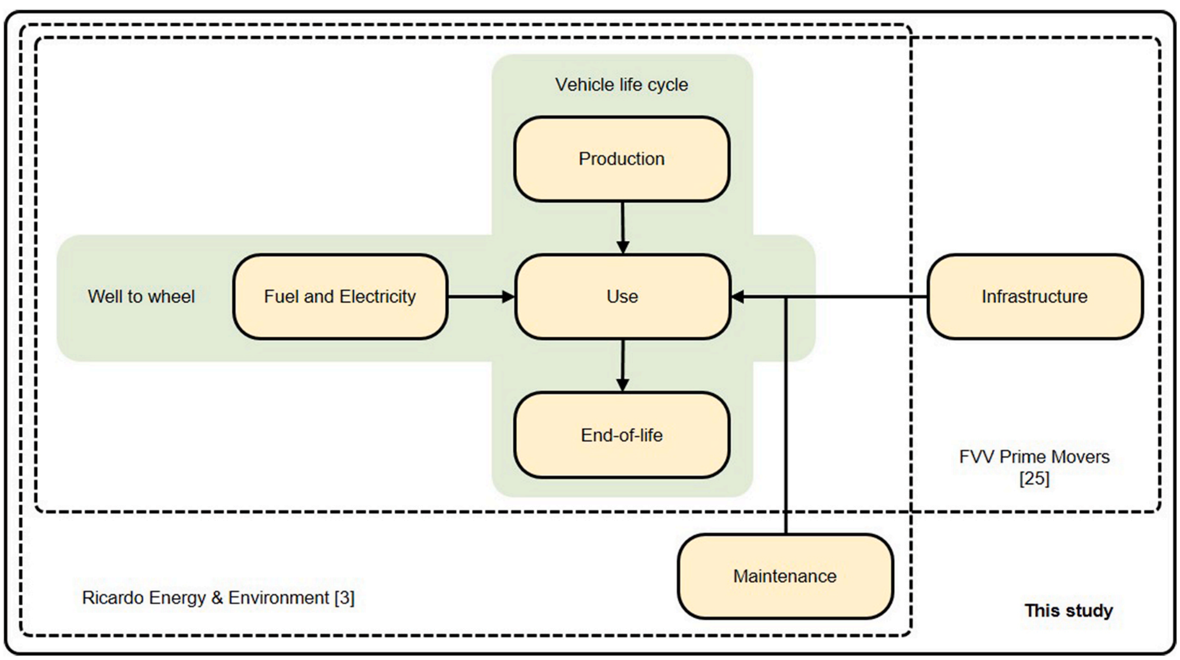

Fig. 2. System boundary covered in this study.

[3] and FVV Prime Movers [25]. All the publications in the two review studies were not cited in this study because, as a criterion to assess the quality of the publications, only peer-reviewed publications were selected.

Subsequently, 332 peer-reviewed papers published until 2020 were selected (see Appendix). Then, 22 publications from Ricardo Energy & Environment [3] and FVV Prime Movers [25] were collected. The remaining 310 publications were obtained from the Web of Science by searching using an appropriate key word such as “life cycle assessment vehicle,” “life cycle assessment automobile,” and “life cycle assessment car.”

2.2. Meta-analysis-based approach

The analytical flowchart for the meta-analysis-based approach used in this study is shown in Fig. 3. The meta-analysis-based approach consisted of aggregate analysis and inventory meta-analysis within comprehensive and specific perspectives. Aggregate analysis quantitively perceives the characteristics of an automobile LCA study by aggregating the number of collected papers from comprehensive and specific perspectives. From a specific perspective, the meta-analysis-based approach in this study corresponded to the aspects of “globalization in life cycle (globalization),” “social expansion in technology (social expansion),” “country diversity in use (country diversity),” and “country factor in battery degradation (battery degradation)” as previously mentioned in Section 1. However, the battery degradation aspect was excluded due to the extremely limited sample size with only four relevant studies (see Appendix).

The aggregate analysis in the meta-analysis-based approach accounted the number of papers as an analytical index and published year, purpose type, system boundary, vehicle type, powertrain type, and the quality of methods (inventory analysis, impact assessment, uncertainty analysis) as analytical items. The quality of methods used in the selected papers was evaluated based on four levels: Level 1) inventory analysis, Level 2) impact assessment, Level 3) inventory analysis with uncertainty analysis, and Level 4) impact analysis with uncertainty analysis.

The aggregate analysis from the comprehensive perspective had

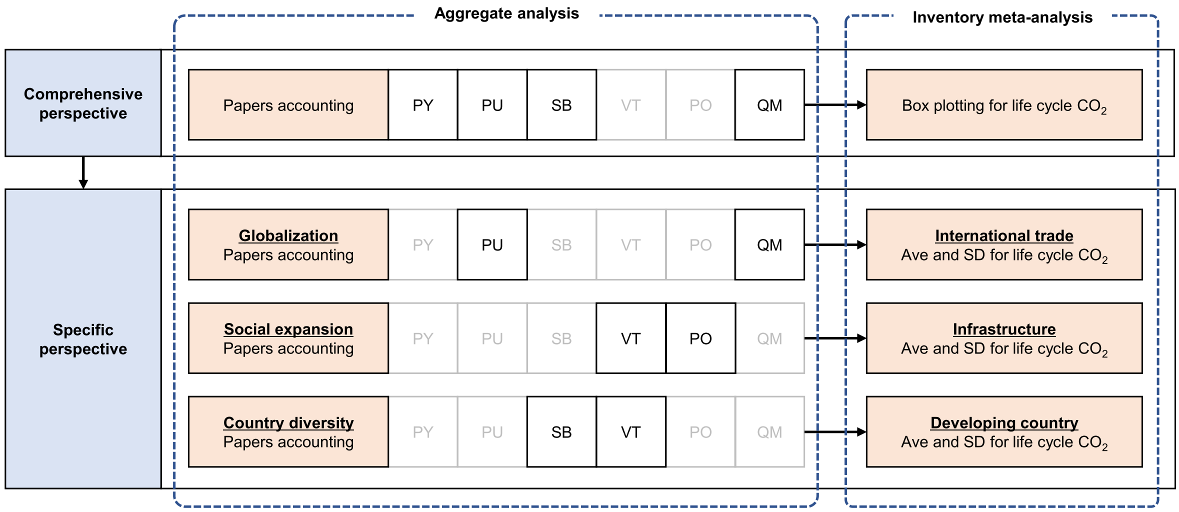

Fig. 3. The analytical flowchart showing the meta-analysis-based approach used in this study. PY, PU, SB, VT, PO, and QM represent published year, purpose type, system boundary, vehicle type, powertrain type, and quality of methods, respectively. Ave and SD represent average and standard deviation, respectively.

published year, purpose type, system boundary, and the quality of methods as the analytical items. Especially, purpose type, system boundary, and the quality of methods are the novel analytical items used in this study when compared to previous review studies [3,25]. Vehicle and powertrain types were excluded from the aggregate analysis at the comprehensive perspective due to the overlap of these analytical items with the aggregate analysis by Ricardo Energy & Environment [3] which had a sample size similar to that of the present study.

The aggregate analysis with the specific perspective of globalization had purpose type and the quality of methods exploratively determined in the analytical items. Whether or not a reviewed paper has the globalization aspect was determined by whether or not the paper included international trade with export and import specified in the system boundary. The aggregate analysis with the specific perspective of social expansion had vehicle type and powertrain type exploratively determined in the analytical items. Whether or not a reviewed paper has the social expansion aspect was determined by whether or not the paper includes the infrastructure stage in the system boundary. The aggregate analysis with the specific perspective of country diversity aspect had vehicle type and system boundary exploratively determined in the analytical items.

Inventory meta-analysis examines the effect of powertrain type from a comprehensive perspective and the effect of globalization, social expansion, and country diversity aspects from a specific perspective by utilizing the life cycle CO_2 emissions. Analysis of the effect of globalization was focused on the consideration of related international trade in the system boundary. Analysis of the effect of social expansion was focused on the consideration of related infrastructure in the system boundary. Analysis of the effect of country diversity was focused on the differences between developed and developing countries in CO_2 emissions at the use stage.

Inventory meta-analysis was used to perform a conventional meta-analysis by targeting the results of life cycle CO_2 emissions in the collected papers with comprehensive and specific perspectives. Life cycle CO_2 emissions obtained from the collected papers were modified by considering one vehicle life with a total of 150,000 km as the functional unit. In this inventory meta-analysis, CO_2 emissions by life stages and powertrain types in passenger cars and trucks were selected; hence, a total of 705 samples were used from 101 papers among the 332 collected papers. Box plot was used for the inventory meta-analysis from a comprehensive perspective with sufficient sample size. Average and standard deviation (SD) were used as the analytical index for the inventory meta-analysis from a specific perspective with relatively insufficient sample size.

3. Results

3.1. Results of the meta-analysis-based approach from comprehensive perspective

The results of the meta-analysis-based approach from a comprehensive perspective to automobile LCA studies including 332 collected papers are categorized by aggregate analysis and inventory meta-analysis. The results from the aggregate analysis to automobile LCA studies are presented in Fig. 4.

Fig. 4(a) shows the time trend of the automobile LCA studies according to the published year between 1996 and 2020. The first paper was published in 1996, and the number of papers fluctuated with an increasing tendency and remained at less than 10 papers until 2011. In 2012, the number of papers considerably increased from 30 to 50. Hence, the automobile LCA study had received significant scientific attention in recent years.

Fig. 4(b) presents the contribution of each purpose type to the automobile LCA studies. The order according to the purpose type was technology comparison (60%), specific technology evaluation (22%), fleet-based LCA (15%), and others (3%). Technology comparison, with the highest contribution, comprised the assessment of advanced technologies, in comparison with conventional technologies.

The system boundaries of the automobile LCA studies are described in Fig. 4(c). The system boundary type was divided into three types: 1) well to wheel (WTW), 2) vehicle life cycle (VLC), and 3) WTW and VLC. The contribution of WTW decreased by 40% (21 papers) from 1996 to 2010, 28% (22 papers) from 2011 to 2015, and 22% (46 papers) from 2016 to 2020, while that of VLC increased by 19% (10 papers), 21% (17 papers), and 33% (66 papers), respectively. The contribution of VLC increased because studies on end-of-life and light-weight technologies rapidly increased in number from 2016 to 2020. Thus, these results emphasize the directional shift from fuel-oriented WTW to vehicle-oriented VLC without expanding the system boundary in automobile LCA studies.

Fig. 4(d) shows the quality of methods used in the automobile LCA studies. The contribution of Level 1 based on inventory analysis, which was considered to have the lowest method quality, decreased by 40% (21 papers) from 1996 to 2010, 32% (26 papers) from 2011 to 2015, and 23% (46 papers) from 2016 to 2020. In contrast, the contribution of Level 4 based on impact assessment and uncertainty analysis, which was

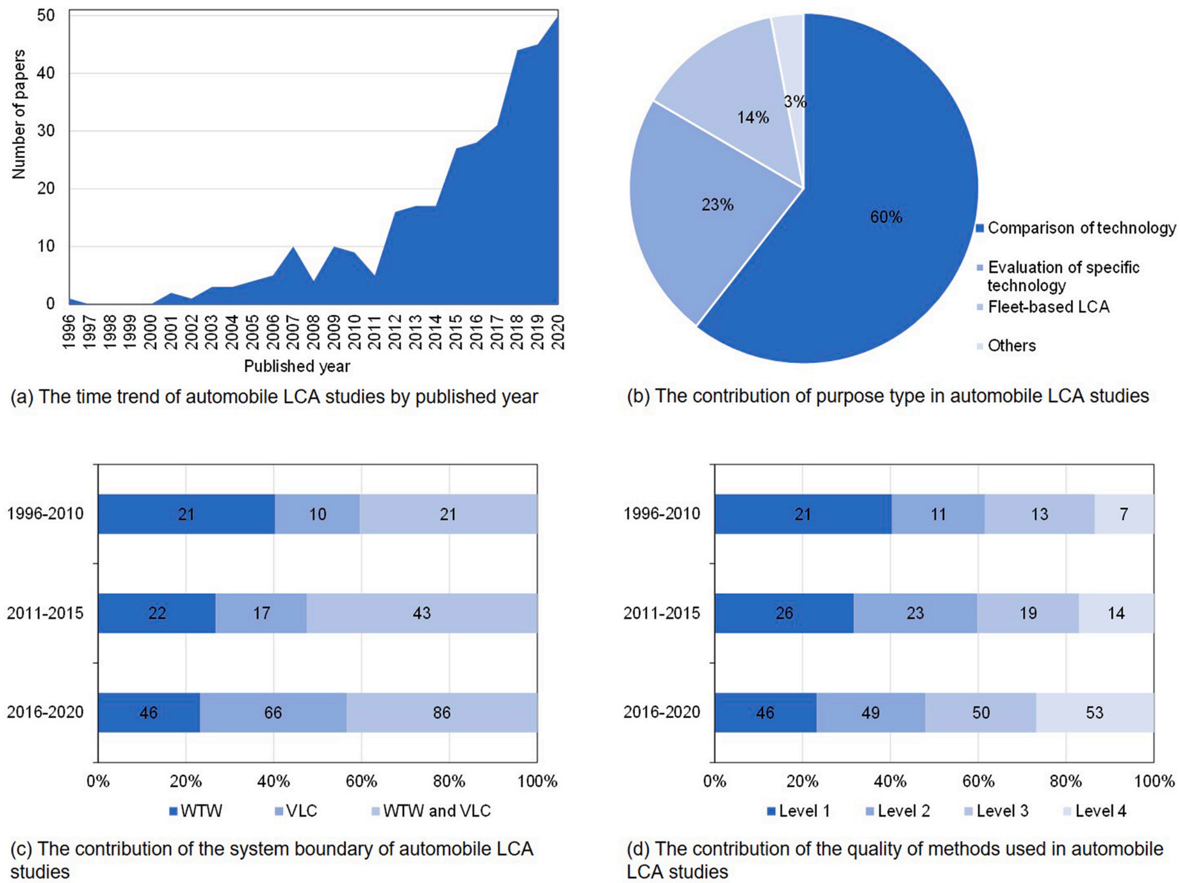

Fig. 4. The results for aggregate analysis to automobile LCA studies from a comprehensive perspective. WTW stands for Well to wheel, and VLC stands for Vehicle life cycle.

considered to have the highest method quality, increased by 13% (7 papers), 17% (14 papers), and 27% (53 papers). The trend of Level 2 based on impact assessment and that of Level 3 based on inventory analysis and uncertainty analysis could not be observed. These results confirmed that the methods adopted in automobile LCA studies have progressed from specific inventory analysis to a more comprehensive analysis including impact assessment and uncertainty assessment.

The results of the inventory meta-analysis from a comprehensive perspective are summarized in Fig. 5. This figure shows the comparison results for life cycle CO_2 emissions by life stage according to the powertrain type in passenger cars. The terms ICGV, ICDV, and PHV in Fig. 5 represent internal combustion gasoline engine vehicle, internal combustion diesel engine vehicle, and plug-in hybrid vehicle, respectively. This comparison utilized the median, 25th percentile, 75th percentile, minimum value, and maximum value as the assessment indices and excluded outliers.

As shown in Fig. 5(a), the results from ICGV, as median and 25th-75th percentile, in descending order of life cycle CO_2 emissions, were as follows: use stage with 26 t per vehicle and 23–32 t per vehicle, production stage with 6.5 t per vehicle and 5.0–9.7 t per vehicle, fuel and electricity production stage with 4.9 t per vehicle and 3.9–6.8 t per vehicle, and maintenance stage with 1.9 t per vehicle and 1.0–3.2 t per vehicle, respectively. Life cycle CO_2 emissions at the end-of-life and the infrastructure stages were negligibly small (less than 1.0 t per vehicle). The maximum values were observed at the production and the fuel and electricity production stages with 16 t per vehicle and 9.9 t per vehicle, respectively, which were over twice the corresponding median values. Life cycle CO_2 emissions at the production stage of ICGV were obtained from the inventory meta-analysis by FVV Prime Movers [25]. The median values in this study and the FVV Prime Movers study were 6.5 t per vehicle and 6.0 t per vehicle, respectively. The 25th-75th percentile values in this study and the FVV Prime Movers study were 5.0–9.7 t per vehicle and 4.5–7.5 t per vehicle, respectively. A comparison between both studies showed that the trends were generally similar. The difference in the results between both studies may be due to the difference in their sample size.

As shown in Fig. 5(b), the results from ICDV, as median and 25th-75th percentile, in descending order of life cycle CO_2 emissions, were as follows: use stage with 23 t per vehicle and 18–27 t per vehicle, production stage with 6.0 t per vehicle and 5.0–10 t per vehicle, fuel and electricity production stage with 3.6 t per vehicle and 2.1–4.3 t per vehicle, and maintenance stage with 3.2 t per vehicle and 8.0–3.3 t per vehicle, respectively. Life cycle CO_2 emissions at the end-of-life and infrastructure stages were negligibly small (less than 1.0 t per vehicle). The maximum value was observed at the production stage at 12 t per vehicle, which was over twice the median value. Life cycle CO_2 emissions at the production stage of ICDV were obtained from the inventory meta-analysis by FVV Prime Movers [25]. The median values in this study and the FVV Prime Movers study were 6.0 t per vehicle and 6.0 t per vehicle, respectively. The 25th-75th percentile values in this study and the FVV Prime Movers study were 5.0–10 t per vehicle and 4.5–10 t per vehicle, respectively. The results were almost the same between both studies.

As shown in Fig. 5(c), the results from HV, as median and 25th-75th percentile, in descending order of life cycle CO_2 emissions, were as follows: use stage with 18 t per vehicle and 14–20 t per vehicle, production stage with 7.4 t per vehicle and 5.2–11 t per vehicle, fuel and electricity production stage with 4.5 t per vehicle and 3.1–6.0 t per vehicle, maintenance stage with 1.9 t per vehicle and 1.0–3.2 t per vehicle, and end-of-life stage with 1.1 t per vehicle and 0.90–2.1 t per

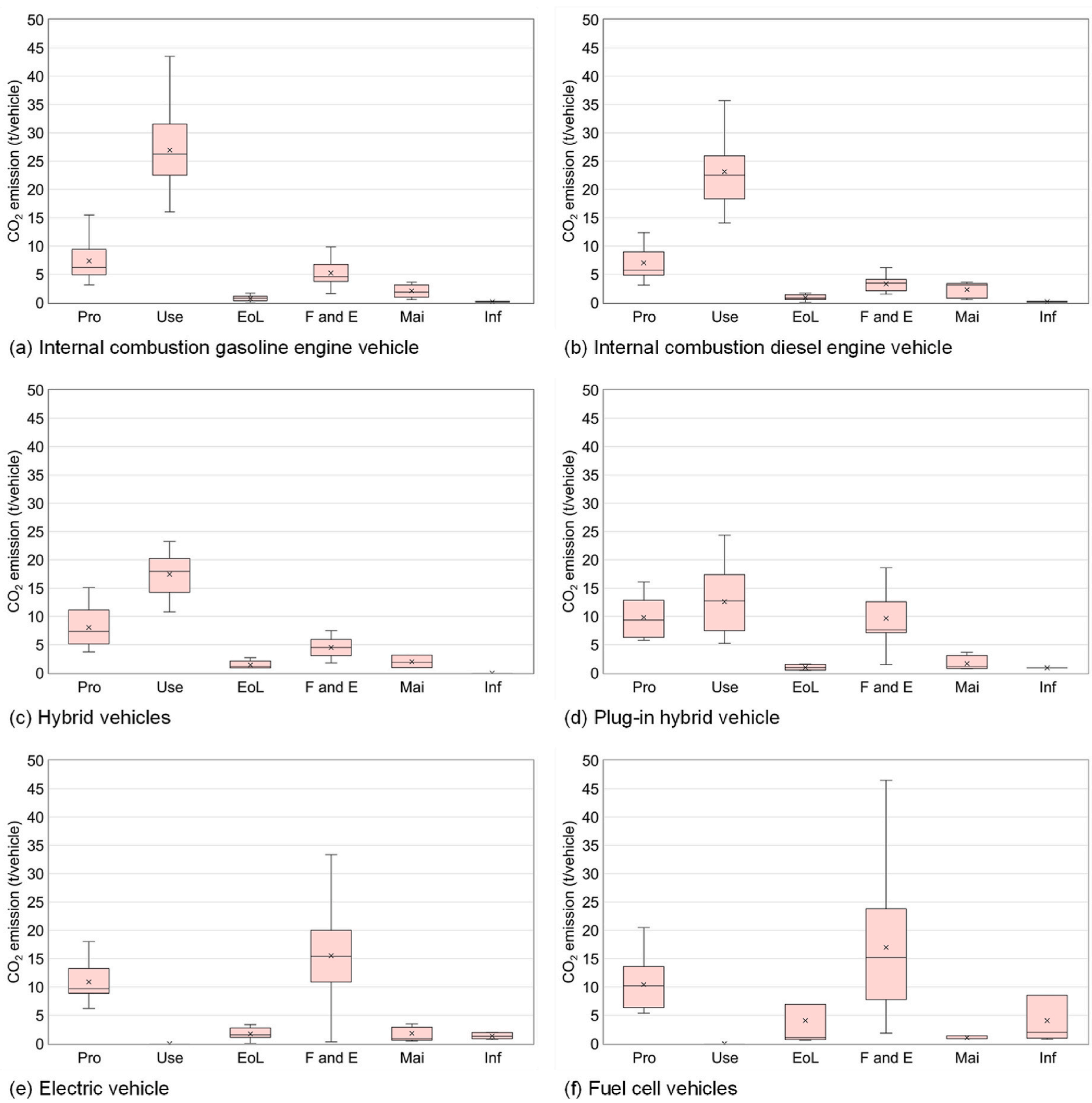

Fig. 5. The results of the inventory meta-analysis on automobile LCA studies from a comprehensive perspective. Pro, Use, EoL, F and E, Mai, and Inf represent production, use, end-of-life, fuel and electricity, maintenance, and infrastructure stages.

vehicle, respectively. Life cycle CO_2 emissions at the infrastructure stage were negligibly small (less than 1.0 t per vehicle). The maximum values were observed at the production and the end-of-life stages with 15 t per vehicle and 2.7 t per vehicle, which were over twice the corresponding median values.

As shown in Fig. 5(d), the results from PHV, as median and 25th-75th percentile, in descending order of life cycle CO_2 emissions, were as follows: use stage with 13 t per vehicle and 7.7–17 t per vehicle, production stage with 10 t per vehicle and 6.3–13 t per vehicle, fuel and electricity production stage with 7.7 t per vehicle and 7.1–13 t per vehicle, maintenance stage with 11 t per vehicle and 0.79–3.1 t per vehicle, and end-of-life stage with 1.0 t per vehicle and 0.52–1.5 t per vehicle, respectively. Life cycle CO_2 emissions at the infrastructure stage were negligibly small (less than 1.0 t per vehicle). The maximum values were observed at the fuel and electricity production and the maintenance stages with 19 t per vehicle and 3.7 t per vehicle, which were over twice the corresponding median values. The fuel and electricity production stage had the minimum value which decreased to one-fifth of the median.

As shown in Fig. 5(e), the results from EV, as median and 25th-75th percentile, in descending order of life cycle CO_2 emissions, were as follows: fuel and electricity production stage with 16 t per vehicle and 11–20 t per vehicle, production stage with 9.8 t per vehicle and 9.0–14 t per vehicle, end-of-life stage with 1.6 t per vehicle and 1.1–3.0 t per vehicle, and infrastructure stage with 1.3 t per vehicle and 0.90–2.0 t per vehicle. Life cycle CO_2 emissions at the maintenance stage were negligibly small (less than 1.0 t per vehicle). The maximum values were observed at the fuel and electricity production, maintenance, and the end-of-life stages with 33 t per vehicle, 3.5 t per vehicle, and 3.4 t per vehicle, respectively, over twice the corresponding median. The minimum value at the fuel and electricity production stage with the largest median was less than 1.0 t per vehicle. Life cycle CO_2 emissions at the production stage and the fuel and electricity production stage of EV were obtained from the inventory meta-analysis by FVV Prime Movers [25]. The median and the 25th-75th percentile values at the production stage were 9.8 t per vehicle and 9.0–14 t per vehicle in this study and 10 t per vehicle and 7.5–13 t per vehicle in the FVV Prime Movers study. At the production stage, the trends were generally similar in both studies. The difference in the results between both studies may be due to the difference in their sample size. The median and the 25th-75th percentile values at the fuel and electricity production stage were 16 t per vehicle and 11–20 t per vehicle in this study and 14 t per vehicle and 12–19 t per vehicle in the FVV Prime Movers study. At the fuel and electricity production stage, both studies showed generally similar trends. The difference in the results between both studies may be due to the difference in their sample size.

As shown in Fig. 5(f), the results from FCV, as median and 25th-75th percentile, in descending order of life cycle CO_2 emissions, were as follows: fuel and electricity production stage with 17 t per vehicle and 9.1–27 t per vehicle, production stage with 10 t per vehicle and 6.4–14 t per vehicle, infrastructure stage with 2.1 t per vehicle and 0.99–8.6 t per vehicle, maintenance stage with 1.4 t per vehicle and 0.9–1.4 t per vehicle, and end-of-life stage with 1.1 t per vehicle and 0.72–6.9 t per vehicle. The maximum values were observed at fuel and electricity production, production, infrastructure, and end-of-life stage with 47 t per vehicle, 21 t per vehicle, 8.6 t per vehicle, and 6.9 t per vehicle, which were over twice the corresponding median values. The minimum value at the fuel and electricity production stage with the indispensable median had the largest rate of decline, to one-tenth of the median. Life cycle CO_2 emissions at the production stage and the fuel and electricity production stage of EV were obtained from the inventory meta-analysis by FVV Prime Movers [25]. The median and the 25th-75th percentile values at the production stage were 10 t per vehicle and 6.4–14 t per vehicle in this study and 12 t per vehicle and 9.5–14 t per vehicle in the FVV Prime Movers study. At the production stage, the trends were generally similar in both studies. The difference in the results between both studies may be due to the difference in their sample size. The median and the 25th-75th percentile values at the fuel and electricity production stage were 17 t per vehicle and 9.1–27 t per vehicle in this study and 22 t per vehicle and 17–36 t per vehicle in the FVV Prime Movers study. At the fuel and electricity production stage, both studies showed differences in the median and the 25th-75th percentile values. A larger median was observed in the FVV Prime Movers study because most of the studies covered by FVV Prime Movers employed hydrogen production methods with high CO2 emissions. A larger 25th-75th percentile value was observed in this study possibly because the studies covered in this study employed various hydrogen production methods.

A comprehensive comparison of the results based on the powertrain types (Fig. 5(a)–(f)) showed that ICGV and ICDV that utilize internal combustion engines with direct emissions dominate the use stage in life cycle CO_2 emissions. HV and PHV exhibited a different tendency: CO_2 emissions at the use stage were lesser than those of ICGV and ICDV owing to the electric motor with high energy efficiency, whereas production stage emission was higher than that at the use stage attributed to the battery in the electricity motor. With respect to EV and FCV with the same tendency at the production stage as HV and PHV, their fuel and electricity production stage emissions and their dispersion considerably increased from zero emission at the use stage, because EV and FCV use electricity depending on the country energy mix and hydrogen with various production methods.

A comparison of the results based on the powertrain types (Fig. 5(a)–(f)) did not reveal any evident differences between ICGV and ICDV. The different characteristics of HV and PHV were evident at their use and fuel and electricity production stages. At the use stage, the emission of PHV and its dispersion slightly decreased and increased, respectively, more than those of HV owing to the possibility of fuel use in PHV. In the fuel and electricity production stage, the emission of PHV and its dispersion increased from those of HV owing to the difference in country energy mix. The comparison results of EV and FCV revealed an increase in the emission dispersion at the production, end-of-life, fuel and electricity production, and infrastructure stages from established EVs to unestablished FCVs.

3.2. Results of the meta-analysis-based approach from a specific perspective

The results of the meta-analysis-based approach on automobile LCA studies from specific perspectives, focusing on the aspects of globalization, social expansion, and country diversity, are summarized in this section. The meta-analysis-based approach results for each aspect are explained below.

3.2.1. Globalization aspect

The aggregate analysis results for automobile LCA studies from the globalization aspect are shown in Fig. 6. This figure presents the number of papers categorized by the quality of methods, the purpose types, and the contribution of the papers to the globalization aspect (see Fig. 3). In this aggregate analysis, the consideration of the globalization aspect was judged by whether or not international trade was explicitly addressed in the system boundary of the paper.

Among the total 332 collected papers, 25 papers (7.5%) had considered globalization. In terms of the quality of methods, 11 papers (12%) among 93 papers in Level 1 of inventory analysis, 5 papers (6.0%) among 83 papers in Level 2 of impact assessment, 6 papers (7.3%) among 82 papers in Level 3 of inventory analysis with uncertainty analysis, and 3 papers (4.1%) among 74 papers in Level 4 of impact analysis with uncertainty analysis were observed to consider globalization. Automobile LCA studies that considered the globalization aspect and focused on the purpose types were 14 papers (7.0%) among 199 papers on comparison of technology, 7 papers (9.5%) among 74 papers on evaluation of specific technology, and 4 papers (6.8%) among 59 papers on fleet-based LCA and others. Hence, the studies that considered globalization were limited to less than 10% in automobile LCA studies. Furthermore, low-quality method studies tend to consider globalization aspect more than high-quality method studies.

Fig. 7 shows the results of the inventory meta-analysis on automobile LCA papers from the globalization aspect. In this figure, CO_2 emissions at the production and the fuel production stages, utilizing gasoline, diesel, compressed natural gas (CNG), and ethanol, in ICV-type passenger cars were compared between papers with and without the globalization aspect using average and standard deviation (SD). In this inventory meta-analysis, globalization was evaluated by the description of international trade in the system boundary of the collected paper, similar to that shown in Fig. 6. The reason for choosing the specific life stage, powertrain type, and vehicle type in this inventory meta-analysis is the limitations in the number of the collected papers.

As shown in Fig. 7, CO_2 emissions at the production stage were at 7.6 $\pm$ 3.7 t (average $\pm$ SD) per vehicle without the globalization aspect and 7.7 t per vehicle with the globalization aspect. CO_2 emissions at the gasoline production stage were at 5.8 $\pm$ 2.6 t per vehicle without the globalization aspect and 3.9 $\pm$ 0.57 t per vehicle with the globalization aspect. CO_2 emissions at the diesel production stage were at 4.0 $\pm$ 2.5 t per vehicle without the globalization aspect and 2.9 $\pm$ 0.85 t per vehicle with the globalization aspect. CO_2 emissions at the CNG production stage were at 3.7 $\pm$ 1.3 t per vehicle without the globalization aspect and 7.1 $\pm$ 0.38 t per vehicle with the globalization aspect. CO_2 emissions at the ethanol production stage were at 7.1 t per vehicle without the globalization aspect and 7.9 t per vehicle with the globalization aspect. The SDs for the production stage with globalization and the ethanol production stage with and without globalization could not be calculated, as there was only one sample.

CO_2 emissions at the use stage with globalization were expected to have higher values than those without globalization because of the global reuse of automobiles across countries from developed countries to developing countries [7,8]. However, the inventory meta-analysis results could not include the use stage owing to the limitation in the number of the collected papers; therefore, a negative effect of globalization was not observed. In the inventory meta-analysis results, the difference between the with and the without globalization categories

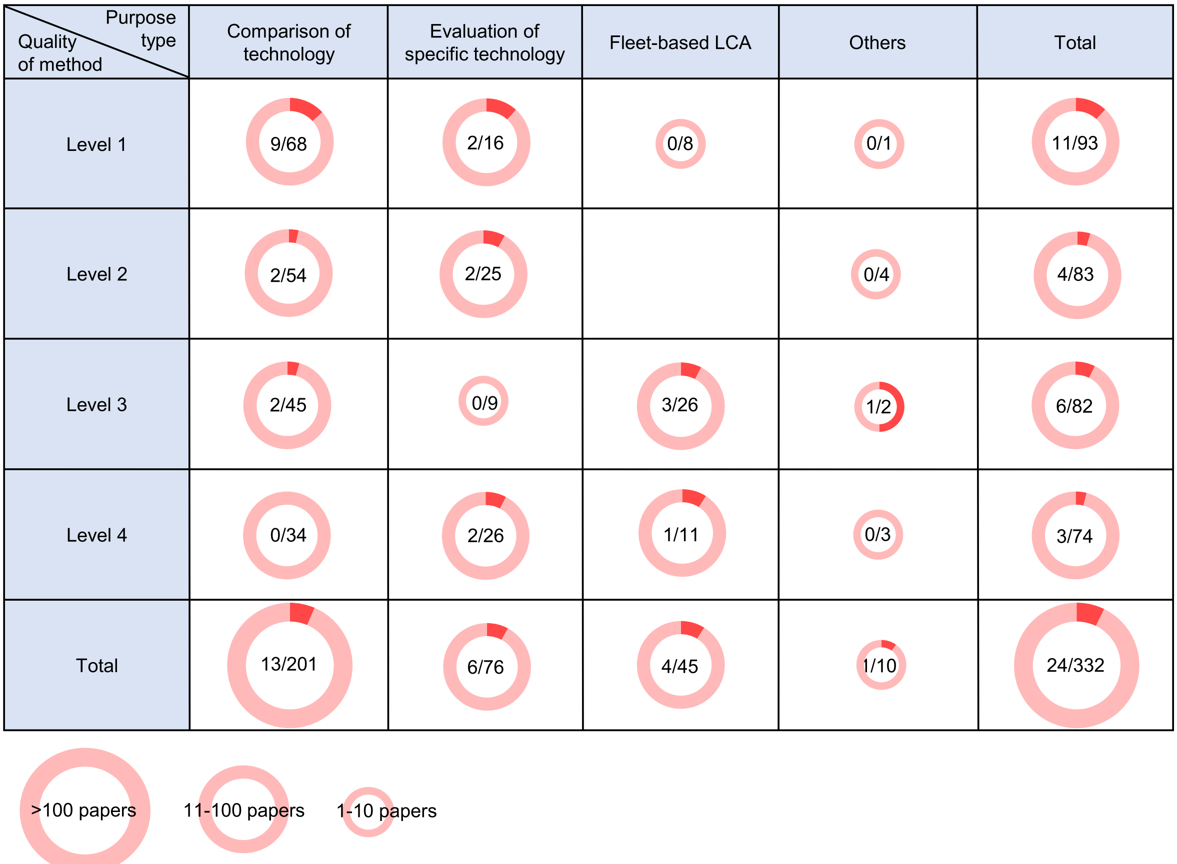

Fig. 6. Aggregate analysis results for the number of papers categorized by the quality of methods, purpose types, and the contribution of papers to the globalization aspect.

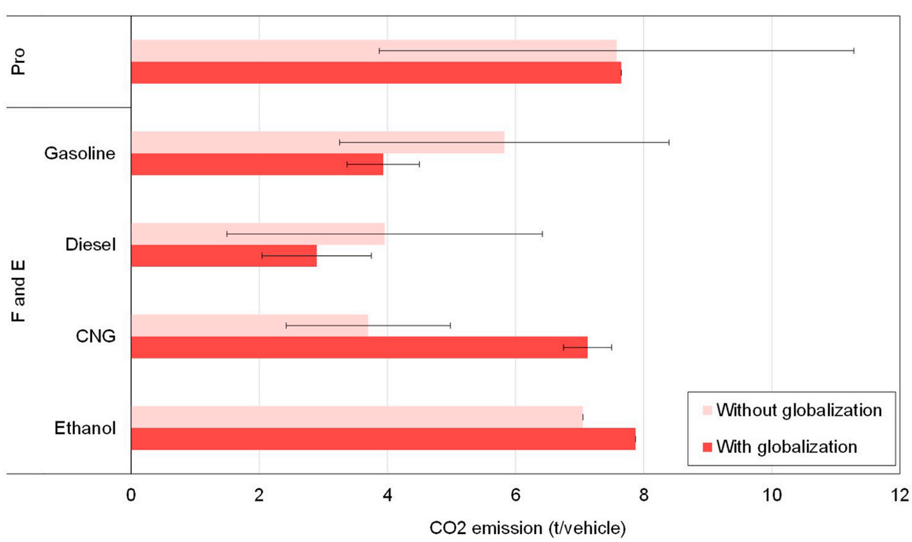

Fig. 7. The results of the inventory meta-analysis on automobile LCA studies from the globalization aspect. Pro and F and E represent production stage and fuel and electricity stages. CNG represents compressed natural gas.

exhibited various tendencies at the production and fuel production stages. In particular, the tendency for the fuel production stage originated from the large scattering results without the globalization aspect, including the various conditions for estimation of the CO_2 emissions such as country-specific energy mix situation.

3.2.2. Social expansion aspect

The results of the aggregate analysis on automobile LCA studies from the social expansion aspect are shown in Fig. 8. This figure shows the number of papers categorized into vehicle and powertrain types and the contribution of papers to the social expansion aspect (see Fig. 3). In this aggregate analysis, social expansion was judged by whether or not the infrastructure stage was explicitly addressed in the system boundary of

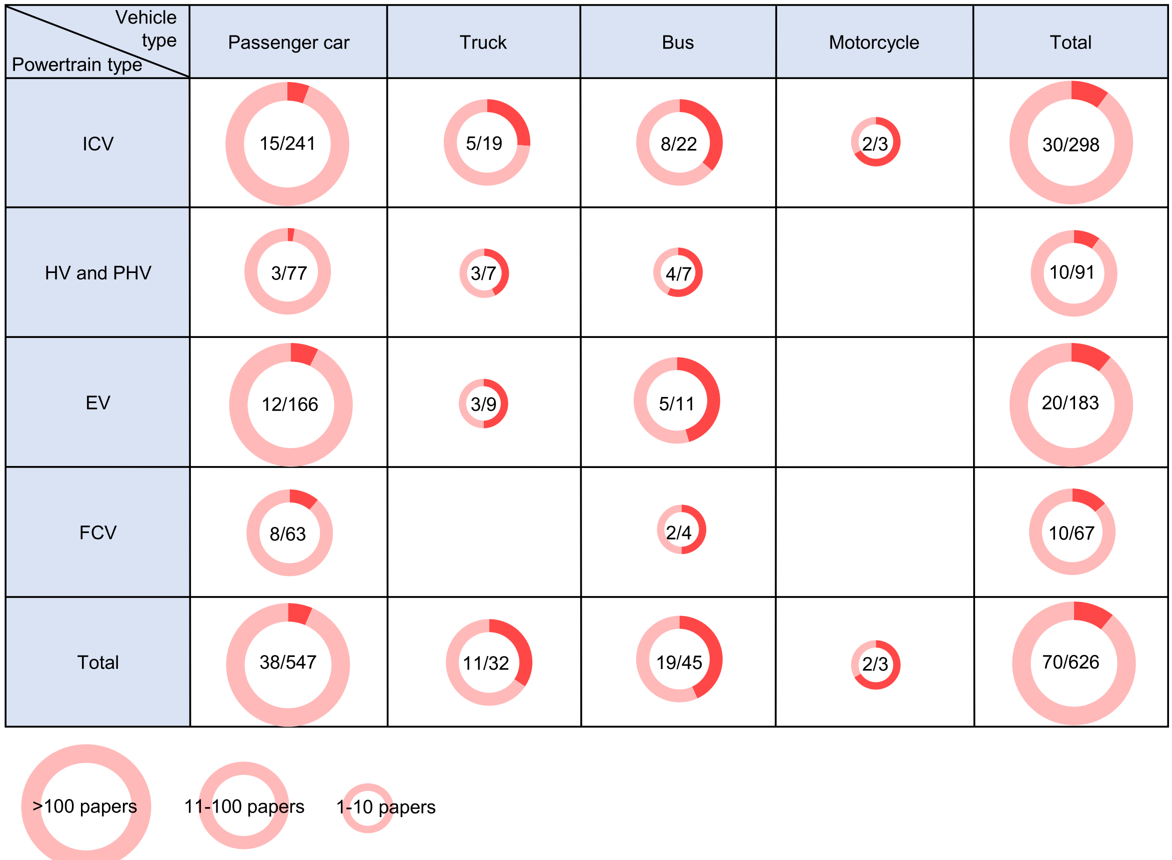

Fig. 8. Aggregate analysis results pertaining to the number of papers categorized in powertrain and vehicle types and the contribution of the papers to the social expansion aspect. ICV, HV, PHV, EV, and FCV represent internal combustion engine vehicle, hybrid vehicles, plug-in hybrid vehicle, electric vehicles, and fuel cell vehicles, respectively.

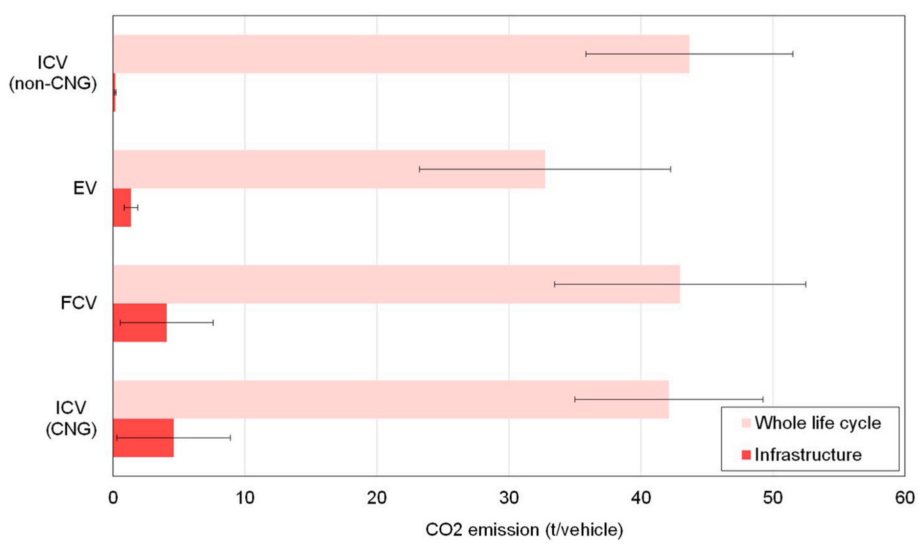

Fig. 9. The results of the inventory meta-analysis on automobile LCA studies from the social expansion aspect. ICV, EV, and FCV represent internal combustion engine vehicle, electric vehicles, and fuel cell vehicle, respectively. CNG represents compressed natural gas.

the collected paper. The total number of papers in this aggregate analysis is higher than the 332 collected papers because one paper usually targets several vehicles and powertrain types.

As shown in Fig. 8, among the total 626 papers, 70 papers (11%) had considered the social expansion aspect. Focusing on the powertrain types, 30 papers (11%) among 285 papers on ICV, 10 papers (11%) among 91 papers on HV and PHV, 20 papers (11%) among 183 papers on EVs, and 10 papers (15%) among 67 papers on FCV were observed to have considered social expansion. The papers that considered social expansion and focused on vehicle types were 38 papers (6.9%) among 547 papers on passenger cars, 11 papers (34%) among 32 papers on trucks, 19 papers (43%) among 44 papers on buses, and 2 papers (67%)

among 3 papers on motorcycles. Hence, the LCA papers on FCVs exhibited a tendency to consider the social expansion aspect by adding the infrastructure stage than those on ICV, HV and PHV, and EV. Furthermore, our results indicate that the contribution of the LCA studies to the social expansion aspect increased in the order of passenger cars with mainly private use, trucks with mainly business use, and buses with mainly public use. The interpretation for the papers on motorcycles was difficult due to the small sample size.

Fig. 9 shows the results of the inventory meta-analysis on automobile LCA studies from the social expansion aspect. To assess the effect of the social expansion aspect in LCA, CO_2 emissions at the infrastructure stage and life cycle CO_2 emissions in passenger cars were compared using the inventory analysis results from the collected papers. This comparison targeted three powertrain types: ICV, EV, and FCV. ICV are categorized into CNG vehicles and others (non-CNG vehicles). The average and SD were used as the analytical indices. The SD of life cycle CO_2 emissions was calculated by the error propagation method to integrate the SDs of CO_2 emissions from each life stage.

As shown in Fig. 9, the average and SD of life cycle CO_2 emissions and CO_2 emissions at the infrastructure stage in non-CNG vehicles in ICV were 44 ± 7.8 t per vehicle and 0.18 ± 0.06 t per vehicle, respectively, while those in CNG vehicles were 42 ± 7.1 t per vehicle and 4.6 ± 4.3 t per vehicle, respectively. The average and SD of life cycle CO_2 emissions and CO_2 emissions at the infrastructure stage in EVs are 33 ± 9.5 t per vehicle and 1.4 ± 0.51 t per vehicle, respectively, and those in FCVs were 43 ± 9.5 t per vehicle and 4.1 ± 3.5 t per vehicle, respectively.

The results of the inventory meta-analysis indicate that the effect of the CO_2 emissions at the infrastructure stage in specific use vehicle such as FC bus and CNG trucks accounted for approximately 10% of their life cycle CO_2 emissions. The calculation of CO_2 emissions at the infrastructure stage relies on the balance between the infrastructure and the corresponding vehicles in their social expansion scenario. For example, when some hydrogen refueling stations exist despite the limited expansion of FCVs, the effect of the infrastructure stage becomes large. Thus, the social expansion aspect could generate a large effect of the infrastructure stage on life cycle CO_2 emissions.

3.2.3. Country diversity aspect

The results of the aggregate analysis on automobile LCA studies from the country diversity aspect are shown in Fig. 10. The country diversity aspect focuses on LCA studies targeting developing countries, where the environmental impacts on the use stage is expected to be higher than those in developed countries due to older vehicles, poor emission standard, and traffic congestion. Fig. 10 shows the number of papers categorized by vehicle types and system boundaries and the contribution of papers considering developing countries. The total number of papers in this aggregate analysis is higher than the 332 collected papers because one paper may target several vehicle types.

As shown in Fig. 10, considering the country diversity aspect, 82 papers (24%) were spotted from 345 papers. In terms of the system boundary, 26 papers (28%) among 93 papers in well to wheel (WTW), 20 papers (20%) among 100 papers in vehicle life cycle (VLC), and 36 papers (24%) among 152 papers in WTW and VLC were observed to have considered the country diversity aspect. Moreover, the papers that considered the country diversity aspect and focused on the vehicle types were 68 papers (23%) among 297 papers on passenger cars, 5 papers (25%) among 20 papers on trucks, 8 papers (32%) among 25 papers on buses, and 1 paper (33%) among 3 papers on motorcycles. With respect to WTW, 3 papers (50%) among 6 papers on trucks and 5 papers (63%) among 8 papers on buses were found to have considered the country diversity aspect. Hence, the LCA studies that considered WTW in trucks and buses for commercial use have a tendency to consider the country diversity aspect, because developing countries are highly concerned with WTW analysis of commercial use vehicles that require fuel cost performance improvement. Furthermore, our results indicate that the papers on motorcycles are quantitively limited, even though motorcycles constitute the major transport mode in developing countries, especially the Association of Southeast Asian Nations (ASEAN) [45].

Fig. 11 shows the results of the inventory meta-analysis on automobile LCA studies from the country diversity aspect. Life cycle CO_2

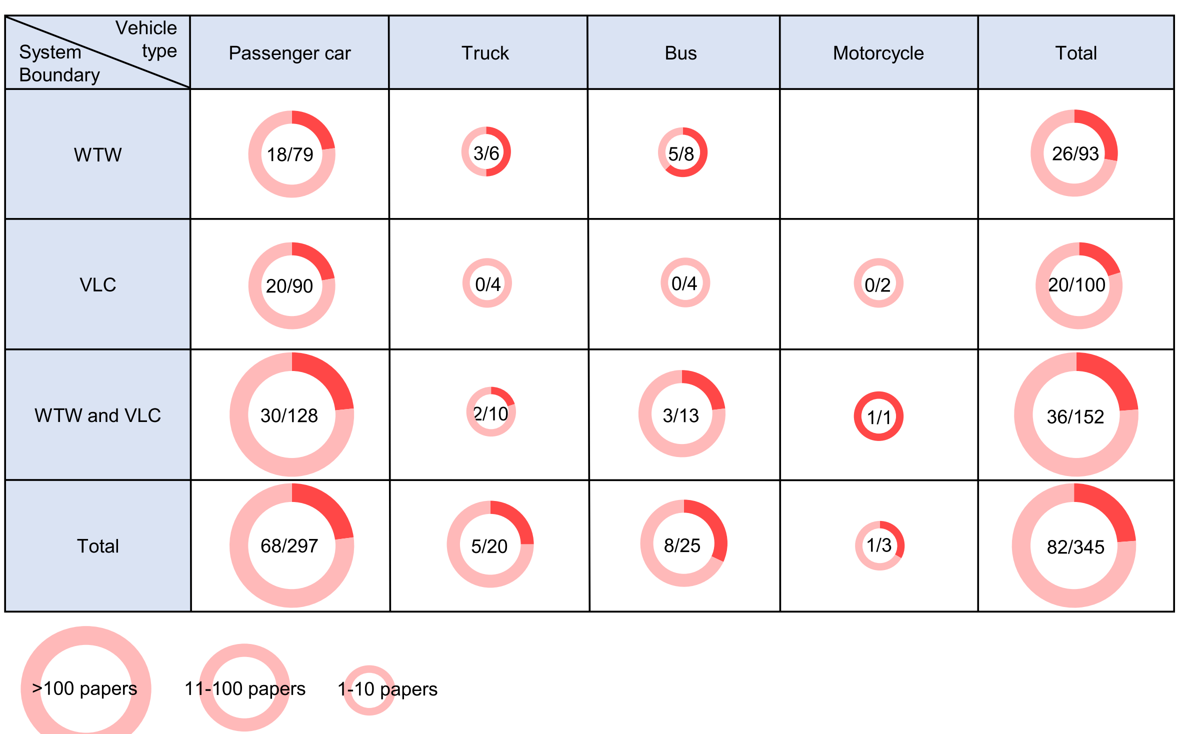

Fig. 10. Aggregate analysis results pertaining to the number of papers categorized by system boundaries, vehicle types, and the contribution of papers to the country diversity aspect. WTW and VLC represent well to wheel and vehicle life cycle, respectively.

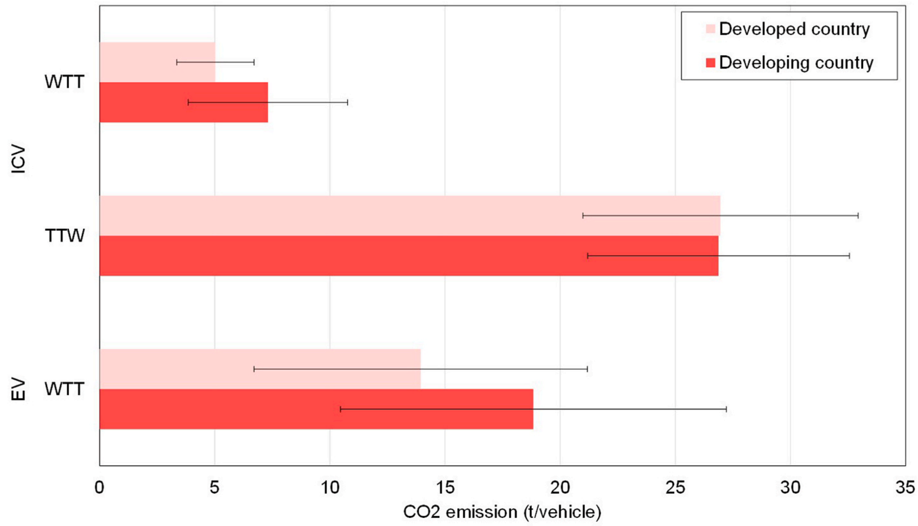

Fig. 11. The results of the inventory meta-analysis on automobile LCA studies from the country diversity aspect. ICV and EV represent internal combustion engine vehicle and electric vehicles, respectively. WTT and TTW represent well to tank and tank to wheel, respectively.

emissions from the WTW system boundary in passenger cars were compared between developed and developing countries using the inventory analysis results from the collected papers. The WTW system boundary can be divided into well to tank (WTT) and tank to wheel (TTW). This comparison focuses on ICV and EV. TTW for EV that became zero because zero emission occurred in the use stage were excluded from Fig. 11. The average and SD were used as the assessment indices. The SD of life-cycle CO_2 emissions was calculated by the error propagation method. As shown in Fig. 11, the average and SD of the WTT CO_2 emissions in ICV in developed and developing countries were 5.0 $\pm$ 1.7 t per vehicle and 7.3 $\pm$ 3.5 t per vehicle, respectively; the WTT CO_2 emissions in EVs in developed and developing countries were 14 $\pm$ 7.2 t per vehicle and 19 $\pm$ 8.4 t per vehicle; and the TTW CO_2 emissions in ICV in developed and developing countries were 27 $\pm$ 6.0 t per vehicle and 27 $\pm$ 5.7 t per vehicle. The difference in WTT CO_2 emissions in ICVs and FCVs between developed and developing countries was due to the emission calculation that considered the country diversity in fuel production and energy mix. However, a difference in TTW CO_2 emissions in ICV between developed and developing countries could not be observed. In developing countries, high CO_2 emissions in ICVs at the use stage are expected, owing to their long lifetime in vehicle factors, poor emission standards in emission control factors, and traffic congestion in driving factors. Therefore, it was inferred that the previous LCA studies did not sufficiently consider the country diversity aspect, focusing on the differences in vehicles, emission control, and driving factors between countries.

4. Discussion

This study comprehensively reviewed automobile LCA studies using a meta-analysis-based approach. First, the findings from the meta-analysis-based approach from a comprehensive perspective are discussed below.

The results of the meta-analysis-based approach from a comprehensive perspective indicate the progress of automobile LCA studies in technology assessment. For example, comparison of technology and evaluation of specific technology were the most common purposes of automobile LCA studies with a trend of covering the entire vehicle life cycle (VLC) and using a high-quality method (see Figs. 2–4). An in-depth understanding that the relative advantages of ICV and EV depend on the country's energy mix is achieved through the comparison of ICV and EV (Fig. 5). The above-mentioned progress in automobile LCA studies in technology assessment signifies a challenge in the expansion of LCA studies to system design, which is the next step. For example, an automobile LCA study for system design should aim for a fleet-based LCA to assess the environmental impacts of total vehicles existing in a target society. Conventional LCA determines the individual VLC for a specific vehicle and powertrain type, whereas a fleet-based LCA aggregates the VLC of various vehicle and powertrain types on a specific spatiotemporal scale [2,20]. Thus, fleet-based LCA enables policy makers and consumers to support environmental policy (e.g., subsidies for EVs and FCVs) and vehicle choice (e.g., ecolabeling) by modeling the vehicle configuration in the aggregated fleet [46,47].

Next, the findings from the meta-analysis-based approach from specific perspective are discussed, as follows. As the specific perspectives, this study focused on the aspects of globalization, social expansion, country diversity, and battery degradation.

The results of the meta-analysis-based approach on automobile LCA studies from the globalization aspect revealed that few studies have considered international trade in their system boundary, which is mainly limited to the fuel production stage. In the terms of the other life stages, especially the use and the end-of-life stages, no automobile LCA study has followed the international trade of used automobiles and parts, automobile-related scraps, and automobile-related wastes, which are known as global reuse, global recycling, and global land filling, respectively [48,49]. In particular, the significance of the global reuse of automobiles from the environmental and social impact perspective has been reported by the UNEP and our previous studies [7–11,50]. Thus, the next challenge of automobile LCA studies would be to consider the globalization aspect, especially focusing on global reuse through spatial expansion in the use stage of the system boundary. This challenge is also affected by trade statistics pertaining to the collection of trade data on used automobiles and auto parts. This difficulty is categorized into identification problem and mirror statistical problem [8,51–55]. The identification problem refers to the difficulty in identifying new and used products in trade statistics owing to the aggregation of the product classification of new and used products. The mirror statistical problem represents the difficulty in choosing whether the trade data from the importing country or from the corresponding exporting country should be used in both trade statistics. The active use of previous methods to solve identification and mirror statistical problems can help overcome the challenge faced by automobile LCA studies from the globalization aspect [8,51,56–59].

The results of the meta-analysis-based approach on automobile LCA studies from the social expansion aspect revealed the tendency of the studies, including the effect at the infrastructure stage. Automobile LCA studies on CNG vehicles and FCV without well-developed CNG and hydrogen refueling stations tended to consider the social expansion aspect; however, other studies on conventional vehicles with well-developed gas stations did not tend to consider the social expansion aspect. To include the social expansion aspect in the LCA on non-specific use vehicles, simply adding the infrastructure stage in the system boundary is sufficient. The point to consider in the social expansion aspect in automobile LCA is the balance between the demand for in-use automobiles and the supply of the corresponding infrastructure. For example, the imbalance in the demand and the supply of current EV or FCV has increased the environmental impacts of the infrastructure stage allocated to the function unit due to the oversupply of electric charging or hydrogen refueling stations in the early phase of social expansion [24,25,60,61]. To reflect the demand-supply balance in automobile LCA, a fleet-based LCA that directly describes the social expansion of in-use demand for forecasting automobile fleet may be adopted [24]. Hence, the next challenge in automobile LCA studies is to expand fleet-based LCA to consider not only the in-use demand but also the related infrastructure supply. In such an expansion, previous studies on infrastructure planning targeting hydrogen refueling stations are useful [62–64]. The expanded fleet-based LCA also generates the additional value of automobile LCA by supporting the social expansion of EVs and FCVs through infrastructure planning.

The results of the meta-analysis-based approach on automobile LCA studies from the country diversity aspect showed that the well to wheel (WTW) analysis for commercial use vehicles requiring fuel cost performance is generally concentrated in developing countries. However, automobile LCA studies targeting motorcycles as the major transport mode in developing countries were found to be quantitively limited. Although some automobile LCA studies target developing countries, as observed from the aggregate analysis results, these studies did not sufficiently reflect the unique environmental impacts of ICV at the use stage in developing countries in the inventory meta-analysis results. These environmental impacts are serious air pollution due to the long lifetime and driving distance as vehicle factors, poor inspection and maintenance systems and poor emission standards as emission control factors, and poor pavement and traffic congestion as driving factors [28–31]. The unique environmental impacts of ICV can apply to LCA studies considering motorcycles as a major mobility mode in developing countries [32–35]. In addition, these impacts are related to the previously mentioned globalization aspect, because automobiles used in developed countries are massively exported and reused in developing countries [7,8]. Hence, the next challenge for the automobile LCA studies is to consider the unique environmental impacts of ICVs especially in motorcycles in developing countries by integrating the International Vehicle Emissions (IVE) model and fleet-based LCA [25,31]. An IVE model funded by the U.S. Environmental Protection Agency (USEPA) to estimate vehicular emissions in developing countries include vehicle factors, emission control factors, and driving factors. IVE models are utilized in the atmospheric environment research field [32,65,66]. Fleet-based LCA requires considering the shift from motorcycle to four-wheeled vehicles caused by economic growth in developing countries. Such hybrid use of the IVE model and fleet-based LCA generates an additional value for automobile LCA by providing integrated and organized support to the behavior change by drivers, advanced inspection and maintenance by automobile companies, and emission standard making by governments to reduce air pollution from in-use automobiles in developing countries.

This study focused on the globalization, social expansion, country diversity, and battery degradation aspects as the review scope in the meta-analysis-based approach. The meta-analysis-based approach of this study excluded the battery degradation aspect because of the limited number of previous LCA studies in the selected sample. However this section discusses the battery degradation aspect based on the previous literature related not to LCA but to the EV battery. The UNEP reported exports of used EVs from the EU and Japan [7]. The recipients of the EVs from EU are mainly developing countries, such as Jordan and Ukraine, and those from Japan are mainly developing countries, such as Mongolia, Sri Lanka, and the Russian Federation [7]. Previous studies on EV battery have addressed the aging-induced annual capacity loss in EV batteries [36,37,39]. This UNEP report and previous studies have revealed the global reuse of EVs and their impacts on battery replacement such as long lifetime and driving distance. These studies have also referred to the annual capacity loss in EV batteries under ambient temperature [36,37,39]. This suggests that the battery in used EVs imported to hot or cold countries (e.g., Sri Lanka or Russian Federation, respectively) degrade owing to the ambient temperature. Previous fleet-based LCA studies on EVs have showed a reduction potential in the environmental impact associated with future social expansion of EV [67–75]. However, these studies did not consider the aforementioned battery degradation. Hence, the social expansion of EVs may not always result in an environmental impact reduction from the battery degradation aspect. In summary, battery replacement and degradation, considering the long lifetime, long driving distance, and the ambient temperature in the importing countries in the global reuse situation, represent the linkage of globalization, country diversity, and battery degradation in future social expansion of EVs. The next challenge in considering the battery degradation aspect in automobile LCA is spatial expansion of the system boundary of EVs to include global reuse. In this challenge, the environmental impacts of EVs in developing countries should be considered using the information on the long lifetime, long driving distance, and the ambient temperature within the framework of fleet-based LCA from the linkage of globalization, social expansion, country diversity, and battery degradation aspects.

Therefore, our review highlighted the urgency to expand the automobile LCA studies from technology assessment to system design, including policy making and decision-making related to governments and drivers. In addition, our review identified the upcoming challenges in advancing automobile LCA from the aspects of globalization, social expansion, country diversity, and battery degradation.

Future work on automobile LCA review studies can be categorized based on the review scope and the review method. A review scope is required to cover the social impact of automobiles such as traffic accidents and congestion, a new system to use automobiles such as car sharing, advanced technology including automated vehicles, and alternative transport modes such as delivery drones. This study used a meta-analysis-based approach and analyzed the targeted papers as data samples under a given review scope, similar to the review method. A new direction for the review method would be to introduce a citation network analysis, which classifies automobile LCA studies based on the relationships among them inferred from their citation information, in the review of automobile LCA studies [76,77].

5. Conclusion

This study comprehensively reviewed automobile LCA studies using a meta-analysis-based approach. In our meta-analysis-based approach which included 332 peer-reviewed papers, the trends of the automobile LCA studies were revealed from a comprehensive and specific perspectives based on the aspects of globalization, social expansion, and country diversity. The meta-analysis-based approach was not used on the battery degradation aspect, due to the limited number of relevant studies.

The results of the meta-analysis-based approach from a comprehensive perspective indicated the progress of automobile LCA studies in technology assessment. The results signify the upcoming challenge for automobile LCA studies to expand the conventional LCA studies for system design using fleet-based LCA.The results of the meta-analysis-based approach from the globalization aspect revealed that few studies have considered international trade in the fuel production stage. The upcoming challenge from the globalization aspect is to deal with global reuse through spatial expansion in the use stage.The results of the meta-analysis-based approach from the social expansion aspect indicated that studies on CNG and fuel cell vehicles tend to consider the infrastructure in the system boundary. The upcoming challenge for automobile LCA studies is to expand the fleet-based LCA to consider not only the in-use demand but also the related infrastructure supply.The results of the meta-analysis-based approach from the country diversity aspect showed that the well to wheel analysis of commercial-use vehicles is generally concentrated in developing countries.The upcoming challenge is to consider the unique environmental impacts of conventional vehicles, especially motorcycles, in developing countries by integrating the International Vehicle Emissions (IVE) model and fleet-based LCA.Based on the findings from the globalization, social expansion, and the country diversity aspects, the next challenge from the battery degradation aspect is to expand automobile LCA using information on the long lifetime, long driving distance, and ambient temperature within the framework of fleet-based LCA.

Future review scope of automobile LCA studies should cover the social impact of automobiles, a new system to use automobiles, advanced automobile technology, and alternative transport modes. As a future review method, the relationships among the automobile LCA studies in the review items in this study would be investigated through a citation network analysis.

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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.

Appendices.

Table A.1
Reference No.1-49 of automobile LCA studies reviewed in this study. GL, SO, CO, and BA represent globalization, social expansion, country diversity, battery degradation aspects, respectively.

No.	Authors	Publication information	GL	SO	CO	BA
1	Eriksson at al.	Sci Total Environ 1996; 189–190:69–76				
2	Pehnt at al.	Int J Hydrog Energy 2001; 26 (1):91–101	✓			
3	Nigge at al.	Int J Life Cycle Assess 2001; 6:334–8				
4	McCleese at al.	Int J Life Cycle Assess 2002; 7 (4):230–6				
5	Castro at al.	Int J Life Cycle Assess 2003; 8 (5):297–304				
6	Pehnt at al.	Int J Life Cycle Assess 2003; 8 (5):283–9	✓	✓		
7	Mierlo at al.	Proc Inst Mech Eng part D–J Automob Eng 2003; 217 (7):583–94				
8	Hu at al.	Renew Energy 2004; 29 (14):2183–94			✓	
9	Kim at al.	Transp Res Part D: Transp Environ 2004; 9:229–49				
10	Schmidt at al.	Int J Life Cycle Assess 2004; 9 (6):405–16				
11	Spatari at al.	Environ Sci Technol 2005; 39 (24):9750–8				
12	Wang at al.	Fuel Process Technol 2005; 86 (7):831–45			✓	
13	Yamada at al.	J Jpn Inst Met 2005; 69 (2):237–40				
14	Colella at al.	J Power Sources 2005; 150 (1):150–81				
15	Zamel at al.	J Power Sources 2006; 162 (2):1241–53				
16	Wagner at al.	Energy 2006; 31 (14):3062–75	✓			
17	Schafer at al.	Energy 2006; 31 (12):2064–87				
18	Silva at al.	Sci Total Environ 2006; 367 (1):441–7	✓			
19	Granovskii at al.	Int J Hydrog Energy 2006; 31 (3):337–52	✓			
20	Duval at al.	J Clean Prod 2007; 15 (11–12):1158–68				
21	Tharumarajah at al.	J Clean Prod 2007; 15 (11–12):1007–13	✓			
22	Funazaki at al.	J Jpn Inst Energy 2007; 86 (1):32–8	✓			
23	Hussian at al.	Appl Therm Eng 2007; 27 (13):2294–9				
24	Facanha at al.	Environ Sci Technol 2007; 41 (20):7138–44		✓		
25	Ally at al.	J Power Sources 2007; 170 (2):401–11		✓		
26	Granovskii at al.	J Power Sources 2007; 167 (2):461–71				
27	Spielmann at al.	J Clean Prod 2007; 15 (11–12):1122–34				
28	Zah at al.	J Clean Prod 2007; 15 (11–12):1032–40	✓		✓	
29	Zhang at al.	Energy 2007; 32 (10):1896–1904			✓	
30	Samaras at al.	Environ Sci Technol 2008; 42 (9):3170–6				
31	Kim at al.	Bioresour Technol 2008; 99 (12):5250–60				
32	Dhanushkodi at al.	J Environ Inform 2008; 11 (1):36–44				
33	Geyer at al.	Environ Sci Technol 2008; 42 (18):6973–9				
34	Gonzalez–Garcia at al.	Renew Sustain Energy Rev 2009; 13 (8):1922–33				
35	Luo at al.	Renew Sustain Energy Rev 2009; 13 (6–7):1613–9			✓	
36	Jaramillo at al.	Energy Policy 2009; 37 (7):2689–95				
37	Huo at al.	Atmospheric Environ 2009; 43 (10):1796–1804				
38	Panichelli at al.	Int J Life Cycle Assess 2009; 14 (2):144–59	✓		✓	
39	Puri at al.	Int J Life Cycle Assess 2009; 14 (5):420–8				
40	Lee at al.	Int J Hydrog Energy 2009; 34 (20):8455–67	✓			
41	Liu at al.	Energy Policy 2009; 37 (4):1479–88			✓	
42	Melamu at al.	Int J Hydrog Energy 2009; 34 (2):1126–34				
43	Pleanjai at al.	J Clean Prod 2009; 17 (9):873–6	✓		✓	
44	Zackrisson at al.	J Clean Prod 2010; 18 (15):1519–29				
45	Kantor at al.	Int J Hydrog Energy 2010; 35 (10):5145–53				
46	Kim at al.	J Ind Ecol 2010; 14 (6):929–46				
47	Baptista at al.	Int J Hydrog Energy 2010; 35 (18):10024–30				
48	Lee at al.	Int J Hydrog Energy 2010; 35 (6):2213–25		✓		
49	Subic at al.	Int J Veh Des 2010; 53 (1):89–109				

Table A.2
Reference No.50-115 of automobile LCA studies reviewed in this study. GL, SO, CO, and BA represent globalization, social expansion, country diversity, battery degradation aspects, respectively.

No.	Authors	Publication information	GL	SO	CO	BA
50	Du at al.	J Clean Prod 2010; 18 (2):112–9			✓	
51	Du at al.	Energy 2010; 35 (12):4671–8			✓	
52	Hao at al.	Appl Energy 2010; 87 (10):3212–7	✓		✓	
53	Mejeau–Bettez at al.	Environ Sci Technol 2011; 45 (10):4548–54				
54	Witik at al.	Compos Part A: Appl Sci Manuf 2011; 42 (11):1694–709				
55	Ferreira at al.	Int J Hydrog Energy 2011; 36 (21):13547–58				
56	Esteban at al.	Mater Des 2011; 35 (3):1317–28				
57	Das	Int J Life Cycle Assess 2012; 16 (3):268–82				
58	Gonzalez–Garcia at al.	Sci Total Environ 2012; 438 (1):1–8				
59	Hsu at al.	Energy Fuels 2012; 45:41–47				
60	Szczechowicz at al.	Int J Life Cycle Assess 2012; 17 (9):1131–41				
61	MacPherson at al.	J Ind Ecol 2012; 16 (5):761–73				
62	Faria at al.	Energy Coversion and Management 2012; 61:19–30				
63	Ma at al.	Energy Policy 2012; 44:160–73	✓			
64	Gao at al.	Energies 2012; 5 (12):605–20				
65	Bastani et al.	Transp Res Part A: Policy Pract 2012; 46 (3):517–48				
66	McKenzie et al.	Transp Res Part D: Transp Environ 2012; 17 (1):39–47		✓		
67	Berger et al.	Environ Sci Technol 2012; 46 (7):4091–9				
68	Nanaki et al.	J Clean Prod 2012; 20 (1):14–9				
69	Chester et al.	Environ Res Lett 2012; 7 (3):034012				
70	Hacatoglu et al.	Int J Hydrog Energy 2012; 37 (13):9933–40				
71	Kendall et al.	Environ Sci Technol 2012; 46 (5):2557–63				
72	Huo et al.	Energy Policy 2012; 43:37–48			✓	
73	Mayyas et al.	Energy 2012; 39 (1):412–25			✓	
74	Gonzalez–Garcia et al.	Int J Life Cycle Assess 2013; 18 (4):783–95				
75	Feraldi et al.	Int J Life Cycle Assess 2013; 18 (3):613–25				
76	Hawkins et al.	J Ind Ecol 2013; 17 (1):53–64				
77	Weinberg et al.	Bioresour Technol 2013; 150:420–8				
78	Singh et al.	Transp Res Part D: Transp Environ 2013; 25:106–11		✓		
79	Cooney et al.	J Ind Ecol 2013; 17 (5):689–99		✓		
80	Bartolozzi et al.	Appl Energy 2013; 101:113–11				
81	Ehrenberger et al.	JOM 2013; 65:1306–9				
82	Lang et al.	Energies 2013; 6 (5):2663–85				
83	Gujba et al.	Energy Policy 2013; 55:353–61	✓	✓	✓	
84	Luk et al.	Environ Sci Technol 2013; 47 (18):10676–84				
85	Patterson et al.	Bioresour Technol 2013; 131:235–45				
86	Biswas et al.	Int J Hydrog Energy 2013; 38 (1):246–54				
87	Chlopek et al.	Eksploat Niezawodn–Maint Reliab 2013; 15 (1):44–50				
88	Mitropoulos et al.	Transp Res Rec 2013; 2344 (2344):88–97				
89	Pourbafrani et al.	Environ Res Lett 2013; 8 (015007):1–12				
90	Kanchanapiya et al.	Environ Prot Eng 2013; 39 (1):101–14			✓	
91	Onat et al.	Sustainability 2014; 6 (12):9305–42				
92	Chatzikomis et al.	Eur Transp Res Rev 2014; 6 (4):365–76				
93	Buekers et al.	Transp Res Part D: Transp Environ 2014; 33:26–38				
94	Faria et al.	J Power Sources 2014; 262:169–77				
95	Nanaki et al.	Transp Policy 2014; 35:311–8				
96	Hutchinson et al.	Appl Energy 2014; 119:314–29				
97	Li et al.	Environ Sci Technol 2014; 48 (5):3047–55				
98	Messagie et al.	Energies 2014; 7 (3):1467–82				
99	Dhingra et al.	J Clean Prod 2014; 85:347–58				
100	Kim et al.	Energy Policy 2014; 73:620–30				
101	Dai et al.	Energy Fuels 2014; 28 (9):5988–97		✓		
102	Lewis et al.	Appl Energy 2014; 126:13–20				
103	Patterson et al.	Int J Hydrog Energy 2014; 39 (14):7190–201				
104	Trudewind et al.	J Clean Prod 2014; 70:38–49				
105	Singh et al.	J Ind Ecol 2014; 18 (2):176–86				
106	Koffler et al.	Int J Life Cycle Assess 2014; 19 (3):538–45				
107	Papong et al.	Renew Energy 2014; 65:64–9			✓	
108	Archsmith et al.	Res Transp Econ 2015; 52(c):72–90				✓
109	Bachmann et al.	J Transp Eng 2015; 141 (4):1–8				
110	Bauer et al.	Appl Energy 2015; 157(c):871–83		✓		
111	Bi et al.	Appl Energy 2015; 146 (8):11–9		✓		
112	Domingues et al.	J Clean Prod 2015; 107:749–59				
113	Ercan et al.	Energy 2015; 93(P1):323–34		✓		
114	Ercan et al.	Int J Life Cycle Assess 2015; 20 (9):1213–31		✓		
115	Garcia et al.	Int J Life Cycle Assess 2015; 20 (9):1287–99				

Table A.3
Reference No.116-181 of automobile LCA studies reviewed in this study. GL, SO, CO, and BA represent globalization, social expansion, country diversity, battery degradation aspects, respectively.

No.	Authors	Publication information	GL	SO	CO	BA
116	Girardi et al.	Int J Life Cycle Assess 2015; 20 (8):1127–42				
117	Huo et al.	Atmospheric Environ 2015; 108:107–16				
118	Abdul–Mana et al.	Energy Policy 2015; 87:1–7				
119	Mitropoulos et al.	Transp Res Part D: Transp Environ 2015; 41:147–59				
120	Noshadravan et al.	Int J Life Cycle Assess 2015; 20 (6):854–64				
121	Onat et al.	Appl Energy 2015; 150:36–49				
122	Rangaraju et al.	Appl Energy 2015; 148(c):496–505				
123	Sanfelix et al.	Appl Energy 2015; 137(c):925–30				
124	Singh et al.	Transp Res Part D: Transp Environ 2015; 41:160–4				
125	Wang et al.	Sci China Technol Sci 2015; 58 (4):659–68			✓	
126	Zhao et al.	Energy 2015; 93 (2):1277–86		✓		
127	Ahmadi et al.	Int J Hydrog Energy 2015; 40 (38):12905–17				
128	Vinolles–Cebolla et al.	Energy 2015; 83:125–36				
129	Kim at al.	Environ Sci Technol 2015; 49(16):10209–16				
130	Liu et al.	J Clean Prod 2015; 96:102–9		✓	✓	
131	Notter et al.	Energy Environ Sci 2015; 8 (7):1969–85				
132	Poulikidou et al.	Mater Des 2015; 83:704–12				
133	Shahraeeni et al.	J Nat Gas Sci Eng 2015; 24:26–34				
134	Simons et al.	Appl Energy 2015; 157(c):884–96				
135	Daylan et al.	Renew Energy 2016; 89:578–87				
136	Zucaro et al.	Bioresour Technol 2016; 219:589–99				
137	Ding et al.	J Ind Ecol 2016; 20 (4):818–27			✓	
138	Taptich et al.	J Ind Ecol 2016; 20 (2):329–40				
139	Belboom et al.	Waste Manag 2016; 50:184–93				
140	Chester et al.	Transp Res Part D: Transp Environ 2016; 43:49–58				
141	Cuellar et al.	CTF–Cienc Technol Futuro 2016; 6 (3):123–34			✓	
142	Garcia et al.	Resources 2016; 5 (41):1–15				
143	Hooftman et al.	Energies 2016; 9 (2):1–24				
144	Liu et al.	Transp Res Part D: Transp Environ 2016; 48:267–83		✓		
145	Li et al.	J Clean Prod 2016; 117:176–87			✓	
146	Li et al.	Energy 2016; 94(c):693–704	✓		✓	
147	Onat et al.	Int J Life Cycle Assess 2016; 21 (7):1009–34				
148	Sanfelix et al.	Energies 2016; 9 (8):584				
149	Shi et al.	J Clean Prod 2016; 137:449–60			✓	
150	Taglia et al.	Chem Eng Res Des 2016; 112:298–309				
151	Yuksel et al.	Environ Res Lett 2016; 11 (4):044007				✓
152	Zackrisson et al.	J Clean Prod 2016; 135:299–311	✓			
153	Zhao et al.	Transp Res Part D: Transp Environ 2016; 47:195–207		✓		
154	Zhao et al.	Sustain Prod Consum 2016; 8:18–31		✓		
155	Delogu et al.	J Clean Prod 2016; 139:548–60				
156	Dong et al.	Int J Energy Res 2016; 40 (15):2105–16			✓	
157	Gupta et al.	Energy 2016; 96(c):699–712			✓	
158	Hardwick et al.	Int J Life Cycle Assess 2016; 21:1616–23				
159	Kim et al.	Environ Sci Technol 2016; 50 (20):11226–33				
160	Luk et al.	Environ Res Lett 2016; 11 (4):044011				
161	O’Reilly et al.	J Clean Prod 2016; 135:750–9				
162	Reuter et al.	Int J Interact Des Manuf 2016; 10 (3):217–27				
163	Morganti et al.	Appl Energy 2017; 208:1538–61				
164	Folega et al.	Transp Probl 2017; 12 (2):147–53				
165	Cai et al.	Energy Policy 2017; 100:314–25			✓	
166	Choma et al.	J Clean Prod 2017; 152:497–507			✓	
167	Chuen et al.	Transp Res Part D: Transp Environ 2017; 50:192–201			✓	
168	Deng et al.	J Power Sources 2017; 343:284–95				
169	Deng et al.	Energy 2017; 123:77–88			✓	
170	Hao et al.	Transp Res Part D: Transp Environ 2017; 56:68–84			✓	
171	Hao et al.	Resour Conserv Recycl 2017; 122:114–25			✓	
172	Helmers et al.	Int J Life Cycle Assess 2017; 22 (1):15–30				
173	Hernandez et al.	Resour Conserv Recycl 2017; 120:119–30				
174	Hernandez et al.	Int J Life Cycle Assess 2017; 22 (1):54–65				
175	Ke et al.	Appl Energy 2017; 188:367–77			✓	
176	Lombardi et al.	Int J Life Cycle Assess 2017; 22 (1):1989–2006				
177	Moro et al.	Int J Life Cycle Assess 2017; 22 (1):4–14				
178	Qiao et al.	Appl Energy 2017; 204:1399–411			✓	
179	Sen et al.	J Clean Prod 2017; 141:110–21				
180	Wang et al.	Environ Sci Pollut 2017; 24 (2):1251–60			✓	
181	Wolfram et al.	Appl Energy 2017; 206:531–40				

Table A.4
Reference No.182-247 of automobile LCA studies reviewed in this study. GL, SO, CO, and BA represent globalization, social expansion, country diversity, battery degradation aspects, respectively.

No.	Authors	Publication information	GL	SO	CO	BA
182	Woo et al.	Transp Res Part D: Transp Environ 2017; 51:340–50				
183	Bicer et al.	Int J Hydrog Energy 2017; 42 (6):3767–77				
184	Danilecki et al.	J Clean Prod 2017; 141:208–18				
185	Delogu et al.	Mater today commun 2017; 13:192–209				
186	Evangelisti et al.	J Clean Prod 2017; 142 (4):4339–55				
187	Ghodrat et al.	Metall Mater Trans E 2017; 4:77–88				
188	Hao et al.	Clean Technol Environ Policy 2017; 19 (5):1509–22			✓	
189	Mayyas et al.	J Clean Prod 2017; 167:687–701				
190	Miotti et al.	Int J Life Cycle Assess 2017; 22 (1):94–110				
191	Nakano et al.	J Mater Cycles Waste Manag 2017; 19 (1):505–15				
192	Sharma et al.	Energy 2017; 133(c):1132–41				
193	Song et al.	Energy 2017; 140 (1):966–78			✓	
194	Sorunmu et al.	ACS Sustain Chem Eng 2018; 6 (8):10001–10				
195	Wang et al.	Biofuels Bioprod Biorefining 2018; 12 (6):1037–46	✓		✓	
196	Wang et al.	J Clean Prod 2018; 183 (4):653–61	✓		✓	
197	Plotz et al.	J Ind Ecol 2018; 22 (4):773–84				
198	Moro et al.	Transp Res Part D: Transp Environ 2018; 64:5–14	✓			
199	Giordano et al.	Transp Res Part D: Transp Environ 2018; 64:216–229		✓		
200	Cimprich et al.	Int J Life Cycle Assess 2018; 23 (10):2024–42				
201	Wu et al.	J Clean Prod 2018; 20 (6):1233–44				
202	Yu et al.	Transp Res Part D: Transp Environ 2018; 65:409–20			✓	
203	Keshavarzmohammadian et al.	J Clean Prod 2018; 202:770–8				
204	Onn et al.	Transp Res Part D: Transp Environ 2018; 64:15–22			✓	
205	Cox et al.	Environ Sci Technol 2018; 52 (8):4989–95				
206	Dreier et al.	Transp Res Part D: Transp Environ 2018; 58:122–138			✓	
207	Karaaslan et al.	Int J Life Cycle Assess 2018; 23 (2):333–47		✓		
208	Yang et al.	Nat Commun 2018; 9 (2429):1–10				✓
209	Gawron et al.	Environ Sci Technol 2018; 52 (5):3249–56				
210	Yang et al.	Sustainability 2018; 10 (12):1–21		✓	✓	
211	De Souza et al.	J Clean Prod 2018; 203:444–68			✓	
212	Raugei et al.	J Clean Prod 2018; 201:1043–51				
213	Hooftman et al.	Appl Sci 2018; 8 (7):1016				
214	Song et al.	Int J Life Cycle Assess 2018; 23 (38):1916–27			✓	
215	Garcia et al.	J Ind Ecol 2018; 22 (2):288–99				
216	Deutz et al.	Energy Environ Sci 2018; 11:331–43				
217	Peng et al.	Chem Eng Res Des 2018; 131:699–708				
218	Bicer et al.	Resour Conserv Recycl 2018; 132 (1):141–57				
219	Wu et al.	J Clean Prod 2018; 190:462–70			✓	
220	Lozanovski et al.	Sustainability 2018; 10 (5):1480				
221	Cecchel et al.	Metall Ital 2018; 2 (2):46–55				
222	Cecchel et al.	Int J Life Cycle Assess 2018; 23 (9):2043–54				
223	Chen et al.	Int J Environ Sci Technol 2018; 15 (10):1–8				
224	Del Pero et al.	Procedia Struct Integr 2018; 12:521–37				
225	Silva et al.	J Clean Prod 2018; 184:286–300			✓	
226	Yoo et al.	Int J Hydrog Energy 2018; 43 (41):19267–78				
227	Koj et al.	Transp Res Part D: Transp Environ 2018; 64:23–35				
228	Luk et al.	Transp Res Part D: Transp Environ 2018; 62:1–10				
229	Jhaveri et al.	Sustain Mater Technol 2018; 15 (23):1–8				
230	Yuan et al.	Pet Sci 2018; 15:644–56			✓	
231	Rocco et al.	Appl Energy 2018; 232 (11):583–97				
232	Pastor et al.	Int J Life Cycle Assess 2018; 23 (5):940–56			✓	
233	Paulino et al.	Environments 2018; 5 (2):21	✓	✓		
234	Yi et al.	J Cent South Univ 2018; 25 (8):1870–8			✓	
235	Navas–Anguita et al.	Energies 2018; 11 (5):1185				
236	Ishizaki et al.	Trans JSME 2018; 84 (866):18–50				
237	Burchart–Korol et al.	J Clean Prod 2018; 202:476–87				
238	Ajanovic et al.	J Sustain Dev Energy Water Environ Syst 2019; 7 (3):416–31				
239	Almeida et al.	Sustainability 2019; 11 (8):2366				
240	Shinde et al.	Clean Technol Environ Policy 2019; 21 (15):605–24			✓	
241	Bekel et al.	Int J Life Cycle Assess 2019; 24 (5):2220–37		✓		
242	Sen et al.	J Clean Prod 2019; 209:1033–43				
243	Burchart–Korol et al.	Promet–Traffic Transp 2019; 31 (2):195–204				
244	Burchart–Korol et al.	Transp Probl 2019; 14 (2):69–76				
245	Cusenza et al.	J Clean Prod 2019; 215:634–49				
246	Deng et al.	J Ind Ecol 2019; 23 (4):986–94				
247	Gawron et al.	Transp Res Part D: Transp Environ 2019; 73:130–41				

Table A.5
Reference No.248-313 of automobile LCA studies reviewed in this study. GL, SO, CO, and BA represent globalization, social expansion, country diversity, battery degradation aspects, respectively.

No.	Authors	Publication information	GL	SO	CO	BA
248	Glemsor et al.	Sustainability 2019; 11 (22):6332			✓	
249	Held et al.	Transp Res Part D: Transp Environ 2019; 75:87–105				
250	Qiao et al.	Resour Conserv Recycl 2019; 140:45–53	✓		✓	
251	Jursova et al.	Environments 2019; 6 (3):38		✓		
252	Kawamoto et al.	Sustainability 2019; 11 (9):2690				
253	Kim et al.	Sustainability 2019; 11 (23):6657				
254	Marques et al.	J Clean Prod 2019; 229:787–94			✓	
255	Rupp et al.	Appl Energy 2019; 237 (11):618–34				
256	Nordelof et al.	Transp Res Part D: Transp Environ 2019; 75:211–22	✓			
257	Onat et al.	J Clean Prod 2019; 212:515–26				
258	Onat et al.	Appl Energy 2019; 250:461–77				
259	Patella et al.	Transp Res Part D: Transp Environ 2019; 74:189–200				
260	Patella et al.	Sustainability 2019; 11 (6):4328				
261	Qiao et al.	Energy 2019; 177(c):222–33			✓	
262	Rosenfeld et al.	J Clean Prod 2019; 238:117879				
263	Sen et al.	J Ind Ecol 2019; 24 (1):149–64		✓		
264	Sen et al.	Resour Conserv Recycl 2019; 146:502–513				
265	Shi et al.	J Clean Prod 2019; 228:606–18			✓	
266	Vargas et al.	Int J Life Cycle Assess 2019; 24 (10):1878–97			✓	
267	Wu et al.	Appl Energy 2019; 256 (1):113923			✓	
268	Xiong et al.	Energies 2019; 12 (5):834			✓	
269	Akhshik et al.	Clean Technol Environ Policy 2019; 21 (4):625–36				
270	Milovanoff et al.	Environ Sci Technol 2019; 53 (4):2199–208				
271	Chen et al.	Energies 2019; 12 (15):3031			✓	
272	Ferreira et al.	J Mater Res technol 2019; 8 (3):2549–64				
273	Ferreira et al.	J Clean Prod 2019; 230:613–21			✓	
274	Hoque et al.	Atmosphere 2019; 10 (7):398				
275	Khan et al.	Appl Energy 2019; 242:1738–52	✓		✓	
276	Hannach et al.	Int J Hydrog Energy 2019; 44 (16):8575–84				
277	Palazzo et al.	Environ Impact Assess Rev 2019; 75:47–58				
278	Salonitis et al.	Energies 2019; 12 (13):2557				
279	Sun et al.	J Clean Prod 2019; 220:1–8			✓	
280	Upadhyayula et al.	J Clean Prod 2019; 209:1604–13			✓	
281	Wu et al.	Environ Sci Technol 2019; 53 (18):10560–70				✓
282	Deng et al.	ACS Sustain Chem Eng 2019; 7 (1):599–610				
283	Garcia et al.	Renew Energy 2020; 150:58–77				
284	Beltran et al.	J Ind Ecol 2020; 24 (1):64–79				
285	Jing et al.	J Environ Sci 2020; 90 (9):297–309				
286	Ambrose et al.	Transp Res Part D: Transp Environ 2020; 81 (10):102287				
287	Bouter et al.	Int J Life Cycle Assess 2020; 25:1545–65				
288	Cox et al.	Appl Energy 2020; 269:115021				
289	Helmers et al.	Sustainability 2020; 12 (3):1241				
290	Kemp et al.	Transp Res Part D: Transp Environ 2020; 83:102375				
291	Burchart–Korol et al.	J Clean Prod 2020; 257:120476				
292	Marmiroli et al.	Appl Energy 2020; 260 (88):114236				
293	Petrauskiene et al.	J Clean Prod 2020; 246:119042		✓		
294	Towoju et al.	Energy Rep 2020; 6 (2):315–321				
295	Tucki et al.	Energies 2020; 13 (3):561				
296	Vilchez et al.	Transp Res Part D: Transp Environ 2020; 80 (3):102214				
297	Wang et al.	J Clean Prod 2020; 264:121339				
298	Wang et al.	Resour Conserv Recycl 2020; 154:104628			✓	
299	Yang et al.	Energy 2020; 198:117365			✓	
300	Amatuni et al.	J Clean Prod 2020; 266:121869		✓		
301	Logan et al.	Transp Res Part D: Transp Environ 2020; 85:102350				
302	Morimoto et al.	Sustainability 2020; 12 (14):5713	✓			
303	Pathak et al.	Forsch Ingenieurwesen 2020; 85:431–42				
304	Verones et al.	J Ind Ecol 2020; 24 (6):1201–19				
305	He et al.	Resour Conserv Recycl 2020; 152:104497			✓	
306	Amasawa et al.	Sustain Mater Technol 2020; 25:e00189				
307	Dranka et al.	Energies 2020; 13 (17):4423			✓	
308	Syre et al.	Sustainability 2020; 12 (18):7302		✓		
309	Spreafico et al.	Sustainability 2020; 12 (18):7548		✓		
310	Valente et al.	Int J Hydrog Energy 2020; 45 (47):25758–65		✓		
311	Milovanoff et al.	Renew Sustain Energy Rev 2020; 131:110012				
312	Desantes et al.	Energy Coversion and Management 2020; 221:113137				
313	Kanz et al.	Energies 2020; 13 (19):5120				

Table A.6
Reference No.314-332 of automobile LCA studies reviewed in this study. GL, SO, CO, and BA represent globalization, social expansion, country diversity, battery degradation aspects, respectively.

No.	Authors	Publication information	GL	SO	CO	BA
314	Xu et al.	Transp Res Part D: Transp Environ 2020; 87:102534				
315	Mangmeechai et al.	Clean Technol Environ Policy 2020			✓	
316	Ugurlu et al.	Int J Hydrog Energy 2020; 45 (50):26522–35				
317	Jhang et al.	Energy 2020; 209:118436				
318	Liu et al.	Waste Manag 2020; 117 (1):81–92			✓	
319	Gencer et al.	Appl Energy 2020; 277 (1):115550				
320	Silvestri et al.	J Clean Prod 2020; 273:123083				
321	Sun et al.	J Clean Prod 2020; 273:123006			✓	
322	Wang et al.	J Environ Manag 2020; 274:111236			✓	
323	Wu et al.	Int J Life Cycle Assess 2020; 26 (1):97-113			✓	
324	Liu et al.	Plos One 2020; 15 (11):e0241967			✓	
325	Wang et al.	J Clean Prod 2020; 275 (1):123061			✓	
326	Kabus et al.	Energies 2020; 13 (24):6508				
327	Scharf et al.	Sustainability 2020; 12 (23):10037				
328	Koroma et al.	Energies 2020; 13 (23):6236				
329	Zhu et al.	Int J Environ Res Public Health 2020; 17 (23):8828			✓	
330	Rapa et al.	Energies 2020; 13 (23):6292				
331	Zhang et al.	J Clean Prod 2020; 276:124288			✓	
332	Mao et al.	J Clean Prod 2020; 277:123048	✓		✓	

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