

SYNERGY BETWEEN GREEN STORMWATER INFRASTRUCTURE AND ACTIVE MOBILITY: A COMPREHENSIVE LITERATURE REVIEW

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Abstract

Green stormwater infrastructure (GSI) is increasingly used in urban planning to replace grey infrastructure and achieve socio-environmental benefits. Its design can result in a substantial reallocation of space and thereby contribute to active mobility (walking and cycling), especially when implemented in the right-of-way. Yet, few studies have investigated the relationship between GSI and active mobility. This paper comprehensively reviews 70 scientific articles on GSI and more broadly green infrastructure (GI) in the context of active mobility. Our primary aim is to assess the potential synergy between GSI and active mobility. While empirical studies on GSI and active mobility are lacking, the review highlights the potential effects of GSI based on its common characteristics with GI. The main potential benefits identified are increasing active travel, enhancing road safety and improving street aesthetics. The review also addresses car mobility, safety and aesthetic concerns associated with GSI implementation. Findings demonstrate the

complex relationship between GI, GSI, and active mobility, warranting further studies to understand the nuanced effects of different types of infrastructure on active travel. This study is relevant for researchers and planners seeking insights into GSI specificities to better guide future studies and projects supporting both urban water management and active mobility.

Keywords

Green stormwater infrastructure; Vegetation; Active mobility; Urban design; Integrated planning

Highlights

- Green stormwater infrastructure (GSI) has the potential to support active travel
- Further studies are needed to assess the nuanced effects of different types of GSI
- The existing scientific research on GSI and active travel is mostly qualitative
- New indicators using large-scale data to quantify GSI features are necessary
- Designing multifunctional streets is key to maximize GSI socio-environmental benefits

1. Introduction

Cities are implementing green infrastructure (GI) in urban areas to reduce climate change vulnerability and provide socio-environmental benefits for populations. The term GI refers to “an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife” (Benedict & McMahon, 2012). As shown in Figure 1, GI includes all types of green features including green stormwater infrastructure (GSI). The term GSI is used to define GI primarily designed to capture and infiltrate runoff. In this study, we separate GSI from the rest of GI features to better understand the specific synergies between stormwater management objectives and active mobility. Hence when we synthesize findings from literature on GI, we typically exclude studies on GSI. It is important to note that GI is often used in the literature in reference to stormwater management functions.

GSI is particularly interesting due to the multiple co-benefits that a single infrastructure can support. As such, studies have shown that implementing GSI can reduce heat island effects (Shafique & Kim, 2017), reduce runoff (Luan et al., 2019), improve the resilience of drainage systems (Casal-Campos et al., 2018), and improve air quality (Abhijith & Kumar, 2019), while having the potential to support active mobility (Adkins et al., 2012). Yet, its implementation is a challenge for urban planners due to space competition in dense urban areas. In that sense, cities should optimize its implementation to maximize its secondary benefits (Dagenais et al., 2016), such as active mobility.

An increasing number of cities have come up with a greening strategy, including GSI in their mobility plans to facilitate and promote active mobility (walking and cycling). As shown in Figure 1, GSI can be directly implemented in the street to capture runoff from impermeable surfaces. When implemented in a built environment, its implementation requires a reallocation of the space, often more considerable than other GI types (which are not primarily designed to collect rainwater). GSI is generally implemented between the roadway and the sidewalk. Thus, the redesign of the street might have a significant impact on travel behaviour and individuals’ perceptions. Although several literature reviews have identified studies investigating the socio-economic and environmental benefits of GI (Bartesaghi Koc et al., 2018; Tzoulas et al., 2007), and GSI (Venkataramanan et al., 2020), the effects of GSI on active mobility are little documented in scientific literature.

Green infrastructure (GI)



Figure 1 Examples of green infrastructure and green stormwater infrastructure

The aim of this study is to provide a comprehensive overview of the knowledge on the synergy between GSI and active mobility. To our knowledge, there is no comprehensive synthesis of studies addressing the specific relationship between GSI and active mobility. This article provides an understanding of the current state of scientific knowledge on this subject and identifies further research needs. As GSI is a type of GI and given the few studies that empirically examined the relationship between GSI and active mobility, we decided to also consider GI in our review. Therefore, we first focus on the understanding of the effects of GI on active travel given that GI has been studied more extensively than GSI in that respect. Then, we address the literature specifically on GSI and active mobility while raising the common characteristics between GSI and GI that have the potential to yield similar outcomes for active travel. Thus, through a comprehensive review of the scientific literature published in peer-reviewed journals, we seek to answer the following questions:

- What indicators are used to quantify GI when assessing its effects on active mobility?

- What are the empirical relationships between GI and active mobility?
- What methodologies are used for analysing the synergy between active mobility and GSI in the scientific literature?
- What are the potential benefits of GSI implementation on active mobility?
- What are the gaps in the literature regarding the effects of GSI on active mobility?

This comprehensive review provides a synthesis of the relationships of GI and GSI with active travel, physical activity, road safety, and health. It also provides an overview of the challenges regarding the implementation of GSI in the built environment, namely with respect to the perceptions of the population. This study is of relevance to urban planners, municipal stakeholders, and researchers aiming to better understand issues surrounding the implementation of various types of GSI and their potential benefits regarding active mobility.

2. Methodology for the selection of the literature studies

An exploratory review of previous studies on GSI and active mobility has revealed that few studies focused directly on documenting this synergy. Hence, we first identified and analyzed empirical studies on the effects of GI (excluding GSI) visible from the right-of-way on individuals' behaviours and perceptions during active travel. This allowed us to understand potential effects that GSI can provide for active mobility through its common characteristics with GI (e.g., types of plants, density of vegetation, etc.). Then, we examined the studies that explicitly analyzed types of GSI and addressed their synergy potential with active travel. A literature search was conducted in Scopus and Web of Science, as these databases have been widely used in literature reviews on active transportation and GSI (Arellana et al., 2020; Caparrós-Martínez et al., 2020; Fonseca et al., 2022) and adequately cover the field of natural sciences and engineering (Mongeon & Paul-Hus, 2016). The flow chart for the study selection is shown in Figure 2.

The search methodology was inspired by the article on the process of writing a literature review written by Van Wee & Banister (2016) and the systematic review of Scheepers et al. (2014) on modal shifts. For the Scopus database, the search was limited to articles. For the Web of Science database, irrelevant documents (non-articles) were removed after extraction. Data was extracted on May 31, 2023. There were no restrictions based on the year of issue. The detailed search strategy

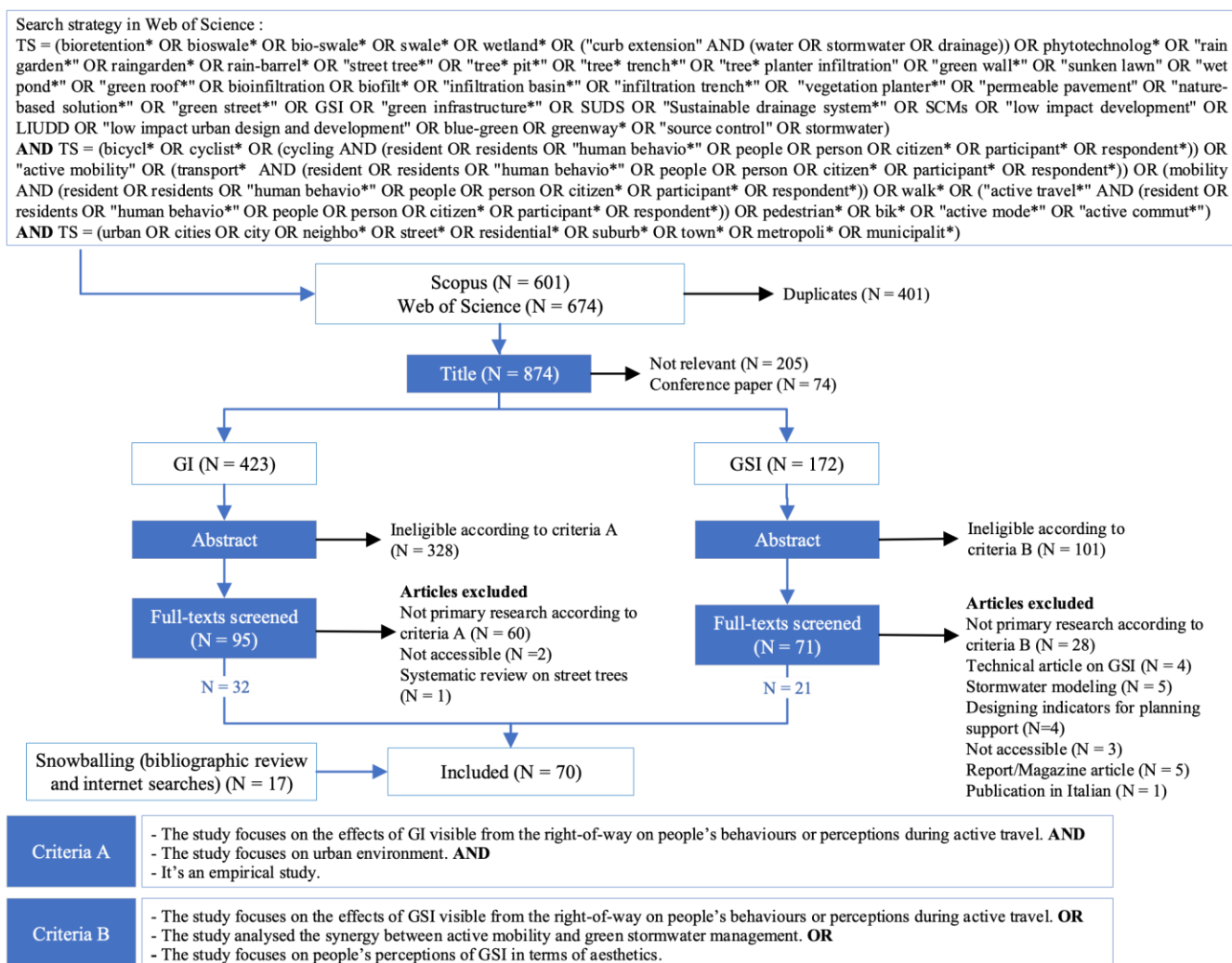


Figure 2 Flow chart for search strategy and selection of studies

used in Web of Science is depicted in Figure 2. The same terms were used in Scopus, but the truncation was adjusted to fit in Scopus. The search strategy was divided into two main subjects: active mobility and GI. Since the focus of the study is on GSI, many specific terms were included such as “bioretention*”, “rain garden*”, “swale*”, etc. All the terms described by Fletcher et al. (2015), in an article reviewing the history of the terms used in urban drainage, were tested. For active mobility, modes included are walking and cycling. An additional category was used to target only studies conducted in urban areas. The boolean operator ‘AND’ was used between the three main categories (active mobility, GI or GSI, and urban areas), and the boolean operator ‘OR’ was used within the categories. One librarian and three researchers tested each term for relevance and optimized and adapted the search for each database. For example, some words such as “cycling”

and “transport” that can have more than one meaning, especially when related to urban drainage, were linked with other words to avoid finding non-relevant articles.

Different inclusion criteria were used to distinguish articles that relate to GI (Criteria A) from those that are specific to GSI (Criteria B). Figure 2 shows the study selection process and describes both sets of criteria. During the selection process, the reading of selected articles led to the identification of themes. For each theme, we analyzed the relevance of the theme to understand the relationship between GSI and active mobility, and then refined the selection criteria. The articles were analyzed by types of infrastructure (GI and GSI). The eligibility criteria for GI are stricter since it is not the main subject of the study.

For GI, selected studies had to focus on the impact of GI located on the right-of-way (street trees, average greenery on the street, green medians, etc.) on individuals’ perceptions or behaviours related to active travel. The identified themes included studies evaluating the effects of GI on walking or cycling activities, physical activity, road safety, and health benefits related to active travel. Studies focusing on parks, green spaces, and greenways out of the street were excluded unless the study specifically mentioned that the infrastructure was visible from the street (e.g., Vich et al. (2019) considered the proportion of park area within a 20 m buffer zone of the individual's route.). Even if these types of infrastructure can contribute to active mobility (Hogendorf et al., 2020; Ki & Lee, 2021; Lu et al., 2018), they meet different needs than street-level infrastructure, especially since they often constitute a destination (Ki & Lee, 2021; Lu et al., 2018). We also excluded studies that evaluated the impacts of the built environment on active travel by including variables such as the street tree canopy without specifically discussing/focusing on it in the analysis.

For GSI, the selection criteria include those for GI, as well as studies analyzing the potential synergy between active mobility and GSI, such as studies investigating people’s perceptions of GSI in terms of street design and road safety. Moreover, we included studies focusing on the aesthetics of GSI since preferences for different types of GSI might influence their effects on active travel.

We excluded, both for GI and GSI, studies focusing on outcomes not directly related to people’s perceptions and behaviour during active travel, such as air quality, thermal comfort, and efficiency of stormwater facilities. During the selection process, we found over 60 studies on thermal comfort

and over 30 studies on air quality. Literature clearly reports that GI and GSI can help improve thermal comfort and air quality for pedestrians and cyclists (Abhijith & Kumar, 2019; Detommaso et al., 2021; Jia et al., 2021; Sylliris et al., 2023; Zölch et al., 2016). Additionally, comprehensive reviews on these impacts of GI and GSI have already been published (Abhijith & Kumar, 2019; Piracha & Chaudhary, 2022; Taleghani, 2018). However, previous studies rarely analyse individual perceptions and behaviours during active travel. While these benefits are important, our study focuses on understanding more specifically how GI and GSI directly influence human behaviour in terms of active mobility, i.e., in addition to the benefits of improved air quality and thermal comfort.

2.1 Summary of the studies

The search strategy led to a final selection of 42 studies on GI and 28 studies on GSI for further analysis, i.e., 70 articles published between 2001 and 2023 in total (including 51 articles published since 2016). Table 1 summarizes the main properties of the reviewed studies. They were mostly conducted in North America, East Asia and Europe. As shown in Table 1, a large proportion of them were conducted on small samples (29 studies with fewer than 1000 observations). A large proportion addressed the following types of vegetation: trees, rain gardens, bioswales, green spaces, and parks. Several studies investigated the effects of global vegetation indices which measure

Table 1 Properties of the reviewed studies

Property	Categories (number of studies)
Year of publication	Published between 2001-2005 (4), 2006-2010 (4), 2011-2015 (11), 2016-2020 (26), and 2021-2023 (25)
Geography	Regions included in analysis are North America (23), East Asia (17), Europe (18), Australia (1), North America and Europe (1), Africa (2), multiple regions (3), and not specified (5)
Study design	Quantitative with more than 1000 observations (20), quantitative with fewer than 1000 observations (29), qualitative – observations, interviews or focus groups – (4), experimental study (1), conceptual framework (9), and description of projects (7)
Main subject of the study	Green infrastructure: active mobility (19), safety (11), health (5), physical and outdoor activities (2), perceptions of street designs with GI (4), and purposes of visiting GI (1). Green stormwater infrastructure: integrated urban projects (11), perceptions of GSI (9), active mobility (6), mobility (1), and outdoor activities (1).
Most common green features analyzed or discussed*	Trees (48), rain gardens and bioswales (22), global vegetation indices (15), green spaces and parks (15), ground vegetation and landscape buffers (6), urban greenways (6), flowers (3), and water reservoir (2).

*Some studies included multiple types of vegetation

the overall proportion of green features in an area. Finally, for GI, most of the studies were on active mobility and road safety. For GSI, most of the studies did not directly assess active mobility.

3. Results

In this section, we first analyse the studies on GI. We describe all types of vegetation included in the reviewed articles. Then, we investigate the effects of GI on active travel, safety, and health. Lastly, we analyze the potential synergy between GSI and active mobility by reviewing the studies that specifically consider GSI. These consist of conceptual frameworks, case studies, and examples of projects.

3.1 Studies on green infrastructure

3.1.1 Types of GI analysed

This section presents a review of the types of vegetation assessed in relation to active mobility, as well as the indicators and methods used to quantify them. Understanding how the different types of vegetation are measured is essential to then examine the relationship between GI, GSI and active mobility. Table 2 presents the indicators used in the reviewed studies. Overall, two types of approaches are predominantly used. The first one measures a global vegetation index, while the second directly assesses the presence of one type of GI (mainly trees). These indicators were found in studies looking at GI, and do not make the distinction between GI or GSI. Measuring the effects of global vegetation indices (i.e., greenness) on active mobility is central to understanding the effects of GI and GSI since these types of infrastructure contribute to increasing the overall greenness of a city.

3.1.1.1 Global vegetation indices

Global vegetation indices presented in Table 2 are intended to measure the density of vegetation within a specific area or along a street segment. The most commonly used indicators are the Normalized Difference Vegetation Index (NDVI) and, more recently, the Green View Index (GVI). The NDVI uses multispectral satellite imagery to measure the density of vegetation, whereas the GVI is calculated from street view images. According to the studies analyzed, the GVI seems to be a better indicator to reflect pedestrians' and cyclists' experiences and adequately includes some vegetation that could be overlooked by the NDVI such as green walls and vegetation under canopies of trees (Ki & Lee, 2021; Lu et al., 2019; Wu, Jiayu et al., 2020). In addition, this indicator allows to measure the average or total vegetation exposure during a trip without having to delimit a buffer zone around the route. Roscoe et al. (2022) used an alternative technique that distinguishes ground cover vegetation (less than 2.5 m) from tree cover vegetation (greater than or equal to 2.5

m). Although these three indicators are used to assess exposure to greenery, they do not measure the overall effect of GI on active mobility, which extends beyond the presence of vegetation.

Table 2 Types and characteristics of the green features' indicators found in the reviewed literature

Indicators	Additional information about the indicators (studies using the indicator)
Global vegetation indices	
Normalized Difference Vegetation Index (NDVI) – 3 studies	
Circular buffer around the centroid of participants' neighbourhood	- 1000 m (Liu et al., 2019).
Circular buffer around home	- 400 m, 800 m and 1600 m (Lu et al., 2019). - 500 m (Sarkar et al., 2015).
Green View Index (GVI) – 10 studies	
Rating of images by participants	- (Dai et al., 2021).
Circular buffer around home	- 400 m, 800 m and 1600 m (Lu et al., 2019). - 500 m (Ki & Lee, 2021). - 800 m (Lu et al., 2018; Yang et al., 2019).
Network buffer from home or from metro stations	- 500 m, 1000 m and 1500 m (Wang et al., 2020)
Mean GVI for each street segments	- (Ta et al., 2021; Wu, Jiayu et al., 2022; Wu, Jiayu et al., 2020)
Mean GVI at census tract level	- (Li & Ghosh, 2018)
Other indicator – 1 study	
Tree-cover (≥ 2.5 m), ground-cover (< 2.5 m), and green walkability (all)	- 1000 m network buffer around home and 50 m road buffer (Roscoe et al., 2022)
Green infrastructure	
Tree canopy density – 6 studies	
Road buffer	- Area between the buildings closest to the road (Harvey & Aultman-Hall, 2015; Harvey et al., 2015) - Area within the public right-of-way (Lee, S. et al., 2022). - The percent of the areas covered by the tree canopy within 15.2 m (50 ft) buffers from the right-of-way (Kim, D., 2019). - Sidewalk focal area on each side of the road (7.5 m beyond the road edge and 1 m overlap with the road) and 50 m buffer (25 m each side of the centreline) for a 500 m, 750 m, 1000 m, and 1250 m network buffer around home (Tsai et al., 2019). - Proportion of road pavement and footpath covered by three canopy (Zhu et al., 2022). - Approximate (Botes & Zanni, 2021).
Circular buffer around home	- 500 m, 750 m, 1000 m, and 1250 m buffers (Tsai et al., 2019).
Number of trees – 6 studies	
Density of street trees within a buffer around home (Nb of trees/area)	- Circular buffer of 500 m around home (Ki & Lee, 2021). - Network buffer of 500 m (Akinci et al., 2021) or 1 km (Sarkar et al., 2015) around home.
Number of trees within a buffer surrounding the road	- Number of trees per unit length for a 15.2 m (50 ft) buffer (Chen, P. et al., 2018). - Number of trees on pavement or footpath per unit road length (Zhu et al., 2022). - Number of trees per unit area for a 20 m buffer (Vich et al., 2019)
Presence of trees – 7 studies	
Physical presence of trees	- (Kweon et al., 2021)
Physical presence of vegetated tree pits	- (Nawrath et al., 2019)
Perceived presence of trees	- (Coleman et al., 2021; Hong et al., 2018; Lee, H. S. & Park, 2015; Ozbil et al., 2021; Takano et al., 2002)
Parks – 1 study	
Percentage of the area covered by parks	- 20 m buffer surrounding the road (Vich et al., 2019).

3.1.1.2 Green infrastructure

GI can take many forms and it can be difficult to analyze a specific type of infrastructure with regards to active mobility. Some types of GI such as street trees, green walls or vegetated curbs are part of the road landscape and can influence daily travelling. Each type of infrastructure, through its diverse characteristics (functions, location, footprint in the urban landscape, etc.), can influence people's perceptions and mobility behaviour differently. As a result, the indicators used to represent GI vary significantly across studies. The most common studied infrastructure are street trees. As mentioned in section 3, we only included studies on GI visible from the right-of-way. We have included one study investigating the effects of parks on walking time since this study measured the area of parks within a buffer from the road (Vich et al., 2019).

There are two principal sources of data for street trees (in studies looking at the influence of GI on active mobility): number of trees and tree canopy, which refers to the ground projection of the crown of trees including leaves, branches, and stems visible from the sky. The selection of the indicator (either road buffer or circular buffer around a location) and the distance considered vary widely (Akinici et al., 2021; Botes & Zanni, 2021; Chen, P. et al., 2018; Harvey & Aultman-Hall, 2015; Harvey et al., 2015; Kim, D., 2019; Sarkar et al., 2015; Tsai et al., 2019; Vich et al., 2019). Harvey & Aultman-Hall (2015) used a method only considering trees in front of the buildings to better capture the streetscape space that would be visible by a street-level user. This technique points out that using an invariable buffer size may lead to mistakes both in considering trees that pedestrians cannot see and in failing to consider some visible trees. As shown in Table 2, other studies have measured perceived presence of street trees (Coleman et al., 2021; Hong et al., 2018; Lee, H. S. & Park, 2015; Ozbil et al., 2021; Takano et al., 2002) or compared scenarios with different configurations of streets sometimes including trees (Kweon et al., 2021; Nawrath et al., 2019). The results obtained with different indicators vary and point to the need to understand which indicator is suitable for a particular purpose.

Some studies attempted to measure other GI such as ground vegetation (herbaceous, low-landscaping and flowers) (Botes & Zanni, 2021; Tsai et al., 2019; Vich et al., 2019). Tsai et al. (2019) analyzed the effect of herbaceous cover and aggregate greenery on active transportation for the road focal area (25 m each side of the centreline) and the circular buffer around home. The authors defined herbaceous cover as herbaceous and emergent wetlands, and aggregate greenery

as trees, herbaceous, woody wetlands, and emergent wetlands. Their analysis showed that an increased density of herbaceous cover reduced the odds of participating in active transportation at least once a week. The aggregate greenery variable was only significant for a circular buffer around home, and an increased density of aggregate greenery was associated with higher odds of participating in active transportation. Since the buffer considered for the herbaceous cover was 50 m wide, this indicator does not specifically assess the infrastructure implemented in the right-of-way, which may have differentiated impacts. For example, planted strips or vegetated curb extension implemented in the right-of-way may modify the configuration of the street by reducing the space allocated to cars and isolating pedestrians from motor vehicles. On the contrary, the presence of herbaceous cover in the backyard of a residence is not visible to a pedestrian.

Many studies used questionnaires with small samples to evaluate the effect of specific interventions (Botes & Zanni, 2021; Nawrath et al., 2019; Piselli et al., 2018). This method allows comparing different interventions including one or more types of GI, and specifically examining individuals' perceptions with respect to these urban landscapes. Conducting studies with questionnaires appears to be relevant to examine how specific GI designs relate to individuals' perceptions and behaviour. In comparison, large-scale data, often focusing on general green features (e.g., tree canopy or global vegetation index) is limited in comprehensively capturing all features of GI that together can impact active mobility. However, conducting questionnaires for a specific intervention can be time-consuming and is often limited to small samples and small study areas due to the scale of the intervention. It can be challenging to extrapolate the results of these studies to different urban contexts.

3.1.2 Effects of GI on behaviours and perceptions during active travel

We now examine the findings on the relationship between the indicators of green features and GI, and active mobility. The indicators are divided between global vegetation indices and green infrastructure as above. Table 3 shows the measured outcomes of global vegetation indices (GVI, NDVI and green walkability) and GI (street trees and parks) on active travel, walking, and cycling. Studies analysing preferences among various types of GI are not included in Table 3 and are discussed later. All the studies on the GVI are located in East Asia, whereas other studies are located across Europe and East Asia.

Table 3 Measured outcomes of green features on active mobility

Green feature	Country	N	Distance, time or frequency of			Probability of choosing the mode			Satisfaction while			Physical activity
			AT	W	C	AT	W	C	AT	W	C	
Global vegetation indices												
GVI												
Ki and Lee, 2021	South Korea	2350		+								
Lu et al., 2019	China	5701						+				
Lu et al., 2018	China	90,445 (6770 ¹)		+				+				
Ta et al., 2021	China	213 (912 ²)							+	+	0	
Wang et al., 2020	China	167			+							
Wu et al., 2020	China	594 (6487 ²)		+/-	+/-	+/-						
Yang et al., 2019	China	10,700 (1083 ¹)		+				+				
NDVI												
Sarkar et al., 2015	England	15,354 (8610 ¹)		+				0				
Other indicator												
Roscoe et al., 2022	England	57,726 (12,986 ³)				+						+
Indicator not mentioned												
Jiao et al., 2022	South Korea	(12,200 ²)			+							
Green infrastructure												
Street trees												
Akinci et al., 2021	Spain	103 (686 ⁴)										0/-
Ki and Lee, 2021	South Korea	2350		0								
Lee and Park, 2015	South Korea	437				+/0						
Nawrath et al., 2019	Germany	1404			+							
Ozbil et al., 2021	Turkey	749						+/0				
Sarkar et al., 2015	England	15,354 (8610 ¹)		+				+				
Vich et al., 2019	Spain	127 (772 ²)		+								
Parks												
Vich et al., 2019	Spain	127 (772 ²)		+								

N : the number of participants, AT : Active travel, W : Walking, C : Cycling.

+ indicates an increase, - indicates a decrease and 0 means no effect.

¹ Number of participants who walked. ² Number of trips. ³ Number of observations with accelerometer information.

⁴ Number of days with data.

3.1.2.1 Global vegetation indices

Many of the reviewed studies have found a positive relationship between active travel and global vegetation indices. Several studies found that the GVI (a measure of eye-level greenness) was positively associated with an increase in walking (Ki & Lee, 2021; Lu et al., 2018; Yang et al., 2019) and cycling activities (Lu et al., 2019; Wang et al., 2020). Ta et al. (2021) found that higher GVI values significantly increase people's satisfaction with active travel (walking, biking, and electric biking). However, when they performed models for individual modes (walking or biking), they only found a significant result for walking. Wu, Jiayu et al. (2020) showed that an increase in the GVI is only associated with an increase in distances travelled (for cycling and walking) for small roads with low traffic. Overall, the literature indicates that GVI has a positive effect on active travel, although more research studying itineraries and built environment characteristics is needed to understand how the effects of green features and GI vary based on street designs and characteristics in which they are implemented.

Regarding other indicators, Sarkar et al. (2015) found that higher values of the NDVI (an overhead measure of greenness) were associated with longer distances travelled, whereas there was no significant relationship between NDVI and the odds of walking. By dividing the vegetation in two levels (vegetation below and vegetation equal or above 2.5 m from the ground), Roscoe et al. (2022) found that the vegetation equal or above 2.5 m (i.e., tree cover) had the highest positive effects on physical activity. Again, these findings illustrate the need for more nuances in the examination of the relationship between GI and active mobility. Specifically, future research would be required to further understand the different impacts of various types of vegetation on active mobility, such as GSI.

3.1.2.2 Green infrastructure

Almost all the quantitative studies studying the effects of GI on active travel analyzed street trees. As shown in Table 3, street trees showed a positive influence on walking activities (Lee, H. S. & Park, 2015; Sarkar et al., 2015; Vich et al., 2019). Interestingly, Ki & Lee (2021) found no significant effect between the number of street trees and walking time when controlling for the GVI. Ozbil et al. (2021) found that children in Istanbul were more likely to walk to/from school when there were shade-casting trees along the roads, according to parents' perceptions. Qualitative analysis conducted in England has revealed that trees were valued in terms of the environmental benefits they can provide such as heat island effect, pollution or carbon sequestration, and providing habitat for wildlife (Coles et al., 2013). People with motor disabilities mentioned that street trees can stimulate physical activity by increasing pedestrians' comfort and safety, improve aesthetics, and increase people's well-being despite possible disservices they may cause (tiles bulging, falling branches, allergies, etc.) (Wojnowska-Heciak et al., 2022).

Several studies compared different types of GI or different levels of greenery. A study using different green streetscapes showed that cyclists were more inclined to cycle on a greener street, and leisure riders would even change their route for a greener one (Nawrath et al., 2019). This result suggests that green streets may be more important for leisure cycling activities (Nawrath et al., 2019). Moreover, it has been shown that increasing overall greenery and combining different mitigation strategies, such as cool pavements, vegetation, and photovoltaic trees can increase pedestrian's perception, comfort, and tolerability of thermal conditions, air pollution, and noise pollution (Piselli et al., 2018). Botes & Zanni (2021) found that people preferred street designs with

ground cover vegetation, whereas street trees and flowers were not significant in most models. Finally, Vich et al. (2019) found a positive association between the presence of large parks along the road and increased time spent walking.

As shown in Table 3, most of the results showed a positive or non-significant relation between GI and active travel. Non-significant results may be due to multicollinearity when several variables representing a green feature are included in the same model or because of differences across socio-demographic groups. Overall, there seems to be a positive effect of GI on walking and cycling activities. However, these findings draw some distinctions between the effects of GI on walking and cycling, the different types of green features, and the built environment in which they are implemented. Since there are fewer studies on cycling, there is less evidence of the effects of green features on cycling activities.

3.1.3 Influence of socio-demographic and contextual factors in the relationship between GI and active travel

Heterogeneity is observed in the relationship between GI and active travel, namely with respect to socio-economic groups and environmental contexts. Wu, Jiayu et al. (2022) found that men are exposed to more greenness (assessed with the GVI) than women when considering the total exposure during a specific period. However, for the same distance travelled, women were likely to be exposed to more greenness than men. Dipeolu et al. (2020) found that the visiting purposes of GI varied based on household size and rank-in-job (a proxy of income level).

Regarding environmental contexts, a study on elderly women conducted in South Korea showed that determinants of walking vary between rural and urban women (Lee, H. S. & Park, 2015). Results showed that proximity to parks and street trees were significantly associated with higher odds of attaining the recommended level of walking for rural women. In addition to these differences across urban or rural areas, some places can have particularities that influence people. For example, Chang (2020) found that adults in Taiwan living near a greenway with more water features engaged less frequently in outdoors activities. The authors mentioned that this result could be caused by the risk of contracting dengue virus via mosquitoes present near water features. Overall, these results raise the importance of understanding the socio-economic and environmental contexts around the implementation of GI to adequately interpret the potential interplay between GI and active mobility.

3.1.4 Effects of GI on safety and health

In addition to the behaviours and perceptions related to walking and cycling, the literature search also yielded studies on topics closely related to active travel. Ten studies investigated how GI can improve safety and five studies analyzed the benefits of active mobility on physical and mental health in relation to GI. These topics are discussed below as they are intimately linked to the understanding of the benefits of GI and GSI on active mobility.

Several studies investigated the effects of landscape designs on road safety. In the past, trees have been considered a roadside hazard because they would reduce drivers' visibility. Chen, H. et al. (2016) demonstrated that trees that meet a certain standard do not increase the risk of collisions as opposed to trees that do not meet the standard. Furthermore, studies have found that street trees were associated with a lower risk of collisions involving pedestrians (Zhu et al., 2022), including elderly pedestrians (Kim, D., 2019), a decrease in severe crashes (Harvey & Aultman-Hall, 2015), and a decrease in elderly pedestrian fall incidents (Lee, S. et al., 2022). Harvey & Aultman-Hall (2015) suggested that more enclosed, human-scale streetscapes with trees, which reduce drivers' field of vision, can encourage responsible driver behaviour such as driving at slower speeds. The hypothesis that street trees are associated with slower driving speeds has been validated in a pilot study using a driving simulation environment with different landscape designs (Naderi et al., 2008).

Other studies have shown that street trees and buffer landscape can increase perceived safety (Harvey et al., 2015; Kweon et al., 2021; Landis et al., 2001). In some studies, pedestrians were perceiving higher safety and comfort when the lateral separation between the sidewalk and the motor vehicle was larger (Kweon et al., 2021; Landis et al., 2001). Conversely, Coleman et al. (2021) did not find that street trees had a strong significant effect on the safety perception of pedestrians. However, the qualitative analysis of respondents' comments related to street trees revealed that a clear majority had positive feelings toward them regarding aesthetics, shading, cooling, air quality, and other benefits. Using a different approach, Hong et al. (2018) analyzed interaction effects between green spaces and pedestrian safety. They found that within a safe neighbourhood for pedestrians, an increased number of street trees was associated with a higher level of social cohesion (Hong et al., 2018).

Some studies focused on the physical and mental health benefits of GI in relation to active mobility or physical activity. Studies found that higher density of vegetation (Liu et al., 2019) and walking

on green streets (Roe et al., 2020) were associated with higher mental well-being. Green scenery and trees have been associated to a decrease in the heart rate of runners (Paraskevopoulou et al., 2022). Li & Ghosh (2018) found mixed results by studying the effects of the mean GVI at census tract level on the mean body mass index. Higher neighbourhood vegetation density was significantly associated with lower mean body mass index only for certain groups based on age and gender. Takano et al. (2002) found that walkable green spaces such as parks and tree-lined streets were positively influencing longevity of senior citizens in dense urban areas. Overall, these studies point toward the fact that GI can promote active travel by providing safe environments for pedestrians (especially for the elderly) and cyclists. Since the terms used in the search strategy did not directly assess physical and psychological health, these results are limited. However, they still point to a relation between GI and people's physical and psychological health and need to be further investigated.

3.2 Studies on green stormwater infrastructure

So far, most studies analyzed do not distinguish between GI and GSI. This section examines the studies that explicitly analyze GSI. These studies consist of conceptual frameworks (9 studies), qualitative and quantitative studies (12), and examples of specific projects (7). The conceptual frameworks discuss general concepts of urban planning that bring active mobility and GSI together. The qualitative and quantitative studies analyzed the effects of GSI on the perceptions of a specific group by conducting surveys, interviews or focus groups. Unlike the studies on GI discussed in Section 3.2, the main focus of these studies is not active mobility. The examples of projects are studies describing and discussing projects that have implemented GSI, and some authors support their ideas with quantitative measures such as vehicle speeds or collisions. By analyzing these studies, including several qualitative studies, we aim to understand how the potential synergy between GSI and active mobility is addressed in the literature and identify potential co-benefits and barriers.

3.2.1 Conceptual frameworks

Within the selected articles, we identified few studies conceptually discussing how GSI can be implemented and the potential benefits it can provide, including supporting active mobility. In general, these studies focus mainly on the benefits in terms of stormwater management (e.g., reducing runoffs and peak flows) (Condon & Isaac, 2003; Engel-Yan et al., 2005; Low et al., 2008;

Moretti & Loprencipe, 2018; Rayan et al., 2022; Rybicki et al., 2022; Wen et al., 2022). Nonetheless, many studies highlighted the necessity to build multifunctional streets and open spaces to optimize the space (Artmann et al., 2019; Condon & Isaac, 2003; Engel-Yan et al., 2005; Moretti & Loprencipe, 2018), often considering the mobility function of the streets/spaces. For example, Condon & Isaac (2003) studied the East Clayton green infrastructure plan in British Columbia, Canada. This plan focused on stormwater management, active mobility and lowered infrastructure costs. In addition to the benefits of trees on moderating hydrologic fluctuations and shading the street, they mentioned that open spaces and parks can be used to implement naturalized wetland and overflow ponds, which can make parks more attractive and support recreational walking. Along riparian areas, they recommended implementing greenways and riparian parkways to provide a multi-use transportation corridor that can play an important role in water management and provide a safe environment for cyclists and pedestrians. The benefits emphasized in the plan suggested that a project that aimed at densifying and diversifying services, and setting up green streets to encourage active travel should reduce the modal share of motorized travel by offering an interesting alternative (Condon & Isaac, 2003). Along the same line, some studies raised the importance of understanding the interactions between infrastructure systems (for water, transportation, and buildings) to design sustainable neighbourhoods (Engel-Yan et al., 2005; Rybicki et al., 2022). For instance, Engel-Yan et al. (2005) emphasized that trees can intercept rainfall (i.e., reduce stormwater runoff), create sidewalk shading, act as a barrier to traffic noise, and provide shade and wind barriers for buildings. Another study emphasized that GSI can reduce the risk of flooding, which can compromise the safety of road users, especially pedestrians (Moretti & Loprencipe, 2018).

In line with these studies, Ferguson (2012) proposed a conceptual framework to assess the multiple functions of a street. The author mentioned that different elements in the street are interacting and can be designed to enhance the functions of other features. Ferguson (2011) discussed the spatial allocation of GI and GSI in order to enable human and environmental functions. The framework highlights that it is necessary to understand how different zones (e.g., the pedestrian through zone, the furnishing zone between pedestrian path and the curb, the moving zones for vehicles, etc.) relate to each other and what the activities are within each zone. Then, it is possible to take advantage of the multiple potential roles of the street by implementing new infrastructure such as GSI to meet nature and human goals. For instance, the pedestrian through zone should enable pedestrians to

move without obstacles, whereas the furnishing zone must meet several needs, such as space for transit stop, bike storage, access to parked cars, seating, GSI (Ferguson, 2012). These elements should be designed to ensure all human and environmental functions are met. The Green Axes, an ongoing project in Barcelona, Spain, has been described as an example of multifunctional streets that aim to facilitate active travel, create human spaces, maximize greening, and improve natural drainage (Magrinyà et al., 2023). The interconnected streets were designed to prioritize active modes over motorized modes and allow social use of the space by creating square gardens at the intersection of the green axes. The design provides a continuous structural soil suitable for plant growth and a sustainable drainage system that maximises on-site infiltration (Magrinyà et al., 2023). Overall, the frameworks, although mostly focusing on sustainable stormwater management, consider the potential benefits on mobility through multifunctional streets and reallocation of space.

3.2.2 Qualitative and quantitative studies

The literature search revealed a few case studies that looked into perceptions and behaviours related to the implementation of GSI (6 studies), preferences across different types of GI and GSI (5 studies), and affordance of GSI for children (1 study). Table 4 summarizes the 12 case studies by providing the sample, the main goal of the study, and the co-benefits and barriers to implementation. As in the previous section, the review of the studies revealed that the main objective behind the implementation of GSI was to improve stormwater management (e.g. Hérivaux & Coent (2021) and Mottaghi et al. (2021)), whereas active mobility was considered a side benefit. In this section, we focus on the potential co-benefits and barriers of the implementation of GSI related to active mobility found in the qualitative and quantitative studies reviewed. These are: improved aesthetics, increased attractiveness of the street for walking and cycling, allocated space for walking and cycling, creation of recreational opportunities for children, and increased safety.

Regarding mobility, several concerns were related to cars. These include GSI making it more difficult to access certain places by car from the perspective of drivers (Seymour et al., 2010), increasing traffic congestion levels (Ferreira et al., 2021) or reducing parking spaces (Everett et al., 2015). Hérivaux & Coent (2021) highlighted that implementing an ambitious nature-based solutions (NBS) policy by reducing the place for cars can be a source of inequality for people living

further from the city centre and having no alternative to the car. Conversely, people living near the city centre have more concerns about air quality and temperature regulation. With respect to active mobility, Seymour et al. (2010) found that bioswales, native vegetation, and walking paths could improve the attractiveness of active travel. Fischer & Gopal (2021) found that people were willing to change their walking or cycling route to use green street corridors.

However, some concerns were mentioned about safety and aesthetics of bioswales. Everett et al. (2015) found that people appreciated the function of the bioswale, but complained about plant choices, waste in the bioswales and, in general, aesthetics. However, Suppakittpaisarn et al. (2020) found no relation between perceived messiness of the bioswales and overall preferences for a specific type of GSI. People are worried that tall vegetation in bioswales might obstruct drivers' sight, which could compromise pedestrians' safety (Everett et al., 2015). Similarly, it has been shown that cyclists prefer a dense tree canopy cover while limiting the height of shrubs to ensure good visibility (Shan et al., 2022).

Regarding preferences between types of GI and GSI, trees were the most preferred (Ferreira et al., 2021; Fischer & Gopal, 2021; Suppakittpaisarn et al., 2020), whereas Suppakittpaisarn, Larsen, et al. (2019) found that flowers were the most preferred, followed by street trees and well-maintained bioretention cells. A combination of multiple features such as trees, bushes, and low landscaping was also associated with a high level of preference (Fischer & Gopal, 2021; Jakstis et al., 2023). These findings illustrate the various factors that come into play when designing a GSI, beyond the level of vegetation.

Although some of the reviewed studies revealed that some people are aware of the GSI benefits such as shading and cooling effects as well as stormwater management (Seymour et al., 2010), other studies found that respondents were not aware of the main benefits of GSI such as stormwater management and filtration of pollutants (Everett et al., 2015). Shandas (2015) compared the perceptions of GSI from people living in different neighbourhoods and having received different levels of education materials about GSI. The results showed that people who received high levels of outreach and education materials on the project were more likely to be positive towards the implementation of GSI (Shandas, 2015). Moreover, stakeholders' low awareness and insufficient

Table 4 Qualitative and quantitative studies analyzing the effects of green stormwater infrastructure

Study (locality)	Sample	Goal	Results – Potential co-benefits and barriers of implementing GSI
Seymour et al., 2010 (Los Angeles, US)	Five focus groups with 39 participants living near alleys. The study areas were dealing with issues of flooding, safety or trash pollution, and had poor park conditions. One alley had already been turned into a green alley.	Investigate perceptions of green alley projects in low-income residential neighbourhoods following the creation of a Green Alleys Program that aims to reduce runoff and increase active mobility and safety.	Mobility: Participants were concerned about maintaining access for vehicles in the alley. The authors mentioned that bioswales, native vegetation, and walking paths in the alleys can promote active living. Preferences: Participants indicated that the design of green alleys should prioritize utility, safety, cleanliness, and recreational opportunities for children. They were responsive to the idea of adding GSI. Awareness: The participants mentioned some benefits such as shading, cooling effect, aesthetics, room to sit, room for walking or cycling, limiting puddles and standing water, and stormwater infiltration.
Adkins et al., 2012 (Portland, US)	Survey among 748 people. One study area with “deluxe” green street facilities (planted basins with attractive plants and some trees), one with “basic” green street facilities (standard lawn-covered planting strips with trees), and two control areas.	Understand how two different types of green streets influence the attractiveness of walking. The measure of attractiveness was obtained by asking respondents to identify on a map on which segment they like to walk.	Mobility: The “deluxe” green streets were more attractive for walking than normal streets. However, the “basic” green streets were not significantly better than normal streets. The presence of an adjacent park to the street also significantly increased the attractiveness of walking. Separation of the sidewalks from the street by sidewalk setbacks or on-street parking also significantly increased the attractiveness of walking, but at a lower level than “deluxe” green streets and parks.
Shandas, 2015 (Portland, US)	A survey in 2009 (650 responses) and a follow-up survey in 2011 (132 responses). The study site includes six neighbourhoods where the city planned or had undergone construction of GSI and two control neighbourhoods.	Understand how the implementation of GSI (in the right-of-way) affects perceptions of neighbourhood quality and services and if demographic factors increase the likelihood of adopting stewardship behaviours to maintain the GSI.	Awareness and acceptability: Results suggested that people who received higher levels of outreach and education in the program are more likely to accept the implementation of new green facilities. Stewardship: People who rated their neighbourhood with higher average scores were more likely of stewarding a public stormwater facility. In the two neighbourhoods where facilities were installed, fewer people were interested in stewardship. There were differences in the variables that influence the likelihood of adopting stewardship behaviours when analyzing income groups. Being older was associated with a lower interest in stewardship.
Everett et al., 2015 (Portland, US)	Interviews with 45 residents living in a residential neighbourhood with bioswales in the right-of-way.	Understand attitudes, perceptions, and behaviours of people living near bioswales.	Mobility: Few respondents complained about losing parking spaces. Safety: Residents mentioned that people can fall into the bioswale, and tall vegetation can obstruct drivers’ sight. Aesthetics: Many complains were about mess and littering as many respondents found that there is a lot of waste in the bioswales. Some residents thought the bioswales were not well-maintained and some would like to change the plants or have the possibility of maintaining them themselves. People generally appreciated trees in the bioswale, but a small minority of people disliked them. Biodiversity: Some respondents complained about having more insects. Awareness and acceptability: Some respondents were not aware of benefits for floods and did not understand how bioswales can filter pollutants. Along with people who were happy with the bioswales, people environmentally engaged were more positive than others.

Table 4 Case studies analyzing the effects of green stormwater infrastructure (continued)

Study (locality)	Sample	Goal	Results – Potential co-benefits and barriers of implementing GSI
Mottaghi et al., 2021 (Malmö, Sweden)	Survey among 328 households near a park and observations of children's behaviour in the park.	Analyze the affordance of GSI (ponds, bioswale and paved canals connected to a large sunken lawn) installed in a park for younger children (3-6 years) and middle-aged children (7-10 years).	GSI preferences: People living with children used the sunken lawn more frequently than other GSI. Potential activities: The classification of the affordance of the GSI showed that there are meaningful action possibilities in the GSI for the children such as running, cycling or walking in the sunken lawn when it is dry, hiding in the vegetation, and using bio-waste such as woody debris as tools or treasures. Parental influence: Observations of children's behaviour and the different paths taken has shown that children's behaviour depends on their parents' use of space and on the time spent in the park.
Suppakittpaisarn et al., 2020 (photographs from US cities / 390 participants from US and Canada, and 37 not specified or from elsewhere)	Survey among 427 participants. It consists of 54 images based on six photographs of US cities. Using three levels of tree densities and three levels of bioretention planting densities, each photograph was manipulated to create nine different street configurations.	Analyze people's preferences of different GI by investigating perceived naturalness, safety and messiness of images showing different configurations of streets with different levels of tree density and bioretention density.	GI preferences: Respondents preferred, in order, the landscapes with many trees, few trees and no trees. They preferred landscapes with a lot of bioretentions to no bioretention. However, the difference between no or a little bioretention and little or a lot of bioretention was not significant. Naturalness, safety, and messiness: Results showed that as tree density increases from no tree to few trees to many trees, the perceived naturalness and safety scores also increased. There was no significant relation for perceived messiness. For bioretentions, the difference was significant only between no bioretention and a lot of bioretention. For an increase from no bioretention to a lot of bioretention, there was a small increase in perceived naturalness, safety, and messiness. However, the authors analyzed to what extent the perceived naturalness, safety and messiness can predict the preference. They found that only perceived naturalness and perceived safety were related to preference.
Suppakittpaisarn, Jiang, et al., 2019 (photographs from US cities / participants mostly from US)	Three surveys among 1473 participants. The responses analyzed are preference scores for 145 photographs with GI.	Evaluate preferences of different densities of vegetation for trees, understory, bioretentions and overall vegetation.	Preferences: A higher density of vegetation, either for total vegetation, trees, understory and bioretentions, was significantly associated with a higher preference. The study found that the combination of different types of vegetation was not affecting the relationship between preference and density of vegetation. For overall vegetation, trees and understory, the relation between density of vegetation and preference can be described by a power curve (at low levels of density, an increase of density leads to a high increase of preference, and then the increase in preference gradually attenuates for the same increase in density). The nature of the relationship could not be clearly defined for bioretention.
Suppakittpaisarn, Larsen, et al., 2019 (photographs from US cities / mostly from US)	Survey conducted among 497 laypeople and 117 designers. Analysis of preferences of 55 photographs showing GI, GSI, and barren urban landscape.	Evaluate preferences of different GI and GSI (messy bioretentions, neat bioretentions, lawns and retention ponds, green roofs, street trees, and flowers).	GI preferences: Landscapes with GSI are significantly preferred to landscapes with no GSI. Among all the studied GI and GSI, the preferred types were, in order of preference, flowers, trees, neat bioretentions, green roofs, lawns and retention ponds, messy bioretentions, and the barren category. Overall, the preferences were similar among laypeople and designers. However a t-statistic test revealed a small significant difference for messy and neat bioretention, lawns, and green roofs as designers showed stronger preference for green roofs and neat or messy bioretentions.

Table 4 Case studies analyzing the effects of green stormwater infrastructure (continued)

Study (locality)	Sample	Goal	Results – Potential co-benefits and barriers of implementing GSI
Ferreira et al., 2021 (Elvas and Faro cities, Portugal)	Survey conducted through 75 institutional stakeholders from two Portuguese cities (31 from Elvas and 44 from Faro).	Understand stakeholders' perceptions on implementing nature-based solutions (NBS), and understand what determines the respondents' perceptions of urban challenges, priority interventions, proposed NBSs, and potential benefits.	Mobility: The study showed a relationship between stakeholders who consider improving mobility as a priority and those who are concerned with high traffic levels and value cycle-pedestrian green paths. Health and air pollution: Air pollution, a main concern, was associated with concerns about heavy traffic. While stakeholders generally indicated that NBS provide health benefits, they also indicated that the benefits on air purification would be offset by increased traffic congestion due to an increase in green spaces. Conversely, cycle-pedestrians' green paths were associated with better health conditions. NBS preferences: Implementing urban trees was the most preferred NBS and there was a correlation between people preferring urban trees among other NBS and prioritization of having space for leisure and sports. Creating green shaded areas and riverbank rehabilitation were also highly valued.
Fischer & Gopal, 2021 (39 countries)	Survey conducted among 428 people from 39 countries.	Investigate how people have used green street corridors during COVID-19 partial and complete lockdowns.	Mobility: Participants were mostly willing to change their walking or cycling route to use green streets. GI preferences: When asked which type of GI they preferred between street trees, low landscaping (grasses, perennials, and wildflowers), both trees and low-landscaping, green walls/facades, water retention basins/rain gardens or other types, participants indicated preferring street trees with low-landscaping (72%) and street trees alone (15%).
Herivaux et al., 2021 (Lez Catchment, France)	Survey conducted among 400 households to understand preferences for different GI or GSI implementation.	Analyze people's perceptions of ecosystem benefits and negative effects provided by different levels of NBS.	Awareness and acceptability: Co-benefits commonly cited concerned landscape conservation, air quality, climate change mitigation, local temperature, and biodiversity. Overall, the average number of negative effects was much lower than the number of ecosystem services mentioned. Mobility: The most cited disadvantage regarding NBS concerned mobility issues, especially car travel.
Jakstis et al., 2022 (15 European countries)	Survey conducted among 584 European residents.	Analyze preferences for different green and water features. Investigate greenspace visit frequency and outdoor recreation frequency before and during the pandemic.	GI preferences: Among (1) Trees and bushes, (2) Low landscaping, (3) a combination of trees, bushes, and low landscaping, (4) natural habitat, and (5) none of the above, a combination of trees was preferred (3). Among (1) permanent lake or pond, (2) temporary water retention area, (3) natural or constructed wetland, (4) stream or river, and (5) none of the above, scenarios (1) and (4) were preferred. Mobility: Dominant type of neighbourhood greenspace (private, public or mix) and respondents' access to urban greenspace during the pandemic were significantly related to respondent's greenspace visit and outdoor recreation behaviour.

knowledge about the benefits and challenges of implementing NBS, such as GSI, can explain the mixed results found by Ferreira et al. (2021). Indeed, stakeholders indicated that NBS such as cycle-pedestrians' green paths can provide health benefits. However, they also mentioned that the implementation of green spaces would increase traffic congestion and offset the benefits on air purification initially provided by the NBS. These findings suggest that the benefits of GSI are not yet well understood by citizens and stakeholders. This can influence perceptions and, in turn, active mobility outcomes.

The studies also mentioned outcomes related to stewardship, biodiversity, and potential benefits for children, as shown in Table 4. The studies demonstrate that a particular attention needs to be paid to children, considering that in urban settings, GSI often occupy open spaces that could otherwise serve as playgrounds (Mottaghi et al., 2021). Mottaghi et al. (2021) raised the fact that to better meet the needs of children, it is necessary to understand the social and spatial aspects of children's behaviours. The analysis of focus groups conducted by Seymour et al. (2010) also highlighted that green alleys should prioritize the addition of recreational opportunities for children.

3.2.3 Examples of projects around the world – Identification of potential outcomes

In this section, we discuss seven studies identified in the article selection process that described a total of 22 GSI projects. These studies, summarized in Table 5, consisted mainly of thorough descriptions of projects, together with a discussion of potential outcomes. While the studies presented in the previous section are based on a comprehensive methodological framework to analyze the outcomes of GSI, the focus here lies on the description and discussion of the projects. Some authors support their ideas with quantitative data, such as vehicle speeds or crash rate analysis. These studies revealed that the goals of the projects were related to stormwater management, road safety, active mobility, and the development of high-density neighbourhoods. We focus here on the aspects related to road safety and active mobility.

First, the studies suggested that the implementation of GSI has the potential to increase safety by reducing the width of the road and serving as a traffic calming measure (Clemente, 2020; Greenberg, 2008; Polanski, 2015; Valente et al., 2021). Following the implementation of GSI in the right-of-way in projects in the United States, Polanski (2015) observed a reduction of traffic

Table 5 Examples of projects that implemented green stormwater infrastructure

Study	Description of the project	GSI implemented	Potential outcomes related to mobility
Greenberg (2008)	Ten projects in the United States and Canada: investigating the potential of sustainable projects to bring common benefits related to improvements of movement, ecology, and community concerns.	Infiltration basins and landscaped curb extensions, bioswales, rain gardens, street trees, permeable centre medians, permeable paving, and gravel storage trenches under the permeable paving.	- Improving pedestrian safety by reducing the width of the streets to be crossed, creating shelters in the centre of streets, or adding a physical separation between pedestrians and motor vehicles. - Reduction of vehicle speeds following the reallocation of spaces from motorized vehicles to GSI and active paths.
Girling (2010)	UniverCity, Vancouver, Canada: building a high-density neighbourhood while protecting downstream salmon habitat.	On parcel detention and infiltration, green streets with a variety of GSI, and large-scale detention and infiltration facilities such as ponds within green spaces.	- Reducing the impervious areas of the road network (i.e., reducing the space allocated to motorized vehicles). - The project aims to build a high-density neighbourhood with connected pedestrian and cycling networks and offering transportation choices.
Polanski (2015)	Three projects in the United States: improving stormwater management, securing the street and reallocating the spaces between all users. For all projects, a portion of the space allocated to motor vehicles was reallocated to pedestrians and GSI.	GSI were all implemented on the right-of-way. They include a channel creek as a centre median, street trees, vegetated tree pits, vegetated curbs at intersections, and vegetated chicanes.	- Most of the GSI implemented can serve as traffic calming measures. Reducing the width of the street and adding chicanes can reduce vehicle's speed. - Vegetated curbs at intersections reduce the crossing distance for pedestrians. - Street trees along the sidewalk and in the median centre reduce the optical width of the roadway. - Increasing the space allocated for pedestrians and cyclists.
Shafraay & Kim (2017)	Three walkable urban projects in Seoul, South Korea: the Cheonggyecheon project is a pedestrian walkway of 5.8 km along a water stream that was previously covered by a highway. The Seoulo project is a pedestrian walkway of 983 m with green elements. The Yongdu Park is a pocket park.	Cheonggyecheon project: increase in plant species from 68 to 308 and implementation of waterfalls and fountains. Seoulo project: 684 circular planters and 23,195 trees (215 types/50 families). Yongdu Park: small green space.	- Improving the aesthetic quality of the landscape. - The Seoulo project has improved the connectivity of the pedestrian network by converting a highway to a pedestrian path. - The Cheonggyecheon project contributed to increasing public transit ridership. - The Yongdu Park meets the needs of residents and has the potential to improve landscape design and social interactions.
Clemente (2020)	Cycle networks integrating stormwater management developed in Boston, San Francisco, Zwolle and Copenhagen to prevent roads from flooding when underground drainage networks are saturated.	Boston: permeable pavement, rain garden channels between the street and the path, and tree trenches between the sidewalk and the bicycle path. San Francisco: a raised bicycle path that allows water to be dispersed into a backfill. Zwolle: a bicycle path with a hedge alongside and trees. Copenhagen: a bicycle path with a drainage system underneath.	- Moderating traffic by reducing road widths. - Implementing bicycle paths. - Trees that cover the bicycle path can create shade. - Increasing the safety and attractiveness of cycling paths.
Samuel et al. (2021)	Africa Avenue/Bole Street, Addis Ababa, Ethiopia: reconstruction of an arterial road with a higher width and addition of GI.	GI and GSI were implemented along the arterial road. The authors mentioned bioswales, planter boxes and trees.	The study suggests that developing projects that aim to maximize GI and GSI benefits can lead to more sustainable transport.
Valente et al. (2021)	The State Road 7 bis, Campania, Italy: restructuring the road by adding bicycle and pedestrian paths and implementing GSI to increase safety and mitigate flooding.	Street trees, tree pits, tree trenches, planters, swales, bioretention, green spaces and permeable paving.	- Improving comfort of cyclists and pedestrians by creating shading areas and reducing heat islands. - Some configurations allow cyclists to be isolated from vehicular traffic, which greatly improves the safety of cyclists. - For narrow streets, the proximity of buildings generally provides enough shade for pedestrians and cyclists. Smaller infrastructure such as permeable paving, tall trees, planters, and swales can be implemented.

speed in one project, and anecdotal observations supporting the reduction of speeds for two projects. Conversely, Samuel et al. (2021) observed an increase in pedestrian collisions after the reconstruction of an arterial road in Addis Ababa, Ethiopia, where they implemented GI and GSI, but also increased the width of the road.

Some studies suggested that the development of sustainable neighbourhoods with GSI can improve active mobility. Girling (2010) mentioned that the design of a high-density neighbourhood with green streets can improve the connectivity of the pedestrian and cycling networks. The implementation of GSI is also associated with the potential of reallocating space for active mobility (Clemente, 2020; Polanski, 2015; Shafray & Kim, 2017). For example, the Cheonggyecheon project and the Seoulo project in Seoul, South Korea, described by Shafray & Kim (2017) consisted in converting a space for cars, namely two highways, into pedestrian pathways with GI and GSI. These two projects were also studied by Kim, U. et al. (2021) who conducted a survey among pedestrians to understand their satisfaction and their perception of air quality when walking on those greenways compared to walking on a sidewalk path parallel to each greenway. Results showed that respondents who walked through a greenway had a better perception of air quality compared to sidewalk users for both projects. Pedestrians on the Seoulo greenway also reported higher satisfaction than sidewalk users, whereas the results were not significant for the Cheonggyecheon project. The studies by Shafray & Kim (2017) and Kim, U. et al. (2021) were included in our analysis because they address the synergy between water management and active mobility. Specifically, the authors describe the infrastructure as nature-based solutions with objectives encompassing water cleaning and flood prevention. These studies place significant emphasis on walkability aspects and provide examples of street redesigns that promote active transportation. However, most of the green features implemented could be described as GI rather than GSI. Additionally, the Cheonggyecheon project has faced several criticisms, notably the fact that the restored stream is artificially supplied with water from the Han River and an underground source (Jeon & Kang, 2019). These critiques challenge the relevance of this project in terms of water management. Overall, these studies suggest that the implementation of GSI in the right-of-way can promote active travel by improving safety, increasing the connectivity of cycling and walking networks, and developing new dedicated active paths. These studies also highlight that GSI is often implemented as part of a broader project that can bring other modifications that need to be considered when evaluating the design. These studies demonstrate that GSI design and implementation is often done with a concern for active mobility. They also raise the need for

more comprehensive empirical studies examining the complex interactions between GSI and active mobility.

4. Discussion

4.1 Measured and potential effects of GSI on active mobility

This comprehensive review of the literature identified several measured and potential effects of green features on active mobility in cities. The relationships resulting from this analysis are illustrated in Figure 3. Since very few studies have directly assessed the effects of GSI on active mobility, the relationships between GSI and GI are presented together with the relationships between the measured GI and the active mobility outcomes. More specifically, the links between GSI and measured GI illustrate how different types of GSI include various green features.

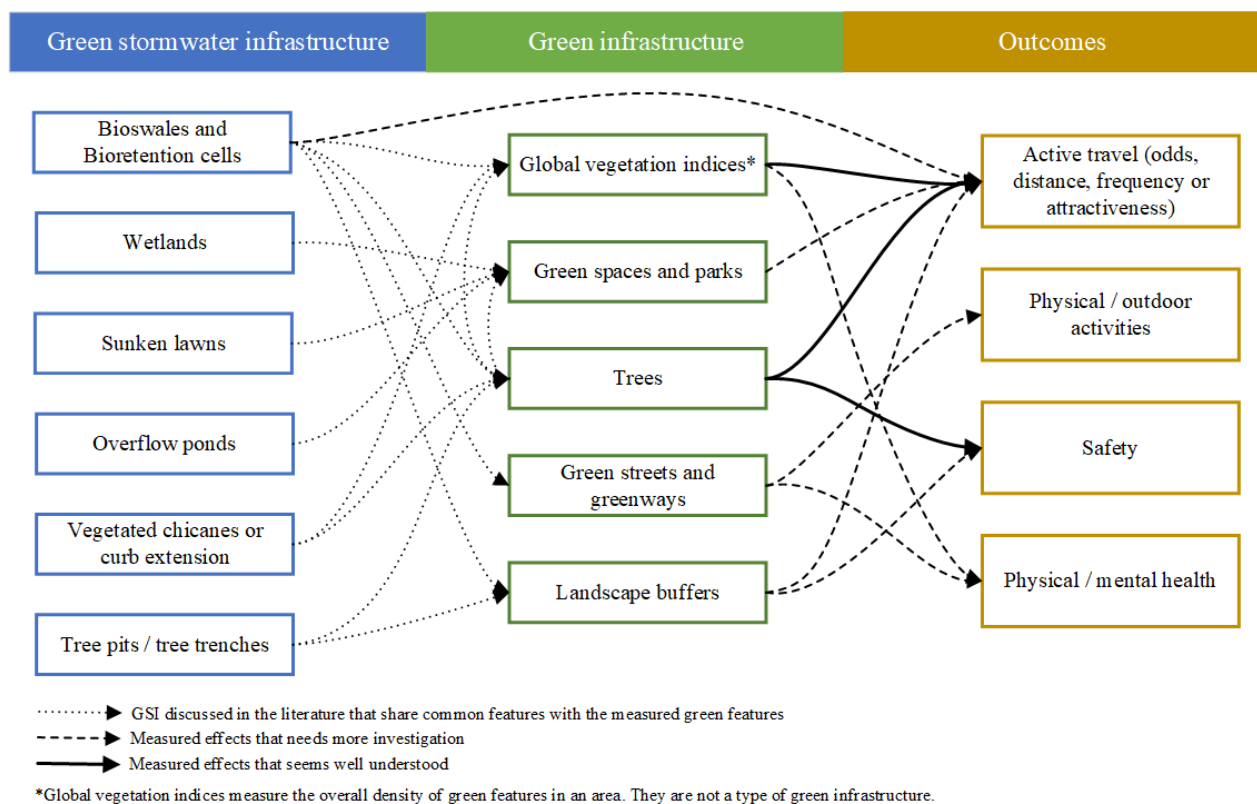


Figure 3 Potential and measured relationships between green stormwater infrastructure and active mobility

These links highlight the close relation between GSI and GI and their potential to lead to similar outcomes on active mobility. Bioswales and bioretention cells are the only GSI for which outcomes have directly been measured, showing that there is a need for more empirical studies directly assessing the effects of GSI on active mobility.

4.1.1 Measured effects of green features on active mobility

The main greenery indicators that have been analyzed in the literature are global vegetation indices and number of trees or tree canopy. Overall, these types of vegetation are associated with positive effects on active mobility. As shown in Figure 3, the global vegetation indices and street trees have been directly associated with active travel, whereas green spaces and parks have been directly associated with physical activities. Furthermore, street trees have been found to be directly associated with road safety. Green spaces and parks have also been associated with positive outcomes for active travel; however, the relation is more complex as more studies found non-significant results.

The reviewed literature also mentioned some measured effects for bioswales/bioretention cells, landscape buffers, and greenways/green streets as shown in Figure 3. However, these effects have only been analyzed in a few studies, which limits the generalization of the results. Their understanding therefore requires further research.

Finally, most measured effects are between global vegetation indices or GI and the outcomes, while there is only one measured relation between GSI and active travel. Therefore, to understand the potential of GSI to promote active travel, the indirect links between the GSI and the outcomes are examined in the next section.

4.1.2 Potential effects of GSI on active mobility

As shown in Figure 3, the reviewed literature on GSI highlighted many links between GSI and the measured green features that are expected to lead to the same outcomes for active travel. Based on these results, we can establish a link between the measured benefits of GI and the benefits that GSI could bring through its common characteristics with GI. First, several GSI (vegetated chicanes, vegetated curb extensions, tree pits, tree trenches, bioswales, and bioretentions) are characterized by the presence of vegetation, whereas the overall density of vegetation visible from the street (measured through GVI) has been shown to support active mobility. Thus, the findings suggest that

the implementation of GSI on the right-of-way, which increases the overall vegetation density, can promote active travel. In addition, as mentioned by Ferguson (2012), it is possible and even easier to plant trees in GSI such as rain gardens, since these types of infrastructure provide more rooting space for urban trees to grow and reach a higher canopy density. In this regard, Grey et al. (2018) demonstrated that tree pits with an underdrain can achieve twice the growth compared to conventional street trees (receiving a lower amount of rainwater). Furthermore, this study highlights the importance of proper drainage to prevent water saturation that hinders tree growth.

The implementation of GSI can also increase the density of street trees and lead to similar benefits as those illustrated in Figure 3 (increase in active travel and improved road safety). Trees can be planted in several types of GSI, such as bioretentions, vegetated chicanes, vegetated curb extensions, etc.

Moreover, the implementation of GSI is often done directly in the right-of-way, which leads to a change in the allocation of the urban space. This specific characteristic of GSI requires particular attention since it seems to bring benefits, but also raises concerns with respect to social acceptability. On the one hand, several studies mentioned that GSI can improve safety by reducing the width of the road and acting as traffic calming measures (Clemente, 2020; Greenberg, 2008; Polanski, 2015; Valente et al., 2021). For example, GSI, such as tree trenches and bioswales, can be implemented between the active path and the motorized path, thereby creating a physical barrier to protect pedestrians and cyclists from motorized vehicles. Studying the use of bicycle lanes to access urban parks, Niță et al. (2018) showed that illegally parked cars were an important factor influencing the use of bicycle lanes. This problem can be overcome by implementing GSI as a physical barrier between the road and the bicycle lane. Moreover, some types of GSI can be implemented as traffic calming measures such as vegetated chicanes or vegetated curb extensions. On the other hand, this reallocation of space also brings concerns within the population. Studies highlighted that there are concerns about car mobility, safety and aesthetics, and that there is a lack of awareness and acceptability for those projects (Everett et al., 2015; Ferreira et al., 2021). The analysis of the literature specific to GSI has raised several considerations, especially among car users that have had to adapt their behaviour to a new street configuration. This highlights the challenges associated with the implementation of GSI. Indeed, the implementation of GSI on a space that was previously dedicated to motorized vehicles, such as implementing roadside bioswales, implies significant changes for users. Research is required to understand the specificities

of GSI that challenge the social acceptability of these projects, notably its footprint, which is larger than GI.

Finally, as shown in Figure 3, several GSI such as sunken lawns and overflow ponds can be implemented in green spaces or parks. These features may be attractive for leisure active travel. The analyzed studies also mentioned the need to reduce impervious surfaces and reduce the risk of flooding by implementing GSI that allows water to infiltrate into the soil instead of using typical drains. By reducing the risk of road flooding, GSI can improve mobility for all users.

Overall, considering the benefits of green features, especially street trees, it seems that GSI can play a similar role and should promote active travel.

4.1.3 Social and contextual considerations

Through this review of the literature, heterogeneity in the relationship between vegetation, GI and active travel was found across age groups, gender, built environment characteristics and regions. Several studies found positive impacts of green features on the mobility and safety of elderly people. GSI can be implemented as a raised median that divides the street into two sections and serves as a refuge for the elderly who need to rest before crossing the second part of the road. When implemented as curb extensions, GSI can reduce the length to be crossed at the intersection. Regarding children, the reviewed studies have shown that GI (buffer landscape and shade-casting trees) can promote active travel, and GSI can promote recreational and educational activities. Moreover, several studies found differences between men and women (Akinci et al., 2021; Li & Ghosh, 2018). However, these differences should be further studied.

Finally, some results suggested that studies should pay attention to differences across regions (rural, urban and suburban), and across areas with different densities of the built environment. Indeed, the review suggests that in residential areas where there is a lot of greenery on private land, the effects of planting trees may not be as large as in dense urban areas where there is almost no vegetation. Conversely, the competition for space might be more intense in densely populated areas.

These findings revealed that age, gender, and the density of the built environment are important variables that may influence the effects of GI and GSI on active travel. These findings highlight

the complexity of the relationship between GI, GSI and active mobility. Further studies should evaluate the effects of GSI in different regions, and across different population groups.

4.2 Research gaps and opportunities

This analysis of the literature on the potential synergy between GI visible in the right-of-way, GSI and active mobility has highlighted research gaps and opportunities relative to the: (i) indicators of green features, (ii) street design and context, (iii) heterogeneity in the population, (iv) distinction between cycling and walking, and (v) social acceptability.

First, the analysis of the indicators used to quantify green features revealed the existence of various indicators representing the same green feature. It is necessary to assess the relevance of different indicators depending on the context of the study and the analyzed outcomes. Although the use of a global index such as the GVI is relevant to understand the overall effects of vegetation (namely since it represents an eye-level view), this indicator does not differentiate the effects by types of vegetation, nor does it consider the surrounding environment. Moreover, the results of the literature search revealed that very few studies evaluated empirically the relation between GSI and active mobility. Thus, further studies should develop new methods for quantifying GSI, while considering the complexity of using a specific indicator.

Furthermore, research is needed to analyze how different street designs and context of the built environment can influence the effects of GI and GSI on active mobility. The analysis of articles on GSI revealed differences in the appreciation of different types of GI and GSI with respect to their specific characteristics (types of vegetation, size, location, etc.). For example, the appreciation of trees seems quite widespread, while the implementation of bioswales, which have a larger footprint, raised several concerns among citizens such as the loss of parking spaces. Moreover, a particular attention should be paid to the differences across regions (urban, suburban, and rural) since the literature review has shown that the perceptions may vary depending on the density and the built environment. As demonstrated by Wu, Jiayu et al. (2020), the effect of green features (assessed with the GVI) on walking and cycling varies depending on the type of road in which they are implemented. Thus, there is a need to further investigate the effects on different types of roads (local, collector and arterial).

In addition to these considerations, further studies should also investigate heterogeneity in the population. Differentiated results have been found across different socio-economic groups,

emphasizing the importance of conducting segmented analysis. Among studies on GI, street trees, landscape buffers and raised medians were associated with an increase of road safety, especially for children and elderly people. The studies discussing GSI also revealed some potential to increase pedestrians and cyclists' safety while implementing GSI. Further studies should analyze how the implementation of GSI can benefit vulnerable populations.

Both in the studies on GI and GSI, there were few studies on cycling compared to walking, and the results of the literature review suggest that the effects of GI and GSI vary depending on the travel mode. The travel purpose might also influence the effects of GSI on behaviour and perceptions. Efforts are therefore warranted to make the distinction between walking and cycling activities.

Finally, the case studies on GSI revealed considerations on the social acceptance of projects involving its implementation. More studies are needed to understand the social acceptance of these projects across different population groups and road users (drivers, pedestrians, cyclists, etc.). The social acceptance of the reallocation of the space seems to be a challenge for car users. However, more case studies are needed to understand the perceptions of other users. Moreover, further studies should analyze how people's awareness of the benefits of GSI on the environment is influencing social acceptance.

Overall, the review of 70 scientific articles discussing both green features in general and GSI provided a clear picture of the actual knowledge on the effects of vegetation on active travel, while identifying relationships that remain poorly understood and that require further investigation. More research is certainly needed to understand the effects of different types of GI, and especially GSI, given its potential to achieve complementary objectives.

5. Conclusion

This comprehensive review of the literature contributes to the understanding of the existing knowledge on the relationship between GSI and active travel, highlighting the nuances in terms of outcomes, and identifying relationships that need to be better understood. One of the main findings of this review is the limited number of scientific articles that directly address the relationships between GSI and active mobility. The review of the studies on GSI and active mobility revealed the potential to improve the attractiveness of walking and cycling, reallocate space for active paths and improve safety, through the implementation of GSI. Moreover, we identified some common characteristics between GSI and GI that positively influence active mobility. For instance, both for

GI and GSI, some features are visible from the street and they often create a separation between the motorized and non-motorized modes. Through its common characteristics with GI, GSI has the potential to improve active travel, physical activity, road safety, and health.

To guide the design of future studies, we identified gaps in the literature and nuances that require more research. There is a need to develop indicators to identify and characterize different types of GI and GSI in the built environment. The wide variety of indicators used to measure GI demonstrated the need to better understand how to choose the proper indicator based on the purpose of the study. There is a need for more empirical studies investigating how the benefits of GSI materialize in different contexts, across population groups, depending on the travel mode (walking or cycling), and depending on the types and features of GSI. This scientific contribution will help researchers develop studies that will hopefully lead to evidence-based recommendations regarding the implementation of GSI. For now, the findings from our comprehensive review of the literature can support decision makers at the municipal level in better considering potential active travel benefits when planning the implementation of GSI.

Competing interests

The authors declare that they have no financial and non-financial competing interests.

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