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Review Article

Integrated Determinants of Persistent Wild Poliovirus Transmission in Pakistan and Afghanistan: The Roles of Cross-Border Mobility, Hard-to-Reach Populations, and Micro-Transmission Hotspots, 2010-2025

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Background: Wild poliovirus type 1 (WPV1) remains endemic in Pakistan and Afghanistan, the last global reservoirs of the virus. Despite a reduction in global incidence since 1988, persistent transmission in these two countries continues to undermine eradication efforts. This study provides an integrated assessment of determinants sustaining WPV1 transmission between 2010 and 2025, focusing on cross-border mobility, immunity gaps in hard-to-reach populations, and localized micro-transmission hotspots.
Methods: A scoping review was conducted in accordance with PRISMA-ScR guidelines. Literature published between 2010 and 2025 was searched across PubMed, Embase, Scopus, Web of Science, and WHO/GPEI repositories.
Results: Findings demonstrated that genomic and phylogenetic evidence confirmed Pakistan and Afghanistan as a single epidemiological block, with more than 85% of isolates showing cross-border genetic linkage. Immunity gaps persisted among nomadic, displaced, and conflict-affected children, where routine coverage ranged from 22% to 41% and seroprevalence fell below 70%. Environmental surveillance identified 12 persistent hotspots, with year-round WPV1 detection in Karachi, Peshawar, Quetta, and Kandahar. Operational constraints, including campaign delays, insecurity, and funding shortfalls, were consistently associated with higher case counts and reduced surveillance sensitivity.
Conclusion: The continuation of WPV1 in Pakistan and Afghanistan reflects a convergence of factors—cross-border movement, immunity gaps among marginalized groups, and entrenched transmission hotspots exacerbated by operational challenges. Public health implications include the urgent need for synchronized cross-border campaigns, targeted strategies for mobile and marginalized groups, strengthened surveillance, and sustained financing. Rapid interruption of WPV1 in this corridor is essential not only for eradication but also to end the escalating cVDPV2 emergency.

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Introduction

Poliomyelitis, an acutely paralyzing disease caused by wild poliovirus (WPV), has been targeted for global eradication since the launch of the Global Polio Eradication Initiative (GPEI) on May 13, 1988[1]. Remarkable progress has been achieved over the last three decades because indigenous WPV transmission has been interrupted in all but two countries (Afghanistan and Pakistan), and the global incidence of WPV has declined by more than 99.9% from an estimated 350,000 cases in 1988 to just 28 confirmed WPV type 1 (WPV1) cases in recent times as of November 15, 2025[2].

Five of the six World Health Organization (WHO) regions have been certified wild poliovirus-free as of November 2025. These certified regions include the Americas in 1994, the Western Pacific in 2000, Europe in 2002, South-East Asia in 2014, and the African region in August 2020, which have been certified free of WPV[2][3]. However, the Eastern Mediterranean Region remains uncertified due to ongoing challenges in parts of Pakistan and Afghanistan, contributing to the endemicity of WPV1 only in these two countries, making this cross-border epidemiological corridor the last natural reservoir of WPV on Earth[2].

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The health and socioeconomic implications of continued WPV1 transmission are profound. Each undetected chain can paralyze 100 to 200 children for every clinically recognized case, producing irreversible lower-motor-neuron damage that imposes lifelong disability, high rehabilitation costs, and lost productivity[4]. Beyond individual suffering, persistent endemicity undermines global certification, sustains the risk of international spread, and requires the continued expenditure of approximately US$1 billion annually on global containment and response activities[5].

The resurgence of exported WPV1 in previously polio-free countries, including Malawi and Mozambique in 2022, demonstrates that no country remains safe until the final reservoirs of transmission are eliminated[6]. Over the past fifteen years (2010–2025), WPV1 transmission has become increasingly focal yet resilient in Pakistan and Afghanistan, persisting despite substantial global eradication efforts[7]. Despite achieving national third-dose oral polio vaccine (OPV) coverage exceeding 87% and conducting more than 200 large-scale supplementary immunization activities (SIAs), recurrent outbreaks continue in well-defined geographic pockets[8].

Genomic and environmental surveillance data indicate that the virus circulated undetected for extended periods within localized transmission hotspots[9]. This persistence is driven by several overlapping factors: extensive cross-border movement along the porous 2,640-km Durand Line; large hard-to-reach populations, including nomadic groups, internally displaced people (IDPs), conflict-affected communities, and remote rural settlements[10]. Ongoing vaccine hesitancy and refusal are driven by misinformation and historical mistrust, while security challenges periodically disrupt immunization campaigns and surveillance, and weaknesses persist in routine immunization systems, cold-chain logistics, and real-time data use[11].

Year-round WPV1 detection in Karachi, Peshawar, Quetta, and border areas, coupled with genetic evidence, shows that viral exchange between Pakistan and Afghanistan remains frequent; over 85% of isolates since 2015 share cross-border links[7]. These findings underscore that Pakistan and Afghanistan function as a single epidemiological block, where localized immunity gaps and operational bottlenecks perpetuate silent transmission despite macro-level progress[10].

Understanding the precise interplay of structural, behavioral, ecological, and programmatic factors that sustain WPV1 in these final reservoirs is critical. Without evidence-based, context-specific strategies that simultaneously address cross-border dynamics, close focal immunity gaps, enhance surveillance sensitivity, and strengthen health-system resilience, global polio eradication will remain unattainable.

Although this review focuses on WPV1, its persistence in Pakistan and Afghanistan has made the region the world's epicenter of circulating vaccine-derived poliovirus type 2 (cVDPV2), a linked and escalating threat. The same immunity gaps that sustain WPV1 allow excreted Sabin type-2 viruses to circulate undetected, mutate, and revert to neurovirulence[12]. The 2016 global switch from trivalent to bivalent OPV accelerated type-2 immunity decline in low-coverage areas, triggering fewer than 700 paralytic cVDPV2 cases and fewer than 100 emergent lineages across both countries since 2019[13].

Co-circulation of WPV1 and cVDPV2 in shared hotspots such as Quetta, Kandahar, and Karachi creates a strategic deadlock: monovalent OPV2 risks new seeding where WPV1 is active, often forcing reversion to trivalent OPV and perpetuating the cycle[14]. Over 40% of recent campaigns in core reservoirs have targeted cVDPV2, diverting critical resources from WPV1 efforts. Even the more stable novel OPV2 (nOPV2) has seen reversion in these same inaccessible pockets[15]. In short, while WPV1 remains endemic, large-scale cVDPV2 outbreaks are inevitable. Rapid WPV1 interruption is therefore not only essential for wild-virus eradication but is also the single most effective way to end the global cVDPV2 emergency[16].

Vaccine Type	Intended Benefit	Limitation in Core Reservoirs
Monovalent OPV2 (mOPV2)	Rapid response to cVDPV2 outbreaks	High risk of reseeding new outbreaks where WPV1 is active
Novel OPV2 (nOPV2)	Greater genetic stability, reduced reversion risk	Still shows reversion in inaccessible areas (e.g., Quetta, Kandahar, Karachi)
Trivalent OPV (tOPV)	Broad coverage against WPV1, WPV3, and cVDPV2	Reinforces OPV dependence, complicating eradication timelines

Table 1. Comparison of OPV2 vs. nOPV2

This study assesses the determinants of persistent wild poliovirus transmission in Pakistan and Afghanistan from 2010 to 2025, focusing on cross-border mobility, immunity gaps in hard-to-reach populations, and localized micro-transmission hotspots. It also examines operational and health system limitations that hinder immunization and surveillance, providing evidence to inform targeted strategies to accelerate WPV interruption in the region.

Methodology

Study Design

This study was conducted as a scoping review in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines[17] and World Health Organization (WHO) evidence synthesis standards. A scoping review approach was selected to comprehensively map the breadth of evidence on determinants of persistent WPV1 transmission in Pakistan and Afghanistan, integrating epidemiological, genomic, serological, environmental surveillance, and programmatic data across heterogeneous study designs.

Search Strategy

A systematic literature search was conducted covering the period from January 1, 2010, to November 15, 2025. The following electronic databases were searched: PubMed, Embase, Scopus, and Web of Science. In addition, the WHO, UNICEF, Global Polio Eradication Initiative (GPEI), and Independent Monitoring Board (IMB) repositories were searched to capture relevant gray literature and programmatic reports. The search strategy combined controlled vocabulary and free-text terms related to poliovirus transmission and geographic focus, including: *("poliomyelitis" OR "polio" OR "wild poliovirus" OR "WPV1") AND ("Pakistan" OR "Afghanistan") AND ("transmission" OR "genomic" OR "phylogenetic" OR "cross-border" OR "mobility" OR "immunity gap" OR "seroprevalence" OR "environmental surveillance" OR "hotspot" OR "operational")*.

Weekly WHO and GPEI surveillance updates and outbreak reports were hand-searched through November 2025 to ensure inclusion of the most recent data.

Inclusion criteria:

Studies and reports were eligible for inclusion if they:

1. Were published between 2010 and 2025
2. Focused on Pakistan and/or Afghanistan
3. Reported original data or analyses related to:
   - WPV1 epidemiology or transmission dynamics
   - Molecular or genomic analyses
   - Environmental or acute flaccid paralysis (AFP) surveillance
   - Immunization coverage, immunity gaps, or serological findings
   - Population mobility, cross-border transmission, or operational determinants
4. Included peer-reviewed articles, WHO/GPEI technical reports, surveillance summaries, or IMB assessments
5. Were published in English

Exclusion criteria:

Studies were excluded if they:

- Focused exclusively on cVDPV without relevance to WPV1
- Addressed regions outside Pakistan and Afghanistan
- Lacked original data or analytic content (e.g., editorials without evidence)
- Provided insufficient methodological detail for data extraction

Study Selection

All retrieved records were imported into a reference management system, and duplicate records were removed. Two reviewers independently screened records and extracted data on study design, study period, geographic focus, surveillance modality, immunization indicators, genomic findings, and operational determinants. Findings were synthesized narratively and organized into four predefined thematic domains: (1) cross-border transmission dynamics, (2) immunity gaps in hard-to-reach populations, (3) localized micro-transmission hotspots, and (4) operational and health system constraints. No statistical pooling or quantitative meta-analysis was conducted, in keeping with the scoping review methodology.

Results

Study Selection and Characteristics

A total of 1,500 records were identified through database and gray literature searches. After the removal of duplicates (n = 300), 1,200 records underwent title and abstract screening. A full-text review was conducted for 300 reports, of which 52 met the inclusion criteria. These comprised 40 peer-reviewed articles and 12 institutional or surveillance reports published between 2010 and 2025 (Figure 1). Included studies reported epidemiological, genomic, serological, environmental surveillance, and operational data related to WPV1 transmission in Pakistan and Afghanistan.

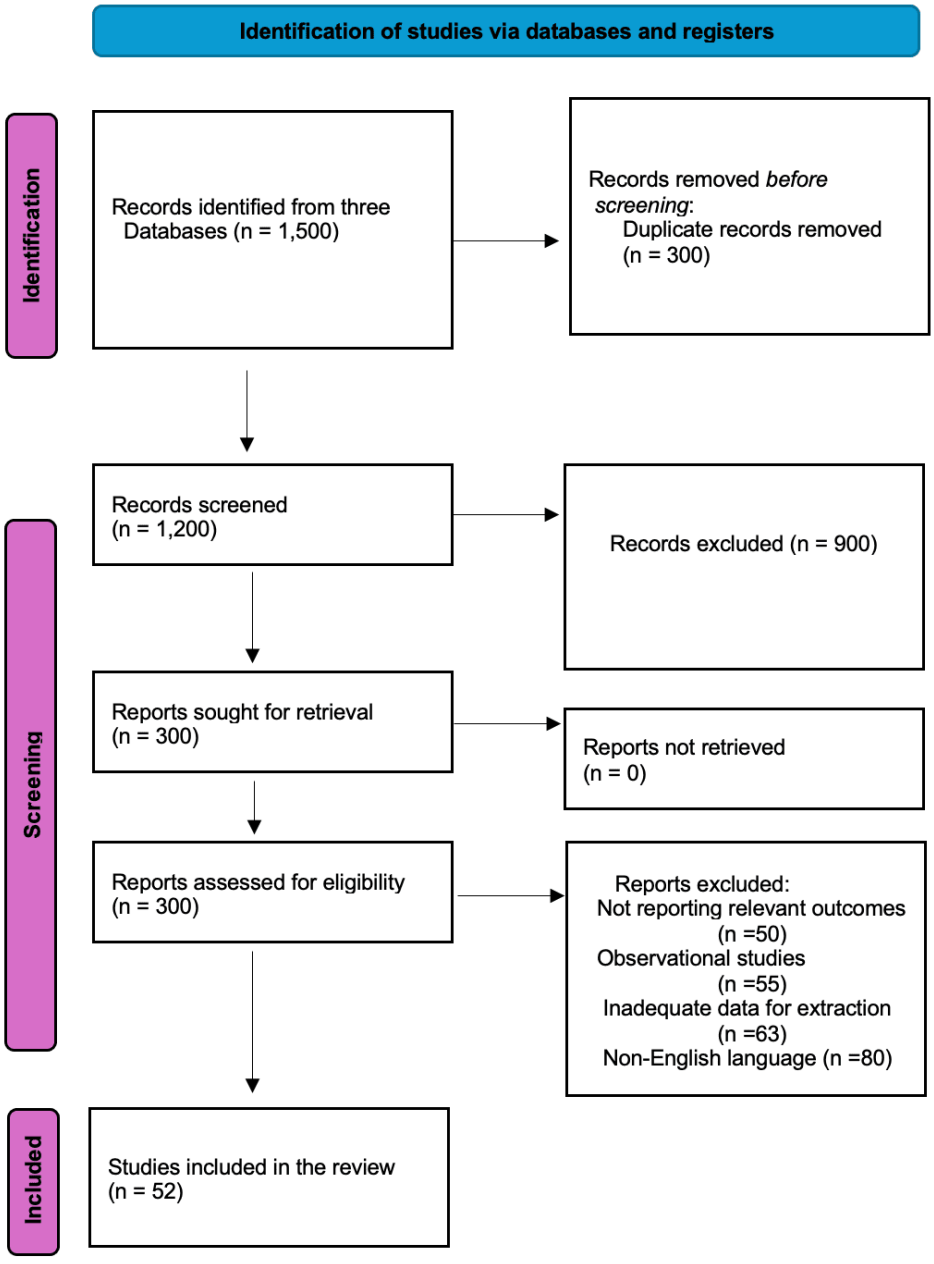

Figure 1. PRISMA chart

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Cross-Border Transmission

Genomic and phylogenetic evidence consistently demonstrated intense cross-border transmission between Pakistan and Afghanistan. Across studies published between 2015 and 2025, more than 85% of WPV1 isolates exhibited cross-border genetic linkage, supporting the characterization of the two countries as a single epidemiological block[7][8][10][13][14][18][19][20][21][22][23][24]. Analysis of VP1 sequences showed that approximately 85% of cross-border isolate pairs shared ≥99.5% nucleotide identity, indicating recent and repeated viral exchange[22][24]. Phylogenetic reconstruction identified bidirectional transmission in approximately 72% of border-adjacent cases, particularly along the Torkham and Chaman corridors[7][16][23].

Indicator	Finding
Isolates with cross-border genetic linkage	>85% of WPV1 isolates shared Pakistan–Afghanistan linkage
VP1 nucleotide identity (2015-2025)	≥99.5% in 85% of cross-border isolate pairs
Bidirectional transmission	72% of border-adjacent cases confirmed by phylogenetic reconstruction
Impact of unsynchronized campaigns	Prolonged transmission duration
Effect of transit-point vaccination	28% reduction in risk of importation in border-adjacent populations

Table 2. Genomic and Cross-Border Transmission Evidence (2010-2025)

Studies showed that transmission modeling in the Pakistan–Afghanistan epidemiological block indicates that the timing and synchrony of supplemental immunization campaigns substantially influence the duration of poliovirus circulation[18][19]. Modeling studies further showed that unsynchronized supplementary immunization activities (SIAs) were associated with prolonged viral circulation, whereas transit-point vaccination strategies reduced the risk of poliovirus importation by approximately 28% in mobile border populations[19].

Immunity Gaps in Hard-to-Reach Populations

Substantial immunity gaps were consistently reported among hard-to-reach and marginalized populations[7]. Geographic isolation, including mountainous terrain and conflict-affected zones, limits access to vaccination teams, while insecurity prevents the safe delivery of immunization services[25]. Several studies in developing countries have documented persistently low vaccination coverage among nomadic, displaced, and conflict-affected children, with an estimated 2.1–3.4 million children affected annually[26][27][28].

Studies found that mobile and migratory groups, such as nomadic communities, seasonal laborers, and internally displaced persons, frequently move across districts or national borders. These groups often miss both routine immunization and supplementary campaigns[29]. Again, socioeconomic and cultural factors compound these challenges: children in low-income urban settlements, informal communities, or socially marginalized groups may face barriers to vaccination due to limited health service access, caregiver awareness, or cultural resistance[30]. Operational constraints, including inadequate staffing, cold chain limitations, incomplete microplanning, and inconsistent campaign quality, further prevent uniform vaccine coverage in these populations[31]. Environmental surveillance confirms that WPV1 can circulate silently in these under-immunized pockets, often without reported paralytic cases, allowing localized immunity gaps to persist undetected[32].

Population Group	Routine Coverage (%)	Seroprevalence (%)	Estimated Children Affected Annually
Nomadic / Migratory	22–35%	<70%	2.1–3.4 million
Displaced / Conflict-affected	22–41%	<70%	2.1–3.4 million
Urban low-income settlements	~35–45%	~90% (variable)	Cluster-specific
National average (OPV3 coverage)	>87%	≥95% overall	—

Table 3. Immunity Gaps in Hard-to-Reach Populations

In Pakistan and Afghanistan, high-risk districts including the Quetta block and Karachi in Pakistan, and Kandahar, Helmand, and Nangarhar in Afghanistan have consistently reported low routine polio immunization coverage, typically ranging from approximately 22–35% in core transmission districts and rarely exceeding 40–45%, substantially below national averages[33][34][35]. Serological surveys revealed heterogeneity in WPV1 immunity. While overall seroprevalence among children aged 6–23 months exceeded 94–95% in many high-risk districts, immunity levels fell below 90% in specific subnational settings, particularly in Balochistan, parts of Karachi, and other low-socioeconomic urban clusters[35][36]. Population-level evaluations in urban low-socioeconomic settings similarly showed variability; approximately 90% in some clusters in Pakistan, reinforcing evidence of heterogeneous protection across and within regions[37]. Concurrent environmental surveillance continues to detect WPV1 in traditional reservoirs, consistent with ongoing transmission in areas with persistent immunity deficits[38].

Localized Micro-Transmission Hotspots

Analysis of epidemiological, serological, and environmental surveillance data identified localized micro-transmission hotspots as persistent foci of WPV1 circulation in Pakistan and Afghanistan from 2010 to 2025[38]. These hotspots were geographically constrained but epidemiologically significant, often embedded within broader areas reporting high overall immunization coverage[36].

Localized micro-transmission hotspots of WPV1 in Pakistan and Afghanistan arise from the convergence of multiple factors that allow the virus to persist in specific geographic and demographic pockets, even within areas reporting high overall vaccination coverage[20]. Serological surveys indicate that while WPV1 immunity exceeds 95% in most high-risk districts, certain provinces such as Balochistan and urban low-socioeconomic clusters, including parts of Karachi and Peshawar, exhibit lower seroprotection, around 90%, creating focal susceptibility within otherwise well-immunized populations[35].

Operational and programmatic challenges further exacerbate these vulnerabilities. Children in conflict-affected or hard-to-reach areas often miss routine immunization and supplementary immunization activities due to insecurity, difficult terrain, or population displacement, resulting in pockets of unprotected individuals within districts that otherwise report high coverage[25]. Population movement and mobility also play a critical role; frequent internal migration and cross-border travel between Pakistan and Afghanistan facilitate viral spillover into susceptible clusters, while mobile or nomadic populations often evade vaccination campaigns entirely[39].

Hotspot Location	Detection Type	Key Findings
Karachi	Environmental surveillance	Year-round WPV1 detection despite high coverage
Peshawar	Environmental surveillance	Silent circulation in urban clusters
Quetta Block	Serological + environmental	Immunity gaps ~90% seroprotection, recurrent detection
Kandahar	Environmental surveillance	Persistent WPV1 detection, cross-border spillover
Helmand, Nangarhar	Surveillance reports	Low routine coverage (<40%), recurrent outbreaks

Table 4. Persistent Micro-Transmission Hotspots

Evidence showed that socioeconomic factors compound these challenges of micro-hotspot transmissions of WPV1. For example, children residing in low-income urban areas, informal settlements, or regions affected by conflict experience reduced access to health services, leaving them disproportionately unvaccinated and forming reservoirs for continued viral transmission[40]. Environmental surveillance reinforces these findings, with repeated WPV1 detections in sewage from traditional reservoirs such as Karachi, Quetta Block, and Peshawar, often in the absence of reported clinical cases, highlighting silent circulation that sustains these hotspots[41].

Operational and Health-System Constraints

Operational and health-system constraints have been consistently documented in both earlier and more recent studies of polio eradication in Pakistan and Afghanistan. Between 2010 and 2015, much of the literature emphasized security barriers and campaign fatigue, noting that repeated supplementary immunization activities placed unsustainable demands on frontline workers while insurgency limited access to large populations[42]. Studies from this period often highlighted the Quetta Block and FATA regions as emblematic of areas where insecurity and mistrust undermined vaccination coverage[33][37][41].

Constraint	Impact on Transmission
Security barriers (2010–2015)	Large inaccessible populations, campaign delays
Campaign fatigue	Reduced quality of supplementary immunization activities (SIAs)
Urban informal settlements	Silent circulation detected in sewage despite high coverage
Weak routine immunization	Coverage collapses rapidly when SIAs are disrupted
Funding shortfalls	Reduced surveillance sensitivity, higher case counts
Cross-border coordination gaps	Sustained transmission along the Torkham and Chaman corridors

Table 5. Operational and Health-System Constraints

By contrast, more recent analyses from 2016 to 2025 have shifted attention toward urban informal settlements and micro-transmission hotspots, particularly in Karachi and Peshawar[43]. Environmental surveillance data repeatedly detected WPV1 in sewage samples from these cities, even in the absence of clinical cases, underscoring the role of silent circulation[44]. Contemporary studies also emphasize the weak integration of polio campaigns with routine health services, showing that once SIAs are disrupted, coverage collapses rapidly due to fragile routine systems[42][45][46].

Cross-border coordination challenges have remained a constant theme across the 2010–2025 period. Earlier reports described the porous nature of the Torkham and Chaman corridors as a major obstacle to synchronized campaigns, while more recent work has documented how population displacement and seasonal migration continue to sustain transmission despite intensified border vaccination efforts[47][48].

Discussion

This scoping review synthesizes evidence published between 2010 and 2025 to explain why wild poliovirus type 1 (WPV1) transmission persists in Pakistan and Afghanistan despite sustained global eradication efforts. Collectively, the evidence indicates that persistence is driven not by a single failure but by the convergence of cross-border population mobility, focal immunity gaps among marginalized populations, and entrenched micro-transmission hotspots sustained by systemic operational weaknesses. Similar multifactorial dynamics have been described in previous analyses of polio-endemic settings, highlighting the limits of vertical eradication strategies when underlying structural vulnerabilities remain unaddressed[16][18][19][20].

A central finding emerging from the evidence is that Pakistan and Afghanistan function as a single epidemiological block. Genomic and phylogenetic studies consistently demonstrate frequent viral exchange across the international border, underscoring the limited effectiveness of country-specific eradication strategies in the absence of coordinated cross-border planning[7][10][22][23][24]. Population movement for trade, seasonal labor, displacement, and social ties facilitates continual viral reintroduction into susceptible communities, eroding localized gains. Modeling studies further suggest that

asynchronous supplementary immunization activities can prolong transmission, reinforcing the need for synchronized campaigns and shared surveillance intelligence across the corridor[18][19].

Immunity gaps concentrated within hard-to-reach and socially marginalized populations represent a second critical determinant of persistence. While national indicators often suggest high immunization coverage, the reviewed evidence shows that aggregate metrics obscure substantial subnational heterogeneity. Nomadic groups, displaced populations, conflict-affected communities, and residents of informal urban settlements are disproportionately missed by routine immunization and supplementary activities[25][26][27][28][29][30][31]. These localized immunity deficits create conditions that permit sustained poliovirus circulation, often without detection through paralytic surveillance, allowing transmission chains to persist silently[32].

The spatial manifestation of these immunity gaps is evident in the persistence of localized micro-transmission hotspots. Recurrent detection of WPV1 in specific urban and peri-urban settings illustrates how small clusters of susceptibility can sustain transmission even within districts reporting high overall coverage. Environmental surveillance has been particularly important in revealing these hidden reservoirs, challenging assumptions that declining case counts necessarily indicate interrupted transmission[9][38][41]. These findings emphasize the need for eradication strategies that move beyond administrative boundaries and explicitly target high-risk clusters at the community level.

Operational and health-system constraints further exacerbate these vulnerabilities. Earlier studies emphasized insecurity and access limitations in rural conflict zones, while more recent evidence highlights delivery failures in densely populated urban environments[33][37][42][43][44]. Weak integration between polio campaigns and routine immunization services, campaign fatigue among frontline workers, funding instability, and incomplete microplanning have collectively reduced campaign effectiveness. When supplementary immunization activities are disrupted, coverage declines rapidly, revealing the fragility of gains achieved through repeated mass campaigns alone[42][45][46].

The implications of persistent WPV1 transmission extend beyond wild poliovirus eradication. Continued circulation in Pakistan and Afghanistan has created favorable conditions for the emergence and spread of circulating vaccine-derived poliovirus type 2 (cVDPV2). The same immunity gaps that sustain WPV1 allow vaccine-derived strains to circulate, mutate, and establish transmission, complicating outbreak response and diverting resources from wild virus interruption[12][15]. As long as WPV1 remains endemic in this corridor, large-scale cVDPV2 outbreaks are likely to continue, prolonging global reliance on oral poliovirus vaccines and delaying eradication certification[16].

Taken together, the evidence underscores the need for a strategic shift in eradication efforts in the final reservoirs of WPV1 transmission. Sustainable interruption will require institutionalized cross-border coordination, targeted vaccination strategies for mobile and marginalized populations, expansion of environmental surveillance beyond urban centers, and stronger integration of polio activities within routine health systems. Addressing the structural determinants of immunity gaps, rather than relying exclusively on repeated mass campaigns, is essential for achieving durable eradication.

Limitations

This review was limited to published literature between 2010 and 2025, excluding earlier data and unpublished programmatic insights. Variability in study quality, incomplete surveillance from conflict-affected areas, and methodological differences in serological surveys reduced comparability. Evidence was concentrated in urban centers such as Karachi, Peshawar, Quetta, and Kandahar, leaving rural and nomadic populations underrepresented. Security challenges and campaign disruptions often interrupted data collection, while environmental surveillance tended to emphasize urban hotspots. Differences in reporting systems between Pakistan and Afghanistan further hindered seamless integration, and findings may not be generalizable beyond this corridor.

To overcome these constraints, future work should broaden evidence sources, standardize surveillance and serological methods, and expand coverage to rural, nomadic, and displaced populations through mobile teams and community partnerships. Strengthening security coordination, integrating immunization with routine health services, and extending environmental surveillance to rural areas would improve data completeness. Harmonizing cross-border reporting systems and conducting comparative studies in other endemic regions would enhance integration and generalizability.

Conclusion

Persistent WPV1 transmission in Pakistan and Afghanistan reflects the convergence of three reinforcing determinants: intense cross-border mobility, chronic immunity gaps among hard-to-reach and marginalized populations, and resilient micro-transmission hotspots sustained by systemic operational weaknesses. Despite substantial progress in reducing global incidence, these overlapping challenges have

prevented eradication in the last remaining reservoir. Genomic evidence confirms the two countries function as a single epidemiological block, underscoring the need for synchronized campaigns and integrated surveillance.

Addressing focal immunity gaps through mobile vaccination teams, community engagement, and strengthened routine services is essential, as is expanding environmental monitoring beyond urban centers. Sustained financing and cross-border coordination remain critical to interrupt transmission. Interrupting WPV1 transmission in this corridor is essential for global certification and represents the most practical pathway to resolving the growing cVDPV2 crisis, securing the final milestone in polio eradication.

Statements and Declarations

Funding

No specific funding was received for this work.

Potential Competing Interests

No potential competing interests to declare.

Ethics

Not applicable. As this study was a scoping review of previously published and publicly available sources, it involved no human participants, no primary data collection, and no access to identifiable personal information. Accordingly, ethics approval and informed consent were not required.

Data Availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Author Contributions

N.S.G.: conceptualization, writing of drafts. M.O.O.: conceptualization, supervision, methodology, review, project administration, and validation. T.A.: writing of draft and methodology. M.O.A.: review and editing.

Use of Generative AI

The authors used generative AI solely to improve the language, grammar, readability, and formatting of the manuscript. No generative AI tool was used to generate scientific content, interpret data, select references, draw conclusions, or create or alter images. The authors take full responsibility for the accuracy, integrity, and originality of the work.

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