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Systematic Review

Process-Based Mechanisms and Lifecycle Mitigation of Clogging in Interlocking Permeable Pavements: Critical Insights for Sustainable Urban Drainage Systems

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Abstract

Interlocking permeable pavements (IPPs) are increasingly adopted within sustainable urban drainage systems to reduce runoff, improve water quality, and strengthen climate-resilient urban infrastructure. However, clogging remains the principal constraint on their long-term hydraulic performance and wider implementation. This review synthesises current evidence on clogging mechanisms, hydraulic decline, and lifecycle mitigation strategies for permeable interlocking concrete pavements (PICPs), concrete grid pavements (CGPs), and plastic grid pavers (PGPs). The literature is dominated by PICP studies, with CGP and PGP underrepresented, restricting typology-specific assessment. Sediment accumulation within joints, grid openings, bedding layers, and near-surface interfaces is consistently identified as the primary clogging mechanism, while traffic, rainfall-runoff loading, biological processes, pollutant retention, and sediment inputs from adjacent impervious surfaces further influence hydraulic deterioration. The findings indicate that hydraulic performance is influenced not only by pavement age but also by interactions among pavement design, filler or joint material, drainage configuration, construction quality, sediment exposure, monitoring, and maintenance. Effective mitigation therefore requires lifecycle management, encompassing source control, pretreatment, appropriate material selection, construction quality assurance, routine hydraulic monitoring, and timely preventive and restorative maintenance. Future research should prioritise standardised clogging assessment protocols, improved laboratory–field integration, targeted investigation of CGP and PGP, biological and pollutant-linked clogging processes, climate-driven rainfall extremes, and decision-support.

Keywords: permeable interlocking concrete pavements (PICPs); concrete grid pavements (CGPs); plastic grid pavements (PGPs); clogging mechanisms; clogging mitigation strategies; stormwater management; sustainable drainage systems (SuDS)

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Academic Editors: Nitin Muttil and Upaka Rathnayake

Received: 7 July 2026
Revised: 5 August 2026
Accepted: 9 August 2026
Published: 20 August 2026

1. Introduction

As cities continue to expand due to urbanisation, natural and pervious land surfaces are being replaced with more impervious materials such as asphalt, concrete, and roofing. This transformation alters the natural hydrology by reducing infiltration and increasing runoff generation, thereby making urban areas more vulnerable to flooding and water quality issues [1]. During rainfall events, traditional pipe-based drainage systems are expected to collect and convey runoff safely to receiving waters [2]. However, these systems are often challenged by increasing runoff volumes and inadequate capacity. This often leads to surface water flooding and combined sewer overflows (CSOs) [1,3] with subsequent environmental and public health concerns.

Sustainable drainage systems (SuDS) have become a promising solution or complementary approach to conventional drainage systems for managing urban stormwater. Rather than quickly conveying runoff, SuDS control flow at the source by mimicking natural processes, including infiltration, storage, detention, and pollutant removal [4,5]. Among SuDS components, permeable pavement systems (PPSs) are particularly advantageous due to their combined hydraulic and structural functions [4]. PPSs reduce runoff volumes, attenuate peak flows, and promote groundwater recharge [6,7], while improving water quality through filtration, sediment retention, and pollutant removal [8–10]. In addition, they provide adequate load-bearing capacity for light to moderate traffic applications [11,12].

Permeable pavement systems typically comprise a permeable surface layer overlying bedding and sub-base aggregate layers that facilitate infiltration, temporary storage, and controlled release of stormwater, depending on site conditions (see Figure 1) [4,13]. Based on the water management system, PPSs are designed as full (Type A), partial (Type B), or no-infiltration (Type C) systems. Partial and no-infiltration designs incorporate an impermeable liner and underdrain to prevent interaction with underlying soils and to convey stored water. Type B or C is best installed on sites with low permeability or contaminated soils, or where the groundwater is near the surface and needs to be protected [4,14].

Permeable pavement systems are also composed of either monolithic surfaces such as permeable concrete (PC) and porous asphalt (PA), or modular surfaces such as permeable interlocking concrete pavements (PICPs), concrete grid pavers (CGPs), and plastic grid pavers (PGPs) [6,15]. In this review, PICPs, CGPs, and PGPs are collectively referred to as interlocking permeable pavements (IPPs). PICPs are generally made of impervious concrete blocks with gaps through which stormwater infiltrates into the underlying layers. Similarly, CGPs/PGPs are made of concrete or plastic grids with gaps in between, filled with either aggregate, soil or grass where infiltration occurs [16]. IPPs are widely used in car parks, pedestrian areas, residential driveways, and light–moderate traffic environments [6]. Unlike PC/PA, where stormwater infiltrates through pores distributed across the pavement surface, infiltration in IPPs occurs mainly through gaps between blocks [16]. This distinction is important, as it influences how sediments are trapped, how clogging develops, and how maintenance practices are applied.

Although IPPs provide multiple benefits, their wider adoption is often limited by clogging and subsequent decline in hydraulic performance and long-term serviceability [17,18]. Clogging in IPPs is the progressive reduction in infiltration capacity caused by the accumulation of sediments, organic matter, traffic-related particles, and other materials within the gaps through which stormwater flows [19–22]. In PC and PA, clogging occurs mainly within the surface pores distributed across the pavement matrix [11,23]. In contrast, clogging in IPPs is concentrated at the surface joints and may subsequently extend into the underlying layers, particularly the bedding, if maintenance is neglected [16,22,24]. Because infiltration in IPPs occurs mainly through gaps rather than across the entire pavement surface as in PC or PA, the clogging mechanism differs significantly in IPPs compared with PC/PA (see Figure 1). Infiltration in IPPs is not only governed by sediment characteristics, but also by factors such as joint width, joint filling material, opening geometry, vegetation, construction quality, contributing runoff, and maintenance practices [25–30]. Findings from PC or PA clogging studies may not be assumed to apply directly to IPPs.

https://doi.org/10.3390/w18162039

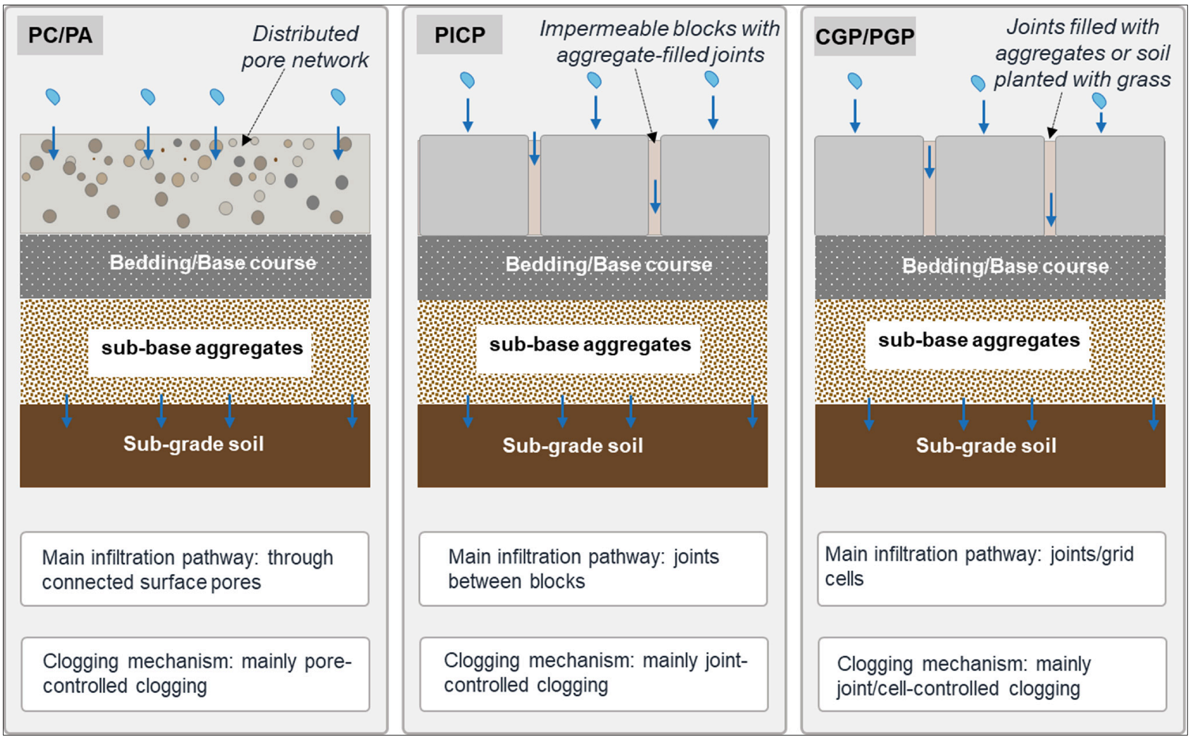

Figure 1. Conceptual comparison of clogging pathways in monolithic permeable pavements and interlocking permeable pavements. Blue arrows indicate the direction of stormwater infiltration through the surface openings, bedding/base layer, sub-base aggregates and underlying sub-grade soil. In PC and PA, clogging is primarily pore-controlled, whereas in IPPs, clogging is predominantly governed by the condition of the joint material, grid voids, or filling material [11,16,20,23].

Current understanding of clogging mechanisms in IPPs remains limited and inconsistent. While some studies report sustained hydraulic performance over extended periods with minimal maintenance [12,31,32], others document rapid declines in infiltration capacity within a few years of operation [17,18,33]. For example, Bean et al. [34] found a significant reduction in infiltration rate (50 mm/h) in CGP after 20 years without maintenance, whereas Rossetto et al. [32] reported that a CGP parking lot of comparable age (15 years) maintained infiltration rates well above regulatory thresholds (97 mm/h) without intervention. These contrasting findings highlight significant gaps in understanding the processes governing clogging and the effectiveness of mitigation strategies.

Though permeable pavements have been widely reviewed, the clogging behaviour of IPPs remains insufficiently synthesised as a distinct built-environment performance issue. Existing reviews have largely treated clogging in permeable pavements generically or have focused exclusively on monolithic systems, where infiltration occurs through distributed surface pores [11,17,23,35–37]. This limits their transferability to IPPs, where infiltration, sediment trapping, and maintenance response are largely governed by joints, bedding materials, opening geometry, fill media, vegetation, traffic exposure, and construction quality [20,22,27,28]. This review therefore provides a focused synthesis of clogging in IPPs, integrating evidence across PICPs, CGPs, and PGPs. Specifically, this review aims to (i) synthesise the mechanisms of clogging in IPPs; (ii) examine how design and construction factors influence clogging susceptibility; (iii) evaluate monitoring and assessment approaches used to detect and quantify clogging; and (iv) critically review maintenance strategies for preserving or restoring hydraulic performance. By focusing on both clogging mechanisms and phase-specific mitigation measures, this review supports improved design, maintenance and long-term reliability of IPPs as climate-resilient urban drainage surfaces.

2. Sources and Methods

This study was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [38], with the literature systematically retrieved from Scopus and Web of Science (WoS) and supplemented by Google Scholar to ensure comprehensive coverage of peer-reviewed research [39,40]. This review focused on three IPP types: permeable interlocking concrete pavements (PICPs), concrete grid pavers (CGPs), and plastic grid pavers (PGPs). Using consistent keyword strings and advanced search functions across databases, peer-reviewed English-language studies published between 1 January 2000 and 31 December 2025 were identified. The start date reflects the expansion of permeable pavement research from 2000 onwards, following earlier foundational work [14]. Additionally, relevant studies published beyond the review period were included in Sections 3 and 4. Studies were included if they addressed clogging processes, infiltration decline, sediment accumulation, maintenance effectiveness, or long-term hydraulic performance in IPPs. Exclusion criteria comprised studies not specific to IPPs, for example, those focused solely on water quality or other performance metrics without relevance to clogging, and grey literature. Furthermore, where studies reported multiple permeable pavement types, only findings relevant to IPPs were extracted. Standardised search strings were applied across databases (Scopus: TITLE-ABS-KEY; WoS: TS) combining IPP-related terms (e.g., “permeable interlocking concrete pavement”, “concrete block permeable pavement”, “interlocking concrete pavers”, “concrete grid paver”, and “plastic grid pavers”) with performance-related terms (e.g., clogging, blockage, infiltration loss, sediment accumulation, long-term performance, service life, and maintenance techniques) and constrained to the review period. The study selection process, including inclusion and exclusion criteria, is summarised in Figure 2.

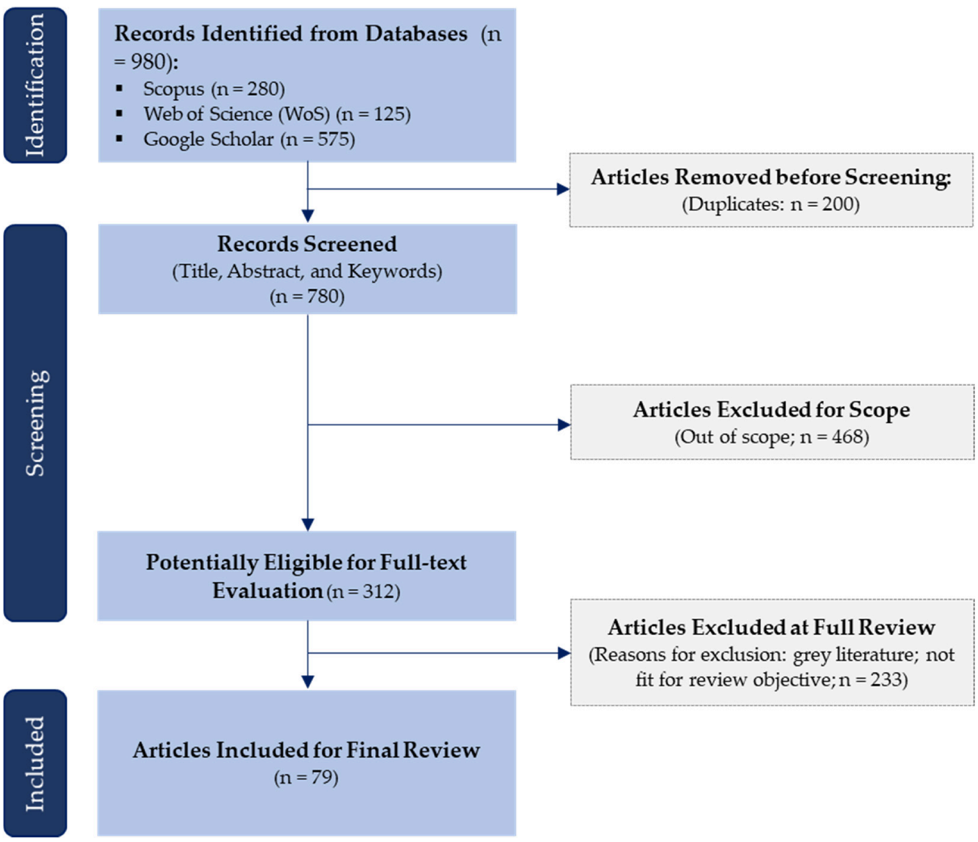

Figure 2. PRISMA flow diagram of the literature search and selection process for studies on clogging in IPPs. Search strings used: Scopus: TITLE-ABS-KEY (“permeable interlocking concrete pavement”

OR "interlocking concrete block pavement" OR "interlocking concrete pavers" OR "concrete block permeable pavement" OR CBPP OR ICBP OR "permeable pavers") AND (clogging OR "infiltration loss" OR "sediment accumulation" OR "long-term performance" OR "service life" OR "maintenance techniques") AND PUBYEAR > 1999 AND PUBYEAR < 2026; and Web of Science: TS = ("permeable interlocking concrete pavement" OR "interlocking concrete block pavement" OR "interlocking concrete block pavers" OR "concrete block permeable pavements" OR CBPP OR ICBP OR "permeable pavers") AND TS = (clogging OR "infiltration loss" OR "sediment accumulation" OR "long-term performance" OR "service life" OR "maintenance techniques") AND PY = (2000–2025). n denotes the number of records retrieved.

The search identified 980 publications (see Figure 2). After duplicate removal, records were screened by title, keywords, and abstract, followed by full-text assessment for eligibility, resulting in a total of seventy-nine articles for detailed analysis (see Supplementary Material, Table S1). For each included study, the following information was extracted: author and year, country, study type, IPP type, pavement age or simulated service period, sediment or clogging input, assessment method, hydraulic metric, reported performance change, maintenance status, clogging drivers, key findings, and reported clogging mitigation measures.

3. Analysis and Discussion

Seventy-nine articles on IPPs in the context of clogging were analysed for this review. The selected articles were synthesised across the following themes: evidence base and publication trends, clogging mechanisms, mitigation measures across design, construction, and monitoring, assessment and maintenance stages, and critical knowledge gaps.

3.1. Evidence Base and Publication Trend

3.1.1. Temporal and Geographic Distribution

Figure 3 summarises the geographical and temporal distribution of included studies. The evidence base was geographically uneven, with studies concentrated mainly in North America, particularly the United States and Canada, while fewer studies were identified from Europe, Australia, South America and Asia. Temporally, publications were recorded between 2002 and 2025, with relatively limited activity before 2013, followed by a noticeable increase from 2013 onwards. Peaks were observed around 2013, 2018, and 2023, although publication output fluctuated over the years. Overall, the upward trend suggests growing research interest in the topic, but the uneven geographical distribution indicates that current findings may be shaped by a limited number of regional contexts.

3.1.2. IPP Types

A further limitation is the dominance of clogging studies on PICP (see Figure 4). PICP is widely used and therefore better represented in the literature, but CGP and PGP remain comparatively underrepresented [6,12,16]. This imbalance means that conclusions about IPP clogging are more robust for PICP than for grid-based systems. A possible reason for the limited studies on grid-based pavements may reflect their design and specific application, which are mainly limited to parking lots and other applications with mild exposure to traffic [6,22]. The large voids (20–50% for CGP, 90–98% for PGP) in these pavement surfaces, usually filled with gravel/vegetated topsoil [16], while good for infiltration, may compromise their overall structural strength, compared to their PICP counterpart. Furthermore, these types of pavements are more suitable in countries with colder climates to sustain the vegetated soil in the gaps. In hotter climates, the vegetation may die off due to heat stress that could lead to erosion of the soil in the voids during extreme rainfall events [16,22].

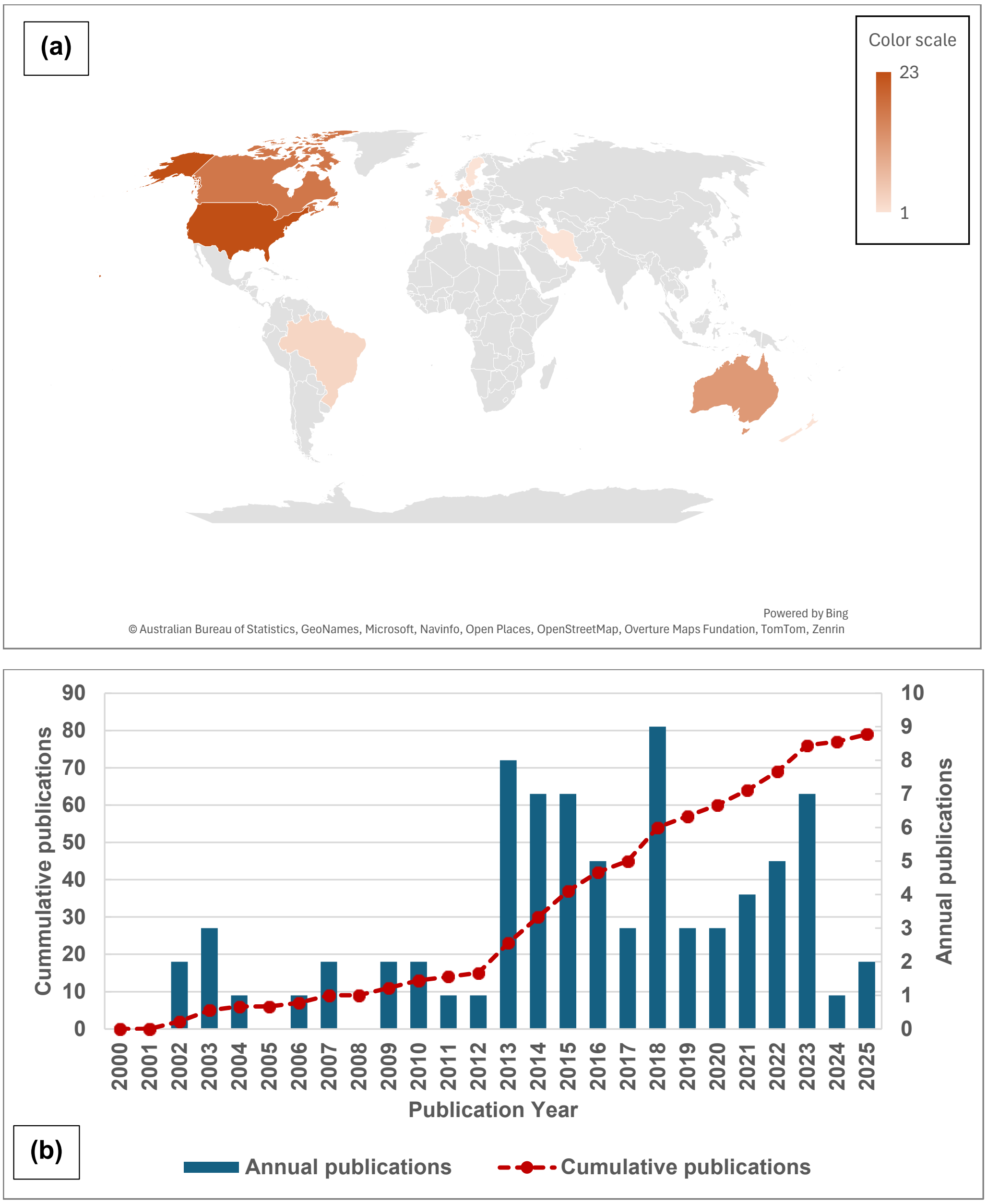

Figure 3. Distribution of published studies over the review period (2000–2025): (**a**) geographical distribution by country; (**b**) temporal distribution of published articles.

3.1.3. Drivers of Clogging

Several interacting drivers of IPP clogging were identified across the literature, including sediment inputs, organic and biological material (e.g., organic matter, leaf litter, and grass in joints), traffic-related particles, high run-on ratios, winter sanding and de-icing materials, oil and grease, construction-related fines, and inappropriate joint or bedding materials [20,22,27,28,41–44]. Sediment accumulation was the most frequently reported cause of hydraulic decline. This was followed by biological and traffic-related clogging. However, evidence further revealed clogging as the combined effect of sediment source, particle size distribution, hydraulic loading, pavement geometry, traffic loading, construction quality, and maintenance history [16,25,26,28,30,45–48]. Fine sediment can penetrate the joint aggregate and bedding layer, gradually reducing void space and hydraulic conductivity [22,28,44,47]. In contrast, coarser sediment and organic debris may accumulate at the surface, forming crusts or mats that reduce the effective opening area of joints or cells [18,22,47]. Traffic loading can further compact joint material, knead sediment into the pavement surface/joint, and generate fine particles from tyre, road, and brake wear [26–28], all of which contribute to clogging. Additionally, runoff from adjacent impervious areas can concentrate sediment loading at the upgradient edge of the permeable pavement, causing spatially uneven clogging [41,44,49]. Poor construction quality, particularly the use of unwashed aggregate or sand-rich bedding and joint materials, can also cause early hydraulic failure that maintenance may not fully reverse [20,25,46,48,50].

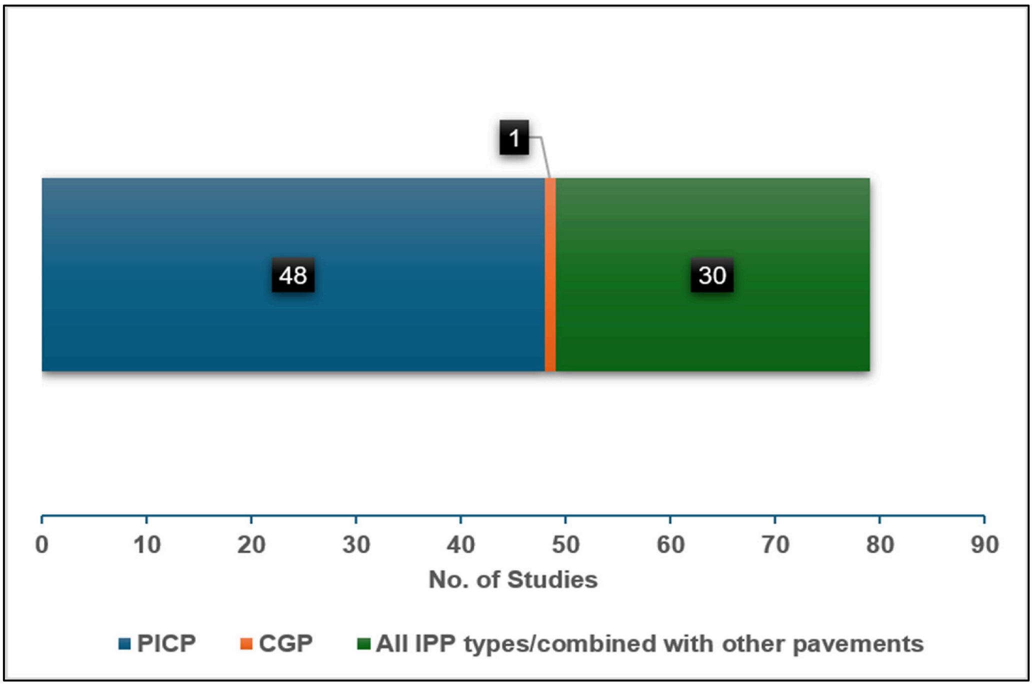

Figure 4. Number of studies based on IPP types.

3.2. Clogging Mechanisms

Clogging in IPPs is a progressive reduction in infiltration capacity due to the accumulation of sediments, organic matter, and others within the pores and joints of the pavement. This phenomenon constitutes one of the primary limitations affecting the long-term hydraulic performance of IPPs [17]. Research on clogging mechanisms in IPPs has predominantly focused on physical processes, that is, the mechanical trapping and accumulation of inorganic sediment particles within joints [22,28,51]. This may be due to the immediate and measurable impacts of clogging mechanisms on infiltration capacity, the relative ease of quantifying sediment accumulation, and the direct relationship between sediment particle characteristics and hydraulic performance loss [28,52]. Biological clogging, which results from biofilm formation, plant litter, organic matter decomposition, and microbial activities [53–55], may be more complex to quantify. Clogging in IPPs has thus received less research attention despite its potential long-term impact on the performance of IPPs. Further research is needed to understand the effects of biological clogging on IPPs.

The literature revealed several interrelated factors that govern clogging in IPPs, including the type of IPP and construction quality [25,26,51], particle size distribution of sediments [19,28,41], gap size between paver blocks [26,56], age of pavement [18,46], traffic intensity [27,28,57], location of IPP installation [28,58], amount and concentration of contributing drainage area [30,45,47,59], rainfall intensity and duration [43,60–62], and winter snow ploughing/maintenance activities [14,20,63]. Pollutant accumulation may also contribute to clogging in IPPs. These pavements capture pollutants, including heavy metals, hydrocarbons, nutrients, suspended solids, and microplastics, through filtration, sedimentation, adsorption, ion exchange, and retention within surface joints, bedding, aggregate layers, and geotextile interfaces [10,14,16]. Retained materials can increase particulate load within the pore structure and lead to surface crust formation, pore filling, or geotextile and bedding interface clogging [64]. However, direct studies quantifying the impact of microplastic retention or other pollutants on permeable pavement clogging remain scarce [65]. Understanding these factors is crucial for not only predicting long-term performance but also for designing effective maintenance strategies. Significant inconsistencies exist in clogging behaviour across studies, with marked disparities between laboratory and field studies, and among IPP types (see Figure 5, Table 1). These inconsistencies underscore the complexity of clogging behaviour in IPPs and highlight critical gaps in current understanding. Laboratory findings from Kamali et al. [33] reported complete clogging of PICP after 7 years under accelerated conditions, suggesting severe performance decline. In contrast, the findings of Alsubih et al. [66] showed about a 6% decrease in total outflow after 10 years of clogging without maintenance, with no observed surface runoff, while Tota-Maharaj et al. [67] found approximately 40–50% reduction in hydraulic conductivity over 10 years. Similarly, Pezzaniti et al. [18] reported 59–75% infiltration rate reduction after 35 years of clogging simulation, yet systems remained operational with 89–97% sediment retention. These inconsistencies could be related to differences in sediment loading protocols, IPP design, and operational conditions in laboratory settings, making it difficult to establish consensus on the expected end of service life of these pavements. The disparities in in situ findings emanate from different factors such as construction quality, pavement location, maintenance efforts, and contributing impervious runoff [28,45,46]. While some studies have reported that IPPs can remain effective for many years without maintenance [12,22,49], others have reported otherwise. For example, Al-Rubaei et al. [20] observed that a 6-year-old aggregate-filled PICP outperformed a 1-year-old PICP, attributed to excessive fines in joint-fill aggregates and organic matter accumulation near forested areas in the newer installed pavement. Tirpak et al. [68] also found a 96% decline in surface infiltration rate of PICP of a relatively new installation due to high sediment loading onto the permeable pavement and lack of maintenance. These findings highlight how construction quality and site-specific factors can override age-related clogging behaviour of PICP. Additionally, long-term hydraulic performance varies between CGP, PGP, and PICP systems, with vegetation emerging as a critical differentiating factor. For instance, Rossetto et al. [32] reported that CGP maintained high infiltration rates (>97.2 mm/h) under continuous operation for 15 years without maintenance, demonstrating no significant clogging effect. Their study attributed this resilience to the presence of soil cracks, plant roots, and insect activities within CGP voids that counteracted clogging by maintaining preferential flow pathways and preventing complete pore blockage. The biological activity provided a self-maintenance mechanism that is absent in PICP, where field observations showed infiltration rate decline to 20–25% of initial capacity over a similar timeframe [49]. Al-Rubaei et al. [20] further noted that aggregate-filled CGP systems with minimal fines exhibited higher infiltration capacities than PGP, though both vegetated CGP and PGP systems demonstrated superior long-term performance compared to PICP, emphasising that the combination of larger void spaces, vegetation, and appropriate joint-filling materials critically influences functionality. These inconsistencies reveal that clogging in IPPs depends on complex interactions and factors mentioned earlier, which are inadequately captured by current literature, particularly in accelerated testing methods.

Furthermore, although clogging in IPPs is initiated at the pavement surface, within joints, grid openings, bedding, and geotextile interfaces [22,28,51], its influence on hydraulic performance may differ among Type A, B, and C systems [4,14,34]. Studies comparing clogging progression across these configurations are limited; therefore, the interpretation is based on functional differences rather than configuration-specific clogging findings.

In Type A systems, where runoff is designed to infiltrate the subgrade, surface, or bedding layer, clogging reduces the rate at which water enters the pavement and underlying soil. If fine particles migrate below the surface, reduced exfiltration at the sub-base–subgrade interface may occur, potentially reducing groundwater recharge where subgrade infiltration is intended. In Type B systems, which combine partial infiltration with an underdrain, surface clogging may limit the inflow into the aggregate reservoir. Deeper clogging within the bedding, geotextile, or sub-base may delay the drawdown and increase the reliance on the underdrain. Consequently, Type B systems may continue to discharge water after partial surface clogging; however, their infiltration, detention, and groundwater recharge benefits may be diminished. In Type C systems, characterised by lined pavements and the absence of subgrade infiltration, clogging may impede water entry into the storage layer and underdrain. This results in increased surface ponding, runoff bypass, reduced storage utilisation, increased sensitivity to contamination, and issues related to bedding materials, geotextile clogging, and underdrain blockage.

These configuration-specific differences suggest that clogging assessment should not rely solely on surface infiltration testing, where subsurface drainage is important. In particular, for systems with underdrains, additional indicators such as outflow start time, outflow duration, drawdown time, and underdrain discharge response may provide useful evidence of how clogging affects the overall hydraulic function [66,67]. Further research is required to assess the impact of clogging on system configuration. This will enable practitioners to determine the most suitable configuration for their specific long-term drainage requirements.

Table 1. Summary of selected studies and key findings on clogging investigation in IPPs.

Study Type	IPP Type	IPP Age	Key Findings	Sources
Field	PICP	8 years	1. PICP system was very effective at retaining sediments from stormwater runoff	[22]
			2. Overall infiltration performance of PICP remained satisfactory after 8 years of continuous service	
Field (accelerated)	PICP		1. PICP surface infiltration rates decreased significantly from over 10,800 mm/h to approximately 250 mm/h after clogging	[52]
Laboratory	CBPP	10 years	1. Clogging led to 6.4% decrease in total outflow and outflow rate, and 10% increase in outflow start time	[66]
			2. No surface runoff was observed, indicating efficient operation for at least 10 years without maintenance	
Field	PICP	1–6 years	1. Infiltration performance of PICP decreased significantly over its service life, primarily due to the entrainment of fines into pores and aggregates	[42,49]
			2. The long-term in situ infiltration performance and its decline are dependent on the grain size of aggregates used for joint filling, and partly on the ratio of openings and pore size of blocks	
			3. Infiltration rate decreases steadily after installation but stabilises between 20–25% of initial infiltration rate after approximately 10 years	

Table 1. *Cont.*

Study Type	IPP Type	IPP Age	Key Findings	Sources
Laboratory	PICP	7 years	1. PICP was completely clogged after 7 years	[33]
			2. Despite clogging, over 90% of all tested pavements met the required infiltration standards for their respective regions	
Laboratory	PICP	10 years	1. Hydraulic conductivity of PICP reduced by 44–51% over 10 years due to clogging	[67]
			2. Sub-base aggregates had very little influence on the clogging behaviour of PICP	
Field	CGP	15 years	1. CGP maintained high infiltration rate that exceeded the minimum requirement of 97.2 mm/h without maintenance for 15 years	[32]
			2. Vehicular traffic compaction negatively impacted infiltration capacity of CGP leading to reduced infiltration rates	
			3. The presence of soil cracks, plant roots, and insect activities within CGP voids contributed to maintaining infiltration capacity, counteracting clogging	
Laboratory and Field	PICP	35 years	1. Surface infiltration capacity reduced by 59–75% with a mean sediment retention of 89–97%	[18]
			2. Maintenance on the pavement surface achieved only about 12% difference to sediment concentration in the outflow	
			3. In situ observation showed high infiltration rate in locations less prone to sediment and very low infiltration rate in locations with high coarse and organic sediment loads	
Field	PICP	1–12 years	1. Infiltration capacity of PICP decreased with pavement age due to a combination of evolving construction practices, maintenance, and gradual clogging by sediment	[46]
			2. PICP showed 100% efficiency in sediment retention (total suspended solids)	
Field	CGP, PICP	1 to 14 years	1. Surface infiltration was reduced due to lack of regular maintenance and inappropriate joint filling materials, with vegetated CGP showing higher infiltration capacities than gravel-filled CGP	[20]
			2. The long-term hydraulic performance was significantly influenced by the type and age of the system, type of joint filling material, and distance from the pavement edge	

3.2.1. Clogging Mechanism in PICP

Clogging in PICP is primarily a joint-controlled process because stormwater infiltrates through aggregate-filled gaps between otherwise impermeable blocks [16]. In newly constructed systems, high surface infiltration capacity is maintained by open joint voids and clean bedding aggregates [4,14,69]. As runoff enters the joints, sediment is progressively trapped at the surface–joint interface, within the joint aggregate matrix and, where fine particles migrate deeper, at the bedding or geotextile interface [22,47,53,57].

The initial stage of clogging often involves partial filling of joint voids without visible surface ponding (see Figure 6). At this stage, infiltration capacity may remain above regulatory or design thresholds even though sediment has begun to accumulate [12,70]. Continued sediment input can produce a denser surface crust, reducing the effective porosity and opening area of the joints [49,52]. As the surface layer becomes increasingly blocked, infiltration becomes slower, ponding becomes more likely, and runoff may begin to bypass the pavement surface. This process could further extend into the bedding layer, where the majority of the sediments are retained [22]. At this stage, if maintenance is neglected, the pavement may behave like a traditional impervious pavement where ponding on the surface would be visible. Other studies have shown that this stage can stabilise rather than progress to hydraulic failure. Borgwardt [49] suggested that infiltration performance of PICP declines during service life but may stabilise at residual capacity. Similarly, Wang et al. [71] reported that PICP clogging evolves through three stages: rapid clogging, transition and stabilisation. In their study, permeability decreased non-linearly as particles accumulated, indicating that clogging is fastest early when pore space remains available, before the system approaches a lower, stable hydraulic state. These findings suggest that PICP clogging does not always decline linearly to blockage; infiltration may decrease, and then enter a transitional phase and stabilise at a lower or near-failed hydraulic state depending on sediment load, particle size distribution, pore structure, rainfall loading, and maintenance condition. However, residual infiltration capacity may fall below design or regulatory requirements, so stabilisation should not be interpreted as satisfactory long-term performance without monitoring and maintenance.

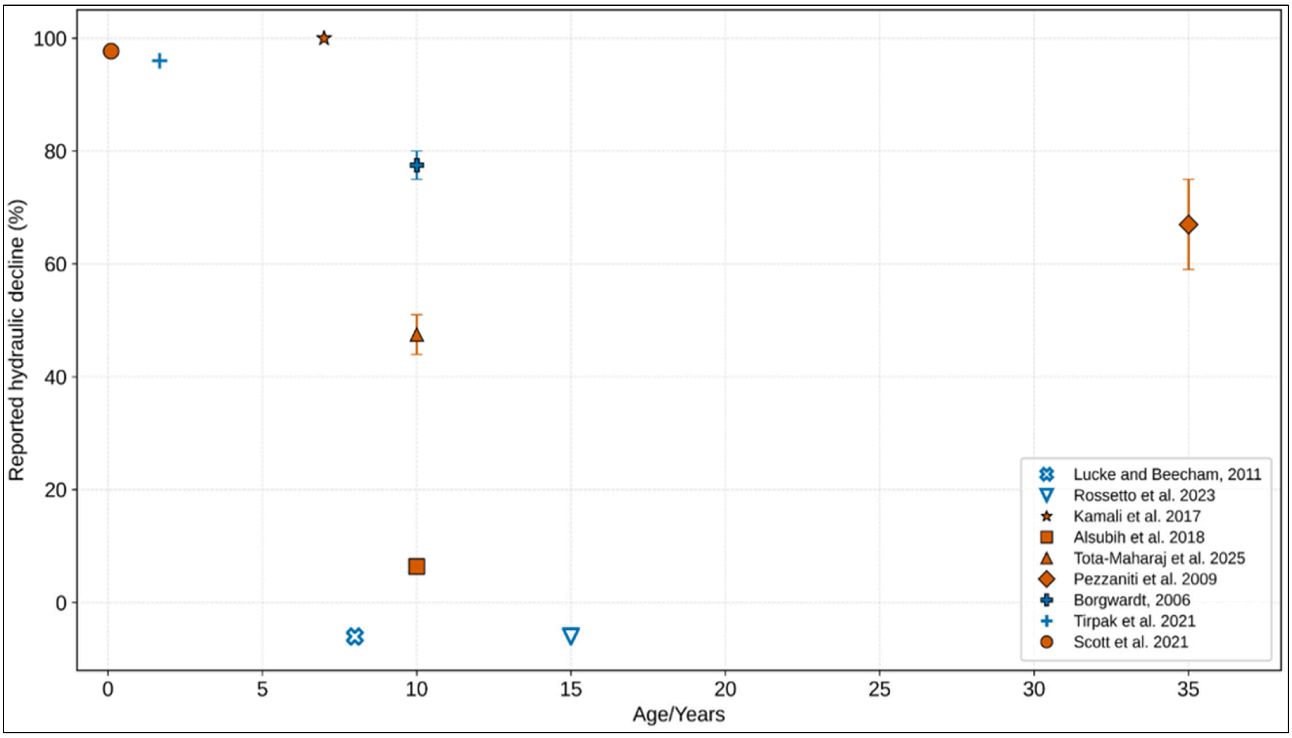

Figure 5. Reported hydraulic performance decline for selected IPP studies. Values are shown as reported percentage reduction where initial and final surface infiltration rates were available. Vertical lines with horizontal caps indicate the reported range of hydraulic decline where minimum and maximum values were available. Differences between studies reflect IPP type, sediment loading, particle size distribution, construction quality, test method, maintenance history, and drainage context [18,20,22,32,33,48,51,65,66].

The particle size distribution has a significant effect on the clogging process. For example, Nichols and Lucke [28] identified 251–550 µm as being associated with most sites having the lowest infiltration rates. This size range is particularly critical, as the particles are small enough to enter joints and penetrate deep but also large enough to form a stable crust across pore throats that could subsequently trap finer sediments. Fine particles (<0.063 mm) represent another critical size fraction of particular interest when examining clogging processes in PICP. Al-Rubaei et al. [20] noted that sediments less than 0.063 mm were critical to the infiltration capacity of PICP installations. Their study showed that a one-year-old PICP site containing a large quantity of fines in joint material had the lowest infiltration capacity (108 mm/h) compared with an older PICP site with fewer fines in the joint filling material (240 mm/h). Particles up to 1.18 mm and larger also play a critical role in the clogging dynamics of PICP. Nichols et al. [43] found that natural sediment (1.18 mm) caused a surface infiltration reduction of more than 88% compared with finer sediments in accelerated laboratory testing. The inclusion of larger sediment particles produced considerably different clogging behaviour in PICP models compared with samples where larger particles were removed.

Hill and Beecham [41] further emphasised the effects of the order of clogging in PICP joints, that is, whether fine or large particles pass through the pavement joints/layers first. Their results demonstrated that PICP displayed a smaller reduction in infiltration rate when coarse sediments were applied prior to finer sediments, compared with the reverse sequence. This suggests that PICP clogging mechanisms vary fundamentally with sediment size application order. That is, if coarse sediment accumulation occurs first, followed by finer sediments, this could lead to minimal surface infiltration reduction because the coarse particles tend to create a protective filter. In contrast, if finer sediments accumulate first, followed by coarse sediments, this could result in a large reduction in surface infiltration rate as the fine particles deeply penetrate the joints and are locked in place by overlying coarse sediments.

Furthermore, the correct joint material specification is critical for both initial hydraulic performance and long-term clogging resistance, as it provides sufficient void space for infiltration while creating a filter matrix that preferentially traps sediment in the upper joints, facilitating easier removal during maintenance activities [51]. Danz et al. [59] found that removal and replacement of aggregates between PICP joints resulted in more than a 200% increase in infiltration capacity, demonstrating that the joint material could serve as both the primary infiltration zone and clogging location.

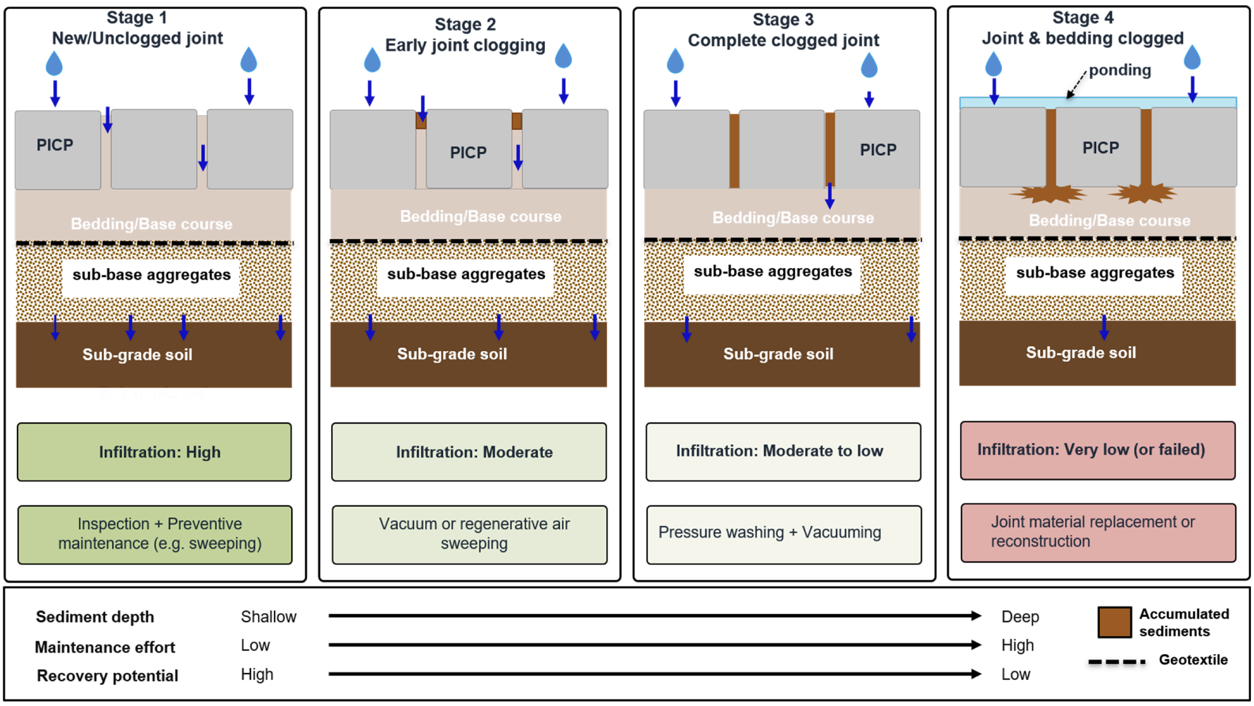

Figure 6. Conceptual progression of joint-controlled clogging in PICP, linking sediment accumulation depth with hydraulic decline and maintenance intensity. Blue arrows indicate the direction of stormwater infiltration through the surface openings, bedding/base layer, sub-base aggregates and underlying sub-grade soil. The progression from clean joints to surface crusting, joint filling, bedding migration, and ponding is consistent with reported field and accelerated clogging observations [22,41,43,49,52,66].

3.2.2. Clogging Mechanism in CGP/PGP

Clogging mechanisms in CGP and PGP generally follow a pattern similar to PICP, with progressive sediment accumulation reducing surface infiltration pathways and subsurface hydraulic connectivity (Figure 6). However, clogging in grid pavement systems may be more complex due to larger openings, different fill material options, such as aggregate, sand, or soil, and vegetation. These characteristics mean that grid pavement systems may experience a more gradual, spatially variable clogging progression than PICP [6]. Nevertheless, the limited number of CGP and PGP studies makes their long-term clogging behaviour challenging to generalise.

In aggregate- or sand-filled CGP, clogging occurs mainly through fine sediment accumulation and reduction in voids between the fill material. Larger openings in CGP and PGP, compared with PICP joints, may trap and retain coarser particles [25], while finer particles may penetrate deeper before being retained, increasing the risk of clogging in the bedding layer, geotextile, or sub-base. Fill material is therefore a key control on clogging behaviour. Winston et al. [25] found sand-filled CGP more susceptible to clogging, whereas gravel-filled CGP retained larger pore spaces and showed resistance.

Vegetated grid systems introduce biological and soil-structure controls that may reduce or intensify clogging. Vegetation can counteract clogging through root growth, soil cracking, and biological activity [32]. Older vegetated CGPs have been reported to have higher infiltration capacities than younger gravel-filled CGPs [20]. Rossetto et al. [32] found that a 15-year-old CGP maintained effective infiltration without maintenance, attributed to plant roots, soil cracks, and insect activity within pavement voids. This is further corroborated by the findings of Boogaard et al. [72]. In a full-scale infiltration assessment of 33 grass-filled grid pavement sites across six Dutch cities, infiltration rates ranged from 50 to 1400 mm/h, with a median of approximately 344 mm/h. Their results showed that grass-filled grid pavers can retain functional infiltration capacity over time, but performance is strongly influenced by system age, compaction, soil and vegetation position, antecedent moisture, vegetation condition, and repeated testing during wetter conditions. Clogging in vegetated CGP and PGP fillers should be interpreted differently from conventional PICP clogging. In aggregate-filled systems, hydraulic decline is associated with infilling of voids by mineral sediment, organic matter, and traffic-related particles. In soil- or grass-filled systems, clogging is complex: compaction, vegetation loss, soil crusting, and wind-blown sediment accumulation may reduce infiltration, while root growth, worm channels, soil cracking, and biological activity may create flow pathways that counteract clogging [32]. Boogaard et al. [72] found that system age had the only statistically significant relationship with infiltration performance, with older systems showing lower infiltration rates. However, older grass-filled systems retained higher infiltration than impermeable pavement, suggesting decline involves both degradation and stabilisation. The filler position and condition are also important. Grass and soil below the pavement surface were associated with higher infiltration rates as this reduced tyre loading, compaction of growth medium and vegetation damage; whilst soil or vegetation above the grid surface is exposed to traffic loading and compaction, increasing infiltration risk. This supports CGP observations that vegetation, soil cracks, roots, and biological activity may maintain flow pathways, but poor vegetation establishment, exposed soil and compaction can have the opposite effect.

Plastic grid systems introduce a clogging pathway absent in concrete grids. Plastic grids in PGP may be affected by ultraviolet exposure, thermal cycling, oxidation, traffic abrasion, deformation, or cracking. If they degrade, fragments could mix with sediment, organic matter, and filler, potentially causing secondary blockage within grid openings, bedding layers, or geotextile interfaces. However, PGP-specific evidence linking plastic

https://doi.org/10.3390/w18162039

grid degradation to clogging or infiltration decline remains limited. Existing studies and reviews indicate that plastic-based permeable pavements can be engineered for drainage applications, but highlight uncertainty regarding microplastic release, durability, and assessment [65,73]. Therefore, this should be treated as a plausible, under-quantified mechanism requiring further investigation.

Overall, evidence suggests CGP and PGP clogging should be interpreted through filler and grid behaviour. In vegetated systems, key clogging processes include filler compaction, vegetation condition, root development, biological activity, and sediment accumulation. For PGP, studies should assess polymer ageing, grid deformation, plastic fragment release, and interactions between plastic particles, mineral sediment, and organic matter. Thus, PICP joint clogging findings cannot be transferred without considering filler type, vegetation dynamics and plastic durability.

4. Lifecycle Mitigation Measures for Clogging in IPPs

Clogging mitigation in IPPs should be considered a lifecycle process rather than a single maintenance action applied only after a decline in hydraulic performance. The reviewed evidence indicates that maintenance effectiveness is strongly influenced by earlier design and construction decisions [4,25,46,48,50,74]. Inappropriate joints or bedding materials containing excessive fines may cause early hydraulic failure and limit the effectiveness of maintenance [20,46]. Similarly, poor site grading or high run-on ratios can concentrate sediment at pavement edges, resulting in spatially uneven clogging that routine sweeping alone may not address [41,44,49,68]. Therefore, effective mitigation measures require holistic actions across the design, construction, operation, and monitoring and maintenance stages.

4.1. Planning and Design-Stage Mitigation Measures

Design-stage decisions strongly influence clogging risk as they determine the volume and quality of runoff entering the pavement, the hydraulic capacity of joints or grid cells, and the ease with which maintenance can be performed [4,16,44,49]. Key design considerations include joint width, joint aggregate specification, bedding material, contributing impervious area, and pretreatment measures (Table 2).

Joint opening size and filling material are particularly important for PICP because the joints provide the main infiltration pathway [16]. Coarser, clean, angular aggregates with minimal fines generally provide better hydraulic capacity and clogging resistance than sand-rich materials [46,53,75]. For example, Borgwardt [42] tested four joint filling materials (crushed aggregates 2–5 mm, crushed aggregates 1–3 mm, mixed aggregate and sand 0–5 mm, and sand 0–2 mm) and found a correlation between the hydraulic performance of PICP and the joint fill material. Coarser aggregates with minimal fines demonstrated higher infiltration rate, while finer material exacerbated clogging. Sehgal et al. [26] also observed that old PICP installations with small joint openings (3–4 mm) were more prone to clogging compared with large-sized PICP joint openings (13–14 mm) with better infiltration rate, after maintenance. However, joint design must balance hydraulic and structural requirements, as overly large openings may create stability or accessibility concerns under traffic and pedestrian use [26,76].

Another critical design-stage control for clogging mitigation in IPP is pretreatment and sediment-load reduction, as clogging is also influenced by the quantity, particle size, and spatial distribution of sediment reaching the pavement surface and joints. Therefore, it is crucial to manage the ratio of contributing impervious areas to the permeable pavement area, as high run-on ratios can transport substantial sediment loads from adjacent roads, parking lots, roofs, and landscaped areas onto the IPP surface. This process accelerates localised clogging at upgradient edges, low spots, and traffic entry points [41,44,45,49,68].

Tirpak et al. [68] demonstrated that excessive loading ratio (27.6:1) and concentrated sediment can exacerbate clogging and reduce the effectiveness of permeable pavements. Design guidelines, such as the UK SuDS Manual, advise limiting the contributing impervious area to permeable pavement area ratio to 2:1, where feasible [4]. Maintenance routines may also encompass the cleaning of paved impervious contributing areas, such as street sweeping, to mitigate source materials. Although this constitutes maintenance, facilitating access to contributing drainage areas should be considered during the initial planning and design stages. When it is unavoidable to reduce the run-on ratio and runoff from adjacent impervious areas, pretreatment and source control measures should be implemented before runoff reaches the IPP surface or joints. These measures include vegetated filter strips, grass channels or swales, sediment forebays, sedimentation chambers, edge interception strips, stabilised kerbs, and protected landscaping interfaces [4,77–81]. Swales and filter strips can function as pretreatments by decelerating runoff, promoting sediment deposition, distributing inflow, and filtering particulates before water reaches the IPP surface [78,79,82]. Kachchu Mohamed et al. [82] illustrated swale effectiveness in stormwater treatment trains comprising a swale and permeable pavement. They found that 50% to 75% of suspended sediment was eliminated within 10 m of the swale. For IPP systems, this indicates that upstream swales can reduce the sediment load reaching pavement surface/joints, reducing clogging on permeable pavement surfaces. Specific evidence, however, on the long-term performance of pretreatment strategies in reducing clogging remains limited. Overall, source-control design should integrate run-on ratio control, inflow distribution, sediment pretreatment, and edge protection, along with the internal joint and bedding properties of the IPP. Future research should aim to provide more quantitative data on pretreatment-linked clogging mitigation strategies.

The reviewed literature also revealed innovative pavement designs to facilitate rapid maintenance and restoration of infiltration capacity in PICP. James and von Langsdorff [83] developed and tested rapid clean-out pavement concepts that incorporated design features to enhance the effectiveness of conventional maintenance equipment. These designs consider sweeper mechanics and pavement geometry to optimise sediment removal efficiency, representing a shift from passive clogging resistance to active pavement maintenance as a design objective. Lucke [48] also incorporated drainage slots within PICP and found between 25% and 366% more sediment deposit beneath the pavers compared to the control pavement. The results suggest that PICP systems with drainage slots cast into their bases would take much longer to clog than traditional PICP pavers. Limited and detailed performance data for these design configurations in the reviewed literature suggest further investigation into innovative design concepts for clogging mitigation and more in situ validation.

Furthermore, pavement type selection should be considered at the design stage as a clogging mitigation decision, as IPP systems respond differently to sediment loading, traffic compaction, vegetation condition, and maintenance access. PICP is generally more suitable where a uniform load-bearing surface, predictable joint-controlled infiltration, and conventional vacuum-maintenance access are required [4,6,16]. In contrast, CGP and PGP may be more appropriate where stormwater management is combined with greening, amenity, cooling, or ecological objectives, but performance depends more on filler type, vegetation condition, compaction, and long-term material durability [6,72]. Evidence shows these systems can retain functional infiltration capacity over time, but performance varies with age, saturation condition, soil and vegetation position, compaction, and vegetation quality [72]. Table 3 summarises suggested engineering selection guidance for interlocking pavement systems.

Table 2. Design-stage clogging risk controls.

Design Decision	Clogging Risk	Suggested Control Measures	Expected Benefit	References
Joint width	Narrow joints may trap sediment rapidly; oversized joints may affect structural performance	Select joint width based on hydraulic capacity, aggregate stability and expected traffic	Balances infiltration and structural function	[16,26,50]
Joint aggregate	Excess fines reduce void space and accelerate clogging	Specify clean, angular, washed aggregate with controlled gradation	Maintains infiltration pathway and improves maintenance recovery	[46,49,75]
Bedding aggregate	Fine bedding may clog early and reduce subsurface flow	Avoid sand-rich bedding unless specifically justified and tested	Protects bedding-layer hydraulic function	[20,46,48]
Run-on ratio and pretreatment control	High sediment loading from adjacent impervious surfaces can accelerate clogging	Limit contributing impervious area or incorporate pretreatment	Reduces sediment load on IPP surface and may delay clogging onset	[68,78–80,82]
Maintenance access	Poor access limits effective inspection/cleaning/maintenance	Design for sweeper/vacuum access and maintenance logistics	Improves long-term maintainability	[46,74]

Table 3. Recommended engineering selection guidance for interlocking permeable pavements.

IPP Type	Application	Key Benefits	Main Limitations	Selection Recommendation
PICP	Car parks, pedestrian areas, low-speed streets	Predictable joint-controlled infiltration; accessible maintenance	Joint clogging; sensitive to sediment run-on	Use where structural regularity and maintenance access are priorities
Aggregate-filled CGP	Overflow parking, access lanes, low-speed areas	Larger voids; fill material can be replaced	Coarser openings may allow deeper fine migration	Use where sediment input is controlled, and surface roughness is acceptable
Sand-filled CGP	Low-load landscaped or lightly used areas	Stable surface and vegetation support	High clogging risk from fine sediment	Avoid in sediment-prone areas unless pretreatment is provided
Grass-filled CGP	Green parking, verges, fire access, low-use areas	Infiltration plus vegetation, cooling and amenity benefits	Compaction, vegetation loss and variable infiltration	Use where traffic is low, and vegetation can be maintained
PGP	Lightweight green parking, temporary or retrofit applications	Rapid installation; green surface potential	Uncertain long-term plastic ageing and deformation	Use where polymer durability and sediment exposure can be monitored

4.2. Construction-Stage Mitigation Measures

Quality control during the construction stage is a crucial factor in determining the long-term hydraulic performance of IPPs [20,46,50]. Unlike conventional impervious pavements, where minor deviations in aggregate grading may primarily affect structural performance, errors in IPP joints and bedding materials can directly compromise the hydraulic function. The use of unwashed aggregates, sand-rich bedding, construction sediment contamination, or premature trafficking over unprotected permeable layers may introduce fines into the pathways intended to convey stormwater [20,46,74].

Al-Rubaei et al. [20] found that an incorrect joint filling material was used in PICP and CGP installations, with sand (0–8 mm) being used instead of the specified aggregates (4–8 mm) in the working drawings. This resulted in little or no improvement in the surface infiltration rate after manually removing the top 20 mm of soil. The joints were completely clogged with significant amounts of fine material. This study highlighted that maintenance practices cannot compensate for poor construction quality and inadequate supervision during the construction phase. Lucke et al. [51] reported a case in which sand was used as the bedding layer instead of 2–5 mm aggregate, resulting in complete clogging at the site. The small sand particles between the PICP blocks were easily blocked by sediment and organic particles. The infiltration rate of the PICP installation was only 5 mm/h, which is significantly below the minimum European PICP infiltration capacity standard of 97 mm/h, demonstrating complete failure. These findings show that certain construction errors can cause permanent damage that cannot be remedied through maintenance practices, highlighting the critical importance of construction quality and sufficient supervision. Quality control steps must ensure the verification of material gradations, inspection of bedding layer installation, monitoring of joint filling procedures, and testing of infiltration capacity immediately following construction.

Furthermore, completed or partially completed IPP surfaces should be protected from construction traffic, sediment-laden runoff, and material stockpiling [4,74]. Where access to permeable layers is unavoidable, temporary protective surfaces, barriers, covers, or sacrificial layers should be used. Final joint cleaning and post-construction infiltration testing for newly installed pavements should be conducted before the handover to establish baseline performance [50,74].

4.3. Monitoring, Assessment, and Maintenance-Stage Mitigation Measures

4.3.1. Monitoring and Assessment of Clogging

Monitoring hydraulic performance during the operational phase is essential for identifying clogging before irreversible or costly performance decline occurs [21,46,84]. The most common approach identified in the literature is field measurement of surface infiltration rate using single-ring or double-ring infiltration tests [24,85]. These tests are widely used and provide a direct measure of surface hydraulic capacity, but they can be time-consuming, require sealant and water, and may be affected by the spatial variability of clogging [24,46,86].

Full-scale infiltration tests provide a more representative assessment because they cover a larger surface area and reduce the risk of unrepresentative results from small test locations [86]. However, they require more water, labour, and equipment, making them less suitable for routine asset management. Rapid field methods, including the Stormwater Infiltration Field Test (SWIFT), may improve practical monitoring by reducing test time and cost, but further validation is needed across different IPP types and clogging conditions [51].

Visual indicators such as ponding, sediment accumulation, vegetation condition, joint loss, organic debris, edge clogging, and surface staining should be combined with infiltration testing. Where possible, monitoring should be spatially distributed as clogging may often be uneven, particularly near upgradient edges, low spots, traffic turning areas, and zones receiving runoff from adjacent impervious surfaces [44,45,58].

Sensor-based approaches, including time-domain reflectometry and water content reflectometers, offer potential for tracking infiltration fronts, moisture movement and clogging progression within pavement layers [21,84,87]. These methods are promising as they provide temporal data and may support remote or semi-automated monitoring. However, their use remains largely research-based and further development is needed before widespread operational application [21,84].

In addition to in situ methods discussed above, some studies also used accelerated controlled tests to assess clogging in IPPs [18,33,43,52,66,67]. Accelerated clogging tests are useful as they allow sediment loading, rainfall application, pavement structure, and maintenance interventions to be controlled within periods. However, comparison among studies remains challenging due to the application of non-unified sediment-or hydraulic-loading protocols. Studies differ in sediment deposition, particle size distribution, application method, rainfall conditions, and wetting–drying periods. Consequently, reported differences in clogging behaviour may reflect experimental design rather than differences in IPP type or material performance, leading to variation in outputs. Accelerated studies have reported hydraulic decline including complete clogging after seven simulated years [33], a 6.4% reduction in outflow after ten simulated years [66], 40–50% hydraulic conductivity reduction over ten years [67], and 59–75% infiltration capacity reduction after thirty-five years of simulated clogging [18]. Whilst these results are valuable, they cannot be compared directly without normalising sediment loading, rainfall boundary conditions, initial infiltration capacity, and maintenance history. Nichols et al. [43] also showed that accelerated clogging outcomes depend on sediment type, particle size, and test duration, confirming the need for standardised reporting. Additionally, capturing real site processes such as traffic-related densification and antecedent conditions remains challenging, limiting transferability to long-term in situ performance. Table 4 presents clogging assessment techniques for IPPs.

Simulation models have also been used to assess the hydraulic behaviour of IPPs, but their application to clogging processes remains limited. The Stormwater Management Model (SWMM) has been applied to assess runoff reduction, layer-by-layer hydraulic response, underdrain discharge, and evaporation behaviour [88–90], while HYDRUS has simulated unsaturated flow through laboratory-scale permeable pavement layers [91]. These studies demonstrate the use of numerical models for hydraulic performance of new unclogged systems rather than simulating sediment accumulation or clogging progression. Other simulation models such as computational fluid dynamics (CFD) have also been explored; however, these have been exclusively on porous asphalt and permeable concrete [92–94]. Recent findings from Wang et al. [71] mark an important step towards clogging-specific modelling of IPP systems. Based on pilot-scale experiments, the authors developed a multi-scenario numerical model to quantify the hydrological performance of clogged PICP under different clogging conditions. Their results showed that clogging evolution involved rapid clogging, transition, and stabilisation. The permeability coefficient decreased non-linearly with increasing sediment load, following a quadratic decay, while accumulated sediment wash-off increased with cumulative runoff volume following exponential saturation. The model simulated runoff volume well (NSE ranged from 0.70 to 0.95), improving infiltration–runoff representation over SWMM static permeability assumptions.

However, although the study provides evidence that staged clogging-state modelling can improve runoff prediction for clogged PICP, evidence is still at an early stage and requires validation under field conditions, IPP configurations, sediment types, rainfall patterns, maintenance regimes, and ageing states. Although the SWMM permeable pavement LID module includes a clogging factor, which reduces pavement permeability as a function of cumulative hydraulic loading [95,96], the parameter remains empirical and does not mechanistically represent sediment transport, particle size effects, clogging location, or maintenance recovery. Future IPP models should build on the findings of Wang et al. [71] coupled with field data to support prediction of clogging progression and service-life performance.

Table 4. Clogging assessment methods and interpretation.

Method	What It Measures	Advantages	Limitations	Application	Sources
Single-ring infiltration test	Local surface infiltration rate	Simple and widely used	Spatially limited; sealant/water required	Routine spot testing	[24]
Double-ring infiltration test	Local infiltration with reduced lateral flow effect	More controlled than single ring	Time-consuming; still spatially limited	Research and detailed assessment	[24,85]
Full-scale infiltration test	Larger-area infiltration response	More representative of field variability	Water- and labour-intensive	Periodic detailed evaluation	[87]
Rapid infiltration field device/SWIFT	Approximate local infiltration	Fast and practical	Requires validation and threshold calibration	Screening and maintenance planning	[51]
Embedded moisture sensors/TDR/WCR	Wetting front and moisture movement	Temporal data; potential remote monitoring	Installation cost; interpretation complexity	Research and advanced monitoring	[21,84,87]
Visual inspection	Surface symptoms of clogging	Low cost; practical	Qualitative and subjective	Initial screening and maintenance scheduling	[51,74]

4.3.2. Maintenance Techniques

Effective maintenance of IPPs is essential to mitigate clogging and sustain long-term performance. Preventive maintenance comprises regular, routine interventions undertaken before significant performance degradation to maintain infiltration above acceptable thresholds throughout the service life [51,75]. In contrast, restorative maintenance involves intensive actions implemented after substantial performance decline to recover lost infiltration capacity [25,26]. The literature emphasised that early and frequent preventive maintenance is more cost-effective and better supports long-term performance of IPPs than delayed restorative interventions [30,49,75,97]. Maintenance frequency is site-specific and influenced by factors such as sediment loads from contributing impervious areas [46,84] and traffic intensity [26–28].

Decision-support approaches for municipal operations and maintenance are scarce for IPPs. Lucke et al. [51] introduced threshold-based criteria from SWIFT tests to categorise PICP maintenance requirements as no action, planned intervention within 1–3 years, or immediate maintenance. Although this method requires further validation, it highlights the need for a standardised maintenance planning framework. Figure 7 illustrates the suggested maintenance decision framework for IPPs. The thresholds in the framework are practical indicators from the literature and are not universal standards. A benchmark of approximately 97 mm/h was maintained, as cited in studies on minimum infiltration requirements and long-term functional performance [32,46]. Values near 50 mm/h indicate reduced infiltration in poorly maintained systems [34], whereas 5–10 mm/h suggests near-complete hydraulic failure due to unsuitable construction materials or ineffective system functions [46]. Percentage-decline triggers are included as absolute infiltration rates may be misleading when initial post-construction rates are exceptionally high. For instance, some studies have reported a 59–75% reduction in infiltration capacity [18], a decline to approximately 20–25% of initial capacity over time [49], and up to 96% under high sediment loading and limited maintenance [68]. Consequently, maintenance classification should integrate the absolute SIR, percentage decline from baseline, and ponding, runoff bypass, or inadequate maintenance recovery.

Table 5 presents a summary of the effectiveness of maintenance techniques for IPPs. Percentage recovery values should, however, be interpreted cautiously, especially when pre-maintenance infiltration rates are extremely low. A small absolute change from a near-zero baseline may produce a disproportionately large percentage increase. The most effective maintenance interventions were achieved by combining pressure washing and vacuuming maintenance techniques [44,59,97,98]. Danz et al. [59] reported improved post-maintenance performance (278–1703%) when aggressive aggregate dislodging techniques (pressure washing plus vacuuming, compressed air plus vacuuming, and manual disturbance) were simultaneously applied to loosen clogged materials in PICP joints along with immediate removal to prevent further migration into the pavement layers. Similarly, the Vac-head technique, which yielded 9000% post-maintenance infiltration performance, combined hydro-pressure washing and vacuuming [44]. The technique used a controlled attachment connected to a hydro excavation truck with two rotating water nozzles to dislodge the sediments and solids deposited between the gaps of PICP and simultaneously vacuumed the mix of water and dislodged solids into the truck.

Winston et al. [25] found a traditional mechanical sweeper to be ineffective for removing the clogging layer in PICP due to lack of suction compared with a regenerative air street sweeper with suction capable of dislodging clogging materials more deeply (6–13 mm). This suggests that the technique could be more suitable for routine preventive rather than restorative maintenance. The technique, however, was also found to be negatively affected by wet weather conditions during operation compared to dry weather conditions. During wet weather operation, regenerative air street sweepers cause clogging material to consolidate into a mat-like network in the PICP gaps, further reducing the surface infiltration rate [30,98]. Additionally, manual removal of the upper 20 mm of clogging at both PICP and CGP sites failed to improve surface infiltration rate due to poor construction quality. The entire joint depth and bedding layer were erroneously filled with unwashed aggregate (0–8 mm) containing significant fines instead of the specified washed aggregate (4–8 mm), suggesting that routine maintenance cannot compensate for improper construction practices [25]. This contrasts with the findings of Bean et al. [34] and James and Gerrits [57], who achieved partial rejuvenation through manual removal of 20–25 mm on properly constructed pavements. This further shows that even the most aggressive maintenance intervention may not overcome fundamental construction errors. Extreme infiltration recovery rates (see Table 5) are attainable only with proper construction quality. Simpson et al. [30] found that interlocking permeable pavement systems where joint aggregates were not topped up post-maintenance exacerbated clogging, with more than 40 mm below the surface significantly affecting the efficacy of maintenance. Overall, the literature revealed a critical shift from viewing maintenance as a one-size-fits-all intervention to recognising it as a diagnostic-driven process where maintenance must match factors such as clogging severity, weather conditions, and construction quality. Also, while there is a consensus that combined maintenance interventions are the most effective, it is important to note that these techniques are costly to implement. This further emphasises the need for less costly preventive maintenance interventions than delayed and costly restorative maintenance [30,49,50,97].

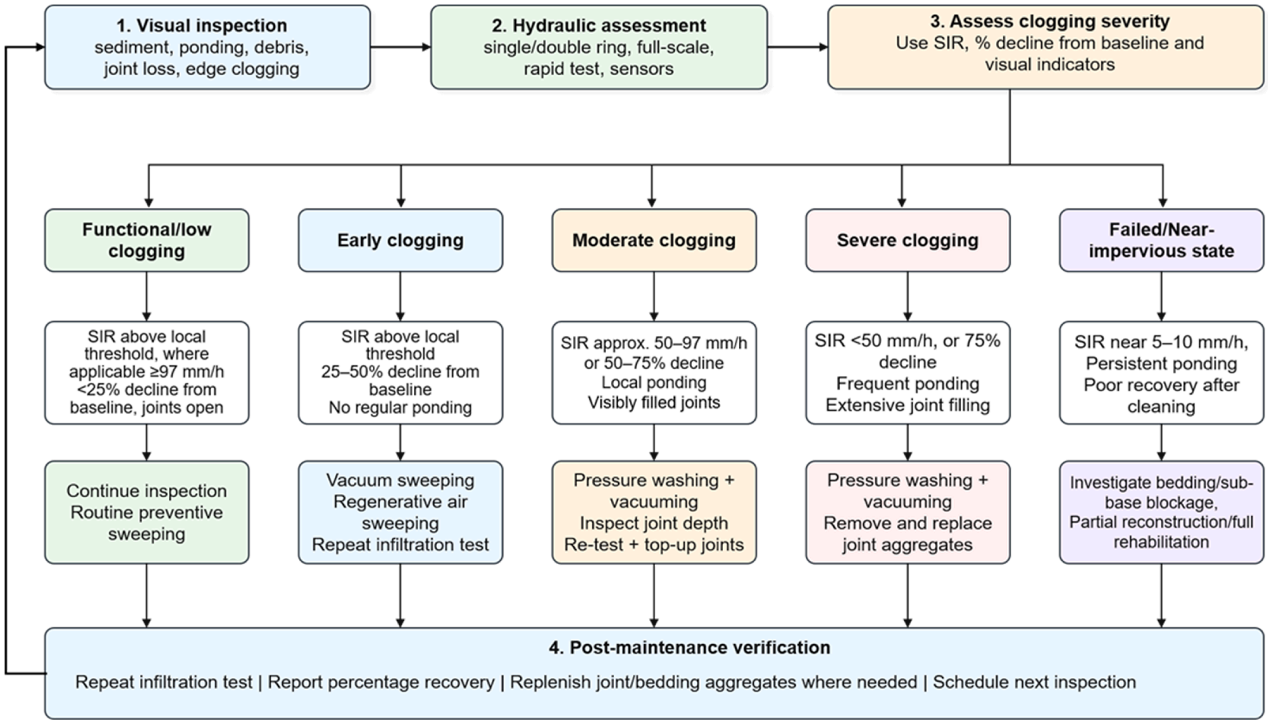

Figure 7. Evidence-informed maintenance decision framework for IPPs, linking visual inspection, surface infiltration rate (SIR), and percentage decline from baseline and clogging severity to preventive, restorative, or reconstruction-based interventions. The thresholds are indicative operational triggers derived from reported infiltration values, minimum benchmark values, and percentage decline ranges in the reviewed literature, and should be calibrated against local standards, test methods, and post-construction baseline infiltration rates [18,32,34,46,49,68].

Table 5. Summary of key maintenance techniques and their effectiveness.

IPP Type	IPP Age	Maintenance Techniques	Existing SIR (mm/h)	Post-Maintenance SIR (mm/h)	% Recovery	Sources
PICP		Regenerative air street sweeper	1166	840	−28	[30,98]
		Machine Cleaning Vehicle (MCV)	1800	3006	67	
		Pressure washer	482	1200	149	
		Pressure washer and Rejuvenater	372	2251	505	
		Rejuvenater	575	6765	1075	
PICP	5 weeks	Regenerative air street sweeper	10,600	12,800	20	[99]
PICP	25 years	Leaf blower and push broom	710	1380	94	[59]
		Vacuum-assisted Street cleaner	770	4880	535	
		Manual removal of PICP joint aggregate	2350	8880	278	
		Pressure washing and vacuuming	3850	10,490	172	
		Compressed air and vacuuming	850	15,310	1703	
PICP	2 years	Regenerative air-sweeper truck	10,890	20,691	90	[44]
		Compressed air	5760	28,800	400	
		Vac-Head (pressure washing + vacuuming)	440	40,040	9000	

Table 5. *Cont.*

IPP Type	IPP Age	Maintenance Techniques	Existing SIR (mm/h)	Post-Maintenance SIR (mm/h)	% Recovery	Sources
PICP and CGP	0.5–11 years	Mechanical street sweeping	60	144	140	[25]
		Regenerative air street sweeper	60	846	1310	
PICP	3–10 years	Suction vacuuming	22–25	900–3025	4000–12,000	[97]
		Pressure wash	36	2916	8000	
CGP	20 years	Manual removal of the top layer (20 mm)	69	131	90	[34]
PICP and CGP	20 years	Manual removal of the top layer (20 mm)	71	121	70	[100]
PICP	15 years	High pressure cleaner	0.36	540–1800	150,000–500,000	[74]

Notes: interlocking permeable pavement (IPP); permeable interlocking concrete pavement (PICP); concrete grid pavement (CGP); surface infiltration rate (SIR).

5. Knowledge Gaps and Future Research Directions

Despite the evidence base on clogging in IPPs, knowledge gaps limit confidence in long-term performance prediction, maintenance planning, and application. These gaps are summarised in Table 6. There is a significant lack of comparability among studies. Differences in pavement type, sediment characteristics and loading, rainfall conditions, duration, infiltration measurement, and maintenance history hinder comparison across laboratory and field studies.

Table 6. Summary of critical research gaps with suggested future research directions.

Gap	Why It Matters	Current Limitation	Future Research Need
Lack of standard clogging protocols	Prevents comparison across studies	Different sediment loads, rainfall, test methods, and thresholds	Harmonised laboratory and field reporting framework
Weak laboratory–field transferability	Limits service-life prediction	Accelerated tests simplify real traffic, organic inputs, and weathering	Include traffic, organic matter, wetting–drying, and maintenance scenarios
Limited CGP/PGP evidence	Filler ageing/clogging may differ from PICP	Few studies isolate vegetated, aggregate, and plastic grid systems	Monitor filler ageing, vegetation, and plastic degradation
Biological clogging underexplored	Organic matter, roots and biofilm affect flow	Difficult to separate from physical sediment clogging	Controlled studies on biofilm, vegetation, and organic debris
Decision-support tools limited	Maintenance timing remains reactive	Few validated thresholds for intervention	Link monitoring data to maintenance triggers and lifecycle cost
Limited pretreatment evidence	Sediment controls may extend service life	Limited IPP-specific clogging-delay data	Test source controls under known run-on ratios or in situ monitoring of IPP facilities with and without pretreatment
Rainfall extremes underexplored	Intense storms may accelerate clogging	Limited IPP evidence on extreme events	Simulate high-intensity storms and recovery periods

A priority is developing standard clogging assessment and reporting protocols. Future studies should report pavement type, age, fill material, sediment loading, particle size distribution, rainfall intensity and duration, antecedent moisture condition, infiltration decline, and post-maintenance recovery. Otherwise, comparing studies and developing transferable maintenance thresholds remains difficult. The transferability of accelerated laboratory testing to real field behaviour remains uncertain. Whilst laboratory studies are useful under controlled conditions, they often simplify field processes such as traffic compaction, wetting–drying cycles, organic matter input, seasonal variation, vegetation growth, and maintenance. Field studies show variable clogging due to the influence of local conditions on sediment delivery and hydraulic response. Paired laboratory–field studies are therefore needed to assess realistic IPP performance.

Evidence is also uneven across IPP types. Studies focus on PICP, while CGP and PGP are underrepresented, limiting understanding of whether clogging progression, filler ageing, maintenance response, and long-term hydraulic performance differ among joint-based, aggregate-filled, vegetated, and plastic grid systems. Future research should address CGP and PGP under fillers, vegetation, traffic, sediment, and climates and examine PGP grid durability, deformation, ageing, and potential fragment release.

Another underexplored area is biological clogging. Most studies focus on sediment accumulation, yet organic matter, biofilm, vegetation, roots, microbial activity, and soil fauna may affect performance. In vegetated systems, roots, soil cracks, and biological activity may maintain flow pathways, while debris, biofilm, and crusting may cause blockage. Studies should examine how physical and biological clogging mechanisms interact over time.

Decision-support tools for maintenance require further development. Although studies have assessed maintenance techniques such as sweeping, vacuuming, pressure washing, and joint aggregate replacement, little is known about when maintenance should be triggered, how long performance is retained, and how timing should vary with land use, sediment exposure, and runoff loading. Monitoring data should be linked to intervention thresholds, recovery after maintenance, and lifecycle cost for evidence-based planning.

Pretreatment and source-control measures are insufficiently quantified for IPP clogging. Swales, filter strips, sediment forebays, sedimentation chambers, edge protection, and stabilised landscaping may reduce sediment reaching pavement surface/joints. However, few studies quantify how they delay clogging under impervious area ratios, sediment loads, and rainfall conditions. Future research should compare systems with and without pretreatment to translate benefits into guidance.

Finally, the influence of extreme rainfall and repeated high-intensity storms remains poorly understood. Studies show rainfall intensity and duration influence sediment mobilisation and clogging, but evidence on extreme events, storm sequencing, and recovery periods is limited. This is crucial as climate change-driven rainfall intensification may increase sediment transport, shorten recovery between events, and accelerate hydraulic decline. Future research should simulate high-intensity rainfall, repeated storm sequences, and antecedent conditions to evaluate clogging mechanisms in IPPs under projected climate stress.

6. Conclusions

This review synthesised current evidence on clogging mechanisms, hydraulic decline, and lifecycle mitigation strategies in IPPs, including PICP, CGP, and PGP. Following the PRISMA framework, 79 peer-reviewed studies published between 2000 and 2025 were systematically evaluated. Although research on IPP clogging has expanded substantially over the past decade, the evidence remains dominated by PICP studies and is geographically concentrated in North America, Europe, and Australia, limiting the transferability of findings across diverse climatic, sediment, traffic, and urban settings.

This review demonstrates that clogging in IPPs should be regarded as a lifecycle hydraulic process rather than solely a maintenance issue. This problem is influenced by interactions between the sediment source, pavement type, joint or grid-cell geometry, bedding and filler materials, rainfall, and maintenance history. Hydraulic decline is primarily driven by sediment accumulation within joints, grid openings, bedding layers, and near-surface interfaces, while traffic loading, rainfall-runoff characteristics, biological activity, and sediment inputs from adjacent impervious areas act as important secondary controls. Clogging behaviour varies among IPP typologies. In PICP, hydraulic deterioration is largely associated with joint and bedding-layer blockage. In contrast, CGP and PGP performance is additionally influenced by filler characteristics, vegetation condition, compaction, and biological processes. Consequently, design recommendations derived from PICP may not be directly applicable to CGP or PGP without accounting for their distinct structural and hydraulic characteristics.

This review reframes IPP clogging as a lifecycle management challenge rather than one that can be resolved through maintenance alone. Effective mitigation should commence at the planning and design stages, involving appropriate pavement selection, control of impervious areas, source pretreatment, joint or filler specifications, drainage configuration, and protection from construction-phase contamination. During operation, early and routine monitoring and preventive maintenance consistently provide greater hydraulic and economic benefits than delayed restorative interventions. Importantly, pavement age alone is a poor predictor of the severity of clogging and overall hydraulic decline. Older systems may remain functional with low sediment exposure and appropriate maintenance, whereas newer systems may experience a decline under unfavourable run-on ratios, sediment loading, construction quality, or maintenance history.

This review also provides a practical decision-support framework to guide asset managers and designers. Maintenance decisions should be guided by multiple performance indicators, including integrating surface infiltration rate, baseline decline, sediment accumulation, ponding, and post-maintenance recovery, rather than relying solely on a single infiltration threshold. Similarly, pavement selection should balance hydraulic performance with expected traffic loading, sediment exposure, maintenance accessibility, surface use requirements, vegetation management, and long-term material durability to maximise whole-life performance. For example, PICP is found to be better suited where joint-controlled infiltration and conventional maintenance access are required, whereas CGP and PGP are more appropriate for stormwater management with greening, amenity, heat mitigation, or ecological objectives, provided that filler and material ageing risks are managed.

Despite these advances, there remain significant evidence gaps. Future research should prioritise harmonised clogging assessment protocols, stronger integration of laboratory and field investigations, and targeted studies on underrepresented IPP typologies, particularly CGP and PGP systems. Further work is also required to quantify biological and pollutant-related clogging processes, evaluate source control and pretreatment measures, assess resilience under increasingly frequent extreme rainfall events and configuration effects, and develop predictive models that couple hydraulic response with sediment loading, particle size distribution, layer-specific permeability evolution, and maintenance recovery. Addressing these knowledge gaps will improve service-life prediction, optimise maintenance planning, and strengthen the role of IPPs as resilient and sustainable urban drainage infrastructure under changing climatic and urban conditions.

https://doi.org/10.3390/w18162039

Supplementary Materials: The full list of the analysed peer-reviewed articles (i.e., [6,12,14,16,18–22,24–28, 30–35,41–44,46,48,49,51,52,55–59,61,63,66–70,74,80,83,84,86,97–129]) and summary of their key findings are provided in the Supplementary Material, which can be downloaded at: https://www.mdpi.com/article/10.3390/w18162039/s1. Table S1. Peer-reviewed articles used within the analysis. PRISMA 2020 Checklist for systematic reviews [130].

Author Contributions: B.S.: Writing—review and editing, Writing—original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. A.S.K.: Supervision, Validation, Writing—review and editing, Conceptualization. C.S.K.: Supervision, Writing—review and editing, Writing—original draft. P.M.-M.: Writing—review and editing, Writing—original draft. A.K.: Writing—review and editing, Writing—original draft. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the EPSRC Doctoral Training Programme (ref. EP/W524542/1).

Data Availability Statement: All data reported were retrieved from published literature and are available upon request from the corresponding authors.

Conflicts of Interest: The authors declare no conflict of interest.

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