The contribution of eco bus technologies to environmental problem mitigation: a systematic review

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ABSTRACT

Substituting diesel technology with eco-technologies in public buses is one of the prominent efforts being made to achieve a sustainable transportation system goal. Among these eco-technologies, commonly used ones include electric vehicles, natural gas fuel, hydrogen fuel, and bio-diesel fuel technology. However, the performance comparison between these technologies in reducing environmental impact at each location where they are implemented remains unanswered by previous studies. Research to measure the effectiveness of each of the eco-technologies in reducing environmental issues has been conducted extensively, employing various methods and metrics. This study conducted a systematic review of 94 articles that met the predefined inclusion criteria to obtain performance comparisons among these technologies. As a result, a general trend has been observed that eco-technologies have successfully achieved their intended goals with various success rates, although electric bus technology has advantages over other technologies based on the articles. However, its effectiveness relies on specific aspects to optimize its environmental performance. Therefore, the suitability of implementation in a region will depend on many factors. This article contributes to determining the extent to which eco-technologies are implemented in buses worldwide, serving as a consideration for decision-makers, and identifying research gaps in this topic.

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1. INTRODUCTION

The current high level of air pollution worldwide is an undeniable phenomenon. Among the various causes, the transportation sector is one of the largest contributors to the increase in greenhouse gas levels and other pollutants in ambient air [1]. Emissions from internal combustion engine (ICE) vehicle exhausts during the operational phase of vehicles are particularly significant, even though the environmental impact of the transportation sector begins with prior phases, which are the extraction of materials and the manufacturing of transportation equipment [2], [3]. Additionally, the environmental impact caused by vehicles waste after their use, especially in developing countries where many motor vehicles end up as waste, poses a serious environmental problem that needs immediate attention [4].

Compared to other impacts of ICE vehicles, the current ambient air pollution is taking special concern, as numerous previous studies have demonstrated a strong connection between deteriorating air quality and worsening human health, especially in urban areas [5]. The trend of deteriorating air quality is expected to continue, posing even greater risks to the survival of future generations [6]. Those of us living in the present must take serious action to prevent these risks from becoming a reality.

Many countries face various challenges in addressing air pollution caused by the transportation sector [7]. On one hand, high transportation activity is a sign of a growing economy and increasing societal prosperity. Restricting the mobility of the population in general would hinder regional economic progress [8]. However, the phenomenon that exacerbates the situation is the increasing ownership and use of private vehicles for daily activities [9]. This phenomenon leads to a direct or even higher increase in emissions from vehicles in urban areas. This phenomenon is particularly prevalent in developing countries where governments are promoting economic growth but are not yet prepared to provide adequate public transportation facilities for the majority of the population [10], [11]. Unattractive and limited public transportation options, combined with the ease of financing private vehicles through financial institutions, contribute to the rapid increase in the number of private vehicles on the road [12]. In a single household, there can be two, three, or even more motor vehicles used by different family members for various purposes. Some of the indicators of this situation are worsening traffic congestion, stagnant public transportation availability, and rapidly growing private vehicle sales.

Referring to this phenomenon, at least two dimensions of solutions can be proposed to prevent even worse air pollution: optimizing public transportation for daily activities and using environmentally friendly vehicles. Large cities with a strong culture of public transportation tend to have better air quality [13], [14]. As for the use of environmentally friendly vehicles, it involves various modes of transportation with lower or even zero emissions. The most ideal scenario, of course, is if the majority of the population walks and bikes to their destinations. However, in large cities where distances between residential areas and activity centers are significant, this may not be possible due to time constraints [15]. The next ideal option is for most of the population to use environmentally friendly public transportation, maintaining a high level of economic activity while minimizing emissions as much as possible [16].

Several cities in the world have been fortunate enough to implement such concepts. Their air quality has significantly improved, serving as a model for other cities [13], [17], [18]. However, in other cities with severe and chronic transportation issues, transitioning from the old transportation patterns to environmentally friendly public transportation is not easy [9], [11]. Challenges include the need for high investments, urban planning restructuring, and entrenched behavior patterns that are difficult to change [19]. To change people's habits from using private vehicles to public transportation, one key aspect is providing comfortable, safe, and affordable public transportation facilities and infrastructure to activity centers [20]. Among the alternative public transportation modes to consider are trains, trams, trolleybuses, or buses. Buses, in particular, offer a more realistic and flexible option for future urban planning changes [21]. Therefore, the use of environmentally friendly buses is often chosen by city governments to implement sustainable transportation systems. The next consideration is which technology to use for environmentally friendly buses, as there are several transportation technologies claimed to reduce environmental impact.

The choice of environmentally friendly transportation technology for buses generally involves low-emission options. Some technologies discussed by academics include gas-powered buses, fuel cell hydrogen, biodiesel, battery electric, and hybrid technologies [22]. Studies and implementations of these technologies have been conducted worldwide, with varying results from one place to another. Some places prefer electric buses, while others opt for hydrogen fuel cells or other technologies. For regions just starting sustainability-focused public transportation projects, a review study is essential to understand why the outcomes differ from place to place. What factors influence decision-making outcomes? and how does the implementation of these solutions affect the environment in that region?. These are fundamental questions that need answers, and a review study comparing the implementation of environmentally friendly technologies in buses has not been found in academic databases.

Briefly, previous review studies have mostly focused on the effects of specific technology vehicles on the environment, such as electric vehicles or gas-powered vehicles, among others. They did not discuss the differences in characteristics and compare the performance of these technologies, especially for public transportation modes such as buses. Thus, there is a lack of adequate references to choose among them in a new location. This article aims to fill the gap in academic research by comparing the use of environmentally friendly technologies in buses across various locations and assessing the effectiveness of these technologies in reducing negative environmental impacts. The findings can serve as a basis for future studies and as a foundation for government policies aiming to implement environmentally friendly public transportation systems.

2. THEORETICAL ANALYSIS

A systematic review study is essential to provide a comprehensive overview of a specific topic within a predetermined time frame. This type of study serves as the primary reference for assessing the extent of research conducted by experts and as a foundation for determining the direction of future research. Therefore, systematic review studies are crucial for evaluating progress on a particular topic of discussion.

Until now, a comprehensive study on the environmental contributions of environmentally friendly technology buses has not been conducted, as previous studies have been specific to certain technologies or focused on specific topics. Requia *et al.* [5] conducted a systematic review of the environmental impacts of various types of electric vehicles (EVs), not just buses. From 65 qualifying articles, it was concluded that EVs have a positive environmental impact as they can reduce greenhouse gas emissions and other pollutant components. Factors that significantly influence the environmental effects include the type of EV, power source, driving conditions, charging patterns, charging infrastructure availability, government policies, and regional climate.

A review of hydrogen fuel cell vehicles and their environmental impact was conducted by Rinawati *et al.* [23]. In this study, a review of 70 articles focused on the technical aspects of the technology used and the research methodologies employed to assess its environmental impact. Life cycle assessment (LCA) was the most commonly used method, with variations including well-to-tank (WTT), well-to-wheel (WTW), and comprehensive approaches. In terms of technical aspects, fuel cell technology was predominantly used for hydrogen fuel applications in vehicles.

A broader review of carbon emissions in transportation, beyond just buses, was also conducted by Huang *et al.* [24], but the environmental impact discussion was primarily focused on CO_2 emissions. This study found that research trends on this topic continue to rise in complexity as various factors influencing greenhouse gas formation within ecosystems become better understood. One crucial element in slowing CO_2 formation is the presence of an appropriate public transportation system.

Sharma *et al*. [25] also examined the environmental and human health impacts of EV adoption but with a spatial distribution focus. This study reviewed 47 articles and found that the impact of EVs is also related to the location where EV components are produced and where EVs are deployed. The environmental impact tends to be higher in the locations where EV components are manufactured compared to where EVs are implemented. Moreover, local factors such as climate conditions, geography, and the local population also determine the final outcomes in terms of air quality improvement and public health enhancement. From this literature review, it is evident that a systematic review study related to the adoption of environmentally friendly technology buses and their environmental impact has not been conducted before. Such a study is necessary to compare different technologies and contribute to the realization of a sustainable public transportation system.

3. METHOD

This article refers to the PRISMA checklist [26], which includes several stages such as identification, screening, eligibility, and inclusion. These stages serve as a guide to enhance the clarity and academic quality of a documented systematic review [27], but there is still room for improvisation based on the characteristics of the study conducted [28]. This study aims to investigate the impact of implementing environmentally friendly technologies in public buses on the environment as a comparison study. The research focuses specifically on the propulsion technology while excluding other vehicle components such as the body and transmission from the analysis. The study is based on well-defined keywords, and a systematic search was conducted on Google Scholar to identify relevant articles. The stages as previously described are detailed in the following section.

3.1. Identification

The first stage is identification. This study is a systematic review that examines the environmental effects caused by the implementation of technologies that are eco-friendlier compared to diesel engines in buses as public transportation vehicles. By reviewing several of these technologies simultaneously, we can compare the characteristics of each technology. The search was carried out from July to August 2023 using the following keywords: ‘electric-bus environmental impact’, ‘low-emission-bus environmental impact’, ‘gas-fueled-bus environmental impact’, ‘hydrogen-bus environmental impact’, ‘cng-bus environmental impact’, ‘hybrid-bus environmental impact’, and ‘biodiesel-bus environmental impact’. Each set of keywords is used in the Google Scholar search engine, where all the results obtained are academic documents that have the potential to be references used in this study. The results might be numerous, but not necessarily relevant to the study's objectives, so it is necessary to proceed to the next step.

3.2. Screening

The second stage is screening. The search results were then filtered based on predefined inclusion criteria. The articles included in this study must have undergone a peer-review process, be written in English, constitute original research, and not be review articles. Original research may involve direct measurement methods, calculations, or simulations using field data or secondary data. Conference papers, theses, technical reports, and book chapters were excluded from this study. Additionally, the articles used had to be indexed in Scopus. There were no restrictions on the timeframe of the research or publication applied in this study. Based on these inclusion criteria, the search results can be reduced to a smaller number but are more relevant to the research objectives. At this stage, each article can be quickly scanned through the title and abstract, allowing irrelevant articles to be eliminated from the list. This screening process can be done using software [29], but in this study, it is done manually by the research team.

3.3. Eligibility

The third stage is eligibility. At this stage, the remaining articles need to be studied more carefully by thoroughly examining their entire content to determine their relevance to the desired outcomes of this study. Each article needs to provide information regarding the environmental impact changes caused by alternative technology buses as previously described. These environmental impacts can be obtained through measurement processes or simulations, and it should be explained whether the environmental impact is positive or negative. Therefore, these environmental impacts must be quantitatively described so that their results can be compared between different studies. The articles also need to explain the location and timeframe of the research conducted, enabling analysis related to these aspects. It may be that some articles investigate only one technology or more, and this is not a problem. Based on this stage, we can determine which articles will be used to proceed to the next review stage.

3.4. Inclusion

The fourth stage is inclusion. Data were extracted from each article meeting the inclusion criteria, including information on the primary author, publication year, publishing journal, research location, types of technology discussed, types of environmental impacts analyzed, and the main conclusions of the articles. The obtained data were then analyzed and compared to identify various environmentally friendly technologies used in public buses and the environmental impacts resulting from their implementation. The analysis also encompasses factors influencing the effectiveness of the implementation of environmentally friendly technology in improving the environment at the research locations. While this study does not conduct quantitative analyses of technology effectiveness overall, the research findings are described in general terms to provide readers with an overview of significant findings from various studies.

4. RESULTS AND DISCUSSION

4.1. General overview

Through the conducted search process, a total of 3,778 results were obtained (Table 1), and after removing duplicate results, 3,742 results remained. Subsequently, a screening process was applied to the titles and abstracts, resulting in the selection of 136 articles that met the inclusion criteria. These selected articles were then read in their entirety, and it was found that some of them did not align with the study's objectives, as they primarily focused on economic, health, or social impacts rather than environmental ones. The final number of articles after this series of processes was 94 (Figure 1). These articles were then subjected to further analysis in this review.

Table 1. Search results based on keywords

Keywords	Results in Google Scholar
electric-bus environmental-impact	2615
low-emission-bus environmental-impact	72
gas-fueled-bus environmental-impact	6
hydrogen-bus environmental-impact	299
cng-bus environmental-impact	42
hybrid-bus environmental-impact	677
biodiesel-bus environmental-impact	67
Total	3778

From the final results, it was found that the first article in this field was published in the year 2000. However, until 2009, the number of articles on this topic was quite scarce, and there were even no articles meeting the inclusion criteria in 2001 and 2004. But starting from 2010, the number of studies on this topic has been steadily increasing, reaching its peak in 2021 with a total of 18 articles. The number of articles in 2022 decreased slightly to 13 articles, while in 2023 up to August, 9 articles were found (Figure 2). However, this does not necessarily indicate that the trend in this field is declining, as research locations are not evenly distributed, and there is still ample opportunity for research, especially in developing countries that are planning emissions reduction in the transportation sector. In general, it can be predicted that the research trend in this field will continue to rise, and the development of more environmentally friendly transportation technologies will be regionally adapted based on local wisdom. Of course, environmental impact analysis is also needed to measure the success of the strategies implemented.

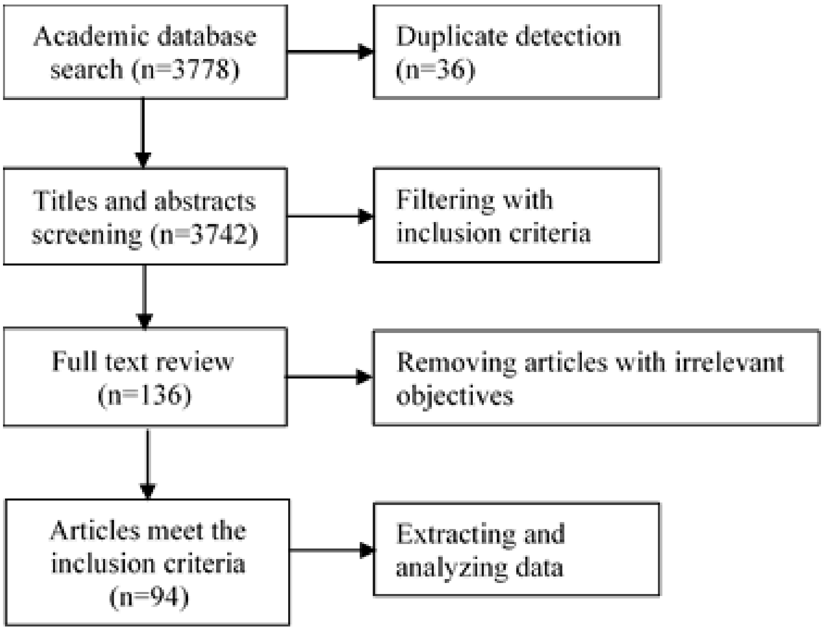

Figure 1. Results selection process

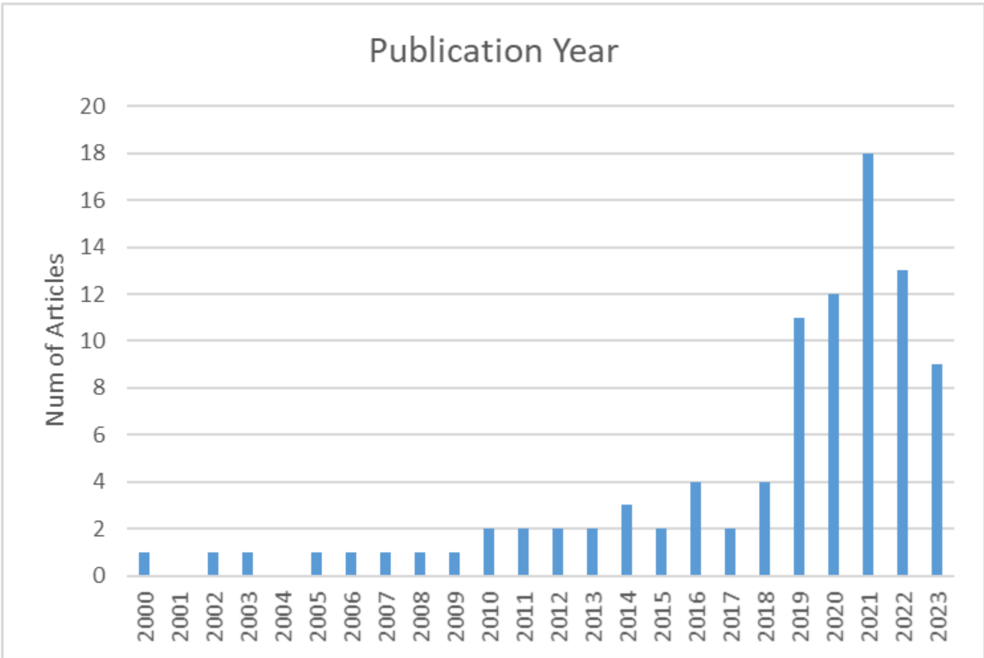

Figure 2. Number of articles by years

In addition to the study's timeline, we also examined the locations where these studies were conducted (Figure 3). The majority of the research was carried out on the European continent, with a total of 47 articles. This corresponds to the more established implementation of sustainable transportation systems in Europe. The countries with the highest number of articles were Italy in Europe, China in Asia, and the USA in North America, each with 9 articles. Africa and Australia, on the other hand, had only 2 articles each on this topic. Based on these findings, it can be concluded that research distribution on this topic is not evenly spread, and there is a need for future research in different locations.

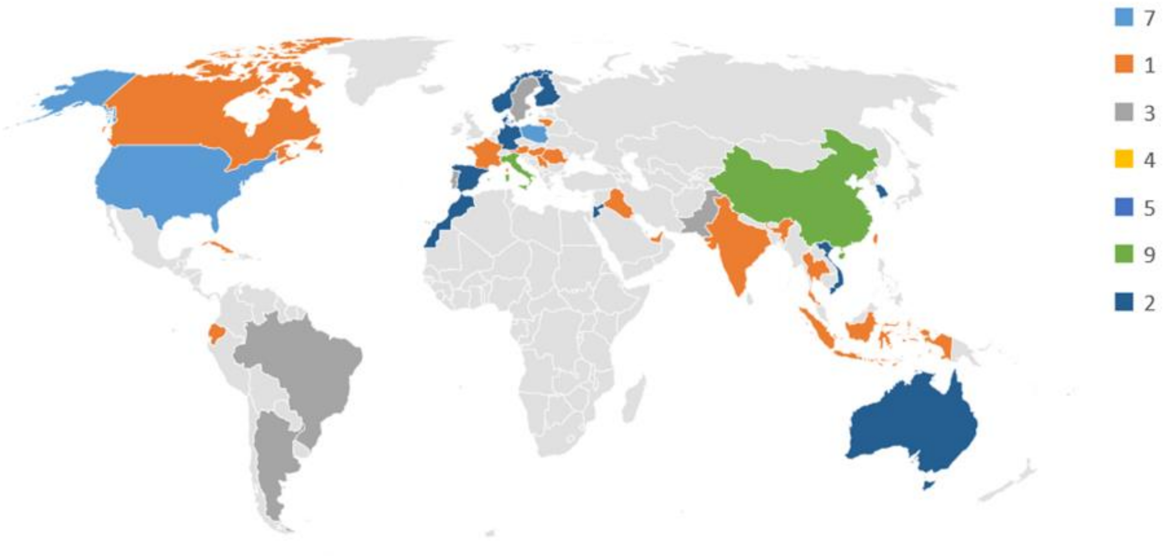

Figure 3. Number of articles by location

Meanwhile, in terms of publishing journals, these articles were found in various journals. However, in this review, we present the top 9 journals that published articles on this topic. Most of these journals are affiliated with ScienceDirect, while others are published by MDPI and ACS Publications (Table 2).

Table 2. Number of articles by publishers

Publisher	Journal	Num of Articles
ScienceDirect	Transportation Research Part D	9
ScienceDirect	Journal of Cleaner Production	6
ScienceDirect	Applied Energy	5
ScienceDirect	Energy	4
MDPI	Energies	4
ScienceDirect	International Journal of Hydrogen Energy	4
ScienceDirect	Science of The Total Environment	4
MDPI	Sustainability	4
ACS Publications	Environmental Science and Technology	3

4.2. The classification of environmentally friendly technologies in public buses and their geographical distribution

Diesel engines have traditionally been used as the power source for buses due to the high torque they can generate. However, diesel engines have been associated with emissions and noise issues that are harmful to the environment. Therefore, alternative environmentally friendly technologies have been introduced for implementation in buses used for public transportation [30]. These technologies include electric buses, natural gas, hydrogen fuel cell, biodiesel, and hybrid combinations [31]-[33]. Each technology will be briefly explained as follows.

EV technology is currently one of the most popular environmentally friendly transportation technologies. EVs can be further divided into battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), and hybrid electric vehicles (HEV) [5]. BEVs rely solely on electric energy from batteries to power the electric motor that drives the wheels. On the other hand, PHEVs and HEVs still use ICE as their power source, but PHEVs have a larger proportion of electric power because they can be charged from external sources [34]. In general, electric motor technology has been used to reduce fuel combustion, which is a major contributor to air pollution and rapid greenhouse gas emissions. BEVs produce zero exhaust emissions, significantly improving air quality on the roads [35]. Another technology that utilizes electric motors is the fuel cell EV, which is categorized separately in this article.

The second type of technology uses hydrogen fuel cells. In this technology, hydrogen reacts with oxygen in a fuel cell, producing heat that is then used to generate electricity [36]. One distinctive feature of this technology is the need for hydrogen storage tanks, which determine the vehicle's range. However, the requirement for these tanks can pose challenges as they require considerable space. Nevertheless, since the end result of this process is electric energy, vehicles using hydrogen fuel cells do not emit exhaust gases and are considered environmentally friendly.

Next is the use of natural gas as a fuel, which can be in the form of compressed natural gas (CNG) or liquefied natural gas (LNG). CNG or LNG is stored in tanks and then fed into the internal combustion engine to generate the required energy for the vehicle [37]. In terms of emissions and noise, this technology is considered superior to diesel technology and has been widely adopted for buses in various cities around the world [38], [39].

Other less popular technologies include compressed bio-gas (CBG) [40], biodiesel [41], and hydro-treated vegetable oil (HVO) [42]. CBG is essentially methane, similar to CNG, but it is produced from the fermentation of waste or other organic materials. Although these technologies are not as commonly discussed, some articles in this study did cover them [32].

From Table 3, it can be seen that EV technology is the most widely discussed in the scientific articles in this study, with a total of 67 articles. Natural gas technology (CNG or LNG) follows with 26 articles, hydrogen fuel cell with 23 articles, and the use of HVO or biodiesel and CBG with 4 and 3 articles, respectively. In Europe, Asia, and the USA, electric buses are the most widely discussed, while in Africa, there are only 2 articles discussing electric buses, and no articles were found on this topic in Australia.

Table 3. Eco technologies discussions by region

Study Location	Electric (BEV, PHEV, HEV)	Hydrogen fuel cell	CNG/LNG	CBG	HVO/bio-diesel	Total
Asia	20	4	7	0	0	31
Africa	2	2	0	0	0	4
Europe	34	12	11	3	3	63
America	11	4	6	0	1	22
Australia	0	1	2	0	0	3
Total	67	23	26	3	4	123

There are various environmental impact metrics used in the analysis of the implementation of environmentally friendly bus technologies. In this article, these environmental impact metrics are classified into 16 groups. Table 4 shows the number of articles that interact between bus technologies and environmental metrics, where one article can have more than one interaction. The classification of environmental impact metrics is based on findings from all articles that meet the inclusion criteria, although some adjustments were made due to the high variation in metrics used in these articles.

In this classification, carbon dioxide equivalent (CO_{2eq}) and CO_2 are assumed to be different environmental impact metrics, even though both refer to the potential for increased global warming caused by greenhouse gases [37], [39]. CO_{2eq} is considered a general metric that represents a conversion of various activities, mainly related to the product life cycle, whereas CO_2 specifically refers to the air component measured in ambient air as a result of an increased number of vehicles on the road. This distinction is crucial for accurately assessing the contributions of various sectors to greenhouse gas emissions and implementing targeted mitigation strategies.

Some components that are considered to have similarities in composition and characteristics are grouped together. For example, NO_2, NO_3, and N_2O are categorized under NO_x [43], $PM_{1.0}$, $PM_{2.5}$, and PM_{10} fall under the PM category [44], and SO_2 and SO_3 are grouped under SO_x [38]. Additionally, some merging of metrics is done for the sake of simplification and approachability, even though there may be differences in the characteristics of the components being combined. For instance, some articles use the terms volatile organic compounds (VOC) and non-methane VOC (NMVOC). NMVOC examples include benzene, toluene, ethylene, isoprene, and various other organic compounds aside from CH_4 [45]. However, in this review, the term NMVOC found in the articles is still categorized as VOC. Another challenging classification involves the term hydrocarbon (HC), where some articles also use terms like volatile hydrocarbon (VHC) [46], total hydrocarbon (THC) [47], and non-methane hydrocarbon (NMHC) [19]. All these terms are included in the HC category in this review. Consequently, there is an overlap between VOC and HC components, but for the sake of simplification, this issue is overlooked.

From the 94 articles reviewed, CO_{2eq} is the most frequently used environmental impact metric, with a total of 71 mentions. Out of these, 35 articles discuss EVs. This indicates that the analysis of the relationship between EVs and CO2eq is the most extensively covered topic. Other commonly used parameters include CO_2, NO_x, PM, CO, energy consumption, HC, and SO_x. These parameters are crucial for understanding the environmental impact and are essential for making informed decisions [48], [49]. CO_{2eq} and CO_2 represent greenhouse gases that play a significant role in global warming. Given the urgency of slowing down global warming, using CO_{2eq} and CO_2 as environmental impact metrics is highly important [50]. Other environmental impact metrics that are closely related to climate change include NO_x, especially N_2O, VOC, HC, especially CH_4, and CFC [35], [51].

Additionally, some environmental impact metrics such as PM, CO, NO_x, SO_x, and black carbon [15], [52] have direct implications for human health. These components can be harmful if they enter the human body through the respiratory system. Toxicity and noise factors [37], [42] also pose health risks, while noise also contributes to social disturbance [53]. Furthermore, energy, fuel, and water consumption can lead to resource scarcity, which can disrupt future human life patterns [54], [55]. Irresponsible consumption patterns can harm the balance of ecosystems balance and indirectly threaten the well-being of future generations.

The low or even zero number of interactions between certain technologies and environmental metrics represents research gaps. For example, the analysis of the implementation of hydrogen fuel cell technology and its effects on toxicity or NH_3 levels related to EV usage or the relationship between CNG/LNG technology and water consumption are topics that can be explored in future studies. Additionally, water consumption in the implementation of biodiesel or CBG technology is also an interesting topic to discuss. Similarly, measuring noise disturbances for each technology is important, as modern society is highly sensitive to comfort related to noise levels.

Table 4. Number of articles based on bus technology type and environmental impact metrics used

Environmental Impact Metrics	Electric (BEV, PHEV, HEV)	Hydrogen fuel cell	CNG/LNG	CBG	HVO/bio-diesel	Total
CO_2eq	35	12	21	0	3	71
CO_2	21	6	13	2	2	44
CO	12	7	10	2	0	31
NO_x	19	10	12	2	1	44
NH_3	0	0	0	1	0	1
SO_x	11	5	7	1	0	24
PM	16	7	8	2	0	33
VOC	2	1	0	1	0	4
HC	9	8	11	1	0	29
Black carbon	1	0	0	0	0	1
Fuel consumption	7	2	2	0	1	12
Energy consumption	17	8	6	0	0	31
Noise	0	0	1	0	1	2
Toxicity	2	0	0	0	1	3
Water consumption	1	1	0	0	0	2
CFC	1	0	0	0	0	1

4.3. The contribution of bus technologies to the environment and influencing factors

Environmental impact assessments are essential to determine whether the aforementioned technologies can contribute positively to sustainable transportation systems in the future. Experts often use LCA [11], [16], [56], [57], and simulation methods [13], [58], which involve various factors in their analysis. LCA encompasses studies like WTT [51], tank-to-wheel (TTW) [59], or WTW [60]. These methods can quantify the environmental impact of bus technologies throughout their product life cycle phases, but they often involve assumptions and generalizations to simplify the analysis. Other researchers use laboratory measurements [61], direct measurements of buses on the road [46], [62], and the immediate surrounding environment [47], [63]. While these methods provide more accurate results, they are challenging to apply throughout the product life cycle, limiting their scope, and typically focusing on the operational phase.

Overall, the majority of these studies have confirmed a reduction in negative environmental impacts due to the use of environmentally friendly bus technologies. However, some studies found that these technologies exacerbated environmental conditions, such as the use of CNG technology resulting in higher greenhouse gas emissions than diesel technology in Italy [64]. This study found that the use of hydrogen fuel technology was the most fuel-consuming [65], and another study in the US found that under certain conditions, CNG technology would produce more NO_x pollutants than diesel [66]. However, this contrasts with another study in China [67] that reported that CNG technology reduced NO_x by up to 50% compared to diesel in public transportation.

Some studies even show that environmentally friendly buses can significantly reduce environmental impacts by over 50% compared to diesel. Villacorta *et al*. [8] stated that EVs reduced energy consumption by up to 70%, while Alrawi *et al*. [68] confirmed that the use of electric buses in Iraq reduced CO_2 by 54-64%. Ally and Pryor [69] and Iannuzzi *et al.* [36] stated that hydrogen fuel cell technology could reduce greenhouse gases by more than 50% over the entire life cycle of a public bus. In another study, it was reported that using biomethane as a bus fuel could reduce greenhouse gas emissions by up to 80% [40].

Other articles reported more moderate reduction values below 50% per year. For instance, Chester *et al*. [70] claimed that CNG reduced energy and greenhouse gas emissions by up to 40%, Hagos and Ahlgren [71] stated that CNG reduced GHG by 15-27% per kilometer traveled, while Pourahmadiyan *et al*. [72] mentioned that CNG only reduced GHG by 4-8%. Grazieschi *et al*. [73] reported that EVs reduced global warming potential by 33%. Fuel cell buses reduced energy consumption by up to 36%, while BEVs reduced energy consumption by up to 44% [74]. Lie *et al*. [75] demonstrated that combining biofuel and EVs could reduce carbon footprint by up to 37% in Norway. Mao *et al.* [76] revealed that the use of EVs in China could reduce CO_2 emissions by 18-23%, with the condition that air conditioning use remained low. When using different environmental impact metrics, positive results were also found. For example, EVs were claimed to reduce NO_x, NMVOC, and PM emissions [77], [78] and improve energy efficiency [57], [79].

The varying degrees of success in different locations indicate that certain parameters influence these differences. Some studies confirm that the renewable energy generation process in a region plays a significant role, especially for EV technology [80]-[82]. While EVs do not produce tailpipe emissions during operation, the emissions generated during electricity generation for charging need to be considered. If electricity generation still relies on older methods with high emissions, such as coal, then the presence of EVs may not significantly reduce overall environmental impacts [32], [83], [84]. Governments should commit to transitioning to renewable energy sources [85], [86]. Similar considerations apply to hydrogen fuel cell technology if the electrolysis process still relies on fossil electricity [73].

Additionally, the availability of supporting facilities for environmentally friendly transportation poses challenges [87]. Importing raw materials and energy sources from other countries can significantly increase emissions. For example, this is related to the production process of the buses themselves [75] or the production of batteries in different locations from EV implementation, where emissions in the implementation area may decrease, but emissions in the production location may increase [88]. Choi and Song [89] also confirmed that the emissions of natural gas-fueled buses in South Korea were higher than those in the US and Europe because most of the natural gas in South Korea is imported. Battery technology levels and the presence of energy-saving systems can also improve the environmental performance of EVs [90], [91]. Especially for EVs, toxicity is a significant concern, especially regarding the material extraction and end-of-life phases of batteries [35]. Therefore, a country's self-sufficiency and technological advancement in handling these aspects during end-of-life phases also determine the extent of environmental impact reduction.

Another factor not to be overlooked is the usage pattern of bus fleets on the road, including the dynamics of the roads on which buses operate [92], [93]. Total mileage and average utilization also affect the total emissions generated [94]. And of course, the public's preferences in choosing transportation modes need to be considered. An increase in the number of public buses in an area should ideally correlate with a decrease in the number of private vehicles on the road. However, if the existing public buses cannot meet public expectations, then the sheer number of buses does not guarantee emissions reduction as hoped.

Furthermore, geographical factors, such as climate and seasons, can also affect environmental analysis results. In winter, EVs tend to be less efficient and produce more greenhouse gasses than ICE vehicles [95], in line with Mao *et al.* [76], who found that the use of air heating systems significantly affected the environmental performance of electric buses. However, in the previous year, Mao *et al.* [96] stated that electric buses reduced CO_2 emissions by 21%.

4.4. Comparison between eco-technologies and future challenges

Some of the collected articles focus specifically on one technology in their discussions [71], [97], [98], while others consider several technologies without making a direct comparison [43], [99]. These articles typically mention that each technology has its advantages and disadvantages without explicitly stating which technology has the best environmental performance from an absolute perspective [3], [100]. However, some other articles provide comparative studies between one technology and another, where one technology is recommended over another based on specific metrics (Table 5). The purpose of these comparisons is not necessarily to declare one technology as the absolute best from an environmental perspective. Although these studies involve comparative analyses, not all types of technology are compared simultaneously. Rather, the intention behind these comparative studies is to see which technology is most frequently recommended by researchers based on the articles included in this review. Based on this analysis, it was found that EV technology is most commonly recommended. However, in studies that directly compared EVs and CNG technology, it was found that CNG had better environmental performance [44].

However, in reality, the comprehensive implementation of environmentally friendly technologies in public buses still requires time. This is due to the challenges that still need to be addressed with the best solutions, supported by appropriate and consistent policies [6]. There needs to be a transition process, both in terms of infrastructure and facilities, as well as in the technology itself. One form of this transition is the hybrid mode, which combines two different technologies to benefit from both. For example, electric and diesel hybrids, hybrids between electric and HVO fuels [103], or electric-hydrogen hybrids [104]. From an environmental perspective, hybrids often do not perform better than single technologies [51], [105].

Another commonly known challenge is the initial cost of new technology. One example is technologies that require significant upfront costs, including manufacturing facilities, charging stations, and the transition from coal-fired power generation to renewable energy sources [41]. This has prevented widespread implementation, especially in developing countries. However, government commitment can have a significant impact, as one study suggests that the investment made can be recouped in less than 10 years, in addition to making a positive contribution to the environment [106].

Furthermore, the production and operational processes of new technologies are not always more efficient. For example, in one study, it was found that EV technology would increase water consumption, especially for its cooling system [55]. Another study stated that fuel cell hydrogen technology has 40% higher operational costs than diesel buses [107], similar to other research that found the implementation cost of hydrogen technology in public buses is high compared to diesel, making it less economically sustainable [45]. Innovative solutions are needed to address these issues in the future.

Table 5. Best environmental performance technology in articles

Best Environmental Performance	References
EV	Hafdaoui *et al.* [74]; Gabriel *et al.* [99]; Tomic *et al.* [95]; Coppola *et al.* [64]; Correa *et al.* [84]; Grijalva and Martinez [101]; Logan *et al.* [102].
Hydrogen FC	Chang and Huang. [81]
CNG/LNG	Ercan *et al.* [31].
CBG	Mastinu and Solari [44].
HVO	Dahlgren and Ammenberg [42].

5. CONCLUSION

This study reviews scientific articles on the implementation of environmentally friendly technologies in public buses and their effects on reducing environmental damage. Technologies such as electric vehicles, hydrogen fuel, natural gas, and biodiesel have been widely studied, showing significant potential to mitigate environmental harm through reduced greenhouse gas emissions, pollutant levels, particulate matter, and energy consumption. While most studies report positive outcomes, some achieving reductions exceeding 50%, a few highlight negative impacts or lower success rates, often pointing to areas for improvement. Among these technologies, electric buses stand out for their frequent mention and substantial environmental benefits, with CO_{2eq} and pollutant gas levels commonly used as key metrics.

Despite promising results, research gaps remain. The environmental benefits of these technologies vary by region, influenced by unique local characteristics, infrastructure, and implementation strategies. Addressing these gaps requires further research tailored to regional contexts, including direct laboratory and field measurements to enhance existing databases. These data are crucial for verifying emission factors and informing strategies to optimize the success of sustainable public transportation systems globally.

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