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Toward holistic sustainability assessment of motorcycles: a systematic review

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Motorcycles are a significant mode of transportation worldwide, serving both as leisure and luxury goods in industrialized countries and as affordable everyday mobility solutions in many emerging and developing regions. In the context of a more sustainable transport future, all three dimensions of sustainability, namely environmental, economic, and social must be considered. This study employs a systematic literature review (SLR) following established review protocols, screening five major scientific databases for peer reviewed studies published between 2010 and 2025 to critically analyze existing research on the sustainability assessment of motorcycles using Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA), and Life Cycle Costing (LCC), with a focus on social aspects. Findings reveal that environmental LCA dominates existing research, with 30 of the 33 SLR studies evaluating environmental impacts, primarily comparing internal combustion engine motorcycles with electric two wheelers. Findings show lower lifecycle greenhouse gas emissions for electric motorcycles, though battery production and electricity mix significantly influence overall results. While environmental LCAs and LCCs primarily address vehicle use and environmental impacts and costs, no dedicated full S-LCA of motorcycles as a product system was identified. Additional non-LCA social studies highlight road safety, noise, and local socioeconomic impacts as prominent social issues. The industry review shows that while some manufacturers use life cycle methodologies for carbon accounting, only two companies publicly report motorcycle LCAs, and none disclose S-LCA results. The findings reveal a significant methodological imbalance: environmental dimensions of motorcycle sustainability are increasingly studied, whereas social aspects are underexplored and treated in a fragmented context specific manner, and rarely assessed across the full life cycle. This gap is especially critical considering the globalized, resource intensive supply chains of motorcycle production and the socio-economic importance of motorcycles in low and middle income countries. The rise of electric motorcycles further amplifies the need for integrated LCSA approaches that consider human rights, working conditions in battery supply chains, and user safety. Future research, such as next steps of this research project (doctoral thesis), should focus on developing standardized social indicators for motorcycles, collecting supply chain data, and aligning sustainability communication with robust LCSA frameworks.

KEYWORDS

LCSA, life cycle assessment, motorcycles, social sustainability, systematic literature review

1 Introduction

Motorcycles are a key means of transportation worldwide—both as a leisure and luxury good in industrialized nations and as affordable everyday mobility in many emerging and developing countries. When discussing their role in a more sustainable transport future, all three dimensions of sustainability need to be considered. Environmentally, they generally produce fewer CO₂ emissions and consume less fuel than cars (Bishop and Stedman, 2008), making them seem to be a more efficient option for short commutes and reducing overall traffic volume. However, they can only transport two passenger and have higher emissions of air pollutants (Bishop and Stedman, 2008). Economically, they offer lower purchase and maintenance costs, contribute to affordable mobility and support local communities through smaller scale manufacturing. Socially, motorcycles enhance accessibility and independence, especially in regions where public transport is limited. However, motorcycle production is based on complex global supply chains; necessary raw materials include cobalt, lithium and rubber, production often takes place in Asia, and sales and use are distributed globally. In such supply chains, key social challenges arise, such as working conditions in the extraction of raw materials, as well as safety and labor law issues in production.

The environmental impacts of the automotive industry, of which motorcycles are a sub-part of, are well known and have been studied using an environmental life cycle assessment (LCA) approach by numerous authors (Traverso et al., 2015; Cox et al., 2020; Spreafico and Russo, 2020; Mikosch et al., 2022; Backes et al., 2024a). Also, the social impacts, especially due to the complex, globalized supply chains in the automotive industry have been already researched (Misereor and Brot für die Welt, 2013; Südwind, 2014; Wormington and Bugalski, 2021; Murphy et al., 2022). They can and should be studied using a life cycle approach through social life cycle assessment (S-LCA) (Traverso et al., 2015; Karlewski, 2016; Tarne et al., 2018; Karlewski et al., 2019; Bouillass et al., 2021), especially since on one hand, within the automotive industry a variety of resources are used, whose extraction poses an inherent risk of human rights violations such as forced labor, child labor or dangerous working conditions like bauxite, which is required for the production of aluminum (Wormington and Bugalski, 2021; Luthin et al., 2024), or cobalt for batteries (Thies, 2021; Manjong et al., 2023, 2024). On the other hand, the social impact of the assembly and manufacturing in Europe represents an important benefit for workers and local communities.

Even if motorcycles are considered a part of the automotive industry quite often, they have several peculiarities and differences compared to cars. This is the main reason why this study will present the results of a Systematic Literature Review (SLR) on the existing literature on LCSA applied to motorcycles. The focus is on the social dimension and the societal impacts of motorcycles, which is also the topic of the overall research project (doctoral thesis), this study is part of. Research in this area focusses on passenger cars and the automotive industry as whole, which is why it is to be expected that a full S-LCA on motorcycles will probably not exist. Given that ISO 14,075 on S-LCA has just been published in 2024 (Traverso et al., 2025), this research therefore focusses on documenting the specific gaps in research and possible

future research opportunities. This will also be complemented by an industry review in the form of case studies, where it will be investigated if environmental LCAs are already performed in the motorcycle industry. The coverage of social aspects within the sustainability communication of motorcycle manufacturers will be part of future research dedicated to this topic. Since LCC is the only method within LCSA that is so far not standardized across industries (Hunkeler et al., 2008; Kloeppfer, 2008), it will play a minor role within this study.

Diverse literature reviews have already been performed to identify current research status as well as existing research gaps within the topic of LCSA in the automotive sector overall. Onat and Kucukvar (2022) evaluated 138 life cycle assessment studies on electric vehicles and inter alia identified research gaps in the area of socio-economic assessment, the representation of the developing world, consideration of integrated modeling approaches and macro-level assessment. In their analysis of 18 automotive-related life cycle sustainability assessment (LCSA) case studies Ostojic and Traverso (2024) found a lack of a harmonized methodological approach, inconsistencies in the application of existing guidelines and insufficient databases on economic and social data. They also showed that the social dimension is a challenge within most of the analyzed studies (about 22%). In 2017, Tarne et al. (2017) examined 63 publications on LCSA and combined this with an analysis of 15 published sources from automotive manufactures, which found that within the industry LCA is already widely used, however social aspects are rarely taken into consideration at product level and with a life cycle perspective, and are instead often considered at company level, such as in sustainability reports. Some studies focused on S-LCA specifically e.g., the one by Gompf et al. (2020) in which 579 social indicators were identified, that were often used to measure the same aspect, and which showed that there was often a lack of a clear assessment method.

This research therefore aims to systematically capture the existing literature regarding LCA, S-LCA and LCC on motorcycles and how the sustainability of motorcycles has been assessed using a life cycle perspective. In this context, it is assumed that the existing literature partially covers LCA and also some LCC aspects but focuses primarily on motorcycle use and emissions. Social aspects might be assessed but are expected to be treated in a fragmented and contextual manner, not systemically along the life cycle. Even though there might be no S-LCA studies dealing specifically with motorcycles, it will be evaluated which social impacts regarding the life cycle of motorcycles have been considered in literature to identify the existing research gaps. Additionally, it will be examined how motorcycle manufacturers address social topics within their sustainability communication. It is expected that social aspects are mainly considered according to regulatory requirements and not systematically considered from a life cycle perspective within the sustainability reports of manufacturers. In contrast, LCA might already be used within the industry, however results are expected to be published only rarely. The specific research questions to be answered within this paper are as followed:

- **RQ1:** Which environmental, economic and social aspects of motorcycles have been dealt with so far in scientific literature using LCA, S-LCA and LCC approaches?

- **RQ2:** In scientific literature, how has the social sustainability of motorcycles been considered and which aspects of social sustainability have been addressed?
- **RQ3:** To what extent have environmental life cycle methods been used in industry to assess motorcycles?

A short overview of some of the research regarding the usage of life cycle assessment methodology in the automotive industry has already been given, the objectives of this research as well as the hypothesis and the research questions that are used to test them are stated, including the relevance for the motorcycle industry (as part of the automotive sector). The scientific contribution of this review lies in offering a systematically derived synthesis of LCSA applications in the motorcycle sector. While previous studies focused mainly on passenger cars, this research identifies and conceptualizes the unique characteristics of motorcycles as a distinct subsector within the automotive industry. By integrating a systematic review of life cycle-based studies with a supplementary scoping review of social aspects, the study moves beyond a descriptive mapping and establishes a first foundation for a subsector-specific LCSA approach.

Hereafter, an introduction to LCSA as a sustainability assessment method (Section 2) is given. In Section 3 the methods used to conduct the systematic literature are explained as well as the approach used within the case studies, followed by a presentation and discussion of the results (Section 4 & 5). Final remarks and the conclusions drawn are presented in Section 6.

2 Theoretical background

Life Cycle Sustainability Assessment (LCSA) is a methodology to assess the sustainability of a product over its life cycle. It refers to all three pillars of sustainability and therefore covers environmental, social and economic aspects in alignment with Elkington's "Triple Bottom Line" approach from 1997, from which the first definition of LCSA was derived by Kloeppfer and Finkbeiner (Backes et al., 2024b). LCSA comprises of three individual techniques, one for each pillar of sustainability: (1) LCA for the assessment of environmental, (2) Life Cycle Costing for the assessment of economic and (3) S-LCA for the assessment of social impacts. Therefore, LCSA is defined as follows (Kloeppfer, 2008; Finkbeiner et al., 2010; Valdivia et al., 2021):

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{S-LCA}$$

However, the equation is considered solely as a formal expression. It does not imply that achieving the sustainability performance of a product over its life cycle can be done by simply adding the results from the three methodologies. Rather, it means that conducting a life cycle sustainability assessment requires applying all three techniques to the same functional unit and within equivalent system boundaries.

LCA, synonymous with the term environmental LCA, is the "internationally accepted standardized method for analyzing environmental aspects and potential impacts of product systems" (Grah and Kloeppfer, 2014). The main reference systems in

performing LCAs are the norms ISO 14040 (ISO, 2006, 2020) and ISO 14044 (Finkbeiner et al., 2006; ISO, 2006, 2020). Of the three techniques within LCSA LCA is therefore the most developed, standardized and most applied one (Grah and Kloeppfer, 2014; Backes and Traverso, 2021; Ostojic et al., 2024). ISO 14040 (ISO, 2006, 2020) defines four phases for an LCA: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation. It is also possible to perform a life cycle inventory study, where the third phase, the impact assessment, is left out. Within inventory analysis the relevant inputs and outputs of a product system are quantified, such as energy and raw material inputs, products and waste, emissions to air and discharges to water and soil, and other environmental aspects. During the phase of impact assessment, the collected data and results from the inventory phase are classified and characterized to evaluate the significance of the potential environmental impacts.

Direct applications where an LCA can be useful are for example product development and improvement, public policy making, strategic planning or marketing (Grah and Kloeppfer, 2014). Life Cycle Costing (LCC) refers to the assessment of the economic performance of a product, where "all costs associated with the life cycle of a product that are directly covered by one or more of the actors in that life cycle [are summarized]" (Kloeppfer, 2008). There are three types of LCC: conventional, environmental, societal. While a conventional LCC is summarizing direct costs to allow comparison of investment alternatives, e and societal LCC are considering environmental and societal externalities respectively. LCC is the only method within LCSA that is so far not standardized (Hunkeler et al., 2008; Kloeppfer, 2008). However, it needs to be mentioned that for the construction sector life cycle cost analyses are based on ISO 15,686-5 (Backes et al., 2024b; ISO, 2017).

The most recently published standardization in the LCSA sphere in form of an ISO Norm is ISO 14075 on S-LCA (Traverso et al., 2025; ISO, 2024). It has been developed starting from the new version of Guidelines for Social Life Cycle Assessment of Products and Organizations, developed by United Nations Environment Program (UNEP) (UNEP, 2020) which is the update of the first version published in 2009 (UNEP and SETAC, 2009). Just as the "societal dimension sustainability captures the impact of an organization, product or process on society" (Finkbeiner et al., 2010) an S-LCA is as "compilation and assessment of the socially relevant inputs and outputs and the potential social impacts of a product system and throughout its life cycle" (ISO, 2024). One major differentiating factor between the LCA, LCC and S-LCA methodologies is the role of stakeholder (categories) and their selection during the goal and scope definition and the heavy dependence on local factors (Backes et al., 2024b) in S-LCA.

Regarding the selection of the relevant stakeholders, there are six stakeholder categories defined and suggested within the Guidelines: workers, local communities, value chain actors, consumers, children and society (UNEP, 2020). For each of those stakeholder categories a certain number of impact subcategories are defined (e.g., subcategory "working hours" within the impact category "working conditions" for the stakeholder "workers") which can be assessed with the help of impact indicators (e.g., "number of hours effectively worked by employees"). Some of those inventory indicators are suggested in the Methodological Sheets

for Subcategories in Social Life Cycle Assessment (S-LCA) (UNEP, 2021) together with examples for data sources that can be used to collect data on each indicator.

The before mentioned dependence on local context results from very diverse societal conditions in different parts of the world. The technological identical production process can have a very different social impact, depending on the local (e.g., working) conditions in two different countries or regions (Benoît Norris, 2014; UNEP, 2020; Backes et al., 2024b).

S-LCA methodology can be used to create transparency and by identifying optimization potential to improve the situation of stakeholders along the value chain of a product.

Just as LCA is used to assess the environmental impact in all sorts of industries like automotive/mobility, construction, food, etc. (e.g., Traverso et al., 2015; Tarne et al., 2017; Spreafico and Russo, 2020; Silvestri et al., 2021; Mikosch et al., 2022; Onat and Kucukvar, 2022; Caspers et al., 2023; Del Rosario and Traverso, 2023; Backes et al., 2024a; Hübner et al., 2024), the S-LCA methodology has been used to assess products and services in different sectors such as: the automotive (Traverso et al., 2015; Tarne et al., 2017; Karlewski et al., 2019; Gompf et al., 2020, 2022; Bouillass et al., 2021; Luthin et al., 2024), construction (Backes and Traverso, 2023; Del Rosario and Traverso, 2023), or food one (D'Eusano et al., 2022; Luna Ostos et al., 2024).

3 Methods

3.1 Systematic literature review

While Kraus et al. (2022) are distinguishing between systematic and non-systematic literature reviews, with the systematic methodology being the determining factor, Snyder (2019) is differentiating review types rather by their purpose. “The aim of a systematic review is to identify all empirical evidence that fits the pre-specified inclusion criteria to answer a particular research question or hypothesis” (Snyder, 2019), whilst a semi-systematic review rather maps a research field, summarizes the state of knowledge and formulates a research agenda; and an integrative review “aim[s] to assess, critique, and synthesize the literature on a research topic in a way that enables new theoretical frameworks and perspectives to emerge” (Snyder, 2019).

The paper on hand fits the criteria of a systematic review since it is “carried out in a systematic way using [a] [...] protocol to guide data curation and analysis” (Kraus et al., 2022). “A strict systematic review process is used to collect articles, and then a qualitative approach is used to assess them” (Snyder, 2019), because the aim is rather to explore and map out the research field, then to use the containing data for e.g., methodological advancements. Hereinafter the term systematic literature review (SLR) will be used.

According to Snyder (2019) any literature review consists of four phases: designing the review, conducting the review, analysis, and writing the review. This logic has been followed within this paper. During the design phase the purpose, scope and research questions were defined, and a search strategy including

search terms, appropriate databases and inclusion criteria were determined. To identify the relevant literature both publisher-specific search portals (SpringerLink, Science Direct, and MDPI), as well as indexing databases (Web of Science and Scopus) were used. This approach was chosen to ensure a breadth in the retrieved literature, especially since preliminary screening showed little results on the research topic. The authors therefore also decided to use more databases than other publications in the domain (see Tarne et al., 2017; Gompf et al., 2020; Spreafico and Russo, 2020; Onat and Kucukvar, 2022; Ostojic and Traverso, 2024), to yield as much relevant literature as possible. Peer-reviewed research and review articles in English language from 2010–2025 were included for the review, if it was indicated, that both of the following criteria applied:

1. The publication must deal with motorcycles (or at least a specific part of a motorcycle).
2. The publication must use a form of life cycle thinking methodology as an approach to evaluate motorcycles or motorcycle components.

To ensure this, the search terms that were used included different notations of the term “life cycle assessment,” “life cycle costing,” “social life cycle assessment,” and “social sustainability” in connection with different terms for “motorcycle.” Specifically, the following search strings were used in all databases:

- (“LCA” OR “Life Cycle Assessment” OR “Life-cycle assessment” OR “Life-cycle-assessment”) AND (“motorcycle” OR “motorbike” OR “two-wheeler”)
- (“LCC” OR “Life Cycle Costing” OR “Life-cycle costing” OR “Life-cycle-costing”) AND (“motorcycle” OR “motorbike” OR “two-wheeler”)
- (“S-LCA” OR “Social life cycle assessment” OR “Social LCA” OR “S-LCA”) AND (“motorcycle” OR “motorbike” OR “two-wheeler”)
- “Social Sustainability” AND (“motorcycle” OR “motorbike” OR “two-wheeler”)

The search terms were chosen as such because, on the one hand, a basic overview of what already exists on the broad term life cycle assessment regarding motorcycles should be given. On the other hand, it is to be investigated whether there are already studies on social sustainability in relation to motorcycles, including motorcycle production since the social aspects of supply chain of motorcycles will particularly be relevant in the overarching research project (doctoral thesis). However, this initial study does not yet specifically address the supply chain stage but rather tries to describe which phases of the life cycle studies on motorcycles have been examined so far as well as which impacts have been measured. The search term “social sustainability” was added to allow for an additional scoping review of social topics within the motorcycle domain, supplementary to the SLR, where the two inclusion criteria are strictly applied. In the scoping review, the second inclusion criteria were less strictly applied. Therefore, eventually a hybrid review was performed: First, a systematic review of LCA, LCS and S-LCA studies strictly following the

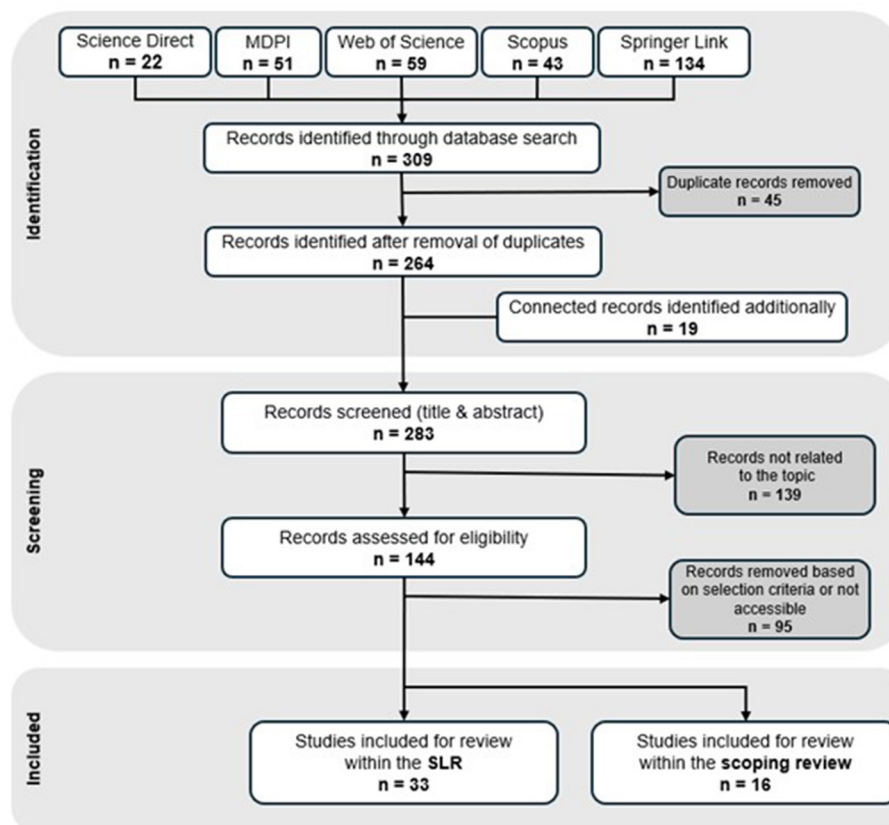


FIGURE 1

Flow diagram illustrating the identification, screening and inclusion process for studies in the systematic as well as the scoping review.

predefined search protocol and a second, supplementary scoping review on social sustainability topics. The results from both streams of evidence are analyzed and reported separately to avoid giving equal weight on less systematically retrieved material. Still, a lot of studies dealing with social impacts along certain stages of a motorcycle's life cycle will be excluded, since they might not be labeled under social sustainability. However, this research will provide an indication, which can be used as a starting point for future research.

The search was conducted in July/August 2025 within the mentioned databases. Since usage methods differed between the databases it was necessary to differentiate between search fields. Within MDPI and ScienceDirect it was only searched within title and keyword, within Scopus also abstracts were included, and within SpringerLink and Web of Science only full text search was possible. This explains why most hits were within those last two, however confidence is high that relevant research was identified, as many papers had to be eliminated already in the first screening step (see Figure 1).

Once the relevant papers were identified through a systematic database search and paper from additional sources were added, the review itself was conducted. During this second phase of an SLR the review was done in stages "by reading abstracts first and making selections and then reading full-text articles later, before making the final selection" (Snyder, 2019). The process of selecting the relevant papers for the review is illustrated in Figure 1.

The identification of papers through databases led to 264 results after the elimination of duplicates. (Duplicates within the search results from one database due to the different search strings were already eliminated as part of the documentation of search results.) This was supplemented by 19 papers from other sources, which led to 283 results for further screening. Here, the first step was a preliminary selection by title and abstract, keeping in mind the beforementioned inclusion criteria.

Whilst applying the inclusion criteria during the screening of titles and abstracts, it became evident that by only focusing on the above-mentioned inclusion criteria, some papers will be eliminated for further evaluation, that could yield interesting insights on the social aspects of a motorcycle life cycle without using a form of life cycle assessment method at all. Papers that might be excluded due to the second criteria included in this phase were included in the results of the scoping review at this point for further evaluation, especially of social aspects (e.g., medical papers dealing with injuries arising typically in motorcycle accidents or reviews of two-wheeler technologies). Evidently, this does not constitute a proper systematic literature review but can merely be an indicator on what social topics might have already been researched along the motorcycle life cycle.

After the pre-selection through the screening of abstract 144 papers were left for further evaluation. In the last step of the study selection process, the full papers were read and again the two

screening criteria were applied. Forty Nine papers were retained for further assessment, of which 33 were included in the SLR data set, since they dealt with motorcycles and were using a form of life cycle assessment method. The 16 remaining studies were the result of the additional scoping review and were analyzed regarding the social topics considered rather than the life cycle methodology used.

After the identification of the SLR data set, as well as the supplementary papers from the scoping review, a two-fold approach was taken for the third phase of the SLR, the analysis (Snyder, 2019). First a descriptive evaluation was done, followed by a more in-depth content-analysis, where the content of the studies was subjectively organized into themes (Kraus et al., 2022). A coding scheme was developed for the structured evaluation of data. As more articles were evaluated, the coding scheme was iterative and gradually developed. Phase 4 of the SLR (writing the review) includes a communication of research needs the SLR is fulfilling and a description of the followed process (Snyder, 2019). Both are included in the previous sections. The findings of the SLR, as well as conclusions drawn will be part of Section 5 and 6.

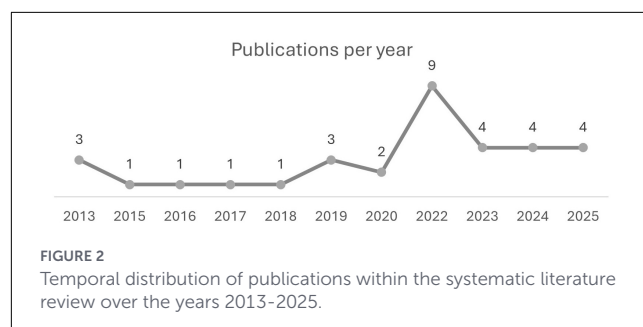
3.2 Industry review

To add the industry's perspective on the usage of life cycle methods to assess the sustainability of a motorcycle a short industry review was performed. This was done in an additional research step by analyzing the sustainability communications from motorcycle manufacturers. The following motorcycle brands were selected for the review: KTM (Austria), BMW Motorrad (Germany), Piaggio (Italy), Harley-Davidson (USA), TVS Motor (India), Hero Moto Corp (India), Honda (Japan), Kawasaki (Japan), Loncin (China) and CFMoto (China). These manufacturers were selected to ensure broad global coverage across major motorcycle markets, capturing regional differences in production structures, sustainability reporting practices, and market relevance. Including companies from Asia, Europe, and North America prevents a size-bias that would otherwise favor Asian manufacturers, who dominate global production volumes.

The analyzed information was extracted from the latest publicly available corporate sustainability reports, annual reports and official websites in English language in January and February 2026. Searches were conducted using combinations of the terms “life cycle assessment”, “LCA” and “carbon footprint.” As disclosures varied by geography and language, results represent only what could be verified in accessible public company sources.

4 Results

The final set of articles of the SLR and the scoping review for evaluation of social topics within the motorcycle life cycle stages underwent a thorough analysis, which are presented in two separate sections.



4.1 Analysis of studies within the systematic literature review

4.1.1 Descriptive analysis

The 33 identified studies first underwent a descriptive analysis, which was only done for the studies within the SLR, basic information about the identified studies was analyzed, which encompasses the author, the publication year, and the journal in which each study was published. Additionally, geographical distribution was considered by examining the affiliation of the first author¹ and the country where the research was conducted. A distinction was made between empirical, theoretical, and mixed publications to categorize the publication type.

All papers were first-authored by different scholars, except for three studies which were all first-authored by Yohén Cuéllar-Álvarez. The 33 studies analyzed are scattered through various scientific fields, since the relevant studies are published in various journals related to e.g., the transportation sector (such as “Sustainable Cities and Society” or the “International Journal of Sustainable Transportation”) or the energy sector (e.g., “Applied Energy” or “Energy Policy”). Many journals can also be subsumed under the topic of environmental sciences, like “Science of The Total Environment,” the “Journal of Cleaner Production” or “Sustainability.” Only one paper was published in journal dedicated to life cycle assessment methods, the “Indonesian Journal of Life Cycle Assessment and Sustainability”. All studies were empirical, except the two by Sansa et al. (2019) and Siwiec and Pacana (2025).

An examination of the publication years showed that there was a steep incline in publications in 2022 with nine publications, which can be seen in Figure 2. From 2013 until 2020 there were only 12 publications in total which matched the criteria. Within the 3 year-span from 2022 until (August) 2025 there were 21 papers published on the topic.

The geographical distribution of the studies was done in a twofold approach, considering the country of the first author's affiliation, but additionally looking at the country of data collection. This is of interest, since many papers deal with transport systems in specific regions, and this could lead to relevant insights into where motorcycles are used and where they have what kind of impact. First author affiliation is distributed around four

¹ where two affiliations are listed, only the first-mentioned is included in the analysis.



continents (Asia: 14, Europe: twelve, North and South America: six, Africa: one), the data collection included the same continents (see [Figure 3](#)), with five studies collecting data in countries in Africa, six in Europe, five in South America, thirteen in Asia and four studies not mention a specific country for data collection. Each country was mentioned in one publication, except Taiwan, Uganda, Spain and Portugal (2 papers each), as well as Indonesia, India and Colombia (3 papers). One publication applies its data to a “European scenario;” however, Europe in total was not marked in [Figure 3](#).

4.1.2 Content-based analysis

For the content-based analysis first the 33 studies were classified regarding their “motorcycle-specific topic,” meaning the role motorcycles played in each study. It was then identified which types, or which motorcycles were used for the research and for the comparison of different modes of transport it was also identified which other modes of transport were considered. In [Table 1](#) this analysis is presented together with an overview of the sustainability dimensions considered in the studies. Regarding the “motorcycle-specific topic” four types of studies were identified: comparison of different modes of transport including motorcycles (16 studies), comparison of different motorcycles (ten studies), assessment of one motorcycle (four studies), and assessment of a motorcycle component (three studies).

4.1.2.1 Comparison of different modes of transport including motorcycles

All 16 studies comparing different modes of transport are focusing on specific geographical regions (see also [Figure 3](#)) which

are either cities like Lisbon (Portugal), Chennai (India) or Bogota (Colombia) or whole countries like Uganda, Poland or Nigeria. Other studies are using groups of similar countries such as a “European scenario” ([Spreafico and Russo, 2020](#)), “underdeveloped countries” ([Kalifa et al., 2024](#)) or the countries in the Association of Southeast Asian Nations (ASEAN) ([Champeecharoensuk et al., 2025](#)) for the evaluation.

4.1.2.2 Comparison of different motorcycles

All studies under this description compare ICE with electric PTWs. Three studies compared specified brand motorcycles ([Carranza et al., 2022](#); [Schneider et al., 2023](#); [Polanco Vázquez et al., 2025](#)), two studies mentioned the number of motorcycles considered [12 ([Cox and Mutel, 2018](#)) and 156 ([Chien et al., 2023](#))] and the remaining five did not specify the number of PTWs exactly, but elaborated on the specifications on the PTWs considered ([Kerdlap and Gheewala, 2016](#); [Choi and Yun, 2020](#); [Hafidza et al., 2022](#); [Vanatta et al., 2022](#); [Yuniaristanto et al., 2024](#)).

4.1.2.3 Assessment of one motorcycle

Regarding the assessment of one specific motorcycle [Sophia et al. \(2017\)](#) evaluate environmental impacts of using a motorcycle from the raw material production up to the disposal of the motorcycle. Another study also measures environmental impacts, but only of the conversion process and the post-conversion use stage of an internal combustion engine (ICE) motorcycle that was transformed into a battery-powered motorcycle ([Xuan et al., 2013](#)). [La Fleur et al. \(2024\)](#) include the economic dimension in their analysis of an electric motorcycle (EM) by calculating the total cost of ownership. The fourth study did assess one

TABLE 1 Motorcycle-specific topics and sustainability aspects identified within the SLR data set.

Author	Motorcycle types considered [Other modes of transport considered]	Aspects considered (environmental, social, economic)
Comparison of different modes of transport, including motorcycles		
Baptista et al. (2013)	Two electric motorcycles (2/6 kW motor power); one conventional motorcycle (6.7 kW motor power) [two small low powered electric vehicles (4.8/10 kW motor power), one conventional vehicle (60 kW motorpower)]	Environmental
Bastos et al. (2019)	Motorcycles with 2-stroke- and 4-stroke-engines [car, bus, subway, train, and bicycle]	Environmental
Burchart-Korol and Folega (2019)	Motorcycles and mopeds [passenger cars, heavy goods vehicles, buses, agricultural tractors]	Environmental
Champecharoensuk et al. (2025)	Most popular models of EV and ICE vehicles (motorcycle) from 2023 automotive markets for Indonesia, Malaysia, the Philippines, Thailand, and Viet Nam [most popular models of EV and ICE vehicles (sedan) from 2023 automotive markets for Indonesia, Malaysia, the Philippines, Thailand, and Viet Nam]	Environmental
Cuéllar-Álvarez et al. (2024)	Privately owned motorcycles with 2- or 4-stroke engines [passenger cars, taxis, rigid buses, articulated buses]	Environmental, economic
Cuéllar-Álvarez et al. (2023)	Motorcycles, 2- or 4-strokes [Private cars, taxis, traditional buses, bus rapid transit system, special transport buses]	Environmental
Cuéllar-Álvarez et al. (2022)	Motorcycles, 2- or 4-strokes [Passenger cars, taxis, rigid buses, articulated buses]	Environmental
Felipe-Falgas et al. (2022)	Private electric moped; shared electric moped (standard e-moped used by Cooltra); motorbike [walking, private mechanical and electrical bicycle, shared mechanical and electrical bicycle, private e-scooter, car, bus, and train]	Environmental
Gujba et al. (2013)	Motorcycle (urban), Petrol [Car, bus, train]	Environmental, economic
Kalifa et al. (2024)	Motorcycle, weighing 108 kg [14-/29-passenger diesel minibus; 3-passenger gasoline autorickshaw]	Environmental, economic
Kosai et al. (2022)	Internal combustion engine motorcycle fuelled by petrol; Battery electric motorcycle [ICEV (biodiesel), BEV, PHEV, ICE bus (diesel/biodiesel), BE bus]	Environmental
Majumdar et al. (2022)	Electric two-wheelers (e2W), including real-time data from on specific e2W based on independent driving (Electrotherm, Yo Style) [Electric three-wheelers (e3W)]	Environmental, economic
Middela et al. (2022)	Two-wheelers [Three-wheelers, Light-Duty/Medium-Duty/Heavy-Duty Diesel Trucks]	Environmental
Montoya-Torres et al. (2023)	Conventional scooter - 90-kg, 4-stroke engine; Electric scooter - 144-kg [Petrol/diesel/electric car, electric/conventional bike]	Environmental
Peshin et al. (2022)	Photon by Hero MotoCorp - BEV-2W (LFP batteries); Activa 5G/6G by Honda - gasoline [Three-wheelers, four-wheelers, and buses]	Environmental, economic
Spreafico and Russo (2020)	One electric moped; Four motorcycles (4 kW/50 kW internal combustion, 4 kW/50 kW electric) [bicycles, cars, buses, trains, airplanes]	Environmental
Comparison of different motorcycles		
Carranza et al. (2022)	Muvi motorcycle by Torrot (BEV) - with LiNiCoMn battery/with LiMnO battery; Burgman 25 by Suzuki (ICEV)	Environmental, economic
Chien et al. (2023)	156 scooters - internal combustion engine scooters powered by gasoline and battery electric scooters	Environmental, economic
Choi and Yun (2020)	ICE-based conventional two-wheeler, 125 cc, gasoline engine; plug-in series hybrid electric two-wheeler, 3kW brushless direct current motor, lithium battery pack, 125 cc internal combustion engine	Economic
Cox and Mutel (2018)	12 motorcycles - four motorcycle size categories, three powertrain types, a variety of fuel supply chains	Environmental, economic
Hafidza et al. (2022)	Electric vs. conventional motorcycles	Economic
Kerdlap and Gheewala (2016)	Lithium-ion and lead-acid battery electric motorcycles; conventional motorcycles	Environmental, economic
Schneider et al. (2023)	Gogoro S2 (electric battery); SYM Duke 125 (combustion engine)	Environmental
Vanatta et al. (2022)	Electric motorcycle taxis; conventional motorcycle taxis	Environmental

(Continued)

TABLE 1 (Continued)

Author	Motorcycle types considered [Other modes of transport considered]	Aspects considered (environmental, social, economic)
Polanco Vásquez et al. (2025)	Kingway commercial passenger transport motorcycle, model KW-QSA-1500 with lead-acid batteries/with lithium-ion batteries; Italika brand motorcycle, model FT (gasoline powered)	Environmental, social
Yuniaristanto et al. (2024)	Electric vs. conventional motorcycles	Economic
Assessment of one motorcycle		
La Fleur et al. (2024)	Electric motorcycle with dual LFP batteries (not yet fully introduced to the market and produced at large scale)	Environmental, economic
Siwec and Pacana (2025)	Reference electric motorcycle (230 kg) and ten prototypes of that motorcycle	Environmental, economic
Sopha et al. (2017)	Honda Supra X 125	Environmental
Xuan et al. (2013)	Honda CBR400RR	Environmental
Assessment of a motorcycle component		
Purwani et al. (2024)	swap batteries for electric motorcycles	Environmental
Sansa et al. (2019)	Two motorcycle battery technologies	Environmental, economic, social
Simboli et al. (2015)	Motorcycle rear wheel spindle	Environmental, economic

reference EM and ten prototypes for it by applying the developed Cost-Quality-Life Cycle Assessment (Siwec and Pacana, 2025).

4.1.2.4 Assessment of a motorcycle component

For the last category three studies were identified (Simboli et al., 2015) compared eco-innovations by evaluating the environmental and economic impacts of different rear wheel spindle versions using LCA. The other two studies deal with motorcycle batteries: (Sansa et al., 2019) developed a sustainable design model and tested it through implementation in a company producing motorcycle batteries in Tunisia and Tanzania using a simplified LCA and Purwani et al. (2024) did a study on motorcycle battery exchange as a basis for considering recycling process classification and cut-off values before end of life.

To be able to draw conclusions on the sustainability topics studied within the dataset for the SLR the relevant findings from the studies are summarized below, structured according to sustainability dimensions. Table 1 includes an overview of the dimensions assessed in the studies within the SLR and in the following paragraph, only the environmental, economic and social aspects considered will be discussed, by highlighting the most relevant findings from the studies as well as how the LCA methodology has been used to discuss motorcycles.

Additionally, it is described which aspects of the LCA, LCC and S-LCA methodologies are used within the studies, e.g. functional units and system boundaries. This can be found in a tabular format as well in Tables 2, 3 for the LCA and LCC studies. The one study within the SLR data set assessing all three sustainability dimensions using the same functional unit and system boundaries

of each assessment will be discussed below under the social aspects paragraph.

4.1.2.5 Environmental aspects

Out of the 33 studies identified, 30 in total dealt with environmental aspects whereby out of those, 16 discussed solely environmental and no other sustainability aspects. Regarding the LCA methodology used, the wording according to ISO 14040/44 was not used in all studies, however the information given was categorized under the following columns: goal, system boundaries, functional unit and impact indicators/categories, even though the studies did not fully meet the requirements of an LCA study according to ISO 14040/44, but are studies evaluating motorcycles using a life cycle perspective. This categorization can be seen in Table 2. The functional unit used in most of the studies is a form of “passenger per kilometer” (pkm) or yearly/lifetime kilometer. Since the functional unit is linked to the goal of the study, they can be seen side by side in Table 2. One study failed to clearly define the functional unit (Baptista et al., 2013) for their estimation of energy consumption and CO₂ emissions of different technologies, Champeecharoensuk et al. (2025) are using “unit of per vehicles, rather than per kilometer” to assess environmental impacts of electric vehicles and Cuéllar-Álvarez et al. (2022, 2023) are stating the amount of pollutants per year as a reference value to evaluate well-to-wheel emissions of passenger vehicles. For the motorcycle components Sansa et al. (2019) are using “allowing one use of a motorcycle by starting its engine” to assess the environmental performance of different design scenarios and the other two reference to unit of product to compare the environmental performance of two spindle versions (Simboli et al., 2015) and to assess the potential impacts of the one battery pack (Purwani et al.,

TABLE 2 Environmental aspects assessed in the SLR dataset including goal, system boundary, functional unit and impact category.

Author	Goal	System boundary	Functional unit [Reference measure]	Impact categories
Baptista et al. (2013)	Estimate energy consumption and CO2 emissions of different technologies	Well-to-wheels	[CO2emission per km (g/km)]	CO2 emissions
Bastos et al. (2019)	Comparison of six commuting modes in Lisbon regarding their environmental impacts and health implications	Cradle-to-grave	Commuting of one individual for 1 year, which accounts for differences in route length between modes, results per person-kilometer traveled	NRE, GHG, FE, ME, AC, TE/DALY
Burchart-Korol and Folega (2019)	Environmental assessment of the means of road transport in Poland with regard to their operation	Usage	Number of kilometers driven by individual means of transport in 2014	GHG, CAP, VOC/DALY
Carranza et al. (2022)	Evaluate the environmental performance of a battery electric vehicle and compare it with an internal combustion engine vehicle and evaluate the impact that the type of battery has on the electric motorcycle	Cradle-to-grave	80,000 km [...] traveled by each motorcycle across its lifetime	FE, NLT, FET, ULO, FD, PMF, GW, POE, HAT, MD, WD, TA, IR, ME, OD, ALO, MET, TET
Champeecharoensuk et al. (2025)	Investigate the global warming potentials and environmental impacts of electric vehicles in Association of Southeast Asian Nations using LCA	Well-to-wheel, cradle-to-gate and grave-to-cradle	Unit of per vehicles, rather than per kilometer	GW
Chien et al. (2023)	Compare the lifecycle emissions per distance driven among different scooter models to understand the potential carbon trade-offs	Manufacturing, upstream fuel and feedstock production, usage	Nominal lifetime distance traveled of 102,400 km, Results in gCO2/km	GHG
Cox and Mutel (2018)	Comparison of the environmental performance of both conventional (gasoline) and advanced powertrain (battery electric and fuel cell electric) motorcycles	Cradle-to-grave and well-to-wheel	Driving of different motorcycles for one kilometer, averaged over the entire vehicle lifetime	All ReCiPe midpoint and endpoint indicators, most relevant: GW, PMF, POE
Cuéllar-Álvarez et al. (2022)	Compare well-to-wheel emissions of passenger vehicles for various abatement strategies	Well-to-wheel	Tons of pollutants emitted per year (tons/year)	GHG, CAP
Cuéllar-Álvarez et al. (2023)	Estimate well-to-wheel emissions from Bogotá, Colombia's entire fleet of passenger transport vehicles	Well-to-wheel	Amount of pollutants emitted in mass units per year for the total fleet of vehicles	GHG, CAP, VOC
Cuéllar-Álvarez et al. (2024)	Evaluation of Well-to-Wheel emissions from passenger vehicles, encompassing the often overlooked wear and dust resuspension emissions	Well-to-wheel	[Emissions in grams per kilometer and vehicle]	GHG, CAP
Felipe-Falgas et al. (2022)	Using LCA results to assess the environmental impact of the modal change	Cradle-to-grave	Transport of one person over one kilometer, measured in units of passenger-kilometer traveled in the year 2021	GW, PMF, OF
Gujba et al. (2013)	Estimation of life cycle environmental impacts for the current passenger transport system in Nigeria for 2003-2030 and future scenarios	Well-to-wheel and manufacturing of vehicles and infrastructure	The total number of person.kilometers traveled per year	GW, AD, OD, POE, AC, FE, HAT
Kalifa et al. (2024)	Evaluate the environmental performance of passenger transportation in underdeveloped countries using four different internal combustion engine vehicles	Cradle-to-grave	Transport 1 passenger 1 km, stated as passenger-km	AD, FD, GW, AC, FE, HAT, FET, TET, POE, OD

(Continued)

TABLE 2 (Continued)

Author	Goal	System boundary	Functional unit [Reference measure]	Impact categories
Kerdlap and Gheewala (2016)	Evaluate the environmental benefits of lithium-ion battery and lead-acid battery electric motorcycles compared to conventional motorcycles in Thailand	Cradle-to-grave	Reduction of 2,791 kt oil-eq of final energy consumption of the motorcycle fleet in the year 2030 through implementing the necessary amount of EMs	GW, TA, MD, PMF, FD, FET, HAT, MET, TET
Kosai et al. (2022)	Compare the GHG emissions of different types of transportation means in Malaysia	Cradle-to-grave	GHG emissions per km driven	GHG
La Fleur et al. (2024)	Analyze environmental impact and primary energy use of the motorcycle	Cradle-to-grave	One electric motorcycle produced with two batteries, with a usage phase of eight years driven for 90 km/day on 320 days/year	MET, FET, FE, TET, HTc, FD, PMF, TA, GW, OF, TEC, OF, HE, OD, MRS, IR, LU
Majumdar et al. (2022)	(a) analyzing performance and (b) energy consumption, (c) finding the use-phase emissions	Usage	[gCO ₂ /passenger-kilometer]	GHG
Middela et al. (2022)	Identify the alternative with lower emissions between conventional fuel vehicles and the battery electric vehicles for urban freight deliveries	Well-to-wheel and cradle-to-junkyard	1 km freight transport	GHG, CAP
Montoya-Torres et al. (2023)	Comparison of the CO ₂ emissions, at all stages from cradle to grave, of seven types of individual transportation systems used in Ibagué and Venadillo	Cradle-to-grave	Passenger-kilometer	GHG
Peshin et al. (2022)	Estimation of life-cycle GHG and CAP emissions associated with different vehicle classes, vehicle technologies, and fuels operating in each Indian state/union territory	Cradle-to-grave and well-to-wheel	[Emissions per km driven]	GHG, CAP
Purwani et al. (2024)	Determining the cut-off before EoL by assessing the potential environmental impacts of the life cycle and material circularity of swap battery product systems	Gate-to-gate	[One battery pack]	TET, TA, OD, GW, FE, FD
Sansa et al. (2019)	Assess the environmental performance of different design scenarios	Cradle-to-grave	Allowing one use of a motorcycle by starting its engine	HE, EQ, ESR
Schneider et al. (2023)	Establish and compare the environmental impacts of an electric battery and internal combustion motorcycle	Cradle-to-grave	Transport one person over 45,000 km	18 impact categories, focus on: GW, HTc, PMF, TET, TA, MRS, FE, FD
Simboli et al. (2015)	Compare the environmental performance of two spindle versions	Cradle-to-gate	One item of spindle	GW, OD, HAT, POF, PMF, IR, TA, FE, ME, TET, FET, MET, ALO, ULO, NLT, WD, MD, FD
Siwec and Pacana (2025)	Estimation of CO ₂ emissions	Cradle-to-grave	80,000 km traveled by the motorcycle in the life cycle	CO ₂ emissions
Sopha et al. (2017)	Evaluate the environmental impacts of using a motorcycle	Cradle-to-grave	passenger per kilometer	AD, GW, HAT, AC

(Continued)

TABLE 2 (Continued)

Author	Goal	System boundary	Functional unit [Reference measure]	Impact categories
Spreafico and Russo (2020)	Analysis of the environmental impacts arising from transportation by providing an extended comparison between the many alternatives	Cradle-to-grave	Transport of 1 passenger per 1 km of distance within the typical European scenario	CC, TA, PMF
Vanatta et al. (2022)	Quantify the emissions impact of transitioning from conventional gas powered to electric motorcycle taxis	Usage	[kg/year/motorcycle taxi]	GHG, CAP
Polanco Vásquez et al. (2025)	Evaluate and compare the environmental impacts of a commercial electric moto-taxi and a conventional gasoline powered one used for passenger transportation in the state of Yucatán, Mexico	Cradle-to-grave	kg for the manufacturing phase; passenger-kilometer for the use phase	GW, OD, IR, OF, HE, PMF, OF, TEC, AC, FE, ME, TET, FET, MET, HTc, HAT, LU, MRS, FD, WD
Xuan et al. (2013)	Compile, quantify and evaluate the environmental impact of the conversion of an ICE motorcycle	Emissions from conversion and usage	Entire motorcycle	GHG, CAP

AC, Acidification; AD, Abiotic depletion; ALO, Agricultural land occupation; CAP, Crite-ria air pollutants; DALY, Disability-adjusted life years; FD, Fossil Depletion; FE, Freshwater eutrophication; FET, Freshwater ecotoxicity; GHG, Greenhouse gas emissions; GW, Global warming; HAT, Human toxicity; HE, Human health; HTc, Human carcinogenic toxicity; IR, Ionizing radiation; LU, land use; MD, Metal depletion; ME, Marine eutrophication; MET, Marine ecotoxicity; MRS, Mineral resource scarcity; NLT, Natural land transformation; NRE, Non-renewable energy; OD, Ozone depletion; OF, Ozone formation; PMF, Particulate mat-ter formation; POF, Photochemical oxidant formation; TA, Terrestrial acidification; TE, Ter-restrial eutrophication; TEC, Terrestrial ecosystems; TEP, Toxic effect on land ecosystems; TET, Terrestrial ecotoxicity; ULO, Urban land occupation; VOC, Volatile Organic Com-pounds; WD, Water depletion.

2024). Regarding the system boundary cradle-to-grave is used in 17 of the studies, seven studies use well-to-wheel; concerning the impact categories 18 studies used less than four, and twelve used four or more categories (see [Table 3](#) for a detailed overview).

The main topic in more than 60% of the studies, especially those sorted into the motorcycle-specific topic categories “assessment of one motorcycle” and “comparison of different motorcycles” evaluated was the comparison of environmental impacts of conventional and EMs. The authors studying this aspect mainly agree that EMs have less emissions compared to conventional internal combustion engine motorcycles, especially regarding those impacting “Global Warming.” ([Kosai et al., 2022](#)) find GHG emissions of ICE2W (0.064 kg-CO₂eq/km) to be “approximately 1.8 times greater than those of the E2W (0.035 kg-CO₂eq)”; the results of the study by [Carranza et al. \(2022\)](#) “indicate that the ICEV contributes approximately 5 times more in the global warming potential impact category (GWP) mainly due to the consumption of fossil fuels”; test results from ([Majumdar et al., 2022](#)) “revealed that specific energy consumption of electric two-wheelers was about 79% and 82% less than that of conventional scooters and present day ICE motorcycles, respectively.”

[Champecharoensuk et al. \(2025\)](#) found that for both ICE vehicles and EVs the vehicle use phase is main contributor to generating kgCO₂eq, since according to [La Fleur et al. \(2024\)](#) also for the EM the “electricity mix used for battery charging is shown to have a significant impact”. “The electric technologies considered may reduce the Tank-to-Wheel (TTW) energy consumption in average [...] 4 times for the motorcycles. However, the reductions in a Well-to-Wheel (WTW) approach are reduced to a [...] 2 times reduction for motorcycles” ([Baptista et al., 2013](#)).

[Cuéllar-Álvarez et al. \(2022\)](#) conclude, that “electric motorcycles are always more efficient in reducing emissions than conventional ones, regardless of the electricity source” and even converting an ICE motorcycle to an EM “would reduce the life cycle energy consumed and emissions produced [...] by 72 and 45% respectively” ([Xuan et al., 2013](#)). However, it was also found that while EMs have less inventory emissions and/or environmental impacts than conventional motorcycles overall, in some impact categories, like criteria air pollutants² life cycle emissions can increase with the electrification of two-wheelers ([Peshin et al., 2022](#)). Other studies also found a shift of emissions from the usage toward production with the development toward more EMs. [Kosai et al. \(2022\)](#) showed that the highest emissions of CO₂eq come from the operation of the vehicle, regardless of electric or conventional two-wheeler, and [Sophia et al. \(2017\)](#) demonstrated that for a conventional scooter “the process which gives the highest contribution to the environment is the operation (use stage), followed by the manufacturing of the motorcycle.” For EMs [Schneider et al. \(2023\)](#) “obtained partially better results from the operation stage at a generally higher production impact compared to combustion driven motorcycles. In global warming and fossil resource scarcity those higher production impacts

2 Criteria Air Pollutants (CAPs) in Life Cycle Assessment (LCA) are six widespread, regulated pollutants (O₃, PM, CO, NO₂, SO₂ and Pb) used to evaluate, quantify, and mitigate human health and environmental impacts across a product's life cycle. These pollutants, often resulting from combustion, are critical indicators for assessing air quality impacts, including acidification and respiratory health.

TABLE 3 Economic aspects assessed in the SLR dataset including goal, considered life cycle stages, reference measure and the economic aspects considered.

Author	Goal	Life cycle stages considered	Reference measure	Economic aspects/costs considered
Carranza et al. (2022)	Preliminary cost analysis to compare the economic viability of the battery electric and the internal combustion engine vehicle	Acquisition, usage, maintenance, disposal	Cost per km	Total cost of ownership - costs related to the acquisition, the energy to power the motorcycles, the maintenance operations and the waste disposal
Chien et al. (2023)	Calculate total cost of ownership to understand the potential cost trade-offs among two-wheeler purchase options	acquisition, usage, maintenance	Cost per km	Total cost of ownership - vehicle purchase costs, fuel costs, and non-fuel operating and maintenance costs
Choi and Yun (2020)	Compare the ownership cost of an internal combustion engine based two-wheeler and a plug-in series hybrid electric scooter	Acquisition, usage	Annual cost	Ownership cost - initial purchase cost and total annual energy cost
Cox and Mutel (2018)	Comparison of the cost performance of both conventional (gasoline combustion) and advanced powertrain (battery electric and fuel cell electric) motorcycles	Acquisition, usage, disposal	Cost per km	Total ownership costs - purchase cost, fuel and electricity cost, cost for disposal
Cuéllar-Álvarez et al. (2024)	Assessment of Total Ownership Cost of various vehicle types, encompassing both conventional internal combustion vehicles and electric vehicles in a city within the global south	Acquisition, usage, maintenance	Cost per km	Total ownership cost - annualized capital, operational, and replacement costs
Gujba et al. (2013)	Estimation of economic costs for the current passenger transport system in Nigeria for 2003-2030 and future scenarios	Usage	Annual cost/total cost per scenario	Fuel costs - costs of infrastructure and vehicles not considered
Hafidza et al. (2022)	Compare the LCCs of electric and conventional motorcycles in Indonesia	Acquisition, usage, maintenance, battery recycling	Total cost	LCC = tangible costs + intangible costs tangible cost: purchasing costs, operation cost, and residual cost (battery recycling price) intangible costs: purchase restriction cost and driving restriction costs
Kalifa et al. (2024)	Evaluate the economic performance of passenger transportation in underdeveloped countries using four different internal combustion engine vehicles	Acquisition, usage, maintenance	Cost per pkm (pkm: passenger-kilometer)	Life Cycle Cost (LCC): costs during the whole service life of transporting passengers - purchase cost, fuel cost, stage registration, license fees, personal cost, tire costs, maintenance service cost
Kerdlap and Gheewala (2016)	Compare financial costs of conventional and electric motorcycles in Thailand	Acquisition, usage, maintenance	Total cost	Costs for vehicle, gasoline/electricity, maintenance, and parts replacement/battery replacements
La Fleur et al. (2024)	Analyze total cost of ownership during the life cycle of an electric motorcycle	Acquisition, Usage	Total cost	Total cost of ownership - costs of purchasing and all operational costs
Majumdar et al. (2022)	Compare the energy cost of electric transportation (two- and three-wheelers) compared to conventional counterparts	Usage	Cost per pkm (pkm: passenger-kilometer)	Energy cost (charging/fuel cost)
Peshin et al. (2022)	Estimate the monetized damages from air pollution and GHG of life-cycle emissions for different vehicles	Usage	Cost per km	Monetized damages = GHG emissions multiplied by the social cost of carbon in \$/tonCO ₂

(Continued)

TABLE 3 (Continued)

Author	Goal	Life cycle stages considered	Reference measure	Economic aspects/costs considered
Sansa et al. (2019)	Assess the economic performance of different design scenarios	Cradle-to-grave	Net costs of “allowing one use of a motor- cycle by starting its engine”	Net costs for each scenario per life cycle phase
Simboli et al. (2015)	Estimations regarding economic sustainability of the eco-innovation	Manufacturing	annual cost reduction	Estimated production cost reduction
Siwec and Pacana (2025)	Prospective evaluation of prototype purchase cost	Design/prototyping	Total cost	Expected cost of prototype
Yuniaristanto et al. (2024)	Formulating an LCC model that considers social and environmental costs besides consumer-oriented costs	Acquisition, usage, resale	Total cost	LCC = TCE + TCO + TCS TCE: total cost to the environment - air quality external cost, noise cost, greenhouse gas external cost TCO: total cost of ownership - purchase costs, operational costs, resale value TCS: total cost of social - maintenance losses, filling/charging losses, emissions costs to health impacts

could be compensated by lower operation stage impacts after approximately 2 years.”

[Polanco Vásquez et al. \(2025\)](#) compared gasoline-powered moto-taxis with electric moto-taxis using lead-acid and lithium-ion batteries and were able to show that the differences between conventional motorcycles as well as between different battery technologies in EMs have different effects in different impact categories. These findings are emphasized also by the studies from e.g., [Middela et al. \(2022\)](#), [Kosai et al. \(2022\)](#) and [Carranza et al. \(2022\)](#), that highlight the importance of the battery production process, which has a high environmental impact and therefore poses a big potential in emission reduction. But also, the toxic substances within batteries have a high impact and therefore it “is crucial that batteries from electric motorcycles are recycled to avoid 98% of impacts to toxicity” ([Kerdlap and Gheewala, 2016](#)).

Many authors also highlight the critical role of electricity generation with the development toward more battery-electric vehicles, since “the electricity mix is probably the most relevant factor in terms of climate change impact category” ([Carranza et al., 2022](#)). The reduction of climate change potential of EMs compared conventional ones is highly dependent on electricity source, even though “they still offer advantages over conventional motorcycles when charged with electricity from hard coal” ([Cox and Mutel, 2018](#)). Studies in India ([Middela et al., 2022](#)), Colombia ([Cuéllar-Álvarez et al., 2024](#)), Taiwan ([Chien et al., 2023](#)), Thailand ([Kerdlap and Gheewala, 2016](#)) and Malaysia ([Kosai et al., 2022](#)) showed that the effectiveness of emission reduction of EMs compared to conventional ones is highly dependent on the share of renewable energy in the electricity mix.

Regarding the electrification of motorcycles, [Purwani et al. \(2024\)](#) did a study on motorcycle battery exchange as a basis for considering recycling process classification and cut-off values before end of life and recommend “repair treatment, as it

reduces environmental impact and promotes significant material circularity.” [Simboli et al. \(2015\)](#) analyzed the environmental impacts of the production of a motorcycle rear wheel spindle and overall highlighted “the increasing relevance of LCA as a tool to support decision making in manufacturing.”

4.1.2.6 Economic aspects

In total 16 studies evaluate economic aspects of motorcycles or components, which are all presented in [Table 3](#). Three studies considered solely the economic dimension, the rest also the environmental and/or social. Regarding the life cycle stages considered, in contrast to the environmental aspects only one study uses cradle-to-grave ([Sansa et al., 2019](#)). Two studies focused on the manufacturing and design/prototyping respectively, both assess motorcycle components. Most of the studies focus on the ownership period, meaning the costs for acquisition and usage of motorcycles, some considered the usage cost only (e.g., fuel costs, sometimes including maintenance costs). Three of those studies additionally consider the disposal/resale.

As reference measure half of the studies use annual/total cost (of ownership/life cycle costs) whereby life cycle only ever includes acquisition and usage and seven use cost per km/pkm traveled; one study is using “allowing one use of a motorcycle by starting its engine” as the functional unit ([Sansa et al., 2019](#)). [Peshin et al. \(2022\)](#) are evaluating monetized damages of air pollution through social cost of carbon, [Siwec and Pacana \(2025\)](#) calculate the expected cost of motorcycle prototypes, and [Simboli et al. \(2015\)](#) estimate the reduction of production cost for motorcycle spindles.

Most of the studies consider economic aspects of battery-EMs compared to conventional ones. [Chien et al. \(2023\)](#) showed, that in Taiwan “consumers have to pay up to 124% more [...] for e-scooters having 56% lower emissions than their ICE counterparts.” [La Fleur et al. \(2024\)](#) and [Hafidza et al. \(2022\)](#) both highlight for

Kenya and Indonesia respectively the higher initial/purchase cost of EMs, but lower operating costs compared to conventional motorcycles in their studies, while Cox and Mutel (2018) state similar ownerships of both types of motorcycles. Similarly, Cuéllar-Álvarez et al. (2024) find for Bogotá that “despite a higher initial investment, [...] battery electric vehicles will be more cost-effective than internal combustion vehicles in less than 3 years” and Kerdlap and Gheewala (2016) find, that “lead-acid battery electric motorcycles are a more affordable option for consumers in Thailand compared to conventional motorcycles and lithium-ion battery electric motorcycles”. Choi and Yun (2020) find, that in Thailand recuperation of the initial investment for the plug-in series hybrid two-wheeler could take place in around 1.2 years with the fuel savings, in the Philippines this could occur in the vicinity of 2 years.

Carranza et al. (2022) also find the EM to be “more affordable than the ICEV” and included environmental externality costs in their economic analysis, which are lower for the former. Yuniaristanto et al. (2024) also assessed ways to increase the adoption of EMs and found “the number of charging stations and the abolition of purchase and use taxes [to] significantly increase [...] the willingness to adopt EM.” However, Kalifa et al. (2024) found that, compared to public modes of transport like busses or rickshaws in Uganda, “motorcycles were revealed to be the most cost-inefficient alternative. Both LCA and LCC results show that the operational stage owing to fuel consumption has the highest impact on the environment and economy” (Kalifa et al., 2024). Gujba et al. (2013) also “show that bus transport is much more environmentally and economically sustainable than transport by cars and motorcycles”.

Yuniaristanto et al. (2024) are determining life cycle costs for an electric and a conventional motorcycle, each consisting of total cost of ownership, environmental, and social.

Sansa et al. (2019) are assessing different design scenarios for motorcycle batteries and find within the economic assessment that most of the scenarios have significant costs during raw material extraction. Overall, the results depend on the technology, the country of manufacture and use, and the lifespan of the battery.

4.1.2.7 Social aspects

Within the SLR only two studies dealt specifically with social aspects. However, one of those is an LCA study, that compares the environmental impacts gasoline-powered moto-taxis with electric moto-taxis using lead-acid and lithium-ion batteries (Polanco Vásquez et al., 2025). In addition to this environmental assessment the authors consider the social aspects of moto-taxi transport in Umán, Yucatán, Mexico. Here the focus is not on the social aspects of the motorcycle usage itself, but on the social impacts on moto-taxi drivers and the study aims to understand the transportation dynamics and socio-economic challenges in the region. This study cannot be categorized as an S-LCA, however it can be mentioned that it assesses implications for the stakeholder groups ‘consumers’ and ‘local communities’ through the usage of the motorcycle (according to UNEP, 2020).

Sansa et al. (2019) developed a sustainable design model and evaluated it through implementation in a company that produces motorcycle batteries in Tunisia and Tanzania. By using a simplified

version of LCSA the authors evaluate environmental, economic, and social impacts of the different design scenarios for motorcycle batteries. By using the Social Hotspot Database (SHDB), they calculated the work hours at risk for the five social categories labor rights & decent work, human rights, health & safety, governance, and community and therefore the stakeholder group “worker” in the supply chain (UNEP, 2020). It was found that all life cycle phases “have approximately the same percentage of contribution to the work hours at risk for the five social categories. However, it should be noted that the absolute number of work hours at risk varies greatly from one social category to another.” is the only study within the SLR dataset, that is evaluating all three sustainability dimensions. A simplified LCA approach is used and no distinction is made between LCA, LCC and S-LCA, however since the environmental, economic and social impact assessment have been applied to the same functional unit (“allowing one use of a motorcycle by starting its engine”) and within equivalent system boundaries (cradle-to-grave) it fulfills the criteria for a LCSA defined in Section 2.

4.2 Evaluation of studies within the supplementary scoping review

For the studies identified within the scoping review, no descriptive analysis was performed since there was no systematic identification of studies, and no conclusions can be drawn from such an analysis. However, the topics covered are evaluated systematically below, similarly to the content-based analysis of the data set within the SLR. Therefore, this chapter can only be seen as an indication to which topics might be relevant when discussing motorcycle and sustainability issues and give indications toward possible future research agendas.

The studies evaluated below are considered because they all deal with social aspects of the motorcycle, there is no focus in the S-LCA methodology here, meaning that only the first of the two inclusion criteria (see Section 3.1) apply for the studies within the scoping review, as well with the criteria, that they must consider social aspects within the life cycle of a motorcycle. Therefore, they as well can be categorized according to the life cycles stages and sustainability dimensions they address.

As Table 4 shows, three of the studies did examine all three sustainability dimensions. Weiss et al. (2015) performed a literature review on the environmental, economic and social performance of electric two-wheelers, addressing all life cycle stage from production until end-of-life. They concluded among other things, that “if Europe is to decrease transport-related carbon dioxide emissions, urban noise and air pollution, and inner city traffic, policy makers should consider supporting electric two-wheelers.” They found human exposure to pollution, audibility and visibility, urban mobility, road accidents and fatalities, demand for road infrastructure and vulnerability in case of accident to be relevant social topics during the usage of motorcycles concerning consumers directly and society indirectly.

Similarly, Nayak et al. (2023) identified challenges and opportunities with the implementation of electric vehicles in their review of different two-wheeler technologies. Identified

TABLE 4 Additional studies - studies considering all sustainability dimensions.

Author	Relevant topic	Life Cycle Stage(s) considered	Social topics considered	Environmental topics considered	Economic topics considered
Nayak et al. (2023)	Review of different two-wheeler technologies (including environmental and economic aspects) and their opportunities and challenges	Production, usage, end of life	Rider Safety	(CO2) emissions, waste reduction (inter alia)	Cost effectiveness (inter alia)
Weiss et al. (2015)	Literature review on the environmental, economic and social performance and supplemental analysis of economic performance of electric two-wheelers	Production, usage, end of life	Human exposure to pollution, audibility and visibility, urban mobility, road accidents and fatalities, demand for road infrastructure, vulnerability in case of accident	Energy use and CO2 emissions, air pollution, noise pollution, lead toxicity	Price, total user costs
Marimin et al. (2018)	Analysis of the motorcycle tire production process in all three sustainability dimensions through a case study	Design/production (of a motorcycle part)	Employment of local workforce, local worker income, local social activities	Solid, liquid and, gaseous waste, efficiency of water and energy utilization, use of remaining raw materials, impact of chemical processing	Company net profit, stock price, company growth, market growth rate

challenges include battery life, thermal management in batteries, road safety, lack of charging stations, and “overall, the market, while opportunities include lower impacts on climate change or reduction of other pollution factors such as noise as well as job creation ([Nayak et al., 2023](#)). Social topics considered therefore are road safety (for consumers during the usage) and employment opportunities (for workers in production and supply chain).

In contrast, [Marimin et al. \(2018\)](#) took into consideration only the design/production of a motorcycle part, namely the tires. The authors analyzed the motorcycle tire production process in all three sustainability dimensions through a case study and included employment of local workforce, local worker income, and local social activities in their investigation of social aspects, which concerns the workers within the upstream supply chain.

The rest of the studies all focus on the motorcycle usage stage. One study did concern noise levels in road traffic, and twelve studies assess road safety. For example, there were some medical articles on injuries suffered while riding a motorcycle, which were attributed to the social topic rider safety, as will be explained further below.

Regarding the noise levels in road traffic, [Takada et al. \(2022\)](#) analyzed car and motorbike horn use at urban intersections in Taiwan and found that the “equivalent continuous A-weighted sound pressure level (LAeq, 10min) did not change with driver horn use, and increased with the traffic volume of motorcycles”, which ultimately has implication for “society” through other road users and local residents during usage of the

motorcycle. Concerning road safety, two types of studies can be differentiated: analysis of road accidents and medical articles on injuries sustained while riding motorcycles. Therefore, affected stakeholder groups considered are mainly consumers during the usage, but again indirectly also society. Within the first type, four studies in China, India and Turkey identified motorcycles to be a major influencing factor to the occurrence as well as the severity of accidents ([Hu et al., 2022](#); [Kumar et al., 2017](#); [Kumar and Toshniwal, 2015](#); [Karabulut and Ozen, 2023](#)). Other studies focus solely on motorcycle accidents and investigate crash factors and injury severities, like the study by [Atalar and Thomas \(2019\)](#) which analyzed PTW crashes in the UK to investigate crash factor and identified the PTW riders “as the prime contributor in 36% of the multiple vehicle crashes” or the analysis of motorcycle crashes in Hunan province, China by [Chang et al. \(2019\)](#), which aimed to investigate risk factors and improve traffic safety. Similarly, studies by [Tamakloe et al. \(2023\)](#) examined highway motorcycle-barrier crashes in Massachusetts, USA, [Li et al. \(2021\)](#) analyzed the effects on motorcycle severities in California, USA and [Wang et al. \(2023\)](#) identified heterogeneous effects of road characteristics on motorcycle-involved crash severities in London, UK.

In contrast to these influencing factors, the two medical studies included in the analysis deal the specific injuries that occurred to at least in a high number of cases while riding a motorcycle. One article focused on the medical treatment of injuries that

incurred while riding motorcycles (and also bicycles) (Singh et al., 2023). Caldas et al. (2013) analyzed 85 medical cases with posterior cruciate ligament injuries, where half the cases occurred in “traffic accidents, notably with involvement of motorcycles.” The study by Casado-Hernández et al. (2020) is technically not a medical study but draws conclusions on the effects of riding a motorcycle on the body and identified “found a prevalent foot discomfort in motorcyclists.” This might point toward a relevance of social topics within the motorcycle sphere, even though they have been assessed hardly ever with a life cycle methodology yet, as the SLR showed. Especially the topic of rider safety is of high relevance, not only from a medical point of view.

4.3 Current status in industry

In 2017, an investigation on the top 15 car manufacturers Tarne et al. (2017) showed, that except for two Chinese manufacturers, all others applied LCA to assess the environmental sustainability of their vehicles. However, only about half of those disclose the results publicly, and the communication is focused on greenhouse gas emissions.

The investigation within this study on the extent of usage of LCA application in motorcycle industry showed that life cycle assessments are not standard within motorcycle companies yet. Information sources used were sustainability reports, financial reports and company websites. However, some of the companies are not publishing separate reports on their motorcycle business, since they are part of larger automotive or other industry groups, such as BMW Motorrad (BMW Group), Ducati (Audi Group), Honda (Honda Motor Co., Ltd.) or Kawasaki (Kawasaki Heavy Industries).

As presented in Table 5 only two of the 10 companies chosen for the industry review are publicly disclosing whether they are conducting life cycle assessments, of which only one is publishing their results. However, many of the companies are using life cycle assessment methodology to calculate greenhouse gas emissions. It should be noted that the absence of publicly available information does not imply that no LCA-related practices exist, rather it only indicates that such activities are not disclosed in publicly accessible sources.

Looking at the two automotive OEMs within the assessment BMW³ and Audi⁴, which produce motorcycles under the brand BMW Motorrad and Ducati, they are both publishing LCAs according to ISO 14040/44 for their automobiles, but not for motorcycles. Within the BMW Group report it is mentioned that life cycle methodology is used to calculate Scope 3 Emissions, which includes the motorcycle segment for the first time in FY2024 (BMW Group, 2025). On the Ducati website there is a page on environmental sustainability throughout the life cycle, however

no LCA results or reports regarding Ducati motorcycles are mentioned.⁵

Similarly, there was no specific information found on the product sustainability of motorcycles produced by the two OEMs with an extended product portfolio Honda and Kawasaki. Within the Honda ESG Report from 2023, LCA is specifically mentioned, as “Honda has been quantitatively calculating and assessing CO2 emissions from all business activities by using its original Life Cycle Assessment (LCA) system” (Honda Motor Co and Ltd, 2023). Kawasaki does not mention LCA, however information on the Kawasaki Ecological Frontiers System, the Group’s own certification process for environmentally conscious products can be found.⁶

The remaining companies within the assessment manufacture motorcycles as their main business. However, there are still big differences regarding sustainability communication and the usage of life cycle assessments. The US-American manufacturer Harley-Davidson for example mentioned in their Stakeholder Management Report 2022, that they are currently “developing a life-cycle assessment (LCA)-based multi-criteria metric for sustainability.” (Harley-Davidson, 2022) Not additional or more recent information was found on the topic. Pierer Mobility, the Austrian parent company of KTM, “consider[s] the impacts that our products have on the climate and environment even during the product design phase. [...] [They] make use of the very latest life cycle assessment tools to calculate the carbon footprint.”⁷ For the Chinese motorcycle manufacturers CF Moto and Loncin (Chongqing Loncin Motor Co., Ltd. includes the motorcycles brands “LONCIN,” “VOGE” and “BICOSE”) no relevant sustainability information was found through the web search in English language. The only two companies within this investigation openly communicating that LCA on motorcycles are conducted are the Indian manufacturers Hero and TVS. Hero undertakes and publishes cradle-to-grave LCAs in alignment with ISO 14040/44 standards and in FY25 reached a coverage of 75% of the sales volume (Hero MotoCorp Limited, 2025). “TVS Motor Company conducts Life Cycle Assessments (LCAs) in-house using GaBi software and the Ecoinvent database” (TVS Motor Company Limited, 2025).

5 Discussion

Below, the research questions posed in Section 1 will be addressed using the results from the previous sections and first methodological suggestions toward an analytical framework for motorcycle-specific LCSA will be given.

³ Responsibility & Sustainability at BMW Group - <https://www.bmwgroup.com/en/sustainability.html>.

⁴ Audi | Decarbonization - <https://www.audi.com/de/sustainability/environment-resources/decarbonization/>.

⁵ Ducati | Product - <https://www.ducati.com/ww/en/company/environmental-sustainability/product>.

⁶ Kawasaki | Environmentally Conscious Products - <https://global.kawasaki.com/en/corp/sustainability/environment/consideration.html>.

⁷ Pierer Mobility | Sustainable mobility - <https://www.pierermobility.com/en/sustainability/focus-areas/sustainable-mobility>.

TABLE 5 Results of the industry review showing two-wheeler brand, country of headquarters, sales volumes and status of communication on LCA. Information sources were sustainability reports, financial report and company websites.

Two-wheeler brand	Country	PTWs sold in 2024 (in thousands)	LCA performed for PTWs	LCA results published
BMW Motorrad	Germany	210	Not disclosed	-
CFMoto	China	n/a	[no relevant communication was found in English language through web search]	
Ducati	Italy	54	Not disclosed	-
Harley-Davidson	USA	151	Not disclosed	-
Hero	India	5,900 (FY24/25)	Yes	Yes
Honda	Japan	18,800	Not disclosed	-
Kawasaki	Japan	480	Not disclosed	-
KTM	Austria	229	Not disclosed	-
Loncin	China	approx. 1,400	[no relevant communication was found in English language through web search]	
TVS Motor	India	4,700 (FY24/25) (incl. Three-Wheelers)	Yes	No

RQ1: Which environmental, economic and social aspects of motorcycles have been dealt with so far in scientific literature using LCA, S-LCA and LCC approaches?

Life cycle assessment methods have been used in an empirical manner regarding motorcycles. Since 2022 there can be seen a steep increase in studies with 20 studies in only 3 years on the specific topic. However, the highest number of studies published was in 2022 and has been stable around four studies a year since then. Looking at geographical distribution there can be seen a slight asymmetry between first author affiliation and the countries of data collection, which has been done mostly in countries in the Global South. Especially in less advanced economic countries motorcycling is an important transportation mode (Law et al., 2015), while in Western industrialized countries motorcycling developed from serving the purpose of transportation to a leisure activity (Scherhag et al., 2022). Research leadership however is partly concentrated in those countries in the Global North, which could be discussed from a geopolitical point of view in further research.

As highlighted already in Section 4 the functional unit used in most studies was pkm. This aligns with the recommendations made within the final harmonized approach of the TranSensus project for product LCA, meaning that the goal is to evaluate environmental impacts at a point in time where a (nearly) finalized bill of materials is available (TransensusLCA, 2025). TranSensus is a multi-stakeholder project of OEMs, stakeholders within the automotive industry and academia, which was “aim[ing] to develop a baseline for a European-wide harmonized, commonly accepted and applied single life cycle assessment (LCA) approach for a zero-emission road transport system”⁸ At an elevated level, it can be stated that content wise LCA has been widely used

within the literature to examine the environmental performance of motorcycles and LCC does play a significant role. However, S-LCA has not been used to examine motorcycles and social aspects in general do not play a significant role within the motorcycle literature in connection with the product life cycle. Content-wise the main part of the literature within the SLR dealt with a comparison of various kinds of transport including motorcycles (16 out of 33 studies) in a specific geographical region where the motorcycles are used. Evaluating the usage of motorcycles might also be the result of methodological convenience, since data on usage is much easier to obtain than complex data from supply chains or end-of-life treatment. However, not only use stage was considered in the studies as nine studies did use a cradle-to-grave approach. It is important to note that cradle-to-grave boundaries and well-to-wheel approaches are not directly comparable. Since the focus of the study was on the overall application of life cycle assessment methods in the motorcycle domain as well as the final findings of the examined studies, this limitation has carefully been considered. Another key aspect was the comparison of different motorcycles, which ten out of the 33 studies did, and they all compared electric with conventional motorcycles in a way. Whilst the electric vehicle option seems to be the “cleaner” one, a shift between impact categories and from usage to production impacts was noted. This is due to the impact of batteries within the electric vehicles. In terms of battery production, the impacts hinge on sourcing and processing materials—toxicity from mining, emissions during fabrication, and energy intensity of manufacturing. Production-related harmful substances can be mitigated through cleaner chemical processes and recycling of batteries at end of life. When considering electricity generation, the role of the grid mix becomes pivotal: if electricity is produced from fossil fuels, the overall cleaner profile of electric vehicles diminishes; with a cleaner, low-emission grid, the electric option gains a stronger advantage. Across usage, BEVs typically offer lower

⁸ <https://lca4transport.eu/>

tailpipe emissions, but the total environmental benefit depends on the full lifecycle, including production, operation, and end-of-life recycling.

Using life cycle methods, not only environmental aspects were examined but also economic ones. Here as well the focus within the examined studies was found to be on the economic performance of EMs compared to conventional ones. A higher initial investment with lower operation costs over the lifetime, and lower emissions, is observed by most studies. When public modes of transport were considered, their cost and environmental advantages were highlighted.

Two studies did consider the social sustainability dimension. Polanco Vásquez et al. (2025) however focused on the understanding of transportation dynamics and socio-economic challenges in the region and the moto-taxi driving as an occupation, rather than the motorcycle usage. Sansa et al. (2019) on the motorcycle part “battery” considered social sustainability and found relevant social topics in the production to be labor rights & decent work, human rights, health and safety, governance, and community. In an analysis of S-LCA in the automotive industry Karlewski et al. (2019) identified the need to “further investigate the mining, production and disposal processes”. Looking at the topics that came up within this SLR, this seems to be relevant in further research on social sustainability of motorcycles as well, especially when in studies to date the electrification, and with that the need for batteries, plays a significant role when discussion motorcycle sustainability.

To summarize and answer RQ1 the most salient topic regarding motorcycles that have been assessed using a life cycle perspective is a multi-faceted comparison between conventional and EMs regarding the environmental and to some extent the economic performance. Studies contrasting those impacts note that while BEVs generally reduce tailpipe emissions, their overall footprint is highly sensitive to manufacturing and end-of-life processes, particularly battery production and recycling. Equally critical is the role of electricity generation, since cleaner grids amplify the environmental benefits of BEVs and affect long-term sustainability. Economic considerations remain favorable for EMs, driven by lower operating costs and potential policy incentives, yet the analysis of life cycle costs (LCC) reveals regional variations, especially for the Global South, where infrastructure and grid quality, as well as transport patterns, shape broader adoption and modal shifts. Finally, many studies emphasize that LCC analyses must account for the broader context of mode choice and transportation planning to accurately reflect the economic and environmental advantages of EMs.

From these results it can be concluded that motorcycle-related sustainability assessments fall into several distinct methodological categories. To support theoretical development the following typology is proposed: (1) usage-stage assessments focusing on operational emissions or energy use, adopting limited system boundaries, (2) component-level assessments confined to individual motorcycle components such as batteries or tires; (3) vehicle-level studies comparing different motorcycles focusing on environmental impacts; and (4) multi-dimensional studies attempting to integrate environmental, economic, and social aspects. Structuring existing studies into distinct categories

supports clearer theoretical positioning and helps identify the methodological pathways required for a comprehensive motorcycle-specific LCSA framework. A first attempt at an initial conceptual foundation for a motorcycle-specific LCSA approach can be proposed based on three core components: First, motorcycles differ from passenger cars in several ways, including heterogeneous global usage profiles and informal maintenance practices in many regions. The structure of the globalized supply chains needs to be further explored, as well as the implications of different powertrain technologies and vehicle classes. These characteristics need to be explicitly modeled within a sector-specific LCSA framework to, secondly, align the methodological choices within the characteristics of motorcycles. This includes selecting functional units appropriate to mobility outcomes, capturing upstream social risks in component supply chains, and accounting for safety and exposure risks during use. For S-LCA the relevance of stakeholder categories such as workers (e.g., in mining or battery production) or consumers (e.g., road safety) becomes especially pronounced in the motorcycle sector compared to other modes of transport. Finally, an integrated assessment is required to link environmental, economic, and social indicators in a manner that reflects the realities of motorcycle usage and production. This includes addressing uncertainties, making explicit the trade-offs between production and use impacts, and enabling consistent comparison with other mobility options. Because motorcycles play a crucial role in mobility systems across many low- and middle-income countries, the framework must also be sensitive to regional socio-economic contexts. This preliminary LCSA framework forms a first conceptual structure and provides an analytical basis for future empirical work, including the development of harmonized impact indicators, data collection strategies, and sector-tailored S-LCA applications.

RQ2: In scientific literature, how has the social sustainability of motorcycles been observed and which aspects of social sustainability have been addressed?

As discussed above, only with studies within the SLR took social aspects into consideration, and merely one study discussed social aspects using a life cycle perspective. The assumption raised in Section 3, that only few studies would consider social aspects, is found to be true. Since the literature search therefore was supplemented by the search term “social sustainability” and a supplementary scoping review was performed to answer RQ2. Consequently, 16 studies were discovered that dealt with social aspects of motorcycles in a broad sense. However, these studies can only be an indication of what could be relevant topics for future research on the social sustainability of motorcycles.

Most of the studies identified were dealing with the usage of motorcycles, as twelve studies analyzed road accidents and the role of motorcycles. One the one hand, studies dealt with the factors that lead to road accidents which influenced their severity of the accidents themselves and second, they dealt with the factors that influenced the severity of the riders’ injuries. Additionally, the medical point of view regarding the treatment of motorcycling injuries was part of the results. Rider safety therefore seems to be a topic of high concern, even

from different research standpoints. The International Motorcycle Manufacturers' Association (IMA) has defined "safety" as one of their four policy areas⁹ and in 2019 published a white paper on safer motorcycling, suggesting ways to improve road safety for motorcyclists and calling on governments to implement them (IMMA, 2019). Additionally, in 2024 ACEM together with the Federation of European Motorcyclists' Associations (FEMA) and the Fédération Internationale de Motocyclisme (FIM) published 'The Motorcycling Manifesto' calling upon the European legislators to include amongst other topics road safety and better protection of motorcyclists in their legislations (ACEM, FEMA and FIM, 2024).

Another aspect that came up with the scoping review was the noise level during usage, which was found to increase with an increase in the traffic volume of motorcycles. This topic was also mentioned within a literature review on the sustainability of motorcycles together with the topics human exposure to pollution, urban mobility, road infrastructure, as well as, again, road accidents and vulnerability in accidents. Correspondingly, a technology review on motorcycles found road safety as a relevant social topic. A study on motorcycle tires focused more on production and identified the employment of local workforce, local worker income, local social activities as relevant social aspects, similarly to the study by Sansa et al. (2019) within the SLR.

In contrast to the findings of the SLR regarding environmental sustainability of motorcycles, electrification did not come up as a topic with the social sustainability sphere and motorcycles. Further research might be necessary using primary data on motorcycle and motorcycle battery production. This adds to the findings by Karlewski et al. (2019), that conclude that "SLCA with company-specific data is [...] feasible in an industry with complex, international manufacturing and supplier structures such as the automotive industry—at present, however, the method still has some limitations." The authors highlight the need for databases with uniform indicators for different sectors and countries, as well as to further investigate the mining, production and disposal processes as well as to further analyze social aspects to include them in future guidelines. However, their research was done before the development of ISO 14075, which means that at least guidelines have now been established for carrying out an S-LCA analogous to an LCA. However, relevant standardized indicators are still missing within the automotive sector as well as "a clear, transparent, and justified approach to selecting indicators, for instance, conducting a social hotspot analysis to identify the most critical indicators for the social dimension" (Ostojic and Traverso, 2024). A sector-specific investigation within the motorcycle industry might help in answering these questions, however the supply chain structure, including typical production locations, needs to be identified for the most relevant components, since the social conditions can vary heavily for the same production processes in different countries or regions. Primary data availability in this context remains a major concern here.

RQ3: To what extent have environmental life cycle methods been used in industry to assess motorcycles?

In 2017 Tarne et al. found that within the industry LCA is already widely accepted, however social and economic assessments along a car's life cycle could not be found. Similarly, within the results of the study on hand it became obvious that within the motorcycle industry, if even, only LCA aspects are taken into consideration. The only two companies actively communicating on whether full LCA according to ISO 14040/44 are conducted are the two Indian companies within the assessment, which they are obliged to as Business Responsibility and Sustainability Reporting is mandatory in India since 2023 and includes disclosure on risks identified within an LCA study. Others are using life cycle methodology for environmental assessment, but it remains unclear whether full LCA is performed. Accordingly, S-LCA or LCC were not found within the industry review.

Differences between automotive OEMs and motorcycle manufacturers regarding the usage of life cycle assessment methodology might lay in differences in resources, supply chain structure and customer as well as institutional pressure. Regarding social topics, at least three PhD theses within the automotive industry have focused on them.

At Daimler, Karlewski (2016) developed a practical Social Life Cycle Assessment (S-LCA) approach. Meanwhile, at BMW, Tarne (2019) evaluated S-LCA as part of a broader Life Cycle Sustainability Assessment (LCSA) framework and Gompf (2022) focused on S-LCA of mobility services. Karlewski and Tarne both specifically mention the car manufacturer Ford, which incorporates social aspects alongside other sustainability dimensions in its Product Sustainability Index (PSI) to guide vehicle development.

In June 2025 the beforementioned multi-stakeholder project called TranSensus came to its end. In their final deliverable, the 'TranSensus-LCA final harmonized approach' (TranSensusLCA, 2025), they defined mandatory, recommended and optional requirements for all phases and topics within an environmental or social LCA, including the definition of mandatory and optional impact categories. However, only existing impact categories from databases are referred to here and it could be argued that the recommendation of the guidelines is only a summary or aggregation of the indicators within the databases. There was no differentiation made between motorcycles and other typical means of transport like cars or trucks except in the definition of the functional unit (TranSensusLCA, 2025). This leaves room for discussion whether within the 'typical means of transport' differentiation might be necessary, and even more product specific research is needed on individual products, like motorcycles. Whilst the fundamental product specifications might seem very similar (e.g. all vehicles need a motor and tires), the production networks might differ greatly as well as the usage of the specific products. A first attempt at mapping a motorcycle-specific framework was made within the answer to RQ1. Future research should focus on assessing which social aspects are covered within the sustainability reporting of motorcycle manufacturers, specifically examining the stakeholders and life cycle stages considered. To do so, published information from sustainability reports will be compared with S-LCA indicators to determine whether relevant topics are addressed, even if not yet through a systematic S-LCA methodology. This approach will help identify gaps between current reporting practices and a more structured life cycle-based evaluation of social aspects, providing valuable

⁹ <https://www.immamotorcycles.org/policy/>

insights for improving the comprehensiveness and rigor of future sustainability reporting.

The paper at hand has certain limitations that need to be highlighted. Firstly, the screening and identification of relevant studies within the literature review involved a high degree of manual processes. In particular, the within the scoping review required careful consideration, as their relevance to the research was not determined as systematically as the studies included in the systematic literature review (SLR). Consequently, the conclusions drawn from these studies should be regarded only as indications of relevant topics concerning the sustainability of motorcycles. Moreover, while relevant social topics related to motorcycles may be present in the broader literature, they might not have been uncovered through the life cycle-specific search strings used in this research. Regarding the industry review, it is important to note that sustainability reports as well as company websites, being self-disclosures, carry the risk of potential bias. Within this study it was refrained from adding non-company-specific data sources to the review, which could be part of future additional research. It is important to emphasize that the absence of public disclosure does not imply the absence of LCA practice. Rather, it reflects the limitations of relying solely on publicly available reports and English-language sources. Several manufacturers may well conduct internal life cycle assessments or apply life cycle-based tools without publishing corresponding results. Therefore, the findings of this industry should be interpreted as “no evidence found in accessible public sources,” not as evidence that no such practices exist.

6 Conclusion

This study has addressed several key research questions concerning the sustainability assessment of motorcycles, focusing on environmental, economic, and social aspects as analyzed through LCA, S-LCA and LCC methods. The findings confirm that while environmental LCAs and LCCs related to motorcycles exist, they predominantly concentrate on vehicle use and emissions, with a strong emphasis on CO₂ emissions. Social aspects, however, remain largely underexplored and are treated in a fragmented and contextual manner rather than through a comprehensive life cycle perspective. Notably, no dedicated S-LCA studies specifically addressing motorcycles as a product system (only one on a motorcycle battery) were identified in the scientific literature, highlighting a significant research gap. Within industry, environmental life cycle methods are applied, particularly for assessing CO₂ emissions, but the results are rarely published, limiting transparency and broader in-sights. Social sustainability considerations in motorcycle manufacturers' sustainability will be further examined in forthcoming research.

The importance of motorcycles as a primary means of transportation in many regions, especially across Asia, Africa, and Latin America, underscores the critical need for more holistic sustainability assessments. Motorcycles impact millions of users and employees directly, with social issues linked to

production, maintenance (often informal), occupational safety, and road safety. Furthermore, as motorcycles evolve with increasing electrification, particularly regarding battery production and end-of-life management, addressing social impacts alongside environmental ones becomes even more crucial. This study contributes a systematic gap analysis that distinguishes motorcycles as a sub-sector within the automotive industry, enabling a more focused examination of sustainability topics. For practitioners, it identifies critical social impact areas within the motorcycle sector that require deeper investigation and integration into sustainability assessments.

Beyond mapping the existing literature, this review makes a theoretical contribution by demonstrating that motorcycles with their unique technical configurations, globalized supply chains, and pronounced social risks, such as road safety and upstream labor conditions, necessitate a tailored analytical framework for sustainability assessment. Therefore, within answering RQ1 first steps were taken toward a typology that structures the methodological landscape of current research and sector-specific conceptual model for motorcycle LSCA. Together, these contributions establish the groundwork for harmonized, comparable, and methodologically robust LCSCA applications in the motorcycle sector.

In conclusion, while environmental assessments of motorcycles are relatively established, there remains a pressing need to expand research and industry practice to comprehensively include social sustainability aspects throughout the motorcycle life cycle. Future research should focus on company-specific data, supply chain structures, and comparative analyses with the broader automotive sector to support a more inclusive and effective sustainability transition in powered two-wheelers.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft. MT: Conceptualization, Project administration, Supervision, Writing – review & editing.

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MA was employed by BMW Group.

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The author MT declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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