

Article

Nature-Based Solution for Sustainable Urban Pavement Construction in South Africa

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Abstract

As urban areas in developing countries, including South Africa, continue to grapple with the adverse challenges of climate change and rapid population growth, there is an increasing call for nature-inspired solutions. This is because nature-based solutions (NbSs) can significantly enhance urban resilience by managing stormwater, reducing flooding and creating livable spaces within urban centers. One such NbS is permeable pavement, which has gained attention for its ability to allow water to infiltrate rather than run off. However, while its use is growing in developed nations, the story is not the same in South Africa, where the literature is silent on its usage and issues of flooding and other associated disasters have persisted. Therefore, this study adopts a post-positivist approach to investigate the application and challenges of permeable pavements as an NbS in South African urban areas. The study reveals a low level of permeable pavement use, albeit an encouraging level of awareness among built environment professionals. Covariance-based structural equation modelling further revealed the significant causes of this poor application. The findings provide valuable insights for policymakers to create incentives and frameworks that promote permeable pavement adoption in urban areas facing environmental challenges. Moreover, this research contributes to the limited literature on NbSs in South Africa, offering a foundation for future studies and addressing the pressing need for innovative solutions to flooding and urban resilience.

Keywords: flooding; nature-based solutions; pavement design; policy development; sustainable resource management; urban ecology resilience



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1. Introduction

Urban areas worldwide face mounting environmental challenges due to rapid urbanization, unsustainable land use and the impacts of climate change [1]. Major concerns include flooding, water scarcity, air pollution and ecosystem degradation [2,3]. South Africa's urban centers are no exception to these challenges, as they face a unique combination of water-related risks driven by their geographic, climatic and socio-economic conditions [4]. Cape Town, for example, captured global headlines during its 2018 water crisis, where extreme drought pushed the city to the brink of "Day Zero", a scenario in which taps almost ran dry [5]. Moreover, cities like Johannesburg and Durban contend with increasingly frequent and destructive flooding, exacerbated by heavy rainfall and

inadequate stormwater infrastructure [6]. Although conventional flood management techniques are employed, in many cases, they fail to effectively manage changes in weather patterns and urban issues in the country. From the perspective of pavement construction, conventional pavements in South Africa, particularly those constructed using asphalt and crushed stone, tend to fail prematurely due to several factors including unsuitable materials and inadequate construction [7,8]. Nature-based solutions (NbSs) offer a promising, integrated approach to mitigating the dual threats of flooding and drought. According to Asare et al. [9], NbSs leverage natural systems and processes to enhance urban resilience, manage water resources sustainably and support biodiversity conservation. Unlike conventional infrastructure, which often provides a single function, NbSs generate multiple benefits, from flood control and improved water quality to climate regulation and recreational opportunities [3,10].

Permeable pavements are NbS designed to mitigate urban flooding, enhance stormwater management and build urban resilience [11]. Unlike traditional impervious surfaces, permeable pavements allow water to infiltrate the ground, thus leading to reduced surface runoff [12]. This helps replenish groundwater, prevents drainage system overload and minimizes flood risks. According to Öztürk et al. [13], permeable pavements consist of materials, such as porous asphalt, permeable concrete and interlocking pavers, each designed to support pedestrian and vehicle traffic while enabling water infiltration. Their ability to manage stormwater sustainably makes them particularly suitable for urban environments, where space for natural water absorption is often limited [12]. The benefits of these nature-inspired solutions extend beyond flood control. Reducing runoff also enhances water quality by filtering pollutants before water reaches storm drains or groundwater [14]. Additionally, permeable pavements can help mitigate the urban heat island effect by lowering surface temperatures, as their porous structure allows cooler air and moisture to circulate, contributing to a more comfortable urban climate [15].

Despite the failure of conventional pavement and impervious surfaces to adequately address the stormwater challenges of South Africa and the multifunctional benefits of permeable pavements in sustainable urban design, not much has been documented on their broader application and integration within urban infrastructure in South Africa. Existing studies have predominantly focused on their role in water quality performance [15,16] but not on their practical implementation or the factors that hinder their widespread adoption. While these studies provide notable insights, there is a growing need for more contemporary research addressing the evolving urban challenges South African cities face. A quick online search by the authors to ascertain existing studies on awareness, usage levels and challenges of permeable pavement construction from the South African perspective revealed zero articles on the subject, underscoring the importance of this study in advancing the understanding of permeable pavements in South Africa's urban planning context. Therefore, considering the inherent opportunities in the use of permeable pavements, this study aims to answer the question of "what are the challenges facing the use of permeable pavements as an NbS in urban areas in South Africa?". By answering this question, this study hopes to add to the growing global discourse on NbS while providing lessons from a South African perspective, which can inform similar efforts in other developing countries facing urban sustainability challenges.

2. Understanding the Concept of Permeable Pavements in Construction

Permeable pavements represent innovative solutions in modern construction, designed to address urban stormwater challenges by allowing water to pass through the surface layers into the ground below [13]. Unlike traditional impervious pavements that contribute to excessive surface runoff, thereby increasing the burden on drainage systems,

permeable pavements offer an effective means of managing rainwater on-site [12]. According to Fang et al. [17], permeable pavements comprise various layers, including a permeable surface, an aggregate sub-base and a storage layer that filters and temporarily stores water before infiltrating the soil or being conveyed to stormwater systems. Hein [18] noted that several requirements must be considered in designing and constructing permeable pavement. Analyzing and understanding the infiltration capacity of the soil in the area of construction, as well as determining the ideal slope, is crucial. A slope of less than 5% was suggested to prevent rapid runoff. The Minnesota Pollution Control Agency [19] suggested at least a 1% surface slope to give alternate means for drainage should the surface become completely clogged due to lack of maintenance. Additionally, the choice of materials is essential and must be selected for their porosity and durability. Hein [18] warned against using permeable pavement design in areas with high and concentrated traffic, particularly where the pavement is designed to accommodate heavy vehicles like trucks and buses. For structural stability, the pavement must be capable of supporting expected loads, as such, careful consideration must be given to the surface thickness as well as the base and sub-base layers. This sub-base layer, in most cases, is composed of open-graded aggregates that enable easy flow of water. Where the soil is less permeable, additional subsurface drainage systems are integrated, and accommodation for overflow during extreme weather events are considered [20].

The primary advantage of permeable pavements lies in their multifunctionality. They not only contribute to sustainable stormwater management but also improve water quality, reduce flooding and help recharge groundwater systems [14]. By filtering pollutants from runoff, permeable pavements enhance the quality of water entering natural water bodies, which is particularly beneficial in urban areas where impervious surfaces dominate [21]. Additionally, they help mitigate heat island effects by absorbing less heat than conventional pavements, making them more desirable in urban settings. This aligns with the principles of NbS, which emphasize integrating ecological processes into urban planning to create resilient and sustainable cities [11].

Several types of permeable pavements are commonly used in construction. Permeable concrete, for example, consists of a mix of cement, water and coarse aggregates with little or no sand, creating voids that allow water to permeate [22]. Additionally, interlocking concrete pavers are designed with gaps between units filled with permeable materials to facilitate water movement [13]. The choice of type depends on factors such as site conditions, expected traffic loads and maintenance considerations. Permeable pavements have gained widespread adoption in developed countries. In the United States, they are commonly used in parking lots, residential streets and pedestrian areas to reduce runoff and improve water quality [23]. European countries, such as Germany and the Netherlands, have integrated permeable pavements into their urban infrastructure to enhance groundwater recharge and reduce flooding [24]. In Australia, permeable pavements are employed in both urban and suburban settings to manage stormwater and support sustainable urban drainage systems (SUDS) [25]. However, in developing regions like South Africa, the concept of permeable pavements is still gaining traction and faces several challenges, which are discussed in the following section. Initiatives like the use of permeable pavements and sponge cities, which are designed to absorb and manage rainwater effectively while reducing the risk of flooding and drought [26] in South Africa, can help promote sustainable urban areas in the country.

3. Challenges to the Application of Permeable Pavements

Financial challenges present significant barriers to the adoption of NbSs, including permeable pavements, in both developed and developing countries. One common issue is

the perceived high construction cost, which discourages investment despite the long-term benefits of these systems. For example, studies in China have raised concerns about the initial capital required to install permeable pavements compared to conventional asphalt or concrete [27]. Similarly, in the United Kingdom, local governments have been reluctant to invest due to uncertainty surrounding upfront costs and budget constraints [28]. The perceived high maintenance costs further exacerbate this challenge, as routine cleaning and specialized equipment are often necessary to prevent clogging. In Japan and Vietnam, where permeable pavements have been implemented in urban areas, maintenance costs have proven challenging for some municipalities without dedicated funding streams [29]. A lack of financial resources limits the feasibility of adopting permeable pavements in regions where urban infrastructure budgets are already stretched thin. For instance, in Brazil, limited municipal funding has slowed the implementation of green infrastructure solutions in cities facing recurrent flood risks [10]. South Africa faces similar constraints; in Cape Town, local authorities' financial limitations have hindered the broader implementation of water-sensitive urban designs [16]. The absence of financial incentives, such as tax rebates or subsidies, also reduces the economic appeal for private developers. In contrast, countries like Germany have successfully accelerated the adoption of green infrastructure by offering stormwater tax reductions to property owners using permeable surfaces [30].

A lack of long-term commitment to NbSs, including permeable pavements, significantly impedes their widespread implementation. Short-term political cycles often lead to shifting policy priorities, which deprioritize sustainable infrastructure investments. For example, in Mexico City, green infrastructure projects have experienced inconsistent funding and wavering political will, reducing their effectiveness in flood mitigation [31]. Similarly, South African cities have faced discontinuity in NbS initiatives due to changes in local government priorities, undermining progress toward sustainable urban development [16]. Without a sustained strategic vision, realizing the full potential of permeable pavements remains a challenge. This issue is compounded by a lack of urgency among policymakers, who often favor traditional infrastructure solutions over innovative alternatives due to familiarity and a perceived lower risk [32]. Even in developed nations like Australia, regulatory inertia continues to slow the adoption of permeable pavements despite substantial evidence supporting their benefits [25]. Policymakers' reluctance to prioritize sustainable stormwater management exacerbates vulnerabilities to climate-related disasters, as evidenced by the delayed response to rising urban flooding in South Africa [33]. The absence of supportive policy and legal frameworks further compounds these challenges. Countries like the Netherlands offer a positive example, having implemented comprehensive policies that integrate NbSs into urban planning [34]. Such frameworks provide clear guidelines and legal backing for sustainable infrastructure development, unlike regions where regulatory gaps persist. In South Africa, the lack of mandates or incentives promoting permeable pavements leaves implementation decisions to individual municipalities [16]. Consequently, without adequate legal and policy structures, achieving sustainable urban resilience through permeable pavements remains an uphill battle.

The combination of perception and sociocultural factors presents another significant challenge. A prevalent issue is the absence of long-term horizons for benefit accrual, which undermines the willingness to invest in such infrastructure [35]. This challenge is compounded by uncertainty regarding the functionality and performance of NbS, an issue exacerbated by a lack of public understanding and unclear definitions surrounding these solutions [36]. Consequently, public awareness and support for NbS remain insufficient, primarily due to the absence of targeted education and training programs that could build the necessary expertise [32]. As a result, many view NbS as optional add-ons rather than vital components of urban infrastructure, driven by a risk-averse attitude and resistance

to change [35]. This perception is often influenced by a silo mentality in urban planning and governance, where roles and responsibilities are unclear, hindering coordinated efforts to implement and integrate sustainable solutions [32]. Furthermore, the lack of exemplar permeable pavement structures limits public understanding of their potential. At the same time, the insufficient quantification of risk management efficacy and uncertainty regarding the achievability of desired benefits create further hesitation among stakeholders [37]. These complexities in stakeholder roles, coupled with limited time availability for education and implementation, make it even more challenging to generate the momentum needed for the widespread adoption of NbS [35].

Urban space scarcity and poor city coordination are also key issues. According to Castelo et al. [37], misalignments between short-term plans and long-term sustainability goals often lead to fragmented, piecemeal approaches that fail to address broader urban resilience needs. The rapid pace of urbanization and the increasing demand for space further complicate the integration of permeable pavements. Without cohesive, long-term urban strategies and better coordination, the potential of permeable pavements to contribute to sustainable urban development remains constrained. These various challenges are summarized in Table 1.

Table 1. Summary of the challenges facing the use of permeable pavement.

CODE	Challenges	Source(s)
Financial		
CH1	Perceived high cost of construction	[27–29]
CH2	Perceived high maintenance cost	[27,29]
CH3	Lack of financial resources	[10,16,30]
CH4	Absence of financial incentives	[16,30]
CH5	Benefits and costs are complex to estimate	[35,37]
Governance		
CH6	Absence of design standards and guidance for maintenance	[31,34]
CH7	Absence of long-term commitment to NbS initiatives like permeable pavement	[16,31]
CH8	Lack of sense of urgency among policymakers	[32,33]
CH9	Absence of supportive policy and legal frameworks	[16,34]
CH10	Legal constraints	[16,32]
Perception and sociocultural		
CH11	Absence of long-term horizons for benefit accrual	[35,36]
CH12	Uncertainty in functionality and performance	[35–37]
CH13	Lack of public understanding, unclear definitions and concepts	[32,36]
CH14	Lack of knowledge and expertise	[32,35]
CH15	Lack of public awareness and support	[32,35]
CH16	Lack of training programs on NbS, like permeable pavement	[32,35]
CH17	Perception of NbS as an add-on option	[32,35]
CH18	Risk aversion and resistance to change	[35,37]
CH19	Silo mentality	[32,35]
CH20	Unclear stakeholder duties	[32,35,37]
Infrastructure integration		
CH21	Lack of exemplar permeable pavement physical structures	[32,35]
CH22	Insufficient quantification of risk management efficacy	[35]
CH23	Limited time availability	[32,35]
CH24	Complexities in public responsibilities and roles	[32,37]
CH25	Uncertainty regarding risk management efficacy and the achievability of desired benefits	[35,37]

Table 1. *Cont.*

CODE	Challenges	Source(s)
Spatial		
CH26	Urban space scarcity	[10,16,31]
CH27	Poor city coordination	[10,16,31]
Assessment		
CH28	Misalignments between short-term plans and long-term goals	[10,16]
CH29	Occurrence of unexpected events	[10,27]

4. Research Methodology

This study adopted a quantitative research method informed by a post-positivist philosophical stance. Responses were gathered from built environment professionals in South Africa using a structured questionnaire as the instrument for data collection. A questionnaire was used because it allows respondents to give an unbiased view due to its anonymity while offering the opportunity to research a large range of built environment professionals within a short period [38]. The particularity of the study meant that not all built environment professionals could be drawn as part of the target population. Therefore, it was expected that the participants had some knowledge of NbSs and permeable pavement construction to contribute meaningfully to the study. To achieve this, a brief description of permeable pavement as an NbS was presented in the questionnaire, and the respondents were required to complete it only if they were conversant with the concept. The built environment professionals who participated in the survey were architects, engineers, construction managers, quantity surveyors, and green consultants/green star engineers. The approach adopted implied that the conventional approach of determining a target population (in numbers) and calculating an ideal sample frame and size was impossible in this study. This necessitated a snowball sampling method wherein a group of built environment professionals were first identified and invited for the survey. Later, other participants were identified through referral from the first sets of professionals. To avoid sampling bias associated with the snowball sampling method, the initially identified built environment professionals were diverse based on their profession and experience. This was done to ensure that referral for all core professionals were made to ensure their participation in the study, as seen in the background information results. Based on the referral approach adopted, 149 usable samples were obtained across different provinces within 3 months and deemed suitable for data analysis in the study.

A closed-ended questionnaire designed in sections was used. Section one gathered background information on the respondents to determine their suitability for the study. Section two assessed the respondents' understanding of permeable pavement and the extent of application of this NbS in urban areas in the country. Section three determined the challenges facing the use of permeable pavement as an NbS in urban areas in South Africa. The application and challenges were assessed using the five-point usage and agreement scale proposed in [39]. For the extent of usage, respondents were asked to state the extent to which permeable pavement was used within urban areas on a five-point scale where one is 'never', two is 'almost never', three is 'sometimes', four is 'almost every time', and five is 'every time'. They were further asked to rate their level of agreement with the identified 29 challenges on a five-point scale where one is 'strongly disagree', two is 'disagree', three is 'neutral', four is 'agree', and five is 'strongly agree'. The questionnaire was distributed via Google Forms, with a cover letter describing the intention of the study, notifying the respondents of their voluntary participation and assuring them of anonymity.

The data analysis was done using frequency (f) for the background information, while the mean item score ($\bar{X}$) was used to rank the identified challenges in descending order using Equation (1).

$$\bar{X} = \frac{5n_5 + 4n_4 + 3n_3 + 2n_2 + 1n_1}{n_5 + n_4 + n_3 + n_2 + n_1} \quad (1)$$

where n = the frequency of each of the rankings.

Because the built environment professionals were drawn from different organizational types (i.e., consulting, contracting and government), it was necessary to identify any significant difference in their rating of these challenges. As such, the Kruskal–Walis (K-W) H-test, which is the non-parametric alternative of ANOVA, was used. The K-W test can be calculated using Equation (2).

$$H = \frac{12}{N(N+1)} \sum_{i=1}^k \frac{R_i^2}{n_i} - 3(N+1) \quad (2)$$

where N = total sample, k = total number of groups, R_i = sum of ranks of group i , and n_i = sample size of group i .

Furthermore, to understand the crucial challenges and their significance in affecting the current extent of usage of permeable pavements derived in the study, covariance-based structural equation modelling (CB-SEM) was conducted using EQation (EQS) software version 6.4. In conducting CB-SEM, the construct validity and reliability were confirmed, while the structural relationship between these challenges and level of usage was determined through an assessment of the path coefficient and significance of the derived t -value. Furthermore, the derived fit indices were assessed for their acceptability based on predefined thresholds. Figure 1 gives the research approach adopted in the study.

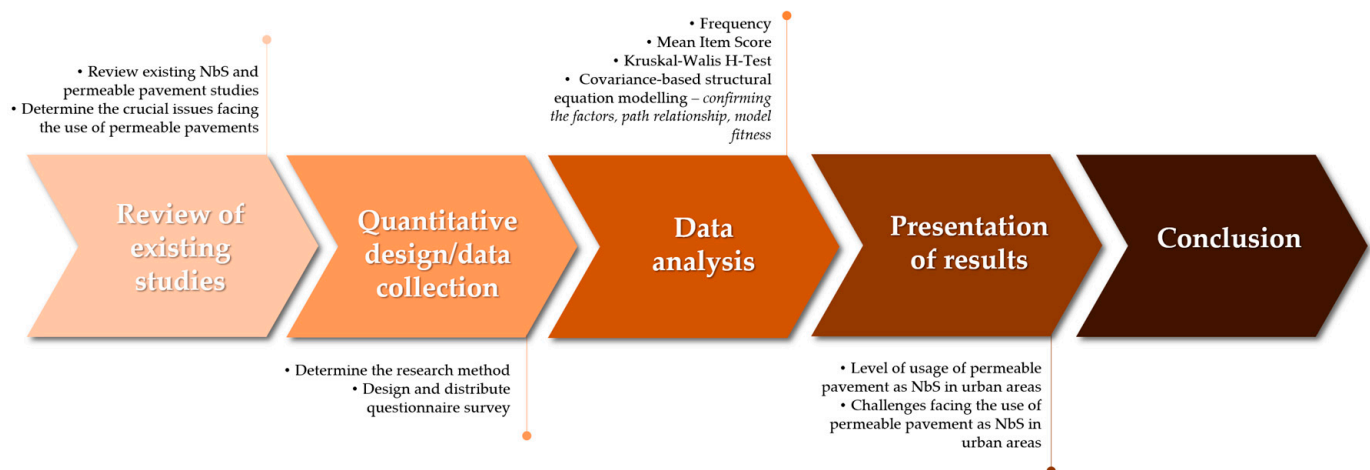


Figure 1. Adopted research structure.

5. Results

5.1. Background Information of Respondents

The results from the analysis of the data gathered on the background information of the respondents indicated a reasonable spread in the targeted professionals with architects ($f = 15$), quantity surveyors ($f = 27$), engineers ($f = 49$), construction managers ($f = 52$) and green consultants/green star engineers ($f = 6$) all participating in the survey. Most of these professionals hold a bachelor's degree ($f = 106$), while 33 have a diploma, and 10 have a master's degree. These professionals were drawn from contracting ($f = 53$), consulting ($f = 53$) and government organizations ($f = 43$). The average number of years of experience

was 8 years, with most of the respondents ($f = 102$) having between 6 and 10 years of working experience in the South African built environment. This background information indicates that the respondents for the study were appropriate and should be able to give logical insights into the application of permeable pavement as an NbS in South Africa's urban centers.

5.2. Application of Permeable Pavement as an NbS in Urban Areas in South Africa

The analysis of the background information of the respondents revealed that all respondents were aware of the concept of permeable pavement and had a high level of understanding ($f = 84$) of the concept. Only 36 noted an average level of understanding, and 29 noted a low-level understanding. However, the findings revealed that the concept has almost never been applied within urban areas in the country. Figure 2 shows that the majority of the respondents indicated that the application of permeable pavement is almost never used ($f = 77$), has never been used ($f = 45$) or sometimes applied ($f = 27$). The extent to which permeable pavements are “sometimes” used is worth further case exploration for a deeper understanding of the actual usage. However, the current result is an indication of the infancy stage of permeable pavement as an NbS in urban areas in South Africa.

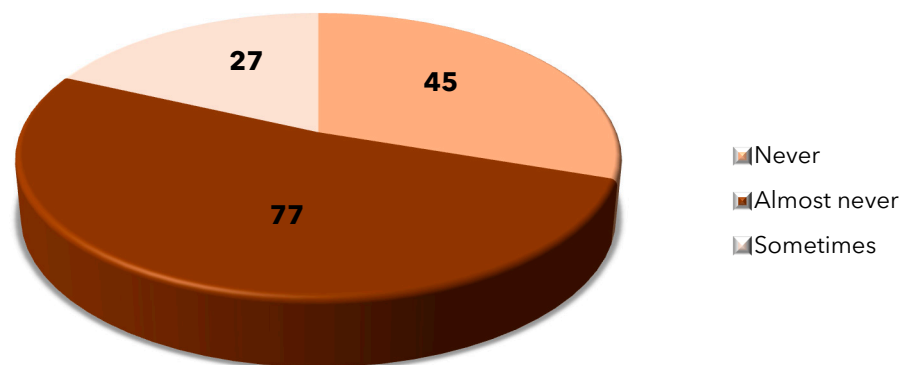


Figure 2. Application of permeable pavements as an NbS in urban South Africa.

5.3. Challenges to the Application of Permeable Pavements as an NbS in Urban Areas in South Africa

Following the understanding that the application of permeable pavement as an NbS for urban areas in South Africa is slow paced, the challenges facing the use of this concept were further explored. The 29 challenges identified and grouped into 6 clusters were presented to the respondents to rate based on their significance. The results presented in Table 2 revealed a group $\bar{X}$ of above average of 3.0 for all 6 clusters of challenges, indicating that these different groups of challenges, to some extent, have a significant impact on the application of permeable pavement in urban areas in the country. Top among these groups are assessments and spatial concerns as well as issues relating to finance, perception and sociocultural view of the concept of permeable pavements. Furthermore, the K-W test revealed a convergent view among the respondents for 29 challenges assessed as p -values above the threshold of 0.05. Careful assessment of the $\bar{X}$ -values from each category of respondents (i.e., consulting, contracting and government) revealed that the ratings by each category were not far off, thus confirming the absence of disparity in the ratings as indicated by the K-W test.

Table 2. Challenges facing the application of permeable pavement as an NbS for urban areas.

	Consult.	Contr.	Govt.	Overall		K-W Test	
Challenges	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$	Rank	<i>h</i> -Value	<i>p</i> -Value
Finance							
Absence of financial incentives (CH4)	3.70	3.53	3.37	3.54	1	2.225	0.329
Perceived high cost of construction (CH1)	3.60	3.51	3.26	3.47	2	2.032	0.362
Lack of financial resources (CH3)	3.62	3.42	3.09	3.40	3	3.398	0.183
Benefits and costs are complex to estimate (CH5)	3.43	3.34	3.35	3.38	4	0.174	0.917
Perceived high maintenance cost (CH2)	3.26	3.51	3.23	3.34	5	1.788	0.409
Group $\bar{X}$				3.43			
Governance							
Absence of supportive policy and legal frameworks (CH9)	3.57	3.38	3.37	3.44	1	1.039	0.595
Lack of sense of urgency among policymakers (CH8)	3.45	3.36	3.47	3.42	2	0.362	0.835
Absence of design standards and guidance for maintenance (CH6)	3.38	3.42	3.35	3.38	3	0.284	0.867
Legal constraints (CH10)	3.09	3.49	3.21	3.27	4	2.630	0.268
Absence of long-term commitment to NbS initiatives like permeable pavement (CH7)	3.23	3.19	3.14	3.19	5	0.166	0.920
Group $\bar{X}$				3.34			
Perception and sociocultural							
Lack of public awareness and support (CH15)	3.66	3.62	3.47	3.59	1	0.746	0.689
Lack of public understanding, unclear definitions and concepts (CH13)	3.58	3.47	3.44	3.50	2	0.510	0.775
Perception of NbS as an add-on option (CH17)	3.40	3.34	3.60	3.44	3	0.987	0.610
Lack of knowledge and expertise (CH14)	3.38	3.38	3.49	3.41	4	0.425	0.808
Risk aversion and resistance to change (CH18)	3.57	3.38	3.23	3.40	5	2.549	0.280
Absence of long-term horizons for benefit accrual (CH11)	3.32	3.36	3.49	3.38	6	0.456	0.796
Lack of training programs on NbS like permeable pavement (CH16)	3.15	3.53	3.42	3.36	7	1.957	0.376
Unclear stakeholder duties (CH20)	3.38	3.36	3.23	3.33	8	0.374	0.830
Uncertainty in functionality and performance (CH12)	3.19	3.36	3.26	3.27	9	0.455	0.797
Silo mentality (CH19)	3.23	3.38	3.14	3.26	10	0.854	0.653
Group $\bar{X}$				3.39			
Infrastructure integration							
Complexities in public responsibilities and roles (CH24)	3.36	3.57	3.40	3.44	1	1.049	0.592
Limited time availability (CH23)	3.38	3.32	3.56	3.41	2	0.913	0.633
Insufficient quantification of risk management efficacy (CH22)	3.32	3.49	3.30	3.38	3	0.723	0.697
Uncertainty regarding risk management efficacy and the achievability of desired benefits (CH25)	3.19	3.53	3.33	3.35	4	1.838	0.399
Lack of exemplar permeable pavement physical structures (CH21)	3.40	3.40	3.14	3.32	5	1.113	0.573
Group $\bar{X}$				3.38			
Spatial concerns							
Poor city coordination (CH27)	3.43	3.75	3.42	3.54	1	3.238	0.198
Urban space scarcity (CH26)	3.34	3.49	3.51	3.44	2	0.876	0.645
Group $\bar{X}$				3.49			
Assessment concerns							
Occurrence of unexpected events (CH29)	3.64	3.68	3.47	3.60	1	0.816	0.665
Misalignments between short-term plans and long-term goals (CH28)	3.38	3.77	3.44	3.54	2	4.116	0.128
Group $\bar{X}$				3.57			

Source: Authors' compilation.

On an individual basis, the results revealed that the absence of financial incentives ($\bar{X} = 3.54$, p -value = 0.329), perceived high cost of construction ($\bar{X} = 3.47$, p -value = 0.362) and lack of financial resources ($\bar{X} = 3.40$, p -value = 0.183) were the top financial factors rated by the respondents. In terms of governance, the absence of supportive policy and legal frameworks ($\bar{X} = 3.44$, p -value = 0.595) and lack of sense of urgency among policymakers ($\bar{X} = 3.42$, p -value = 0.835) were top ranked, while for perception and sociocultural challenges, the lack of public awareness and support ($\bar{X} = 3.59$, p -value = 0.689) and the lack of public understanding and unclear definitions and concepts ($\bar{X} = 3.50$, p -value = 0.775) were rated the highest. For issues relating to infrastructure integration, complexities in public responsibilities and roles ($\bar{X} = 3.44$, p -value = 0.592) and limited time availability ($\bar{X} = 3.41$, p -value = 0.633) were rated highest, while for spatial concerns, poor city coordination ($\bar{X} = 3.54$, p -value = 0.198) emerged as the highest rank. For assessment concerns, the occurrence of unexpected events ($\bar{X} = 3.60$, p -value = 0.665) and misalignments between short-term plans and long-term goals ($\bar{X} = 3.54$, p -value = 0.128) were both rated high.

It is essential to note that while the descriptive analysis shows the factors the respondents considered significant, it does not necessarily indicate the extent of these significances and how these challenges have led to the derived low level of application that was previously observed. As such, CB-SEM was employed to test how these challenges affect the adoption of permeable pavement as an NbS for urban areas in South Africa. To achieve this, the first confirmatory analysis of the challenges was conducted in EQS using the Robust Maximum Likelihood (RML) option for a better outcome. For this confirmation, the derived standardized coefficient (λ) was first assessed using a predetermined threshold of 0.70, as proposed in past studies [40,41]. Using 11 iterations of elimination with the first variable of each group set as a fixed parameter (1.000), as suggested by Kline [42], and carefully considering the importance of each variable to the overall fitness and reliability of the model, 12 variables (CH1,2,5,6,7,10,11,12,16,19,24,26) were eliminated because they produced λ values below the stated threshold. The only variable with a λ of below 0.70 retained was CH26 (urban space scarcity), as deleting it only reduced the reliability of the model, with no positive improvement noted. The 18 variables presented in Table 3 met the construct validity and were further explored. The internal consistency of these variables was further assessed using Cronbach α and Rho alpha (ρ_A) with a threshold of above 0.7 [43]. This test gave an α -value of 0.948 and ρ_A -value of 0.957, which are higher than the set threshold, thus confirming internal consistency.

Table 3 further shows the significance of each of the 18 challenges retained along with their Z-statistics. All 18 challenges were deemed significant as their Z-statistics were above 1.96 (p -value < 0.05). Additionally, the significance of these variables was further confirmed through their coefficients of determination (R^2). The threshold for this test was set at 0.26, 0.13 and 0.02 for acceptable, moderate and weak [44]. This is based on past submissions, which have noted that the acceptable value of R^2 is based on the context of the discipline where the model is being applied, and R^2 values of as low as 0.1 have been considered satisfactory in some social science studies [45]. The result in Table 3 shows that the 18 challenges were deemed acceptable as R^2 values ranging from 0.39 (CH26) to 0.82 (CH28) were derived, implying that these challenges have the power to influence the use of permeable pavement as an NbS for urban areas in South Africa.

Table 3. Confirming the challenges facing the application of permeable pavement as an NbS for urban areas.

Variable	Standardized λ	Z-Value	Significant at 5% Level?	R ²
Finance				
Lack of financial resources (CH3)	0.72	1.000	Yes	0.51
Absence of financial incentives (CH4)	0.75	8.347	Yes	0.56
Governance				
Lack of sense of urgency among policymakers (CH8)	0.77	1.000	Yes	0.59
Absence of supportive policy and legal frameworks (CH9)	0.74	9.214	Yes	0.55
Perception and sociocultural				
Lack of public understanding, unclear definitions and concepts (CH13)	0.71	1.000	Yes	0.50
Lack of knowledge and expertise (CH14)	0.73	8.507	Yes	0.53
Lack of public awareness and support (CH15)	0.70	8.185	Yes	0.49
Perception of NbS as an add-on option (CH17)	0.75	8.739	Yes	0.56
Risk aversion and resistance to change (CH18)	0.73	8.540	Yes	0.54
Unclear stakeholder duties (CH20)	0.84	9.711	Yes	0.70
Infrastructure integration				
Lack of exemplar permeable pavement physical structures (CH21)	0.72	1.000	Yes	0.51
Insufficient quantification of risk management efficacy (CH22)	0.78	9.244	Yes	0.61
Limited time availability (CH23)	0.73	8.638	Yes	0.53
Uncertainty regarding risk management efficacy and the achievability of desired benefits (CH25)	0.79	9.334	Yes	0.62
Spatial concerns				
Urban space scarcity (CH26)	0.63	1.000	Yes	0.39
Poor city coordination (CH27)	0.87	8.634	Yes	0.76
Assessment concerns				
Misalignments between short-term plans and long-term goals (CH28)	0.90	1.000	Yes	0.82
Occurrence of unexpected events (CH29)	0.87	15.395	Yes	0.76
Use				
Usage	0.88	1.000	Yes	0.77

Source: Authors' compilation.

The structural relationship between the challenges and the level of usage of permeable pavement in urban areas in South Africa was assessed by exploring the derived path coefficient (β). Figure 3 shows that perception and sociocultural issues have the highest β -value of 0.92 with a significant t -value of 4.450, above the 1.96 cutoff (i.e., at $p < 0.05$) for a significant variable. This implies that the perception and sociocultural challenges will have a 92% significant impact on whether or not permeable pavements are used within urban areas in the country. Governance issues ($\beta = 0.81$; t -value = 2.946), spatial concerns ($\beta = 0.75$; t -value = 3.127) and infrastructure integration ($\beta = 0.56$; t -value = 3.480) all have high β -values and significant t -values. Although finance-related issues have a high β -value of 0.70, this group revealed a non-significant t -value of 1.486, below the 1.96 cutoff. This result implies that while the finance-related challenges (i.e., lack of financial resources and absence of financial incentives) might affect the use of permeable pavement, they do not

significantly impact the level of usage currently. This might be as a result of other factors that are more pressing within the country's urban landscape. A similar situation is noticed with assessment concerns as a β -value of 0.27 and a non-significant t -value of 1.728, below the 1.96 cutoff, were derived. The reason behind the non-significant nature of this cluster may lie in the fact that once the perception of a new concept is a core issue, as in the case of this current study, it will not be implemented. Therefore, issues relating to finance and assessment concerns of implementation concepts cannot arise. Having established the significance of the paths, the predictive power was measured using the overall R^2 derived. The result revealed an acceptable predictive power of 0.365, as suggested by Cohen [44], thus confirming that the 18 retained challenges have an acceptable level of influence on how permeable pavement is used as an NbS in urban areas in South Africa.

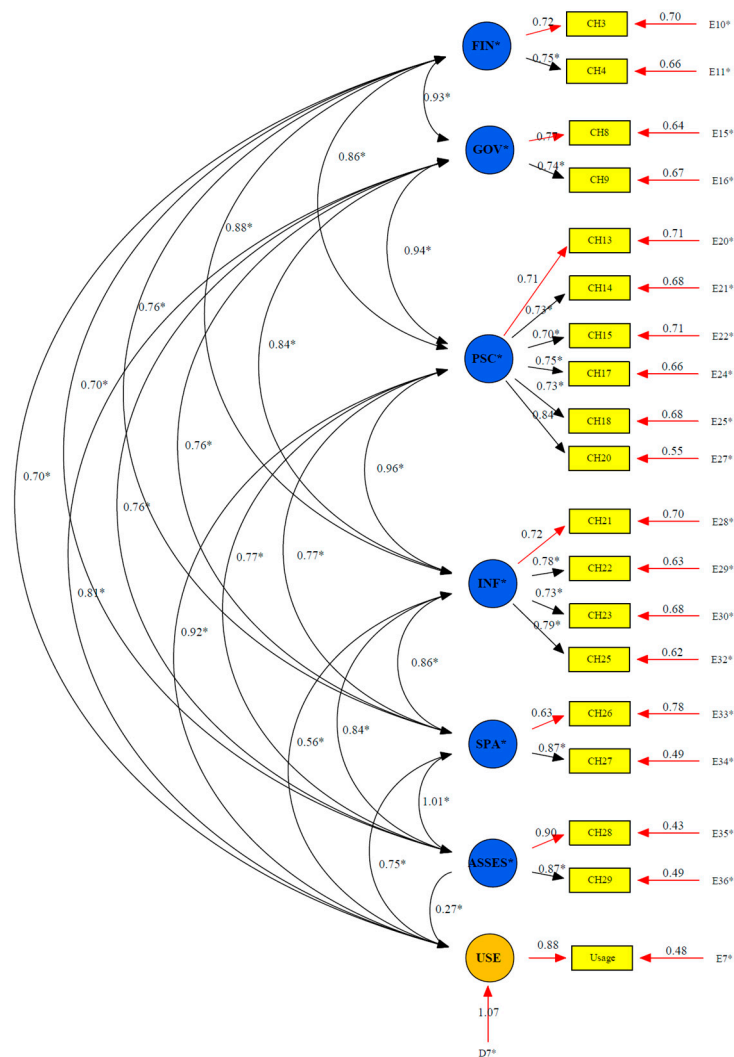


Figure 3. Structural model of the challenges impacting the use of permeable pavement as an NbS in urban areas.

The model fitness of the 18 retained challenges was primarily assessed by the standardized root mean squared (SRMR) along with other fit indices, as suggested Hu and Bentler [46]. SRMR gives the standardized difference between the observed and predicted relationship in the model. The result in Table 4 shows an SRMR of 0.059, which met the acceptable threshold of ≤ 0.08 , as noted in past studies [40,46]. The Root Mean Squared Error of Approximation (RMSEA) which shows how well a model fits the population covariance matrix was also explored with an acceptable threshold of ≤ 0.08 [47]. The RMSEA value of

0.061 was derived indicating an acceptable fit. Other supplemental fit indexes, such as the Comparative Fit Index (CFI), Bentler–Bonnet Non-Normed Fit Index (NNFI), Gamma Hat, McDonald’s Centrality Index (Mc), goodness-of-fit index (GFI) and Bollen’s incremental fit index (IFI), were explored for a more robust fit identification of the development model. The result in the table shows that CFI gave an acceptable value of 0.980, while the NNFI gave an acceptable value of 0.974 and the IFI gave an acceptable value of 0.980 [48]. While the results show an acceptable fit for these diverse parameters, the GFI, which gives the proportion of variance that is explained by the estimated population covariance, was low with 0.841. Some studies have noted that this fit index is sensitive to sample size and the complexity of the model, and this can account for the low value seen in the current study [49]. Nevertheless, the acceptable threshold revealed in the other fit parameters along with the SRMR gives a clear indication of the fitness of the model. Furthermore, the $S-B\chi^2/Df$ derived from RML with a cutoff of <3.0 for a good fit gave a value of 1.267. These derived fit indices indicate that the structural model of the challenges affecting the implementation of permeable pavement as an NbS in urban areas in South Africa is valid, reliable and fit for adoption to improve the use of this concept in the country.

Table 4. Model fit indices.

Fit Indices	Thresholds	Value	Remarks
$S-B\chi^2$	-	165.93	-
Df	-	131	-
$S-B\chi^2/Df$	<3 —good fit	1.267	Accepted
GFI	0 to 1 (0 = no fit; 1—perfect fit)	0.841	Accepted
CFI	0 to 1 (0 = no fit; 1—perfect fit)	0.980	Accepted
NNFI	0.60 to 1.00—acceptable fit	0.974	Accepted
IFI	0.90 to 1.00—acceptable fit	0.980	Accepted
RMSEA	≤ 0.08 —acceptable fit	0.061	Accepted
SRMR	≤ 0.08 —acceptable fit	0.059	Accepted

Source: Authors’ compilation.

6. Discussion and Implication of Findings

One striking observation from this study is the respondents’ high level of awareness and understanding of permeable pavements, indicating a solid foundation for their potential integration into urban infrastructure in South Africa. This trend mirrors findings in global studies [3,50], which highlight the increasing recognition of NbSs in urban planning and development worldwide. Despite this growing awareness, the actual use of permeable pavements in South Africa remains limited, with most respondents indicating that the technology is either “almost never used” or “never used” in practice. This gap between understanding and practical application reflects broader challenges identified in the literature. An emergent implication of this finding is the need for focused efforts to translate knowledge into action through supportive frameworks and targeted interventions. One proven approach is the implementation of pilot projects, which have been instrumental in scaling NbSs globally. Notable examples include the Nature Investment Lab and the Agroecorex REDD Project in Brazil, which addresses legal barriers and costs associated with green infrastructure [8]. Similarly, the RISE Indonesia Project in Makassar City and the Southeast Asia Climate and Nature (SCENE) Coalition have successfully integrated green infrastructure to improve water management and increase green cover [51]. These small-scale implementations allow stakeholders to observe firsthand the positive impacts of NbSs on urban resilience to climate change. Adopting a similar approach in South Africa could gradually scale up the use of permeable pavements, fostering broader acceptance and implementation.

Findings from the CB-SEM analysis emphasize the dominant role of perception and sociocultural issues as primary barriers to the adoption of permeable pavements. Prominent among this group are unclear stakeholder duties, unclear public understanding of the concept, limited knowledge and expertise as well as the perception of NbSs as add-on options. This finding aligns with studies like Kawamoto et al. [29] and Santhanam and Majumdar [11], which stress the importance of public perception and awareness in the acceptance of urban infrastructure solutions. Particularly, sociocultural resistance, often stemming from limited understanding or misaligned priorities, creates substantial challenges. For instance, the lack of clear definitions, public awareness and the perception of NbSs as add-on options observed in this study reflects findings by Deely et al. [36], who showed that low public engagement often hinders the adoption of green infrastructure. Barriers such as unclear stakeholder duties and perceiving NbSs as optional rather than essential further complicate efforts to promote sustainable infrastructure [35]. When NbSs like permeable pavement are deemed optional (mostly as luxury or aesthetics) by the stakeholders, the tendency to prioritize traditional approaches to pavement construction might be high as this traditional approach might be perceived as more cost-efficient. This perception can transcend to limited funding and regulations to promote the use of NbSs like permeable pavement [32,35]. Focused education campaigns and community engagement initiatives have proven effective in encouraging public acceptance and understanding of nature-inspired solutions, such as permeable pavements. Portland's Green Streets Initiative in Oregon uses workshops, public meetings and educational materials to inform residents about the benefits of permeable pavements for stormwater management and flood reduction, which has been key to gaining public support in historically resistant neighborhoods. Similarly, the "Slow the Flow" campaign in London engages communities through public events, interactive workshops and online resources to promote sustainable stormwater management practices. These examples demonstrate the potential of well-executed education campaigns and community engagement to shift public perceptions, increase acceptance and create a supportive environment for NbS adoption. South Africa could adopt similar approaches to address the critical barriers identified in this study.

Governance issues are another critical factor, reflecting the absence of supportive policies and a lack of urgency among policymakers. This aligns with broader challenges in implementing NbSs in developing countries, as noted by Castelo et al. [37]. Although South Africa is among the leading African countries in terms of innovativeness [52], the embrace of sustainable concepts like NbS is still slow paced [53], leading to a lack of supportive policies and legislations. The competing priorities of municipalities and an uncertain economy, as existing legislative frameworks, can deter support for these sustainable initiatives and development of policies to drive their adoption in South Africa [54]. Sack et al. [2] previously noted that governance gaps often result in fragmented efforts and lack of coordination, making it difficult to integrate NbSs into urban planning. Additionally, the absence of clear and supportive policies exacerbates this issue, as municipalities may struggle to prioritize and fund such sustainable infrastructure solutions [35]. This underscores the need for deliberate and strategic policies that not only support the integration of NbSs but also encourage long-term investment in their development. For example, successful governance models in cities like Melbourne, Australia, demonstrate the potential benefits of clear policies and cross-sector collaboration. Melbourne's Water Sensitive Urban Design (WSUD) initiative has effectively integrated green infrastructure, including permeable pavements, into urban planning through robust governance structures that facilitate coordination between various city departments, stakeholders and communities [25]. This collaborative approach ensures that urban planning, environmental protection and public health objectives are aligned, thus facilitating the smoother adoption of green infrastructure solutions. Similarly, in the

Netherlands, the implementation of green roofs and permeable pavements has been made possible by supportive policies that prioritize environmental sustainability and resilience, demonstrating how well-coordinated governance frameworks can lead to the successful integration of NbSs in urban environments [34]. South Africa could draw inspiration from these international examples. The absence of specific regulatory frameworks designed to mandate or incentivize green solutions like permeable pavement construction can limit the integration of this system in urban areas [55]. Moreover, budget constraints in municipalities imply that several projects will compete for the limited available funds, and this can relegate the priority for sustainable approaches like permeable pavement construction within municipalities [56]. To address this issue, the Construction Industry Development Board (CIDB), the Council for the Built Environment (CBE) and the Green Building Council of South Africa (GBCSA) could work closely together to promote stronger partnerships with international organizations and cities that have successfully implemented NbSs. These collaborations could provide much-needed insights and grant access to cutting-edge technologies, methodologies and policy frameworks that support NbS implementation, such as permeable pavements.

Spatial concerns and infrastructure integration also emerged as significant challenges. Barriers such as urban space scarcity and poor city coordination align with findings from past studies. Space scarcity in South Africa, is driven by increases in the population and rapid urbanization coupled with competing land demands. With farmland, infrastructure and development projects competing for limited existing space, consideration for NbSs like permeable pavement is close to non-existent. Moreover, complex land ownership intricacies and emphasis on economic growth often hinder their implementation into these NbS initiatives [57,58]. Furthermore, with rapid urbanization and densification in South Africa, green infrastructure development is affected, and this has led to the increase in urban heat islands and negative impacts on biodiversity [59]. Asare et al. [9] also noted that fragmented coordination between city departments often impedes the adoption of sustainable infrastructure solutions. These challenges are further compounded by a lack of clearly defined roles and responsibilities among stakeholders involved in green infrastructure projects, as emphasized by Qi and Barclay [35]. Additionally, infrastructure integration faces challenges such as the absence of exemplar permeable pavement structures, which reduces the availability of real-world models to guide implementation [60]. The insufficient quantification of risk management efficacy further complicates decision-making, as stakeholders may struggle to assess the effectiveness of permeable pavements in managing stormwater and reducing flooding. This is consistent with findings from Qi and Barclay [35], who emphasized that the lack of thorough data on green infrastructure performance can cause hesitation among policymakers and urban planners. Moreover, limited time availability remains a barrier, with stakeholders often unable to dedicate sufficient time to planning, designing and implementing such solutions. Price [61] highlighted that time constraints, particularly in rapidly urbanizing areas, often lead to a preference for quicker, traditional solutions over sustainable alternatives. This backdrop highlights the importance of coordinated urban planning, exemplified by Singapore's integrated approach. Agencies like the Building and Construction Authority (BCA) and the National Parks Board (NParks) collaborate on the Active, Beautiful, Clean Waters (ABC Waters) program, integrating NbSs such as permeable pavements into urban environments [1]. South Africa's municipalities, in partnership with the GBCSA, could similarly align urban planning roles to incorporate permeable pavements within broader development projects effectively.

The study found that while the finance-related challenges (i.e., lack of financial resources and absence of financial incentives) might affect the use of permeable pavement, they do not significantly impact the level of usage currently. This is as a result of other

factors that are more pressing within the country's urban landscape. However, past studies have noted that while permeable pavement might have a higher initial cost as a result of the need for specialized materials as well as underlying drainage system, they do offer lower maintenance costs in the long run. This is mostly because they require less maintenance when compared to conventional pavements and offer better stormwater management [62,63]. As such, by employing this pavement system in urban areas, South Africa stands a chance of attaining long-term financial gain as against the use of the traditional pavement construction system.

7. Conclusions and Recommendations

Based on the findings, this study concludes that there is a high level of awareness and understanding of the concept of permeable pavements among South African built environment professionals. However, the practical application remains low, highlighting the infancy stage of this nature-inspired solution in urban infrastructure within the country. Further analysis emphasized that perception and sociocultural issues, governance challenges, spatial concerns and infrastructure integration issues are among the most significant barriers that need to be addressed if the nation is to successfully integrate permeable pavements as a viable NbS in urban planning. This study is timely and relevant given the growing pressures on urban areas to tackle the negative effects of climate change, including flooding and water scarcity, issues that have particularly affected major cities, such as Johannesburg, Cape Town, Durban, Pretoria and several others. Additionally, the findings of this study contribute to the ongoing discourse on sustainable urban development and provide a critical foundation for policymakers, urban planners and industry professionals to develop strategies that foster the widespread adoption of permeable pavements, ultimately improving the sustainability and livability of South African cities.

Several recommendations are proposed by the authors to address the key challenges identified in this study. First, public awareness should be raised in major South African cities, particularly those most impacted by urban flooding and water scarcity. This can be done through community engagement, which can be promoted through targeted educational campaigns that highlight the benefits of NbSs, such as permeable pavements, for stormwater management and flood risk reduction. Key construction bodies like the Council for Built Environment and the Construction Industry Development Board with the support of the government through the Ministry of Works can also champion the use of these NbSs through workshops designed to sensitize the built environment stakeholders and public on the inherent benefits of this sustainable method of pavement construction. Moreover, industry collaboration with local governments can go a long way in improving public awareness and buy in by implementing pilot projects to demonstrate the practicality and advantage of this method of pavement construction. Second, governance frameworks must be strengthened to create a conducive policy environment for NbS integration. While initiatives, like the Green Cities Initiative, the City of Cape Town's Green Infrastructure Program and Durban's Municipal Climate Protection Programme (MCP), have made progress, a unified policy approach at both national and local levels is still needed. Aligning these programs with national strategies and promoting collaboration between cities will enhance their effectiveness, while reinforcing regulatory frameworks will provide stability for NbS adoption. It is therefore imperative to establish regulatory standards and provide incentives such as subsidies for contractors and municipalities implementing these initiatives for sustainable infrastructure, as well as grants that will drive the use of permeable pavement and other beneficial NbSs. Third, to address spatial and integration challenges, urban planning efforts must adopt a more integrated approach. Coordination between municipal departments, urban planners and architects is essential for ensuring that NbSs,

such as permeable pavements, align with existing infrastructure and land-use policies. Additionally, involving local communities in the planning process will help ensure that NbSs are contextually relevant and sustainable in the long term.

Theoretically, this study contributes to the limited body of knowledge on the integration of permeable pavements in urban infrastructure, particularly within the South African context. Practically, the findings can guide practitioners in the built environment, such as urban planners and policymakers, in identifying key obstacles that hinder the adoption of permeable pavements. Despite the contributions of this study, a few limitations are worth noting. This study is primarily focused on the perspectives of built environment professionals. While this offers key insights from a technical standpoint, future studies could benefit from incorporating the viewpoints of other stakeholders, including local communities, government agencies and private sector actors. This multi-stakeholder approach would help to capture a more holistic view of the challenges and opportunities associated with NbS implementation. The study also focused on the South African context, and while the findings are valuable within the country, they may not be directly transferable to other developing countries with similar urban challenges. Future research could consider cross-country comparisons to explore whether the CB-SEM-identified and -prioritized challenges in this study are unique to South Africa or if they also apply to other nations facing similar socio-economic and environmental pressures. Although the sample size for the study was considered adequate for the type of analysis conducted, there is a possibility of getting a much deeper understanding of the situation with a much larger sample. Therefore, future studies can explore other sampling methods that can help gather more feedback from a larger sample size. Finally, this current study focused on the hindrances to the effective utilization of permeable pavement in South Africa. Future studies can explore this further through a case study approach by monitoring the performance of constructed permeable pavements, evaluating their cost benefits and their life-cycle and investigating the viability of developing sponge cities in the country.

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