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Systematic Review

Digital Technologies for Advancing Cycling Infrastructure: A Systematic Literature Review

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Abstract

Cycling infrastructure, as a part of the smart mobility concept, plays a sound role in the urban development and enhancement of quality of life of urban residents. Moreover, the growing attention to the development of cycling paths in cities creates benefits for the local administrations and industries. The evolution of the "cycling" trend is embedded in academic discourse and embraces the discussion on its social, economic, and environmental impacts. However, despite the major attention to these issues in the high-quality academic literature, the authors observe fragmented discussion on the implementation of (novel) digital technologies in the cycling infrastructure in the smart cities. To fill this gap, the present research proposes a conceptual framework for the integration of digital technologies into cycling infrastructure within urban environments and corroborates these findings with a systematic literature review (SLR) of the topical journal articles published from 2020 to 2025 and retrieved from the Scopus database; the SLR follows Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA 2020) guidelines. The findings show an uneven implementation of digital technologies, with IoT-based and AI-based solutions emerging as the most relevant technologies for the development of cycling infrastructure. At the same time, the study highlights a gap in the current literature regarding the role of the private sector, which is still mainly presented as a beneficiary of rather than as an active contributor to innovation.

Keywords: smart mobility; cycling paths; sustainable micromobility; digital technologies; systematic literature review

1. Introduction

As of today, digital transformation is a phenomenon that affects the everyday life of society, influences production processes, accelerates the quality and speed of decision-making, makes citizens' lives more convenient, and enables citizens to participate in public governance and directly influence decisions made by authorities. At the same time, digital transformation is not a unitary phenomenon, but rather a set of diverse technologies and technological models, such as artificial intelligence (AI), blockchain, immersive technologies, cloud technologies, and the Internet of Things (IoT) (and the Internet of Everything (IoE)). When combined, these technologies create conditions for the rapid development of solutions across various spheres of life—from addressing people's everyday needs to implementing global projects.

The most relevant example of such a comprehensive application of digital technologies is the smart city. A smart city is a "decentralized, people-centric approach where smart

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technologies are employed as tools to tackle social problems, address resident needs and foster collaborative participation" [1]. A smart city can be considered a starting point for the development of solutions aimed at improving urban infrastructure and enhancing citizens' well-being. A smart city evolves in accordance with the United Nations' concept of sustainable development. In particular, Sustainable Development Goal 11, "Sustainable Cities and Communities," and specifically Target 11.2, aims to "by 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport" [2]. Indeed, the academic literature indicates that a smart city develops along several directions, commonly referred to as "dimensions" [3–5], with smart mobility being one of the core and equally important components of a smart city [6].

Smart mobility solutions embrace "a wide range of technologies and innovations designed to improve the efficiency, sustainability, and inclusiveness of transportation" [7]. In the EU's policy framework on sustainable and smart mobility, digitalization is defined as an essential enabler for the transformation to safer, more efficient, more accessible and more sustainable mobility, where vehicles and infrastructure are interconnected and data is shared to optimize transport systems [8]. Within the smart mobility framework, cycling infrastructure represents an important element of active mobility, contributing to sustainability, accessibility, and system efficiency, and has the potential to become explicitly "smart" when supported by digital technologies, real-time data, and integration with broader urban mobility platforms [9]; "an indirect technology push" for urban mobility was identified in the literature [10]. Indeed, "the pyramid of urban mobility hierarchy" demonstrates that the shift towards more cycling predisposition is one of the most desirable scenarios for sustainable mobility [11,12].

Application of digital technologies to the development of cycling infrastructure becomes an inevitable and important step towards more sustainable urban mobility. So, AI is becoming an important tool used in urban planning with the aim of making cities more habitable and sustainable [13]. This technology makes it possible to collect and process a large amount of useful information to provide insights, for example, into the quality of the road surface on bike paths [14]. In recent years, various studies have been conducted in cities around the world to develop AI-based models and solutions as useful tools for urban planning and improvement. A study conducted in the city of Hamburg presents a digital solution integrated with the Green Light Optimal Speed Advisory (GLOSA) bike app. This solution is based on a GeoAi model that uses artificial intelligence to identify traffic lights along the route as the cyclist approaches, allowing them to adjust their speed accordingly [15]. In addition to speed, AI tools were also used to analyze urban traffic volume. Large language models (LLMs), such as ChatGPT-4o mini, were used to estimate bicycle traffic volume at intersections in the city of Waterloo, Canada. Traffic volume is a key factor in improving road planning and cyclist safety. This tool has made it possible to calculate the average daily bicycle volume, thereby enabling the classification of intersections with traffic lights [16]. A study of Leon County, Florida, relies on the collection of road data using computer vision technology. Through a geospatial model based on artificial intelligence, it is possible to obtain very high-resolution images to identify and map the county's bike lanes and pedestrians. This provides important insights for improving road infrastructure, such as identifying poorly visible traffic signs or other elements that may compromise road safety [17]. AI has also been used in the literature to develop models such as the Bicycle Level of Service (BLOS) for the purpose of evaluating road infrastructure [18] or machine learning methods with the aim of providing information for the maintenance of bike paths and making improvements to cyclist safety [14].

In addition to AI solutions, blockchain-based solutions are also being adopted for urban traffic monitoring that records transactions in interconnected blocks of data [19,20]. One issue arising from the use of these technologies is user privacy regarding the tracking of data on their travels. To address this issue, the literature includes a study on the development of LoChain, a model based on blockchain technology capable of collecting and processing mobility monitoring data while ensuring privacy protections. To ensure that individuals cannot be linked to their movements, this decentralized protocol obscures location data by blurring coordinates and replaces identities with disposable identities [19].

In recent years, a wide range of immersive technologies—augmented reality (AR), virtual reality (VR), and mixed reality (MR)—have become widespread in various industries, including education, medicine, and manufacturing. Immersive technologies enhance the efficiency of training processes, reduce health risks, and optimize manufacturing processes [21–23]. The recent academic literature also focuses on the use of immersive technologies for the development of cycling infrastructure. In this field, immersive technologies are used to study cycling infrastructure users' preferences by simulating various environmental conditions without risk to participants. For example, Khademi et al. (2025) [24] used VR technology to study the factors that influence cyclists' feelings of safety and comfort in Tehran, Iran. Schwarzkopf et al. (2024) [25] apply VR technologies for similar purposes in the city of Chemnitz, Germany; the authors argue that the use of these technologies can improve the quality of participation activities at various stages of infrastructure projects and has great potential in this area. Ramirez Juarez et al. (2023) [26] implemented VR technologies together with eye tracking technologies to explore the cyclists' "perception of the aesthetical elements" in Enschede, the Netherlands. Bialkova et al. (2022) [27] conducted a study using VR technologies to simulate the environment of a Dutch city to distinguish the factors that influence cycling experience.

IoT technologies are an important element of modern cycling infrastructure development. As cycling has become an increasingly popular mode of transportation over the years, cyclist safety is becoming a rising issue for which digital solutions are being identified. For example, the design of warning systems [28], and the development of an algorithm that monitors and analyzes sensor data to identify obstacles and trigger an anti-collision warning system [29]. Research has also been conducted on the use of a smart helmet equipped with sensors that allow the bike to start when positioned correctly, or that can detect the severity of injuries after an accident, enabling timely assistance [30]. IoT solutions connect devices and sensors, allowing real-time data exchange for better traffic management, improved cyclist safety, and more efficient maintenance of cycling infrastructure [31,32].

As demonstrated above, the academic literature already provides important insights into the use of digital technologies in cycling infrastructure; however, it still lacks an integrated framework that systematizes technological advancements within a broader context of smart urban environments. This paper aims to address this gap by developing a conceptual framework for the integration of digital technologies into cycling infrastructure within smart urban environments. In order to corroborate the findings, the authors conducted a systematic literature review (SLR) on the role that digital technologies play for cycling infrastructure stakeholders and how these technologies can support the main dimensions of smart mobility. The main research questions that guided our SLR are: (1) According to recent academic literature, what is the role of digital technologies in creating value for the main stakeholder groups? (2) How do digital technologies support the dimensions of smart mobility?

The rationale of the article is as follows. Section 2 introduces a conceptual framework for smart cycling infrastructure and thoroughly describes the methodological steps of the

systematic literature review; Section 3 presents the evidence extracted from the literature to corroborate the conceptual model. The conclusion summarizes the theoretical inquiries, provides managerial implications, and outlines directions for future research.

2. Materials and Methods

Methodologically, this study was divided into two stages. In the first stage, the authors develop a conceptual model by synthesizing the interplay between digital technologies' advancements, smart mobility dimensions, and key cycling infrastructure stakeholders. In the second stage, the authors conduct a systematic literature review (SLR) to further describe the model, identify the relationships supported in the recent academic literature, and highlight the directions for future research.

2.1. A Conceptual Framework for Smart Cycling Infrastructure

2.1.1. Digital Innovation in Cycling Infrastructure from Stakeholders' Perspective

The starting point for the development of the conceptual framework for smart cycling infrastructure was stakeholder theory [33], which has been revisited and extensively studied over the years [34,35]. This theory is based on a few fundamental concepts. First of all, the main purpose of a business is to create value for its stakeholders. In theory, there is no separation between business issues and ethical issues, and it is a theory of business organization that focuses on normative core [33,36]. Stakeholder theory explains for whom organizations create value; however, it is also applicable in the public sector [37,38]. Based on this approach, we identified the key stakeholder groups involved in the development of cycling infrastructure.

To the best of the authors' knowledge the academic literature points to three main stakeholder groups: the public sector, the direct users of the cycling infrastructure, and the private sector [39–41]. Below, we describe these three stakeholder groups and their interests in more detail:

- Within the public sector group, municipalities and public transport agencies are identified in our research as the primary beneficiaries of cycling infrastructure development. They are interested in improving the quality of life, including enhanced urban accessibility, reduced environmental pollution, the promotion of healthy lifestyles among residents, the alleviation of traffic congestion, and increased urban attractiveness for cultural and creative human capital.
- The users group includes individuals who directly use cycling infrastructure. It comprises city residents and visitors who cycle for recreational purposes or to explore the city; residents who use bicycles for daily commuting; and athletes who may use urban cycling infrastructure to maintain their physical fitness. This stakeholder group is primarily interested in an extensive cycling network, safe infrastructure, and the availability of reliable route and traffic information.
- The private sector group includes bicycle-sharing companies, local retailers, and utility companies. These stakeholders (in particular bicycle-sharing operators and retailers) are interested in increasing the number of cycling infrastructure users. Utility companies (such as electricity and telecom providers), in turn, are directly involved in the construction and maintenance of the digital infrastructure.

Digital technologies may address the interests of each of these stakeholder groups. For the public sector, AI and IoT solutions form a basis for more effective decision-making; environmental monitoring technologies collect data on air quality and noise levels along bicycle routes, enabling prompt decisions on necessary changes and assessing the environmental impact of introducing bicycle paths; smart lighting, adaptive traffic lights, and

charging stations for electric bicycles located along bicycle paths contribute to a safer and more attractive urban environment.

For users, digital technologies improve the cycling experience by increasing safety, comfort, and predictability. AI and IoT-based solutions provide cyclists with up-to-date information on traffic conditions, bike lane congestion, environmental conditions, and the operation of additional infrastructure, such as charging stations or retail outlets. Technologically equipped physical infrastructure, including e-bike chargers and smart lighting systems, enables longer rides and improves road safety.

For the private sector, digital technologies create the conditions for improved performance. Bike-sharing companies can use AI and IoT technologies to predict demand and optimize maintenance. Local retailers benefit from increased accessibility and user adoption of cycling infrastructure. For delivery companies, access to traffic information is especially important, allowing them to optimize routes, reduce delivery times, and lower costs.

2.1.2. Smart Urban Mobility and Digital Cycling Infrastructure

For this part of the study, the authors drew on a study by Aguilar and Mendes (2017) [11], which examines the integral components of the smart urban mobility concept and the application of "computational intelligence" to improve them. The discussed paper identifies three fundamental dimensions along which smart urban mobility should be developed:

- "Smart Road Safety"—this dimension focuses on lowering the number of dangerous road conditions, as well as on the enhancement of the road users' behavior, including observation of basic traffic rules, such as speeding, drunk driving, driving on pedestrian crossings, disregarding road signs, and other similar violations.
- "Smart Traffic Management"—this dimension primarily concerns traffic conditions, including road congestion for different modes of transport, average speed, and travel time, the key lever in this dimension is the data necessary for making informed management decisions;
- "Environment"—in this case, the topic is "air and noise pollution," which, on one hand, can be considered the norm in large cities, but on the other hand, the use of new technologies can significantly reduce these negative consequences of urban mobility.

Figure 1 shows how the smart urban mobility dimensions relate to the benefits that digital technologies provide to cycling infrastructure stakeholders. All the above-mentioned dimensions are included in this framework, but to varying degrees. Digital technologies influence cyclists and the public sector along the *Smart Road Safety* axis; these groups are the most interested in road safety on bicycle paths. Improving *Smart Traffic Management* using digital technologies will have a greater impact on the public and private sectors, as IoT systems, by analyzing large volumes of data, can influence both the business decisions of companies directly involved in developing cycling infrastructure and those of municipal management to improve traffic conditions and cycling comfort. Speaking about the *Environment*, this dimension clearly encompasses all stakeholders, as new technologies help reduce environmental pollution, which improves cyclist comfort and attracts more residents to use bike paths, which positively impacts the private sector and the public sector by supporting their objectives related to sustainability, public health, and urban livability.

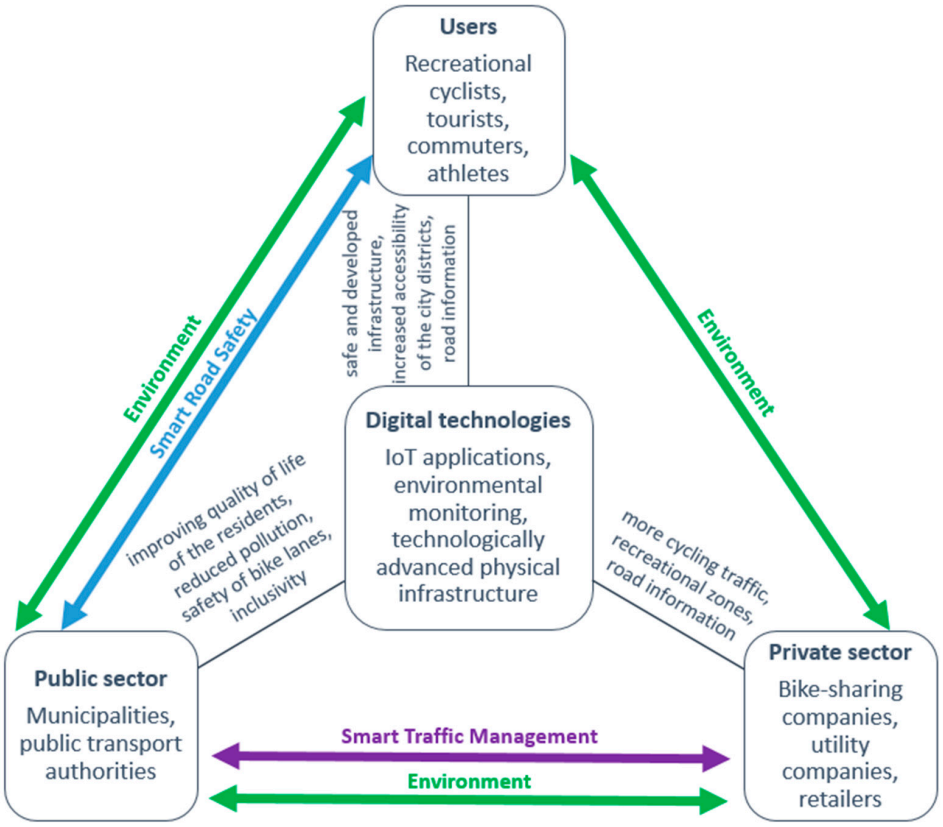


Figure 1. A Conceptual Framework for Smart Cycling Infrastructure. Source: own elaboration based on [11,39–41].

People are most likely to choose cycling options when the infrastructure is safe, green, well connected, and easy to use, but "smart solutions" are also welcome [42]. Indeed, "smart cycling" is seen as "fundamental service" for the citizens' well-being [43]. The rapid development of digital technologies creates new challenges, but also offers opportunities, which must be considered when constructing new cycling infrastructure and renovating existing ones. Sustainable cycling infrastructure therefore requires coordination between the requirements of physical infrastructure, advancements of digital technologies, and long-term urban planning, as stated in [44,45]. It requires cooperation between cycling infrastructure stakeholders—municipalities, public transport authorities, private sector and cycling infrastructure users. Digital technologies should be integrated into the planning, implementation, and maintenance phases of cycling infrastructure development, rather than added only at a later stage, as a useful but not mandatory element.

2.2. A Systematic Literature Review

We conduct a SLR [46] to assess key trends in the debate regarding the use of digital technologies in urban cycling infrastructures. In particular, we examine how the literature describes the enabling role of digital technologies in creating value for the main stakeholder groups and how these technologies support the dimensions of smart mobility. A SLR methodology was chosen for this research as it allows researchers to identify current trends and provide useful guidelines to be developed for future research [47,48]; moreover, it supports critical evaluation of a specific research topic [49,50].

The present study applies the six-step methodology to conduct the SLR [51]:

(1) In the first step, we have defined the research question and chosen the keywords and keyword combinations for the literature retrieval. The central keyword combinations applied for the present study were *cycling infrastructure* and *smart mobility*.

(2) The literature was retrieved from the Scopus database, as it includes only high-quality articles that have undergone a peer review. Document types in the search were restricted to articles and the language was limited to English. A time range of 5 years was applied, so the documents consulted range from 2020 to 2025. This time frame was chosen as the academic literature shows that the COVID-19 pandemic stimulated the increasing use of the bicycles, especially in densely populated cities [52–54]. Moreover, the chosen time frame was determined by the rapidly evolving nature of digital technologies, especially the growing tendency to implement novel AI solutions and AI-related methods for smart city infrastructure development [55–57], allowing the study to identify the most recent trends in the area under investigation. The selected literature should be relevant to the aim of our study and highlight the role of digital technologies for cycling infrastructure stakeholders, or should explain the causal relationships between digital technologies and smart mobility dimensions.

(3) Using the criteria identified at the second step of our research, we obtained a sample of the potentially relevant literature using a query *(TITLE-ABS-KEY (cycling infrastructure) AND TITLE-ABS-KEY (smart mobility)) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar")) AND PUBYEAR > 2019 AND PUBYEAR < 2026.* In this early phase we identified 29 articles for further screening and analysis.

(4) In the fourth step, we screened the identified academic literature. We started with reading the abstracts; after this step all the 29 articles were accepted for the further analysis. However, we were unable to download one article from the sample, so we proceeded with the careful reading of the remaining 28 documents. We then reviewed the full papers and excluded those that were not pertinent as they fell out of scope of our research or did not meet the inclusion criteria, thus obtaining the final sample of 17 articles. Table 1 shows a summary of the articles retrieved for the review, including the reference number, author, year, and country.

Table 1. The list of studies included in the review.

Ref.	Author(s)	Year	Country
[41]	Cheng	2025	Taiwan
[58]	Costa et al.	2024	Portugal, Brazil
[59]	Ferreira and Costa	2024	Portugal
[60]	Kazmi et al.	2025	United Kingdom, Russia, UAE
[61]	Manoj et al.	2025	India
[62]	Roslan et al.	2023	Malaysia
[63]	Manca et al.	2022	United Kingdom, Italy
[64]	Kim et al.	2024	Thailand, Republic of Korea, New Zealand, Finland, Sweden, South Africa, Malaysia
[65]	Wolniak andTuroń	2025	Poland
[66]	Khajehpour and Miremadi	2024	Iran
[67]	Nesmachnow and Hipogrosso	2024	Uruguay
[68]	Li et al.	2020	USA
[69]	Pfaender et al.	2025	China, France
[70]	Malik et al.	2022	United Kingdom
[71]	Oliveira et al.	2020	Brazil, Chile
[72]	Cafiso et al.	2021	Italy, USA
[73]	Fayyaz et al.	2024	Spain, Italy

Table 2 presents the distribution of the retrieved articles by journal and year of publication.

Table 2. Distribution of the retrieved studies by journal and year of publication.

Journal	'20	'21	'22	'23	'24	'25	Tot.
Applied System Innovation						1 [65]	**1**
Construction				1 [62]			**1**
Energy Research and Social Science					1 [66]		**1**
Future Internet			1 [70]				**1**
IEEE Access	1 [71]						**1**
IEEE Transactions on Consumer Electronics						1 [60]	**1**
Infrastructures		1 [72]					**1**
International Journal of Advances in Applied Sciences						1 [61]	**1**
International Journal of Geographical Information Science	1 [68]						**1**
Journal of Smart Tourism					1 [64]		**1**
MethodsX					1 [58]		**1**
Smart Cities					2 [59,73]		**2**
Sustainability (Switzerland)						1 [69]	**1**
Sustainable Cities and Society			1 [63]				**1**
Transportation Research Interdisciplinary Perspectives						1 [41]	**1**
Urban Science					1 [67]		**1**
Total	**2**	**1**	**2**	**1**	**6**	**5**	**17**

The authors conducted the selection and data collection process collaboratively in order to reduce potential assessment bias. The research was conducted in compliance with the PRISMA guidelines [47], the identification, screening and inclusion steps are presented in the PRISMA 2020 flow diagram (Figure 2). The PRISMA checklist is presented as Supplementary Material.

(5) At the fifth stage we proceeded with the synthesis of the retrieved literature. At this stage, the authors of the study conducted a content analysis of the academic literature to determine whether it contains evidence on the role of digital technologies in creating value for the stakeholder groups discussed above and on the support these technologies offer to smart mobility dimensions, so the evidence on the two analytical dimensions derived from the conceptual framework developed in Section 2.1—stakeholder groups and smart mobility dimensions—are the outcomes sought from the retrieved studies. Data was extracted for the following variables: (1) type of digital technology discussed; (2) stakeholder groups addressed (users, public sector, private sector); and (3) smart mobility dimensions supported (smart road safety, smart traffic management, environment). Each included study was read in full by the authors and assigned to the relevant categories based on the primary focus of its findings. Studies that address several variables were coded accordingly.

(6) The results of the SLR present a narrative synthesis due to the exploratory character of the research, and are tabulated and presented broken down by technology type and

by the two analytical dimensions (stakeholder groups and smart mobility dimensions) as reflected in tables in the following section.

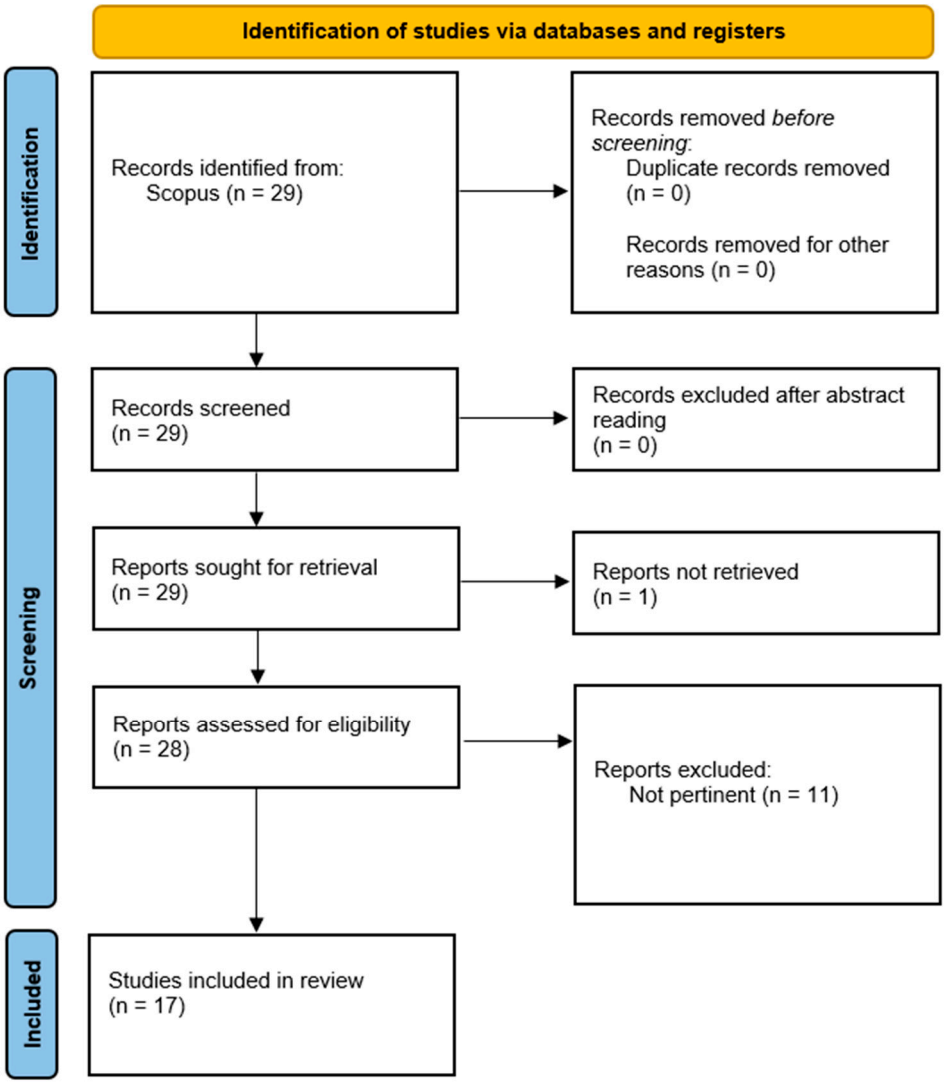


Figure 2. PRISMA 2020 flow diagram. Source: authors' elaboration based on Page et al. (2021) [47].

3. Results and Discussion

The literature analyzed investigates the integration of digital technologies to enhance cycling infrastructure; below we present a summary of the evidence from the 17 articles we identified at the fourth stage of the SLR, divided into two perspectives and reflected in the previous paragraph. In particular, we analyzed (i) the role of digital technologies in enhancing the experience of the cycling infrastructure users and in adding value to public and private sector stakeholders; and (ii) how and to what extent digital technologies contribute to safety, traffic management, and environmental impact of the cycling infrastructures.

3.1. Digital Technologies for Users, Public Sector, and Private Sector

Digital advancements are currently transforming cycling into a data-driven sustainable mobility solution. Digital transformation advancements represent a fertile ground for the development of the enhancement of safety level of the cycling infrastructure for the users [58,59] and also shift their lifestyles towards healthier choices [60]. For individual users, the technological evolution of the bicycle itself is an important step towards experience enhancement. The research of Manoj et al. (2025) [61] offers an overview of the e-bike

advancements and states that modern e-bikes have become "smart mobility solutions" through the integration of lithium-ion batteries, high-efficiency electric motors, and Bluetooth connectivity; these vehicles often have GPS navigation and IoT-based solutions and mobile applications to improve the overall riding experience. The literature demonstrates evidence that cycling infrastructure users are increasingly open to and rely on mobile and dashboard apps to inform their travel choices [41,60,62–64]; user-friendly apps lessen "confusion and frustration" of the users [65]. However, Khajehpour and Miremadi (2024) [66] claim that some users are still "uncomfortable" with the use of online applications; these solutions reveal "negative social issues" in terms of "distributive, procedural, and recognition injustices". Indeed, the research of Nesmachnow and Hipogrosso (2024) [67] demonstrates that local residents may be more reluctant to adopt digital novelties than tourists. The development of smart dockless bike-sharing systems and micro-mobility devices (MMD) supported by the IoT is essential for addressing "first-mile and last-mile" transit challenges [68]. In the public sector, the novel digital technologies can become a leverage for sustainable development in many areas, including the development of cycling infrastructures. Cheng (2025) [41] introduced a conceptual framework that embeds "artificial intelligence (AI), gamified urban networks, and targeted policy incentives" for sustainable and smart cycling infrastructure planning; the author claims that public sector decision-makers should introduce "dynamic" initiatives and encourage public–private partnerships while focusing on the development of cycling infrastructure. Indeed, the major focus of the public sector on cycling (and walking) infrastructure contributes to the worldwide sustainability [69]; as one of the related measures, an "integration" of public transportation with bike-sharing services could be considered [65]. Public authorities may favor the implementation of safety systems developed using innovative digital technologies [70], which enhance the overall quality of the cycling paths [68,71]. Innovative and practical solutions could be developed and integrated by promoting co-design activities that unite local authorities and stakeholders [64]; technological advancements foster implementation of "smart city" initiatives [59] and promote a cycling lifestyle [41]. The private sector is traditionally identified as a pioneer for innovations, so businesses can foster innovation by funding AI-enabled cycling initiatives and "embedding cycling into corporate social responsibility agendas" [41]; digital technologies provide benefits for bike-sharing companies in terms of the provision of better services and fleet management improvement [65,68]. Table 3 summarizes the digital technologies' added value for the three stakeholder groups proposed in the retrieved literature.

Table 3. Digital technologies' added value for the stakeholders.

Technology	Users	Public Sector	Private Sector
AI & related technologies	Personalized cycling motivation [41] AI-powered information on risk alerts [58] Travel mode optimization through the analysis of wearables' data [60] User-specific safety predictions [70]	Fostering "data-driven infrastructure planning" [41] Urban cycling safety planning [58] Embedded learning systems support safer infrastructure [70]	--

Table 3. *Cont.*

Technology	Users	Public Sector	Private Sector
IoT & related solutions	On-bike GPS safety alert system [60] Improved technological equipment of e-bikes [61] IoT-driven micro-mobility tracking [62] Real-time bike availability enhances bike-sharing users' experience [65] GPS data addresses first-mile and last-mile problems in bike-sharing [69] Multi-sensory route quality selection tool [71]	GPS data employed for infrastructure planning decisions [68] Multi-sensory solution helps to identify cycling infrastructure improvement priorities [71]	Real-time monitoring and contactless payment for operational efficiency [65] IoT-powered fleet rebalancing and demand management [68]
GIS	--	GIS-based cycling quality monitoring integrated into smart city ecosystem [59] Implementation of solutions with GIS integration supports sustainable development goals [69]	--
Blockchain	--	Blockchain technologies enable secure citizen data management across administrative levels [60]	--
Mobile & dashboard applications	AI-driven dashboards promote cycling adoption [41] Apps collect data on travel modes, preferences and health metrics for route optimization [60] Mobile apps support informed sustainable travel choices [62,64] Gamified app rewards encourage cycling behavior [63] Real-time app updates reduce user confusion and improve their experience [65]	"Gamified urban networks" help city managers to motivate cycling habits among citizens [41]	--

3.2. Digital Technologies for Road Safety, Traffic Management, and Environment

Safety concerns are at the core of cycling infrastructure development and remain one of the barriers that prevent many users from cycling [69,72]. Costa et al. (2024) [58] present a novel methodology, SafeCycle-Assist, that leverages on AI technology to provide a solution to enhance road safety for cyclists. Ferreira and Costa (2024) [59] implement GPS technologies for the selection of safer route options. Global Navigation Satellite System (GNSS) was employed in the study of Cafiso et al. (2021) [72] to gather evidence on the "objectives risks" of cycling infrastructures. In order to better understand the nature of safety risks, researchers employ deep neural networks to create safety models that predict how infrastructure affects different age and gender groups of users [70]. In the domain

of smart traffic management, the focus is on harmonizing cycling with other emerging technologies. Manoj et al. (2025), [61] in their study on the evolution of e-bikes, argue that their widespread adoption can help reduce traffic congestion, the same impact as bike-sharing services equipped "with real-time monitoring, contactless payment systems, and IoT-driven technologies" [65]. Further digitalization of urban transport systems to enable the safe coexistence of cyclists and autonomous vehicles can improve overall urban mobility and make streets safer, cleaner, and more efficient [73]. Finally, advancements in cycling infrastructure are directly connected to environmental sustainability [57], the transition to e-bikes significantly lowers greenhouse gas (GHG) emissions in comparison with the conventional internal combustion engine (ICE) vehicles [61]. According to Wolniak and Turoń (2025) [65], bike-sharing is often perceived by users as a service that contributes to fewer emissions and less traffic in urban areas. AI advancements embedded in the incentives for the optimization of cycling routes is seen as vital components of a "net-zero" strategy [41]; integration of real-time data from wearable health devices and transport sensors helps to optimize mobility and reduce congestion and emissions, at the same time supporting public health through increased physical activity [60]. Table 4 illustrates how digital technologies advancements support three smart mobility dimensions.

Table 4. Smart mobility dimensions and digital technology enablers.

Technology	Smart Road Safety	Smart Traffic Management	Environment
AI & related technologies	AI-powered cycling risk assessment for urban paths [58] Neural network safety prediction by cyclist profile and infrastructure type [70] The study results highlight safety as a key priority for the cycling paths [73]	AI-powered dashboards support "data-driven infrastructure planning" [41] DRL-driven travel mode optimization reduces motorized traffic [60]	AI incentive framework supports urban net-zero goals [41] Emission minimization through intelligent travel mode selection [60] AI solutions help rout optimization and improve environmental performance [61] Proposed real-time learning system contributes to a greener mobility system [70]
IoT & related solutions	GPS integration provides real-time risk assessment and alerts [59] The developed prediction safety models define the riskiest age and gender groups [70] Multi-sensory route quality metric supports safer path selection [71] GNSS was employed to collect objective risk data [72]	E-bike adoption as an urban traffic congestion relief solution [61] IoT-enabled bike-sharing services reduce car dependence in urban environments [65] Dockless bike-sharing solves first- and last-mile problems [68]	E-bike adoption leads to the lowering of GHG emissions [61] Bike-sharing services contribute to reduced urban carbon footprint [65]
GIS	Implementation of GIS contributes to real-time risk assessment [59]	GIS techniques are the important source of data for urban mobility decision-making [59,69]	--
Blockchain	--	--	--

Table 4. *Cont.*

Technology	Smart Road Safety	Smart Traffic Management	Environment
Mobile & dashboard applications	--	Applications may ease travel mode selection and hence contribute to the traffic reduction [60] Novel solutions implemented through mobile apps help to address first- and last-mile problems [62]	App-tracked travel preferences enable emission-reducing route planning [60] Gamified app incentives accelerate cycling adoption and hence lead to the GHD emissions lowering [61] Digital app engagement positively correlated with sustainable travel choices [63]

3.3. Summary of Results

The results of the SLR generally support the proposed conceptual framework, but at the same time add new insights that make the framework more complete. Speaking about the technologies discussed—from both analytical dimensions, stakeholdersand smart mobility dimensions, we may notice that IoT-based solutions have the most cross-cutting effects as they are relevant for all three stakeholder groups and contribute to all three smart mobility dimensions at the same time;specific cycling solutions such as e-bikes and bike-sharing systems represent vivid examples of this state of affairs., AI-based solutions also appear as an important group of technologies in the SLR. They are less transversal than IoT-based solutions, but they show a strong contribution to road safety, especially through risk assessment tools and predictive safety models. They also contribute to the environmental dimension, for example, through AI-based incentive systems and route optimization solutions. AI-based solutions also support smart traffic management solutions. At the same time two technology categories that are discussed in the recent academic literature, blockchain and immersive technologies, did not appear in the reviewed studies except for the study of Kazmi et al. (2025) [60]. This outcome may confirm that these technologies are still exploratory in the context of digital cycling infrastructure and need further research.

Strong evidence from the retrieved literature concerns the users' dimention, which confirms one of the expectations of the framework. However, some users may experience more difficulties and face barriers with the adoption of novel technologies [66,67]. Also, some areas remain less developed in the analyzed academic literature. The private sector, especially local retailers and utility companies, receives limited attention - the reviewed studies usually present the private sector as a beneficiary of digital cycling infrastructure, rather than as an actor that actively drives innovation in this domain. This evidence partly differs from the assumptions of the framework and suggests an area that needs further research. Finally, while the environmental impact has strong support in the retrieved literature, it also represent a "co-benefit" of solutions mainly designed to improve safety or mobility efficiency. This finding suggests the need for more focused primary research on the direct environmental effects of digital cycling infrastructure.

4. Conclusions

In the concept of smart cities, smart mobility is a fundamental aspect, as it involves the use of technologies and innovations capable of improving transport in terms of efficiency and sustainability [6,7]. Among the EU's goals for sustainable mobility, digital technology is a key element in making mobility more sustainable and efficient, with infrastructure and

vehicles interconnected [8]. Cycling infrastructure, as part of the sustainable and smart mobility system, can also benefit from the implementation of digital technologies. The aim of the paper was to elaborate a conceptual framework for smart cycling infrastructure and understand, through a systematic analysis of the literature in the 2020–2025 timeframe, the role of digital technologies in creating value for the main stakeholder groups and how these technologies support the dimensions of smart mobility.

The results of the SLR generally confirm the proposed conceptual framework. IoT-based solutions appear to be the most transversal technology category, since they create value for all three stakeholder groups and contribute to all three smart mobility dimensions at the same time. AI-based solutions also have an important role, especially for road safety and the environmental dimension. At the same time, the SLR shows some gaps in the current literature—the private sector is mainly described as a beneficiary of digital cycling infrastructure, rather than as an actor that actively contributes to innovation. The direct environmental impact of digital cycling technologies should also receive more specific attention in future research.

From a practical perspective, public authorities should give priority to IoT-based and AI-based solutions when planning or renovating cycling infrastructure. Private sector actors should take a more active role in the development of digital cycling solutions. From the users' standpoint, digital tools should be accessible and inclusive, especially considering the adoption barriers and equity issues identified in the literature.

The limitations of this study mainly concern the primary focus of the research on theoretical findings and hence there is a lack of evidence from the discussed stakeholder groups in the form of primary data. Future research could therefore overcome this limitation; moreover, future research avenues may address the applicability of the model in the real urban environment and focus on collecting data related to specific smart mobility dimensions, for example, on bicycle equipment currently available on the market or under development, and how such infrastructure can interact with and support traffic management, for example, by suggesting speed limits at intersections. Some limitations of the research lie in the organization of the SLR process, as, due to its' explorative aim and a limited number of studies, no meta-analysis was conducted which also leads to a future research avenue once a broader body of topical scientific evidence will be gathered.

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