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Impacts of the COVID-19 Pandemic on Bike-Sharing: A Literature Review

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Abstract: Bike-sharing is recognized as a fast and efficient transport solution in cities, with zero emissions, convenience, speed of movement for short distances and beneficial effects on users' health. In recent years, especially during the COVID-19 pandemic, its use has been rather heterogeneous across countries and significant differences have emerged from empirical studies. However, there has been no systematic review of the empirical studies focused on the impacts that the COVID-19 pandemic has had on the use of bike-sharing. This article aims to review all of the papers that have been published on this topic since the outbreak of the pandemic. In this analysis, we consider several elements, such as the impacts of the pandemic on actual and potential ridership, on the demand for bike-sharing compared to other public transport means, and on commuting and non-commuting trips. We also focus on the factors that have had an impact on the change in bike-sharing usage and the related policy and operational implications that have emerged from the literature. Finally, we highlight the gaps in the literature that require further investigation.

Keywords: bike-sharing; COVID-19; urban mobility; resilience; transport policy

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1. Introduction

Bike-sharing is an increasingly widespread form of mobility. The global market for bike-sharing services is estimated to grow to over USD 13.7 billion by 2026 from USD 3.3 billion in 2020 [1]. Furthermore, although mobility has been severely affected by the COVID-19 pandemic, bike-sharing increased its global revenues by a third in 2020 and is expected to further increase its uptake in the near future [2].

An increasing number of articles have investigated the characteristics of bike-sharing demand, such as users' demographics and preferences, trip purpose and mode substitution, and the policies that should be implemented to support its use [3–5]. Many researchers have also investigated how to properly design and manage the provision of a bike-sharing service in order to have a business model that is profitable, innovative and sustainable [6–8]. To this aim, several papers have focused on predicting the picking up/returning demand at the station, area or cluster level [9], while a stream of the literature has analyzed the potentialities and critical issues caused by the emergence of dockless shared bikes [10]. In the literature, however, there is currently no systematic review of the studies focused on the impacts that the COVID-19 pandemic has had on the use of bike-sharing. The present study aims to fill this gap by reviewing all of the documents that have been published on this topic since the outbreak of the pandemic. Our goal is to provide local administrators and service operators with case studies, information and evidence useful in the design of active mobility policies and bike sharing services capable of improving the resilience of the transport system when disruptive events such as the COVID-19 pandemic occur.

This paper is structured as follows: Section 2 describes the research design; Section 3 illustrates the bibliometric analysis of the papers we collected; Section 4 describes the

content analysis of the documents we have reviewed; and Section 5 concludes by listing the open questions that deserve further investigation.

2. Materials and Methods

We based our literature review on both Scopus and WoS (Web of Science). Scopus is an academic database covering over 36,000 titles, from approximately 12,000 journal editors, in high-level disciplinary fields such as the life sciences, social sciences, physical sciences and health sciences. WoS is a multidisciplinary academic database with indexing coverage from 1900 to the present, including the sciences, social sciences, arts, and humanities. It comprises six online indexing databases, including the Emerging Sources Citation Index with over 7800 journals across all disciplines; the Science Citation Index Expanded with over 9200 journals in 178 scientific disciplines; and the Social Sciences Citation Index, which covers more than 3400 social science journals.

Since we were interested in investigating the impact that the COVID-19 pandemic has caused on bike-sharing use, to collect the papers we used the following string: "bike-sharing" OR "bike sharing" AND "COVID-19". We found only 58 articles potentially useful for our review, and we attributed the limited research carried out in this research field both to the constraints of data availability on the use of bike-sharing during the COVID-19 pandemic and to the fact that the pandemic is a recent phenomenon limited in time. We obtained the same selection of 58 articles with related meta-information, such as title, author, keyword, abstract, academic classification and country, from both databases. After analyzing the abstracts of all the collected papers, we released 25 studies, as they were out of scope, and added 3 articles we deemed relevant to our research. We ended up with 26 articles specifically focused on the relationship between the COVID-19 pandemic and bike-sharing use, these were published from 2020 to 2022 (3 in 2020; 16 in 2021; 7 in 2022), in 18 journals (Figure 1), with an average annual incremental rate of 53%. Our paper selection is smaller compared with other reviews carried out on bike-sharing; however, given the novelty of the specific topic we have chosen to analyze and the urgent need to detect if bike-sharing is a resilient transport mode when dealing with disruptive events such as a pandemic, we deemed this admittedly small but critical research literature important enough to investigate.

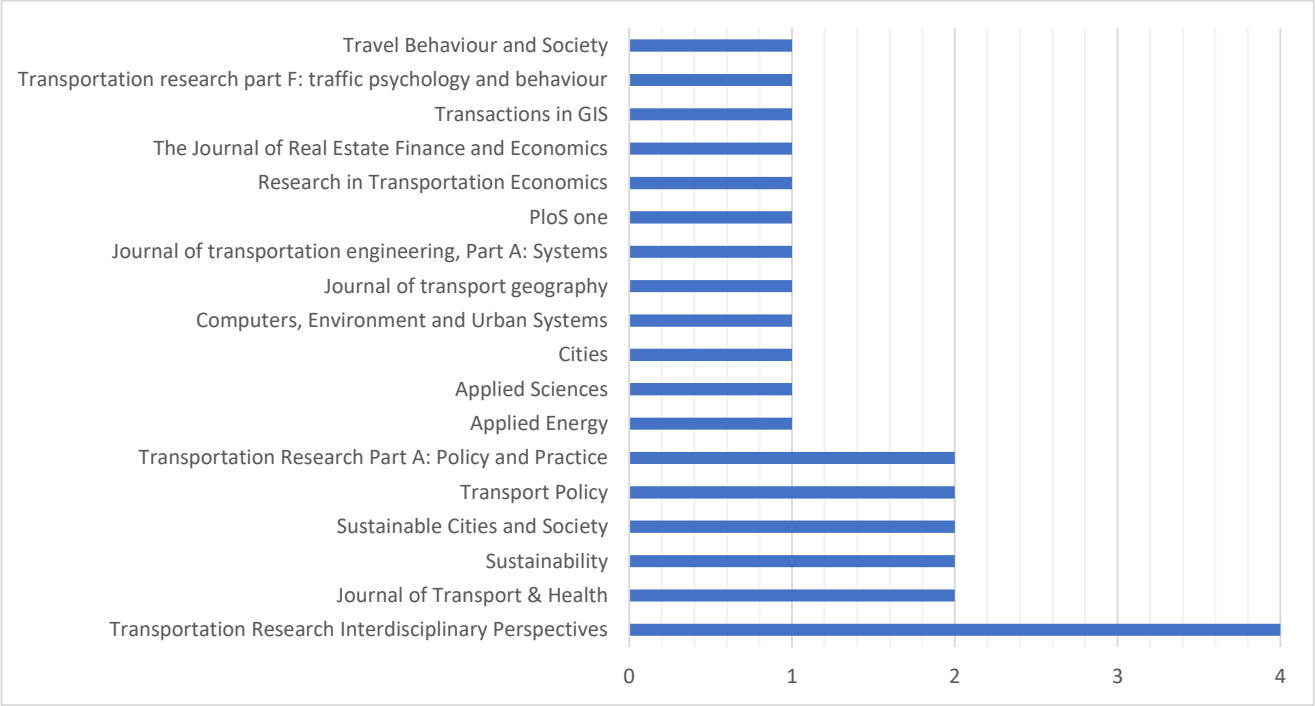

Figure 1. Most relevant journals.

Researchers working in China or the United States of America published most of the articles we reviewed (Figure 2).

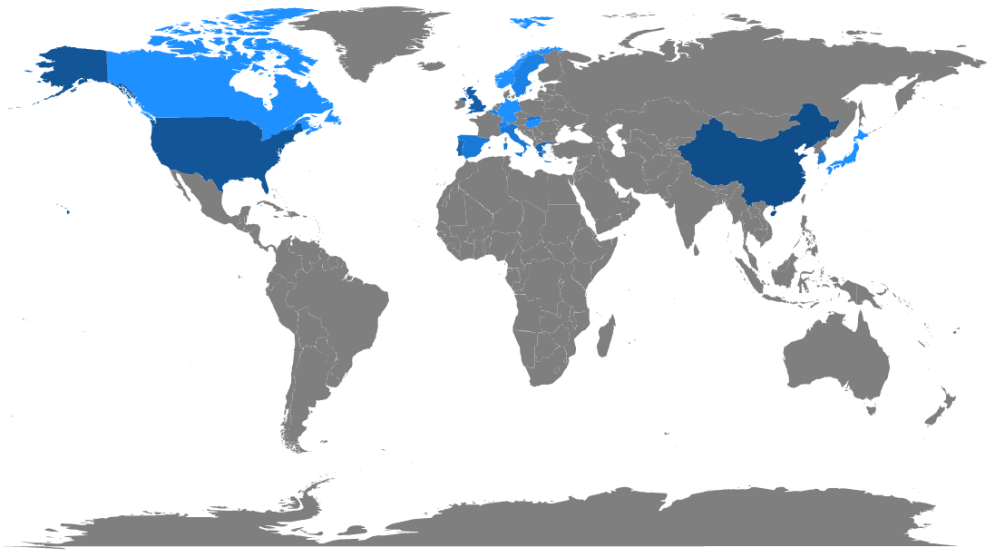

Figure 2. Countries' scientific production (abstracts).

3. Bibliometric Analysis

To present the "overall picture" of the research conducted on the relationship between COVID-19 and bike-sharing, we carried out a bibliometric analysis. This analytical technique is typically used when theoretical and empirical contributions are voluminous, fragmented and characterized by controversial empirical research outcomes. With reference to our specific research topic, we deal with a relatively small number of articles and the results of the empirical research are quite homogeneous; however, we found it useful to conduct a bibliometric analysis as it allowed us to highlight and visualize the main research streams emerging from the selected literature. For this purpose, we used bibliometrix, an open-source tool programmed in R [11].

In line with our expectations, the most used words both in the abstracts (Figure 3) and as keywords (Figure 4) are "bike-sharing" and "COVID-19".

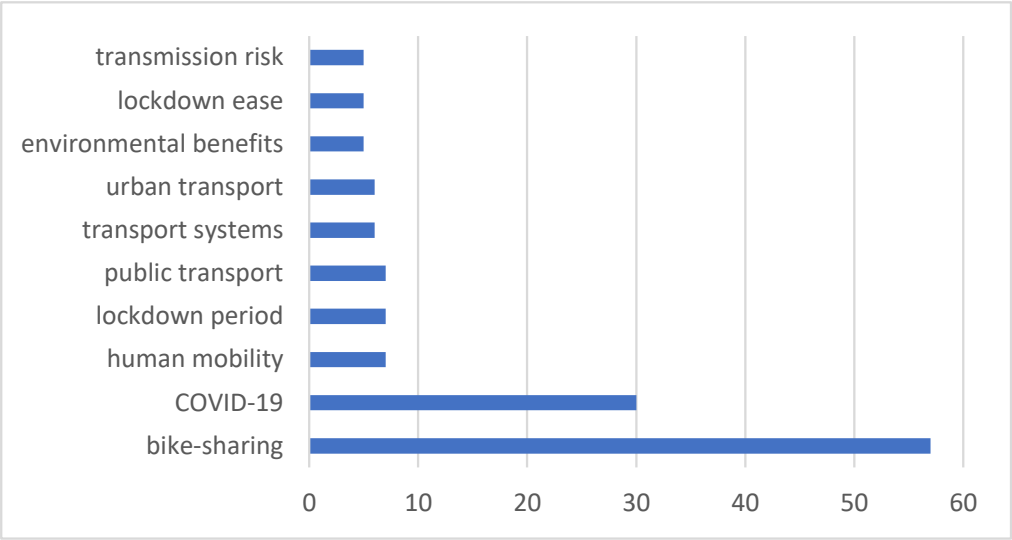

Figure 3. Most frequently used words (abstracts).

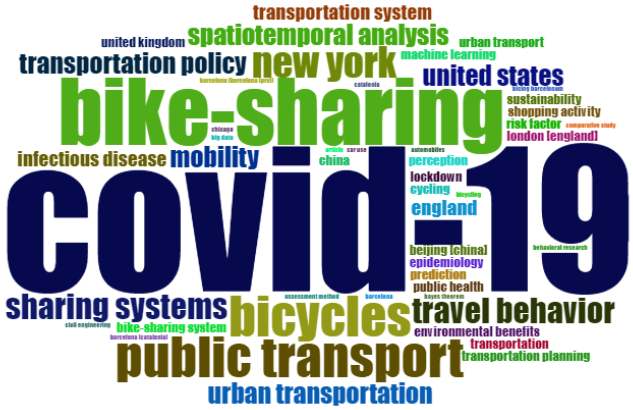

Figure 4. Word cloud of the most frequent keywords.

The countries most cited in the abstracts of the papers we reviewed are Portugal, the United States and China (Figure 5). We did not carry out a trend analysis of the research topics studied as our case study covers a publication span of only three years.

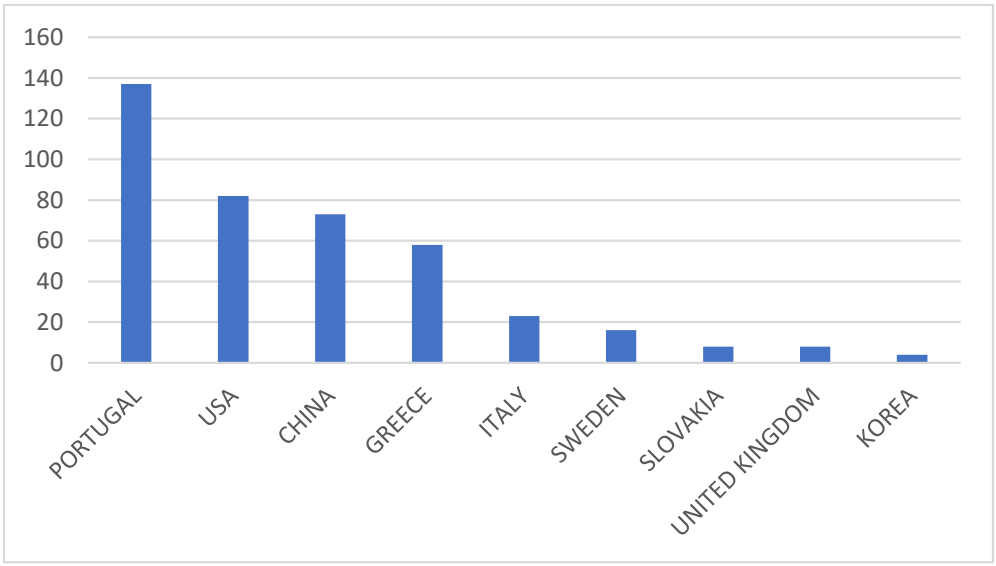

Figure 5. Most cited countries (abstracts).

To trace the conceptual structure of the research framework emerging from the literature, we mapped the word co-occurrence network by clustering the terms extracted from the abstracts, characterized by the highest co-occurrence frequency (Figure 6). We found that "bike-sharing" and "COVID-19" are the most closely related macro themes and their cluster includes both factors closely related to the pandemic, such as "COVID-outbreak" and "lockdown periods", as well as factors depicting the impact that the pandemic has had on mobility systems, public or shared ("public transit", "shared systems"), such as "trips decreased" and "bike usage". The co-occurrence analysis also shows a cluster describing "urban transport" and "urban mobility" including alternative modes of transport to bike-sharing, such as "public transport" and "private car", and some terms related to the impact the pandemic has had on them due to the "publish health" concerns, such as "usage patterns" and "social distancing". Finally, there is a residual cluster focusing on New York City (New York, NY, USA) describing how the pandemic has affected its urban mobility system. In fact, four articles out of twenty-six are specifically focused on this city.

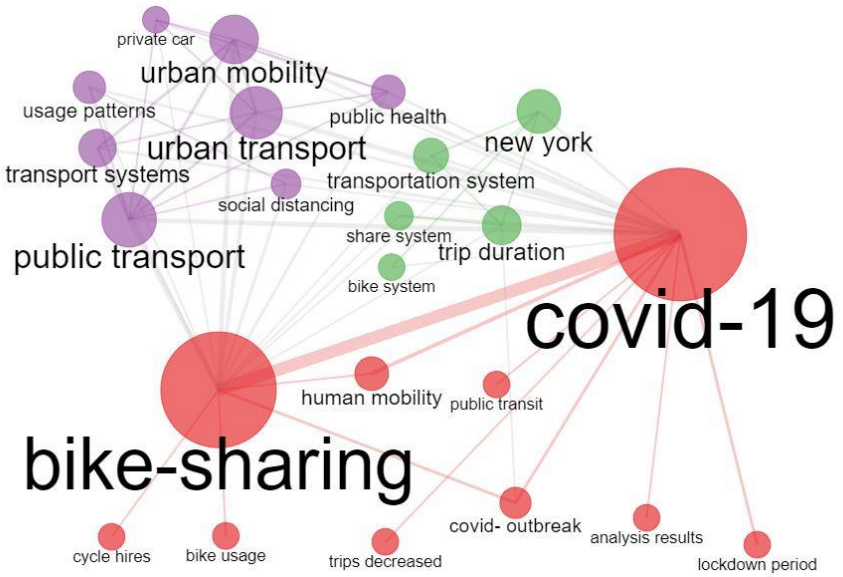

Figure 6. Co-occurrence word network (abstracts).

Finally, we developed a thematic evolution map (Figure 7) that illustrates which research areas are gaining relevance and receiving increasing attention from the scientific community. We found that the analysis of urban mobility and public transport and, although to a lesser extent, the analysis of trip duration, are the most studied topics. The decline in commuting trips, on the other hand, is a less central but still much-debated issue, while the relationship between the pandemic and bike-sharing has the greatest relevance even if it has already reached its maximum development.

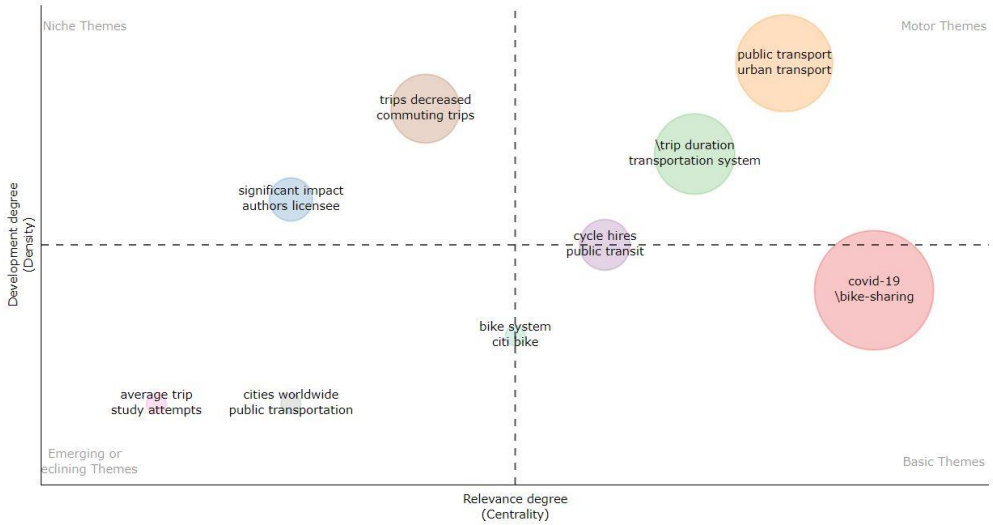

Figure 7. Thematic evolution map (abstracts).

4. Results

Most of the papers we have reviewed assessed how coronavirus has influenced the demand for bike sharing. Ref. [12] studied shared-bike users at different pandemic stages in the city of Beijing and analyzed how shared mobility changed due to the onset of the COVID-19 threat and the consequent administrative restrictions. Ref. [13] performed a longitudinal analysis to trace how the construction of new sharing facilities, the launch of a free-floating bike sharing system and the spread of the COVID-19 pandemic changed bike-share use in Nanjing (China) from 2016 to 2020. Ref. [14] analyzed how the demand for the London cycle hire system changed from 2012 to 2020 with the aim of understanding the prevailing factors affecting bike-sharing use, including the COVID-19 outbreak. Ref. [15] studied the range of

bike share systems' responses to the pandemic in the United States with the aim of providing bike-sharing operators with management strategies to be used during and after such a disruptive event. Ref. [16] investigated the impact of COVID-19 on bike-sharing systems in Seoul with the aim of understanding the type of users more significantly affected. Ref. [17] focused on how bike-sharing use changed before and during the COVID-19 pandemic in the city of Košice, in the Slovak Republic. Ref. [18] studied how the behavior pattern of the bike-sharing users changed in Beijing during the COVID-19 pandemic and estimated the environmental benefits of the bike-sharing system. Ref. [19] investigated how the Coronavirus affected bike-sharing use in the city of Lisbon. Ref. [20] studied how the relevance of a set of factors influencing bike-sharing use in Barcelona changed with the evolution of the COVID-19 pandemic.

Some studies have specifically focused on the initial wave of the disease outbreak. Ref. [21] analyzed the impacts of COVID-19 in New York City, Boston, and Chicago, while [22] focused on the motivations for using bike-sharing during the COVID-19 pandemic in the city of Lisbon. Other studies have compared the demand for bike-sharing and the operation management of the service before and during or after the pandemic. Ref. [23] collected data on the level of usage of bike-sharing systems in the cities of Igoumenitsa, Chania, and Rhodes, in Greece, with the aim of detecting if there was a correlation between the measures implemented against the spread of the Corona virus and the modal choice of residents. Ref. [24] analyzed the demand and the supply of bike-sharing in Nanjing before and after the pandemic outbreak with the aim of understanding how to meet user demand while avoiding spreading the virus. Ref. [25] used three years of bike sharing data collected in Seoul to explore the relationship between particulate concentration ($PM_{2.5}$) and total daily cycling duration before and during the pandemic with the aim of estimating potential health problems caused by the larger number of cyclists exposed to air pollution. Ref. [26] analyzed how micro-mobility trip patterns changed before and during the lockdown in Zurich, Switzerland, with the aim of helping planners and policymakers to better design policies fostering micro-mobility after the pandemic.

Ref. [27] studied what would have happened in terms of demand and duration of bike-sharing trips in London if the COVID-19 pandemic had not occurred, while [28] assessed the impact of the policies adopted in London to limit the COVID-19 contagion on the use of bike-sharing. Only two studies analyzed how COVID-19 affected the potential demand for bike-sharing and travelers' perceptions of bike-sharing systems and bike-sharing usage. Ref. [29] investigated the factors determining the adoption of bike-sharing among potential users in Italy, while [30] studied whether the pandemic could result in a greater or lesser share of trips in the city of Thessaloniki, Greece.

Finally, a group of articles investigated how urban modal share changed due to the pandemic by analyzing the use of bike-sharing during the pandemic compared to other transport modes. Ref. [31] focused on the city of Budapest, Hungary, ref. [32] studied the city of New York, while [33] analyzed the city of Chicago. Ref. [34] focused on the impacts of the stay-at-home policy introduced in Manhattan, comparing the outcomes on bike-sharing and taxi, while [35] and [36] compared outcomes for bike-sharing and the subway system in New York. Finally, ref. [37] analyzed the effects of dockless bike sharing on house prices of the city of Shanghai, taking into account the impact caused by the COVID-19 breakout.

4.1. Type of Data and Analytical Approach

Most of the articles used travel data, including trip start and end station, trip duration and pick-up and drop-off time [12,13,16–18,20,21,24,28,32,34–37]. Some studies were based on the daily use of bike-sharing at the station level [14,25,28,31,33]. Ref. [23] analyzed the number of weekly rides per city provided by bike-sharing operators, while [27] studied the average number of monthly hires and the average monthly hiring time. Only a few studies based their analysis on travel behavior surveys [15,19,22,30] or on stated preference surveys [29].

Some papers were based only on descriptive statistics [13,15,17,19,22,31]. However, regression analysis was by far the most widely used analytical technique. Some authors performed standard OLS regression analysis [16,35,37], while others used random-effects regression models [23]; random parameter least squares regression models [21]; binomial or ordinal regression models [14,29,30] or non-parametric non-linear regression models [33]. Additionally, difference-in-differences regression analysis [12,24,34] and time series models [25,27,28,36] were frequently used. Only two papers used spatial analysis [26,32] or machine learning [20] and big data techniques [18].

4.2. Results

4.2.1. Impacts on Actual and Potential Ridership

The results reported in the literature with reference to the impact that COVID-19 had on bike-sharing ridership are rather heterogeneous and strictly depend on the extent of time horizon (before vs. during the pandemic, rather than before vs. after the pandemic) and the geographical area (small towns, cities and metropolises) taken into account.

Several authors found that the COVID-19 pandemic had significant negative effects on the demand for bike-sharing. In Chicago (IL, USA), ref. [33] observed a decrease of 32.35% in the total number of trips during the pandemic compared with 2019. In Košice (Slovakia), ref. [17] recorded a 46.25% decrease in bicycle rentals in 2020 compared with 2019. Significant reductions in the number of trips during the lockdown period were also reported for Zurich (Switzerland) [26], New York City [32] and Beijing (China) [18]. Ref. [12] estimated that in Beijing (China) the pandemic reduced the use of bike-sharing by 64.8% due to quarantine restrictions and "work from home" mandates, and that the use only increased by 15.9% due to the mitigation of pandemic restrictions.

Indeed, in many cities, such as Chicago, New York City and London (UK), bike-sharing ridership has followed an "increase-decrease-rebound" pattern [28,33,34]. With reference to London, both [14] and [27] reported an initial significant reduction in the use of bike-sharing due to the drastic reduction in commuting. However, ref. [27] also found that the demand rebounded starting in May 2020, remaining in the expected range of what would have been had the pandemic had not occurred. Indeed, the authors concluded that the London bike-sharing scheme was a resilient transport system during the pandemic. Bike-sharing also proved resilient in Nanjing (China), as the number of bike-sharing commuters remained stable over the period 2016–2020, although female and young commuters and the number of combined bike–metro trips decreased [13]. Additionally, ref. [20] reported that the importance of bike-sharing as a means to commute did not decrease after the lockdown period in Barcelona (Spain).

In Lisbon (Portugal), some users decreased or stopped their use of bike-sharing because of fear of contagion, but an almost equal number of individuals increased their number of trips or joined the system during the pandemic. In addition, during the summer of 2020, the modal share of bike-sharing exceeded the levels of use in 2019 by replacing public transport, but also walking and private cars [19]. Ref. [23] also found that in the towns of Igoumenitsa, Chania and Rhodes (Greece), the lockdown led to an increase in the number of trips both during the lockdown period and after the loosening of restrictions. In Thessaloniki (Greece), COVID-19 did not significantly affect the number of people using bike-sharing for their trips; however, bike-sharing was more likely to become the preferable mobility option for people who were previously commuting in private cars as passengers (not as drivers) and people who were already registered users in a bike-sharing system [30]. Even in San Antonio TX, USA, moderate-frequency riders were the segment of the population most willing to increase their use of bike-sharing once the coronavirus restrictions were over [15]. Finally, according to a stated preference survey conducted at the national level in several Italian cities, 32% of the respondents who did not use bike-sharing at the time of the interview stated that they would start doing so once the pandemic was over [29].

4.2.2. Impacts on the Demand for Bike-Sharing Compared with Other Means of Public Transport

Although in many cities the demand for bike-sharing decreased during lockdown periods, compared with other modes of public transport, the reduction in the number of bike-sharing users has been much more contained and the recovery to pre-pandemic levels has been faster. In fact, ref. [16] found that in Seoul (South Korea), the perceived risk of infection using public transport was greater than with other means of transport. Ref. [31] found that in Budapest (Hungary) the demand for public transport decreased by 80%, while cycling and bike-sharing decreased by 23% and 2%, respectively. In Lisbon, the modal share of public transport decreased from 49.9% to 35.5% [19]. Ref. [36] reported that in New York City the use of both subway and bike-sharing initially plummeted (by 95% and 70%, respectively); however, the use of bike-sharing had almost returned to normal at the time the paper was published, while subway traffic had remained substantially below pre-COVID-19 levels. With reference to New York City, ref. [35] also concluded that bike-sharing proved to be more resilient than the metro system, with a less significant drop in users and a modal shift from some metro users to the bike-sharing system. Moreover, according to [34], the demand for bike-sharing has decreased to a much smaller extent and with greater variability than the demand for taxis. Similar results were found by [33] with reference to Chicago, where bike-sharing was more resilient than transit, driving and walking, for which the bounce back was smaller and slower than bike-sharing. Moreover, due to the pandemic outbreak, the relationship between bike-sharing and transit changed from bike-sharing being complementary to a substitute.

4.2.3. Impacts on Commuting and Non-Commuting Trips

The COVID-19 pandemic has not had the same impact on all types of bike-sharing trips, having a much greater impact on commuting than on non-commuting trips. Indeed, in Chicago, usage fell more on weekdays than on weekends, with a significant reduction in commuting trips during the pandemic. Instead, roundtrips, considered leisure travel, increased from 4.58% before the pandemic to 12.69% during the pandemic [33]. Commuting trips in Nanjing also decreased significantly, while trips for health and religion increased significantly [24]. Similarly, ref. [10] found that in Nanjing, before the pandemic, the number of non-loop trip chains (i.e., commuting trips) was significantly higher than that of loop trip chains (i.e., non-commuting trips). However, the non-loop trip chains of bike-sharing-alone commuters were hit hard during the COVID-19 pandemic, and the gap between the number of non-loop and loop trip chains was narrowed. Likewise, leisure bicycle rentals in Seoul increased during the pandemic, and bicycle rentals decreased on weekdays, but increased on weekends [16].

According to [21], bike-sharing trips also decreased more on weekdays than on weekends in New York City, Boston and Chicago (USA). In New York City, the morning peak of bike-sharing trips showed delays and weakness [32]. In Zurich, the decline was greater in the peak hours of workdays, and only slight changes were observed on weekends compared with the pre-pandemic period. In addition, the proportions of household activities, parks and grocery shopping increased, while the percentages of leisure and shopping activities decreased during the block period [28]. In London, morning rush trips and short trips maintained a lower level of use, while the number of other types of trips was much higher than on normal days [28]. The only exception to this general trend was recorded in Lisbon, where bike-sharing commuting trips increased from 22.2% to 27.3% [19].

4.2.4. Impacts on the Characteristics of Bike-Sharing Trips

The COVID-19 pandemic affected the way in which bike-sharing services were used in combination with other modes of transport. The share of bike-sharing-alone trips increased in Lisbon (Portugal), while the percentage of bike-sharing trips in combination with other modes of public transport significantly decreased [19]. Similarly, in Seoul (South Korea), rentals at subway stations and bus stops in business districts significantly decreased

compared with rentals at other stations, that is, bike-sharing alone [16]. Differences were registered also with reference to the type of bike-sharing system. Indeed, [24] in Nanjing (China), found that the rate of decrease in station-based bike-sharing trips (72%) was significantly lower than that of dockless bike-sharing trips (82%).

Many studies found remarkable differences in the duration and the distance travelled by bike-sharing services before and during/after the pandemic. [10] found that in Nanjing (China) bike-sharing-alone commuters had a significantly longer trip duration and travelled longer distances than bike-sharing–metro commuters, although both exhibited a substantial increase in their trip duration and distance travelled after the COVID-19 outbreak. Ref. [33] reported that in Chicago IL, USA, both the average trip duration and the average distance travelled increased during the lockdown periods. Similar results were found by [17] for Košice (Slovakia), by [26] for Zurich (Switzerland), by [21] for New York City, Boston and Chicago (USA) and by [18] for Beijing (China). With specific reference to New York City, NY, USA, an increase in average trip duration and a significant decrease in short-duration riding were also recorded by [35] and Xin et al., 2022, while Wang and Noland, 2021 estimated that the average trip duration increased by between 30 and 60 min.

4.2.5. Impacts According to the Areas within the City/Town

Bike-sharing ridership was differently affected by the COVID-19 pandemic according to the specific urban areas considered. According to [33], in Chicago (IL, USA), open space and residential areas showed a smaller decrease and began to recover earlier compared with the rest of the city. Areas with higher transit ridership generated more bike-sharing trips during regular periods and decreased by relatively slightly less during the pandemic. Larger bike-sharing stations generated more trips in both periods but suffered a more significant relative trip loss during the pandemic. In London (UK), trips near rail stations were reduced by more than those near hospitals; moreover, bike-sharing stations near parks had a much higher rate of increase during the lockdown and the lockdown-easing period [28]. In Beijing (China), people were less likely to engage in bike-sharing in the places where it was more frequently used before the pandemic outbreak [18]. In New York City, the pandemic changed the connection structure and character of the bike-sharing network. The riding connections in the bicycle network were reduced, the number of network communities decreased and the area of community coverage increased [32]. Finally, in Shanghai (China), house prices increased with the usage intensity of shared bikes in neighborhoods relatively far from subway stations. Shared bike usage intensity also has a negative impact on house prices due to bike misplacement. Since the breakout of COVID-19, both positive and negative price impacts had become more evident and bike-sharing reduced the subway premium in house prices [37].

4.2.6. Impacts According to the Demand Segment

Significant heterogeneity was recorded with reference to the segment of the demand impacted by the pandemic. In Chicago, IL, USA, urban areas with higher income and more white and Asian residents suffered a more significant relative decrease in bike-sharing trips during the pandemic [33]. In Nanjing (China), middle-aged and elderly people were more dependent on bike-sharing and were key user groups of dock bike-sharing; indeed, their trip decline and change in travel purpose were the smallest among all age groups [24]. In San Antonio, TX, USA, 43% of the survey respondents who were unemployed due to the pandemic reported increasing their usage of the bike-sharing system, whereas 36% of the employed respondents decreased ridership [15]. Finally, in Seoul, South Korea, the demand from university students significantly decreased [16].

4.2.7. Impacts on Factors Affecting the Demand for Bike-Sharing

In normal conditions, the factors that influence the demand for bike-sharing are difference in altitude, day of the week, number of bike lanes and biking stations, provision of public transport as an alternative to bike-sharing and weather conditions (e.g., rain and temperature). Ref. [20] found that in Barcelona (Spain) these factors significantly

conditioned the demand for bike-sharing, but to a much lower extent compared with the pre-COVID-19 scenario. In addition, gender, age and income were less important determinants of bike-sharing demand after lockdown. Ref. [22] found that in Lisbon (Portugal), before the pandemic, the motivations most strongly affecting the demand for bike-sharing were the convenience of the location of the bike-sharing stations compared with the users' destinations, the availability of shared e-bikes, the pleasure of cycling and the perceived environmental and health benefits. However, during the pandemic, besides the motivations relating to service coverage and quality, avoiding the use of public transport services and maintaining social distance during the trip were as important as the motivations linked to personal interests and well-being. Moreover, new users placed more importance on seeing other people using the system or the influence of their social circle than older users. Finally, in Seoul (South Korea), ref. [25] found that although there was a negative association between concentrations of PM2.5 and total daily cycling duration before the pandemic (2018 and 2019), this association became insignificant during the pandemic in 2020.

4.3. Causes of the Change in Usage of Bike-Sharing

4.3.1. Causes of Ridership Changes

Many authors have found that the reason for the reduction in the use of bike-sharing was not so much the fear of contagion (although for some people this was also an important reason), but purposes for trips no longer existing, mostly due to a decrease in commuting trips caused by smart working. In addition, "stay-at-home" orders restricting the movement of people, and pandemic control strategies forcing most leisure-related facilities to close during the lockdown, caused a drastic reduction in the use of bike-sharing. These were the main reasons that led to a temporary reduction in bike-sharing in Lisbon [19], London [27], Chicago [33], Nanjing [24], Seoul [16] and Zurich [26]. In New York City, in addition to a significant reduction in the number of daily commuters, the number of tourists and business travelers visiting the city dropped dramatically. Furthermore, as in many other cities, schools and universities operated remotely and many businesses were closed or remained only partially open [34].

However, in some cities, such as Košice and Lisbon, people's fear of infection played a significant role in reducing the use of bike-sharing [17,19]. In particular, in Lisbon, while before the pandemic the perceived safety of public transport was similar to that of other means of transport, during the pandemic it was considered by far the most dangerous mode and bike-sharing was perceived as the second least safe mode. Interestingly, the use of a personal bicycle, which was perceived as the least safe mode of transport before the pandemic, became the second safest perceived mode [19].

Other cities, such as New York City and Shanghai, have witnessed a quite different scenario, with a marked modal shift from public transport to bike-sharing, perceived as a safer mode of transport since it allows for social distancing in an open space [32,34,37]. Additionally, in Seoul, cyclists reacted less to the PM2.5 level during the pandemic due to the lack of COVID-19-safe alternative means of transport [25].

4.3.2. Causes of Trip Duration/Distance Changes

During the pandemic, there was a significant increase in rental time. This was because some travelers rented bicycles for longer journeys that were otherwise made on the subway and buses, which were perceived as less safe than bike-sharing, and due to the increase in the number of people renting bicycles for recreational activities, including physical exercise. These were the main reasons found for London [27], but also for Chicago [33] and New York City [36].

In some cities, such as New York City, Boston, Chicago and London, other means of public transport have been temporarily suspended and many people have had no alternative to the option of bike-sharing, forcing them to travel longer distances, normally traveled by metro or bus [21]. This was especially true for low-income residents who

did not have personal commuting vehicles and could not work from home due to the characteristics of their work [28]. In fact, Chicago's low-income workforce experienced only a marginal change in travel behavior as they could not switch to remote work. Additional reasons may have been lower car ownership, lower awareness of virus risks, and less flexibility in switching to other modalities [33].

A further reason for the longer journeys recorded during the pandemic was the increased availability of e-bikes provided by private or public bike-sharing services, reducing obstacles to cycling, such as physical effort and long travel distances. Furthermore, the pleasure of cycling has helped to minimize some of the negative effects on general well-being caused by the lockdown restrictions imposed due to the coronavirus pandemic [22].

Finally, as indoor facilities, including fitness, sports and entertainment facilities, were restricted by strict social distancing rules and working from home was mandatory during the pandemic, longer bike-sharing trips were made for exercise/leisure, and open spaces, such as parks and green spaces, become the most attractive places for bike-sharing users. Larger stations, on the other hand, implied more available bicycles, but also greater potential demand and a greater risk of contagion, so they were less used during the pandemic [16,33].

4.4. Policy and Operational Implications

4.4.1. Financial Support for Bike-Sharing

Bike-sharing acts as a substitute for public transport during a disruptive event such as the COVID-19 pandemic because it is perceived as being able to preserve physical distance, preventing users from switching from public transport to private cars and effectively contribute to the resilience of urban transport systems [22]. Furthermore, bike-sharing was cheaper than buying a personal bicycle, in particular an e-bike, or a pass for public transport which in many large cities could cost up to EUR 30 per month. Therefore, especially during the pandemic, bike-sharing was effectively providing an essential public service [19]. However, the lower volume of users caused by the lockdown restrictions imposed by national governments and local administrators has entailed a great financial burden for operators, reducing the quality and the financial sustainability of the service in some cities. This has led to a vicious circle of declining ridership and quality [31]. Preventing this inefficient outcome requires policymakers to estimate the loss caused by decreasing travel volumes during the pandemic and to devise corresponding schemes to reduce economic losses [32]. Furthermore, as bike-sharing has proven to be more resilient and flexible than modes of public transport such as the subway or buses, local administrators should invest more in the service and in the provision of cycling lanes [28,33,36]. In addition, bike-sharing systems, especially dockless systems and docked mobile stations, can rapidly strengthen transport supply to areas with higher demand, at a fraction of the cost of new road or public transport infrastructures [35].

4.4.2. Bike-Sharing Infrastructures and Regulation

Local administrators must ensure greater safety for cyclists by creating suitable and safe cycle paths [21,22,29,36], avoiding building along busy roads and planting trees on the sides of roads and along bike lanes [25]. Additionally, [35] called for large areas of road space to be reallocated from car use to active, walking and cycling modes of transport.

With specific reference to the COVID-19 pandemic and, more generally, when dealing with any disruptive event, ref. [20] suggested implementing tactical urbanism, that is, investing public resources in low-cost temporary initiatives to rapidly change urban environments and transform streets so that pedestrians and cyclists can enjoy public spaces without fear of contagion. In the same vein, ref. [32] have recommended adding temporary bike lanes and temporary bike stations to recreational areas spread across the city. Moreover, the infrastructures of a city play a significant role in narrowing the social equity gap regarding bike-sharing usage. Including social equity principles in developing the spatial distribution of bike-related infrastructures is a critical planning activity that

local administrators should carefully and properly guide [20]. In doing so, ref. [34] have recommended increasing the use of data-driven planning policies. Finally, ref. [27] have suggested verifying whether some travelers have permanently switched from public transport to bike-sharing, as this could result in a permanent (or at least long-term) change in the urban mobility setting, requiring additional funds and infrastructure to support the provision of bike-sharing services not only in city centers but also the suburbs.

Although the provision of extensive and dense bike lanes has proved to be an essential condition to support the use of bike-sharing during the COVID-19 pandemic, minimizing the risk posed by motor traffic is at least as important and must be pursued through the implementation of traffic-calming measures within the catchment areas of bike-sharing stations [22]. The evidence emerging from the literature is that, during a disruptive event, the mere provision of additional bike lanes is hardly effective unless combined with traffic regulation policies aimed at minimizing the risk posed by car traffic. Reducing the speed limit to 30 km/h has also proven effective in minimizing the risk of collisions between bicycles and motor vehicles. Similarly, ref. [25] suggested reducing the overall level of car use in the city, while [31] has proposed introducing access charges. Finally, ref. [21] have stressed the importance of providing longer and more frequent signal times for bikes and pedestrians.

4.4.3. Policies Aimed at Empowering Disadvantaged Segments of the Population

Bike-sharing has proved to be a viable mode of transport, being more resilient than other public transport alternatives, especially if e-bikes are used, allowing the user to travel longer distances. The current purchase price of an e-bike is still a barrier, particularly for low-income groups. From this perspective, the provision of shared electric bikes at an affordable cost could encourage new users to use bike-sharing while increasing the resilience of the urban mobility system [22]. According to [20], a reduction in electric bicycle rental fees could empower the groups facing socioeconomic barriers that prevent them from considering biking as a viable mode of transport, helping to bridge the relative social equity gap to bike-sharing while promoting mobility in general.

Ref. [13] found that the burden of the pandemic was not evenly distributed among demographic groups, hitting women and young riders the hardest. The authors proposed flexible fare strategies to sustain the development of bike-sharing, with the aim of supporting the disadvantaged segments of the population, attracting new users while increasing the loyalty of existing ones. Special types of cards (e.g., commuter cards) with points and rewards for commuters could be introduced, rather than using a single fare mechanism as currently implemented by most bike-sharing schemes.

Ref. [33], instead, proposed subsidizing the relocation of bikes from urban areas with a lower concentration of vulnerable people to those with more vulnerable people. This policy would increase the turnover rate while helping more people away from the overcrowded transit, a particularly important goal during disruptive events such as the COVID-19 pandemic. Additionally, Refs. [15] and [16] stressed the importance of making bike-sharing accessible to low-income communities, improving the feasibility and robustness of the bike-sharing system. Indeed, ref. [35] have pointed out that bike-sharing has provided a crucial lifeline to low-income families who rely on public transport for commuting and do not have access to cars or private vehicles.

Therefore, bike-sharing operators and policymakers should explore how to best serve unemployed and low-income communities and prepare for a fairer expansion of the user base after the pandemic. New isolated lifestyles and commuting patterns are emerging, and bike-sharing is expected to meet some of the demand previously served by public transport. However, many bike-sharing schemes are instead designed for tourists around downtown amenities and destinations, which are likely to be rarely, if ever, used during a disruptive event [15].

Finally, the duration of bike-sharing trips increased greatly due to the constraints of other means of public transport. Therefore, the original service fee should be revised to accommodate changing travel patterns [28].

4.4.4. Operational Management

From an operational point of view, providers should ensure that the bike-sharing service is able to meet demand according to the changes in the spatial–temporal distribution of commuting and non-commuting trips. As trip duration and travel time increased significantly during the pandemic and reduced the turnover of bikes, the timely transfer of bicycles from idle stations to neighboring stations experiencing high demand is critical [13]. To this end, providers should use predictive models to track travelers' responses to rapidly changing real-world conditions and should review their relocation policies accordingly [34].

In cities where bike-sharing works mainly as a complement to the subway or bus network, operators should create a list of the most frequently used parking places to be constantly monitored and among which to frequently transfer bicycles [37]. However, the pandemic has also shown that bike-sharing can be a substitute for public transport, in which case strategies for redistributing public bicycles from places with lower demand near public stations to hotspots such as hospitals and parks should be adopted [28].

Disinfection should be strengthened, especially in flow-intensive stations, monitoring the spatiotemporal distribution patterns of the origins and destinations of the trips since they might significantly change due to disruptive events such as the pandemic [32,34].

Finally, operators should be prepared to meet the increased demand that follows the easing of lockdown measures or of similar disruptive events, since the reopening of the city can lead to a significant increase in the use of shared bicycles [28].

4.4.5. Real-Time Information and Promotional Campaigns

Operators and local administrators should promote the health and sustainability benefits of the bike-sharing system [23]. They should emphasize that bike-sharing is an excellent outdoor exercise for individuals to keep fit and healthy, preventing virus contagion, and that it is a much more environmentally sustainable option than cars for cities that are facing the disruptive consequences of climate change [16,33]. They should also promote communication campaigns focused on the safety measures implemented to decrease the infection risk associated with using the system or, more in general, to cope with a disruptive event [22].

Bike-sharing operators should expand communication efforts regarding the policies and actions taken to support community health [15], making real-time air quality information available for those engaging in outdoor activities [25].

Finally, publishing real-time bike-sharing flow distribution will also be helpful for citizens when it comes to making decisions about travel [32].

5. Conclusions

Based on our review, we can conclude that, in many cities, COVID-19 has resulted in significantly reduced bike-sharing ridership, at least in the initial phase of the pandemic, although in a less drastic way than that experienced by public transport. The reasons for such a significant impact on the use of bike-sharing included the fear of contagion, but above all the lockdown measures adopted at the national and/or local level to reduce the spread of the contagion (smart working and online lectures). However, with the easing of the lockdown restrictions, the demand for bike-sharing rebounded much faster and more substantially than the demand for the subway, buses and even walking. With the pandemic, however, not only did the number of trips change, but also the way in which bike-sharing was used. Distances traveled and rental times lengthened; commuting trips, especially during peak hours, decreased; leisure trips, especially during the weekend, increased; and travel destinations switched from city centers and business districts to residential and green areas. Furthermore, dockless bike-sharing was more impacted than dock-based services, and the use of bike-sharing in combination with public transport decreased, becoming a substitute for, rather than a complement to, the subway and buses. Substituting public transport with bike-sharing was especially characterized by the low-income segments of the population who, on the one hand, due to the type of jobs performed, could not switch

to smart working and, on the other, did not have the financial resources needed to purchase a car or electric bike.

All things considered, bike-sharing proved to be more resilient than other forms of public transport and preserved at least partially the sustainability of the urban mobility systems. However, is all that glitters gold? Not really, considering that for some large and disadvantaged segments of the population, this form of mobility is impracticable, including people with poor physical fitness, older people and disabled people. The same goes for parents carrying small children who need bikes with child seats, rarely available as a standard service, or for people needing to carry bulky or heavy shopping or business bags. Moreover, in most cities, bike-sharing stations are located near tourist attractions, thus neglecting the suburbs. Furthermore, the rental fees are accessible for tourists occasionally using the service but are unlikely to be affordable for low-income workers or disadvantaged segments of the population. Finally, on average, the number of available bikes is dramatically lower than the potential demand if, due to a disruptive event such as the COVID-19 pandemic, bike-sharing should substitute rather than complement public transport.

In the articles we reviewed, many policies were suggested to enhance the role that bike-sharing could play in improving the sustainability, resilience and inclusion of urban transport systems. From the point of view of the construction and management of transport infrastructure, cycle paths should be built and/or extended, reducing the space dedicated to the circulation or parking of cars, and green infrastructure should be provided along the roads and cycle paths. From the point of view of traffic regulation, it is necessary to reduce the speed of cars to 30 km/h, precluding access to some parts of the city either permanently or at least in certain time slots, resulting in longer and more frequent signal times for bikes and pedestrians. With regard to the location of the bike-sharing stations, the service should be extended to residential and peripheral areas, preferring many small and widespread stations rather than a few large stations. At the level of service management, real-time data should be used to promptly relocate bicycles to the areas of greatest demand and to better define intervention policies such as traffic regulation, the opening of cycle paths and subsidies for bike-sharing rates. Finally, subsidies to private operators could be granted to prove that bike-sharing operates as a complement to, rather than a substitute for, public transport.

In our opinion, there are still some gaps in the literature that require further investigation. For example, in 2020, the Italian government granted EUR 5 million to finance subsidies for sustainable mobility, including the purchase of bicycles and electric bicycles. However, no one has yet studied what impact this type of policy has had on individual mobility habits, or whether it would have been more effective to finance the implementation of bike-sharing services in the suburbs or in cities where the service is still lacking. Not much is known about how bike-sharing rates should be differentiated to encourage a modal shift from car use to the daily use of bike-sharing, without reducing the turnover of the bicycles. The studies that have dealt with the impacts of the pandemic on bike-sharing have not analyzed whether privately managed or publicly owned systems are more resilient. Another issue that should be further studied is whether bike-sharing systems with electric bikes rather than normal bikes are preferable, and whether dockless or dock-based systems are more resilient. Finally, no one has yet analyzed the role of urban planning in determining the success of bike-sharing. Further investigation along these lines of research could help public administrators and private operators to offer a more effective, responsive, inclusive and sustainable bike-sharing service. Although our review is based on a limited number of articles, we hope our work will further stimulate the analysis of how the COVID-19 pandemic has affected the use of bike-sharing. Our concluding remarks are only preliminary and should be further checked and enriched as additional evidence will be published.

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