Assessing the Sustainability Impacts of Telehealth and Digital Inclusion to Inform a Benefit–Cost Framework for a Mid-Atlantic U.S. City

John Afam Ujah, University of Maryland College Park

John Ujah holds a Master of Engineering in Project Management from the University of Maryland and has a background in civil engineering. His research focuses on the sustainability evaluation of digital health systems, telehealth environmental impacts, and benefit–cost analysis of infrastructure technologies. His work explores how telehealth and digital inclusion can contribute to sustainable urban systems and engineering education.

Julius Ogaga Etuke, Morgan State University

Julius Ogaga Etuke is a seasoned civil engineer and Ph.D. Candidate in Civil Engineering at Morgan State University, where his research focuses on sustainable and resilient infrastructure engineering. With over 15 years of consulting and project leadership experience, primarily in Nigeria's infrastructure landscape, he brings a robust, practical perspective to academic inquiry. His doctoral research is at the cutting edge of transportation resilience, integrating virtual and augmented reality (VR/AR), climate adaptation modeling, and data-driven solutions to improve disaster preparedness and risk mitigation in complex transportation systems. As a COREN-registered engineer and member of the Nigerian Society of Engineers, his work emphasizes impactful research and consultancy that bridges structural design principles with urgent sustainability and resilience challenges.

Dr. Oludare Adegbola Owolabi P.E., Morgan State University

Dr. Oludare Owolabi, a professional engineer in Maryland, joined the Morgan State University faculty in 2010. He is the director of the Sustainable Infrastructure Development, Smart Innovation and Resilient Engineering Research Lab, Department of Civil Engineering at Morgan State University.

Dr. Uttam Gaulee
Zita Olugbuo, Arizona State University Tempe, Arizona

Zita is currently a Masters in Sustainability Leadership Student at Arizona State University USA. She also holds a Master's degree in Civil and Environmental Engineering from University of Witwatersrand, Johannesburg South Africa, BSc in Geology from University of Calabar, a Postgraduate Diploma in Environmental Geology from University of Port Harcourt in Nigeria, West Africa. With over a decade of experience as a geo-environmental professional, her background includes experience in water engineering and in oil and gas consulting. Sustainability has remained a core focus throughout her career, bridging academic and professional experience in natural resource management specifically within water resources, sustainable consumption and production, resource efficiency and environmental geology.

Samuel Sola Akosile, Morgan State University

Samuel Akosile is a Ph.D. student in Sustainable Infrastructure and Resilience Engineering at Morgan State University, within the Department of Civil Engineering. He currently works as a Research Assistant, contributing to innovative studies in the field of civil infrastructure. His primary research area focuses on sustainable design for pavement systems, aiming to develop environmentally responsible, durable, and cost-effective solutions for modern transportation networks. Samuel's work explores the integration of green materials, lifecycle assessment, and resilient engineering practices in pavement design. Through his research, he seeks to address key challenges in infrastructure sustainability while promoting long-term resilience in the face of climate change and increasing urban demands

Dr. Olushola V. Emiola-Owolabi, Morgan State University

Olushola Emiola-Owolabi is an engineering pedagogy specialist, researching active learning in engineering classrooms and specializing in qualitative methods research on teaching and learning – particularly in remote synchronous learning environments.

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Abstract

Telehealth has been increasingly accessed as a mechanism for reducing travel-based emissions, reducing patient costs, and boosting access to care. However, poor data consistency and methodological variations in sustainability reporting often prevent their effective use in structured policy and engineering evaluation frameworks. This systematic review synthesizes 124 peer-reviewed studies using PRISMA 2020 guidelines to assess environmental, economic, and digital-inclusion indicators relevant to urban systems.

Although more than 50% of the reviewed literature addressed environmental outcomes, these analyses lacked consistent reference to regulatory emission standards and seldom included economic valuation. Economic savings were often reported, structured benefit-cost analyses were conducted in fewer than 25% of observed cases. The inclusion of specific digital metrics in studies of underserved populations is notably underrepresented.

These findings reveal fragmentation across sustainability dimensions and limited readiness for integration into urban infrastructure planning. In response, this paper proposes a layered benefit–cost sustainability framework that harmonizes boundary definition, standardized metrics, monetization, and equity adjustment. The framework provides a structured pathway for evaluating telehealth within Mid-Atlantic metropolitan contexts characterized by dense transportation systems and uneven broadband access. This study contributes methodological clarity for sustainability modeling and engineering-oriented policy evaluation of digital health systems.

1. Introduction

1.1 Telehealth and Sustainability in Urban Systems

Telehealth has transitioned from pandemic-era emergency use to routine clinical care, reducing dependence on in-person visits [1]. As digital health systems expand across U.S. cities, including regions implementing broadband and Technology Access Zone initiatives [2–3], interest has grown in whether telehealth can advance environmental sustainability, reduce healthcare-related costs, and improve equitable access to care [4]. These questions are increasingly relevant to engineering evaluation, municipal transportation planning, and infrastructure policy [5–7].

Replacing in-person visits with virtual consultations alters travel demand and associated energy use [6,8]. Reduced patient travel affects fuel consumption, emissions generation, and time allocation patterns [6,9–10]. These changes generate measurable environmental and economic consequences that require systematic evaluation within structured analytic frameworks [11–13].

Existing telehealth studies frequently report reductions in travel distance, fuel use, and appointment-related time burdens [6,9–14]. However, sustainability outcomes are characterized by substantial methodological variation [15]. Emission reductions are often estimated using inconsistent distance assumptions or unspecified emission factors [16–19]. Economic outcomes are commonly reported at the patient level but are rarely integrated into formal benefit–cost frameworks [12,20]. Digital access conditions, which determine whether telehealth can substitute for travel, are inconsistently operationalized [2,21–22].

Across the coded literature, environmental estimation most relied on distance-based travel substitution and standard vehicle emission factors [6,9–10], while fewer studies accounted for the lifecycle energy and embodied impacts of digital infrastructure or facility operations [23–24]. In parallel, economic reporting often emphasized patient time and travel costs [6,14,25], but did not consistently translate these metrics into formal valuation structures [12,20,26]. Digital inclusion variables were frequently treated as contextual constraints rather than operational parameters [21–22], which limits the interpretability of sustainability benefits in populations experiencing broadband or device access barriers [2–3].

This fragmentation limits the ability of engineers and planners to evaluate telehealth within urban sustainability strategies [27–28]. A structured synthesis is therefore necessary to clarify what has been measured, how it has been measured, and whether the existing evidence supports integration into transportation and infrastructure decision frameworks [11–12].

1.2 Rationale for a Mid-Atlantic Urban Focus

This study applies its findings to Mid-Atlantic U.S. cities because of their transportation density, commuting intensity, and digital-access disparities [2–3,29]. Metropolitan areas such as North Central Maryland and Washington, District of Columbia, experience high levels of daily vehicular movement, corridor congestion, and multimodal travel dependence along the Potomac corridor [9–10]. Healthcare-related travel contributes to localized emissions and time burdens within already constrained transportation systems [6,9].

At the same time, broadband availability and digital readiness are unevenly distributed across neighborhoods in this region [2–3,21–22]. Access gaps are concentrated in lower-income communities and in certain suburban and peri-urban areas [3,21]. Telehealth sustainability gains therefore depend on the interaction between transportation intensity and digital infrastructure capacity [29–30].

The systematic review does not restrict included studies by geography. A global evidence base was intentionally retained to capture diverse sustainability indicators and valuation approaches [11]. The Mid-Atlantic context serves as a translational application lens. The objective is not to claim regional exclusivity, but to assess whether existing telehealth sustainability evidence can support evaluation within dense urban systems characterized by transportation pressure and digital inequity [12,23].

1.3 Research Objectives

The purpose of this study is to systematically synthesize peer-reviewed evidence on telehealth sustainability outcomes and to assess the methodological readiness of that evidence for integration into structured evaluation frameworks relevant to Mid-Atlantic urban systems [11]. This review does not conduct primary emissions modeling or economic simulation. Rather, it contributes a methodological assessment and indicator mapping derived from systematic evidence synthesis [11,27].

Specifically, the study aims to:

i. Identify how environmental impacts associated with telehealth are measured, including emission estimation methods and reporting transparency.
ii. Examine reported economic outcomes and assess the extent to which formal benefit–cost approaches are applied [12,20].
iii. Evaluate how digital inclusion variables are incorporated into telehealth sustainability analyses [2,21–22].
iv. Determine whether existing evidence supports development of an integrated sustainability assessment structure applicable to urban decision-making contexts [23,31].

1.4 Paper Structure

This paper is categorized into eight (8) sections. In section two (2), it presents a conceptual framework, guided in Triple Bottom Line (TBL) structure and benefit–cost. While Section three (3) describes the systematic review methodology, which includes database selection, eligibility criteria, and data extraction procedures, Section four (4) reports empirical findings from the coded dataset. Section five (5) Synthesizes data to assess the external validity of results in urban contexts. Section six (6) proposes a structured telehealth sustainability assessment framework that is tailored towards Mid-Atlantic cities. Section seven (7) drives study limitations and directions for future research. Section eight (8) concludes with implications for engineering education and policy evaluation.

2. Conceptual and Theoretical Framework

This study is anchored in a structured sustainability evaluation model that integrates the Triple Bottom Line (TBL) framework with benefit–cost analysis (BCA) principles [32–33]. The framework is used to classify telehealth impacts and to assess whether existing literature supports systematic evaluation within urban planning contexts [12,27].

Figure 1: Sustainability Dimensions Underpinning the Telehealth BCA Framework

2.1. Dimensional Framework of Sustainability

The TBL framework conceptualizes sustainability as the interaction of environmental performance, economic efficiency, and social equity [32]. Rather than treating telehealth as solely a healthcare innovation, this structure positions it within broader infrastructure systems that affect mobility patterns, resource allocation, and access to public services [4].

Environmental sustainability addresses whether telehealth alters energy use and emissions associated with patient travel and facility operations [6,9]. Economic sustainability considers whether telehealth generates measurable cost savings or productivity effects that can be incorporated into formal evaluation frameworks [12,20]. Social sustainability examines whether access to telehealth is equitably distributed and whether digital access conditions enable or constrain participation [2,21–22].

These three dimensions are analytically interdependent. Environmental gains depend on actual substitution of in-person visits [6]. Economic savings depend on consistent valuation methods [20,33–34]. Equity outcomes depend on digital readiness and broadband reliability [2–3,21]. The TBL structure therefore provides a coherent classification system for evaluating telehealth sustainability indicators across heterogeneous studies [23,35].

2.2 Environmental Sustainability in Telehealth Systems

Environmental sustainability in telehealth research is primarily associated with travel substitution [6,9]. When patients replace in-person appointments with virtual consultations, vehicle miles travel may decrease. This substitution has implications for fuel consumption, greenhouse gas emissions, and localized air quality [6,9–10].

However, environmental evaluation requires transparent methodological choices. Emissions may be estimated using distance-based calculations, fuel-efficiency assumptions, or standardized emission factors derived from national inventories [16–18]. In more advanced assessments, life-cycle approaches account for the energy use of digital infrastructure and healthcare facilities [23–24,36]. Without methodological clarity, reported emission reductions cannot be reliably compared or integrated into policy models [15,19].

For urban systems such as those in the Mid-Atlantic region, environmental evaluation must consider commuting intensity and modal distribution [29–30]. Telehealth sustainability claims are meaningful only when measurement methods are clearly specified and replicable [16–18].

2.3 Economic Sustainability and Benefit–Cost Logic

Economic sustainability extends beyond reporting nominal savings. In telehealth research, patient-level outcomes often include avoided travel expenses and reduced time burdens [6,14]. System-level outcomes may involve changes in facility utilization, staffing efficiency, or operational overhead [14,25].

For these outcomes to inform infrastructure planning, they must be translated into structured evaluation models. Benefit–cost analysis provides one such framework [33–34]. BCA requires identification of measurable benefits, consistent valuation methods, and explicit comparison against baseline conditions [33–34]. Environmental benefits may be monetized using standardized social cost estimates [26], while time savings may be valued using established wage or productivity assumptions [20,33].

The relevance of BCA to telehealth lies in its ability to integrate environmental and economic effects into a unified decision framework [33]. If telehealth reduces travel-related emissions and generates measurable time savings, these outcomes can be incorporated into transportation and urban planning analyses [12,33]. The extent to which existing literature supports such integration depends on methodological rigor and reporting transparency [12,20].

2.4 Social Sustainability and Digital Inclusion

Telehealth cannot substitute for physical travel without digital access. Broadband availability, device reliability, and digital literacy determine whether virtual consultations are feasible [2,21–22]. Social sustainability therefore requires examination of digital inclusion conditions [2–3,21]. In urban contexts, digital access is uneven across neighborhoods and demographic groups [2–3]. Infrastructure quality, affordability, and user capability influence participation rates [21–22]. If telehealth adoption is concentrated among populations with reliable connectivity, environmental and economic benefits may not be equitably distributed [2,29].

Incorporating digital inclusion into sustainability assessment ensures that telehealth evaluation does not treat environmental gains in isolation. A sustainability framework that omits digital access risks overstating benefits and underestimating structural constraints [21–22]. For Mid-Atlantic cities characterized by both dense transportation networks and documented connectivity gaps, social sustainability is not an ancillary consideration; it is a prerequisite for realizing environmental and economic outcomes [2–3].

3. Methodology

This study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure transparency in identification, screening, eligibility assessment, and inclusion of studies [37]. The objective of the review is indicator synthesis and methodological assessment rather than quantitative meta-analysis [11].

3.1 Search Strategy and Database Selection

A search strategy was developed to capture peer-reviewed research examining telehealth in relation to environmental impact, economic outcomes, and digital inclusion. Five conceptual blocks guided the search design: telehealth terminology, sustainability and environmental terms, economic evaluation language, digital inclusion constructs, and systematic review or modeling indicators [37].

Three databases were selected based on disciplinary coverage and relevance to the research objective. PubMed was included to capture clinical and public health research where telehealth implementation and patient-level outcomes are frequently reported. Scopus was selected for its multidisciplinary indexing, which includes engineering, environmental systems, and policy scholarship. ProQuest was incorporated to retrieve interdisciplinary research and doctoral dissertations that may not appear in medical databases but contain structured methodological analysis [21,29].

These databases collectively span healthcare delivery, environmental assessment, and economic evaluation domains.
Web of Science was not separately searched because of substantial overlap with Scopus in journal indexing within the targeted subject areas.

No geographic restriction was applied during the search process. This decision was intentional. The objective was to synthesize global evidence on telehealth sustainability indicators and to evaluate their methodological readiness [11]. The Mid-Atlantic region is used as an application context during interpretation rather than as a search filter.

The final Boolean search string structure is presented in Table 1.

Table 1: Search strategy by Conceptual Block

S/No.	Concept Block	Terms Used for search
1	Telehealth	"telehealth" OR "telemedicine" OR "virtual care" OR "virtual health" OR "remote healthcare"
2	Sustainability	"sustainability" OR "environmental impact" OR "carbon footprint" OR "carbon emission*" OR "emissions" OR "GHG" OR "greenhouse gas" OR "telehealth emission"
3	Economic	"Cost-benefit analysis" OR "benefit cost" OR "cost benefit" OR "economic evaluation" OR "healthcare efficiency" OR "productivity" OR "cost effectiveness" OR "cost savings"
4	Digital Inclusion & Equity	"Digital inclusion" OR "digital divide" OR "broadband" OR "digital equity" OR "technology access zones"
5	Systematic Review	"Systematic literature review" OR "SLR" OR "PRISMA" OR "quantitative indicators" OR "modeling"

Figure 2: Search strategy by using Conceptual Block

3.2 Inclusion and Exclusion Criteria

Eligibility criteria were established prior to screening and aligned with the study objective of extracting measurable sustainability indicators [37].
Studies were included if they:

i. Examined telehealth, telemedicine, or virtual care delivery.
ii. Reported at least one environmental, economic, or digital inclusion outcome.
iii. Provided sufficient methodological transparency to extract quantifiable indicators.
iv. Were published between January 2010 and December 2025.
v. Were peer-reviewed journal articles or conference proceedings available in English.

Studies were excluded if they:

i. Focused exclusively on clinical effectiveness without sustainability relevance.
ii. Lacked retrievable full text.
iii. Did not report any measurable sustainability-related variable.
iv. Were editorials, commentaries, or opinion pieces without empirical methodology.

Geographic origin was not used as an exclusion criterion. Studies from all regions were retained to allow comprehensive indicator mapping.

3.3 Screening and Selection Process

The selection process proceeded in different stages:

1. Inception Retrieval: Comprehensive searches across the selected databases yielded a total of 794 records, including PubMed (n = 562), Scopus (n = 201), and ProQuest (n = 30).
2. Deduplication: Duplicate records were identified and removed using Zotero reference management software (ZRMS), resulting in a more refined dataset assigned for further screening selection process.
3. Phase I: All remaining records outcome underwent screening to prioritize studies aligned with the review's research objectives and inclusion criteria. The ranking attribute considered relevance to title and abstract, prioritizing studies examining telehealth systems and reporting environmental, economic, or digital inclusion indicators relevant to sustainability assessment.
4. Eligibility Screening: The top-ranked papers were processed for systematic eligibility screening against the inclusion criteria specified in Section 3.2. Screening was conducted using structured data extraction forms assessing publication date (2010 to 2025), peer-review status, telehealth intervention presence, and availability of measurable sustainability indicators.
5. Full-Text Review: Papers passing initial eligibility screening underwent full-text review to confirm inclusion and extract detailed methodological and indicator data.
6. Final Inclusion: Having applied all eligibility criteria, 124 studies satisfied the requirements and were included in the final synthesis, as summarized in the PRISMA 2020 flow diagram (Figure 3).

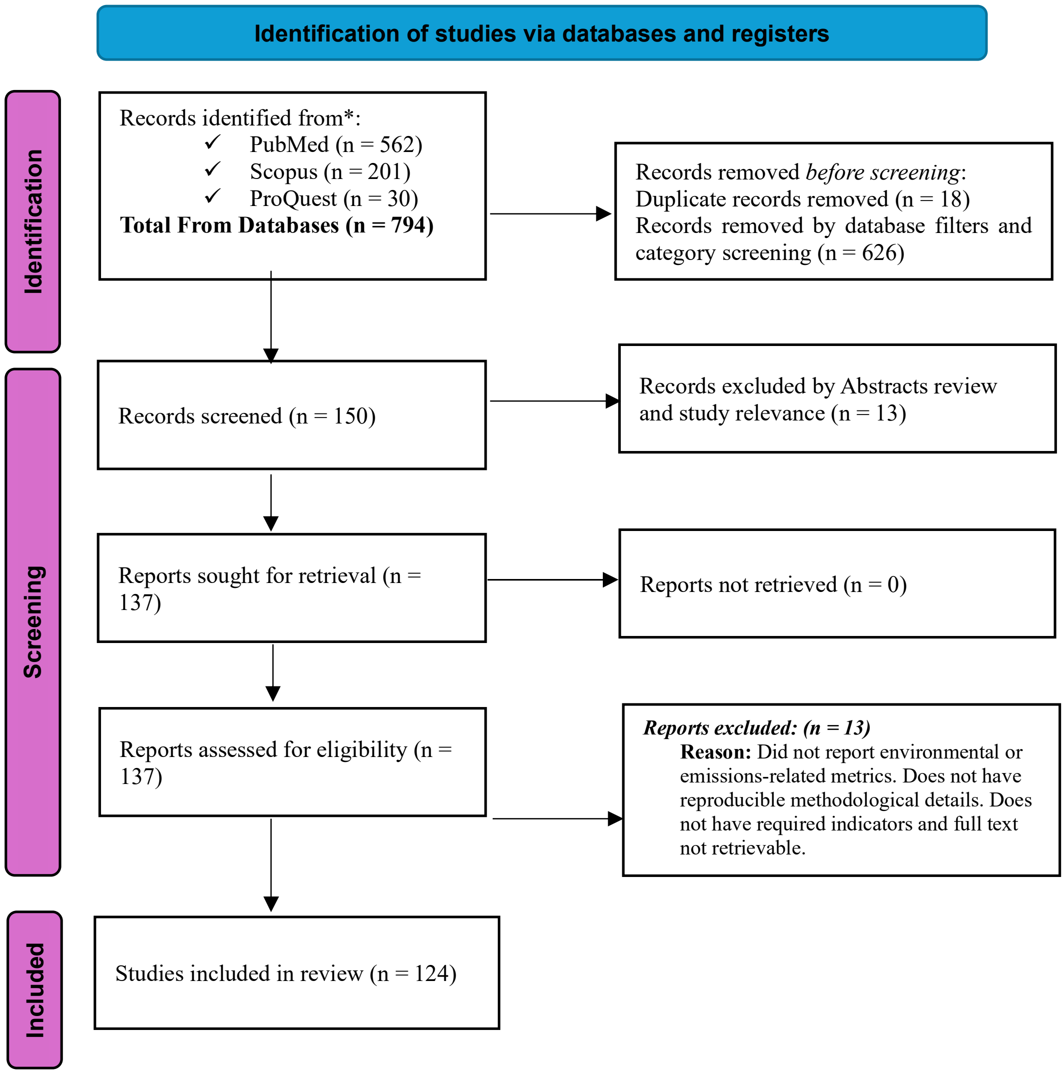


Figure 3: PRISMA 2020 Flow Diagram

3.4 Data Extraction and Coding Procedure

A structured coding matrix was developed in Microsoft Excel to extract sustainability indicators and methodological characteristics from each included study.

The extraction framework classified indicators under three analytical dimensions derived from the conceptual framework [32]:

Environmental indicators (e.g., emissions estimation, travel substitution metrics, energy use).

Economic indicators (e.g., patient-level savings, system-level cost changes, valuation methods).

Digital inclusion indicators (e.g., broadband access, device availability, digital readiness measures).

Additional fields captured study design, geographic setting, valuation method transparency, use of standardized emission factors, and clarity of baseline versus telehealth scenario comparison.

Indicators were frequency-coded based on reported presence within each study. No weighting scheme or composite index was constructed. The objective was descriptive aggregation and methodological assessment rather than effect-size estimation [11].

3.5 Analytical Approach

The analytical strategy consisted of descriptive synthesis and readiness assessment.
First, frequencies of reported indicators were calculated across the dataset to identify dominant measurement patterns.
Second, studies were evaluated for their suitability for integration into structured benefit–cost analysis frameworks [33–34].
Readiness levels were classified based on methodological clarity, scenario specification, and valuation transparency.
However, this review does not conduct primary emissions modeling, cost simulation, or quantitative meta-analysis. Instead, it identifies which indicators are consistently measured, which lack methodological transparency, and which demonstrate potential for structured integration into urban sustainability evaluation [11,12].

4. Results

4.1 Publication and Geographic Distribution

Figure 4 and figure 5 presents the temporal and geographic distribution of the 124 included studies. Publication activity increased substantially after 2020, with peak concentration in 2024 (n = 20) and 2025 (n = 40). Only one study was identified in 2013, indicating that sustainability-oriented telehealth assessment is a relatively recent research focus.

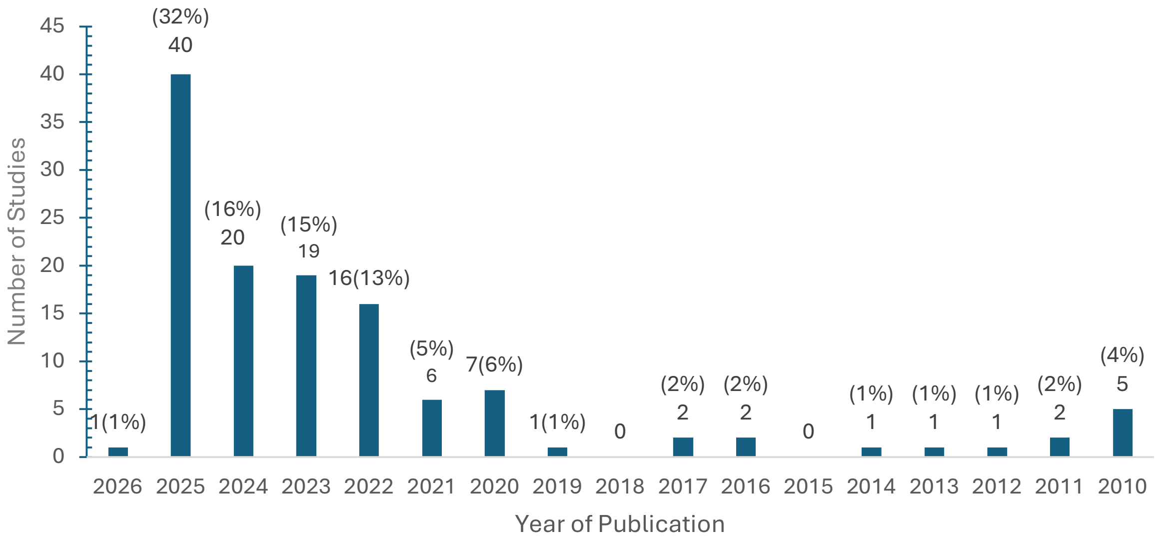


Figure 4: *Publication year of Included Studies (n = 124).*

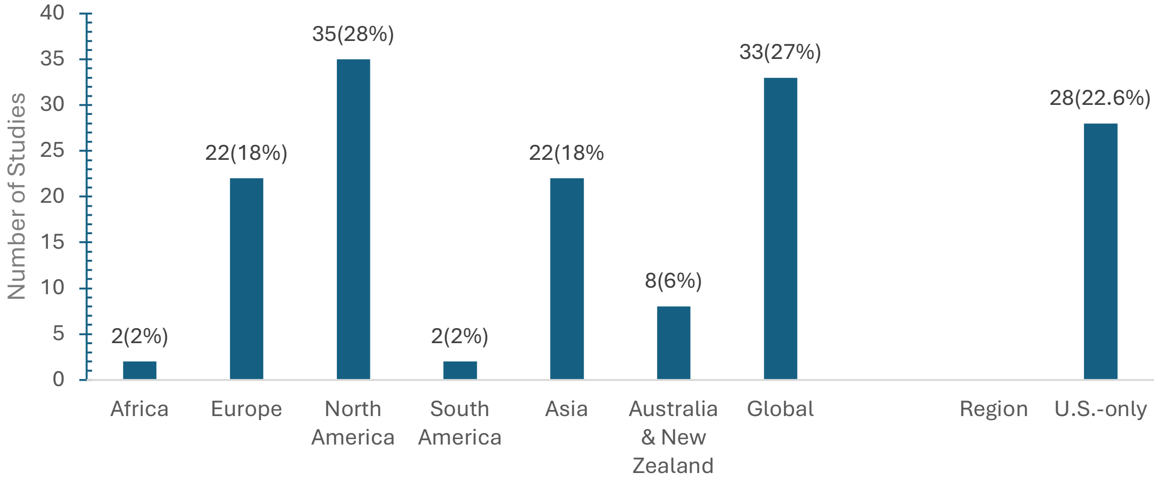


Figure 5: Temporal and Continental Distribution of Included Studies (n = 124).

Geographically, 28 studies (22.6%) were conducted exclusively within the United States. Continental representation shows the largest share of North America (n = 35), followed by Europe (n = 22) and Asia (n = 22). Thirty-three studies were classified as global or multi-region analyses. Urban-only settings were reported in 20 studies, while 42 examined mixed urban–rural systems. Forty-one studies did not clearly specify community context. This distribution demonstrates that although telehealth sustainability has been studied internationally, region-specific analyses applicable to Mid-Atlantic urban systems remain limited.

4.2 Study Design and Economic Evaluation Structure

Table 2 summarizes study design characteristics and economic evaluation reporting.

Analytical study designs dominated the sample (n = 107; 86.3%). Experimental designs were rare (n = 5; 4.0%), while hybrid approaches accounted for eight studies (6.5%). Four studies did not clearly specify design type.

Table 2: Study Design Characteristics and Economic Reporting Structure Across Included Telehealth Sustainability Studies

S/No	Category	n	% of 124
1	Analytical study design	107	86.30%
2	Experimental design	5	4.00%
3	Hybrid design	8	6.50%
4	Formal BCA reported	27	21.80%
5	Healthcare system cost outcome reported	66	53.20%
6	Patient time/cost outcome reported	78	62.90%

Although economic data are commonly generated, structured benefit–cost modeling remains limited. Formal benefit–cost analysis (BCA) was reported in only 27 studies (21.8%). In contrast, 96 studies (77.4%) did not conduct formal BCA. Healthcare system cost outcomes were reported in 66 studies (53.2%), and patient cost or time-saving outcomes were reported in 78 studies (62.9%). Economic indicators were frequently presented without integration into a standardized evaluation framework [33–34].

4.3 Environmental Measurement and Valuation Patterns

Environmental measurement patterns are summarized in Table 3.
Telehealth-related environmental outcomes were explicitly measured in 69 studies (55.6%). However, citation of technical emission standards was inconsistent. EPA emission factors were cited in 16 studies (12.9%), IPCC guidance in 7 studies (5.6%), and USDOT metrics in only one study. Sixty-one studies (49.2%) did not reference any formal emission or energy standard.

Table 3: Environmental Measurement and Valuation Practices in Telehealth Sustainability Studies

S/No	Environmental Evaluation Indicator	n	% of 124
1	Telehealth-related environmental outcome measured	69	55.60%
2	EPA emission factor cited	16	12.90%
3	IPCC emission factor cited	7	5.60%
4	USDOT metric cited	1	0.80%
5	No formal emission standard cited	61	49.20%
6	Life-cycle assessment applied	20	16.10%
7	Monetized environmental benefits	10	8.10%
8	Monetized travel savings only	24	19.40%
9	Reported emission quantities without monetization	48	38.70%
10	Emission unit variability present	Various	-

Methodological approaches varied. Slightly more than half of the included studies (55.6%) explicitly measured telehealth-related environmental outcomes. However, citation of formal emission standards was limited. EPA factors [16], IPCC guidance [17], and standardized carbon accounting methods [18] were inconsistently applied.

Life-cycle assessment approaches were used in 16.1% of cases [23–24]. Monetization of environmental benefits was uncommon, with only 8.1% translating emission reductions into monetary terms. A larger share reported emission quantities without valuation. Emission reporting units varied across studies, with kilograms of CO_2e per visit being the most common format, but no dominant reporting standard emerged [15]. These results reveal methodological fragmentation in environmental valuation and limited integration with economic analysis [12,33].

4.4 Social Inclusion and Sustainability Contribution Typology

Table 4 presents social and digital inclusion reporting patterns.
Seventy-two studies (58.1%) explicitly examined underserved or priority populations. However, only 32 studies (25.8%) reported digital inclusion or broadband indicators. Access or utilization changes were assessed in 32 studies, while 54 studies (43.5%) clearly described baseline versus telehealth comparison scenarios.

Table 4: Social Sustainability and Digital Inclusion Indicators Reported in Telehealth Studies.

S/No	Indicator	n	% of 124
1	Underserved population explicitly studied	72	58.10%
2	Digital inclusion / broadband indicator reported	32	25.80%
3	Access/utilization change assessed	32	25.80%
4	Baseline vs telehealth comparison clear	54	43.50%
5	Composite sustainability index used	3	2.40%

Digital inclusion variables were reported inconsistently despite established recognition of broadband access and digital readiness as structural determinants of telehealth feasibility [2–3,21–22]. Composite sustainability indices were reported in only three studies (2.4%). This indicates that integrated sustainability modeling remains rare [32].

4.5 Sustainability Contribution Types

Table 5 classifies studies according to their contribution across sustainability dimensions.
Only one-quarter of studies (25%) addressed environmental, economic, and equity dimensions simultaneously. A similar proportion focused exclusively on emissions (26.6%). This imbalance confirms that telehealth sustainability research remains dimensionally fragmented [32,35].

Table 5: Primary Sustainability Contribution Type Reported in Included Studies

S/No.	Contribution Type	Number of Records (n)	Proportion of Records (%)
1	Emissions Only	Emissions Only = 33	26.6%
2	Cost Only	Cost Only = 6	5%
3	Equity Only	Equity Only = 13	10%
4	Emissions + Cost	Emissions + Cost = 27	22%
5	Emissions + Equity	Emissions + Equity = 4	3%
6	Cost + Equity	Cost + Equity = 10	8%
7	All three	All three = 31	25%
		Total = 124	100%

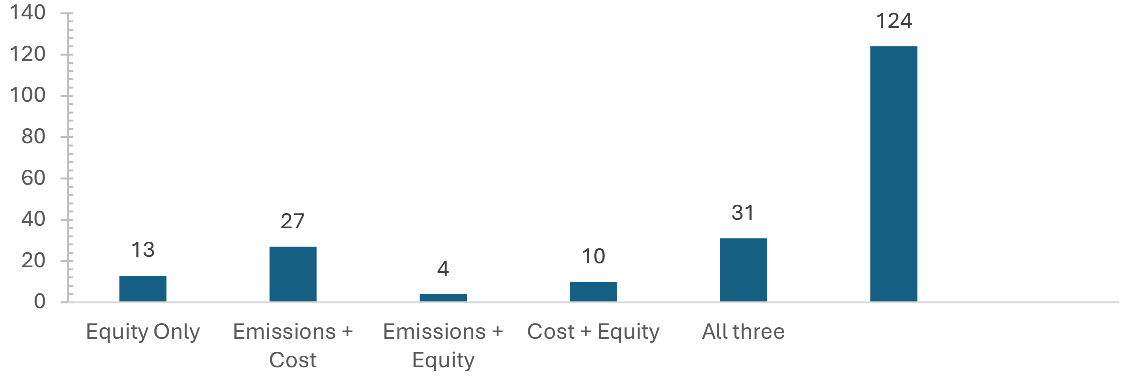


Figure 6: Primary Sustainability Contribution Type Reported in Included Studies

4.6 BCA Readiness Profile

Figure 7 presents the benefit–cost framework readiness classification.
High readiness: 53 studies (42.7%)
Medium readiness: 44 studies (35.5%)
Low readiness: 27 studies (21.8%)

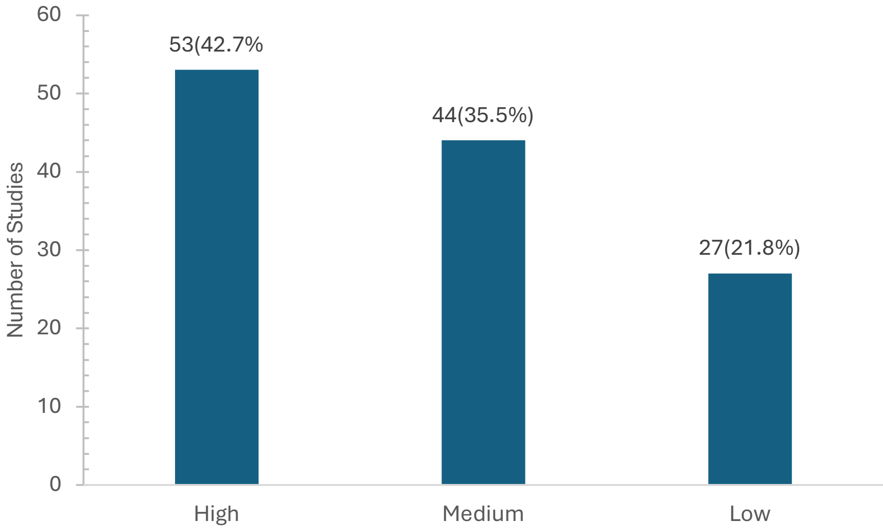


Figure 7: Benefit–Cost Framework Readiness Classification of Included Studies (n = 124)

Although fewer than one-quarter conducted formal BCA, a substantially larger proportion demonstrated structural compatibility with standardized evaluation if harmonized metrics were applied. This indicates potential for methodological advancement through framework integration rather than entirely new data generation [12,33–34].

5. Discussion

The findings of this systematic review reveal a rapidly expanding body of literature evaluating telehealth sustainability; however, methodological fragmentation limits direct application to region-specific policy and infrastructure planning. Although more than half of the reviewed studies measured telehealth-related environmental outcomes, fewer than one-quarter conducted formal benefit–cost analysis. Emission standards were inconsistently cited, monetization was limited, and reporting units varied across studies. These structural gaps constrain comparative evaluation and complicate translation into engineering decision-making frameworks [12,33–34].

5.1. Dimensional Imbalance in Sustainability Assessment

The contribution typology indicates that telehealth sustainability research remains uneven across environmental, economic, and equity domains. A substantial proportion of studies focused exclusively on emissions, while only one-quarter addressed all three sustainability dimensions simultaneously. This imbalance suggests that telehealth is frequently evaluated as a transportation-substitution intervention rather than as an integrated socio-technical system embedded within urban infrastructure [32,35].

Economic indicators were often reported independently of environmental valuation, and equity considerations were frequently discussed descriptively rather than operationalized through measurable digital-access variables. Only a small fraction of studies incorporated composite sustainability indices or formal weighting structures. The absence of standardized integration mechanisms limits the ability of municipalities to compare telehealth investments with alternative mobility or public health interventions [12,21–22,33].

Across the included studies that examined access constraints, broadband reliability, device access, and digital literacy were reported as practical determinants of whether telehealth could substitute for travel, particularly for underserved populations [2–3,21–22]. This implies that sustainability benefits should be interpreted as conditional on digital readiness, rather than as uniform system effects, and supports incorporating digital inclusion as an adjustment parameter in benefit–cost sustainability assessment [33].

5.2 Methodological Constraints and Evaluation Readiness

The readiness classification demonstrates that while relatively few studies performed formal benefit–cost analysis, a larger proportion exhibit structural compatibility with standardized evaluation if harmonized metrics are applied. Many studies reported patient cost savings, healthcare system costs, or emission reductions, yet these components were rarely combined within a unified analytic framework [33–34].

Methodologically, distance-based emissions accounting can be made more comparable when studies explicitly report travel distance assumptions, mode share, emission factor sources, and whether estimates include non-travel components such as facility energy or digital infrastructure [16–18,23–24]. A small but important subset of studies applied more comprehensive carbon accounting approaches, indicating a feasible pathway for advancing standardization without abandoning the pragmatic travel-substitution model that dominates the evidence base [23–24].

This finding suggests that the primary barrier to comprehensive evaluation is not data absence but methodological coordination. Standardizing emission factors, clarifying baseline scenarios, and integrating patient-level time savings into monetized valuation models would substantially increase evaluation comparability [12,33–34].

5.3 Implications for Mid-Atlantic Urban Systems

The geographic distribution of included studies reveals limited U.S.-specific concentration and no targeted synthesis focused on Mid-Atlantic metropolitan regions. Urban systems such as North Central Maryland and Washington, D.C. present distinct infrastructure characteristics, including dense transportation networks, multimodal commuting patterns, and heterogeneous broadband accessibility [2–3,29–30]. Telehealth adoption within such systems interacts with transit behavior, digital inclusion disparities, and municipal sustainability targets [2–3,21–22].

Findings from rural-dominant or globally aggregated studies may not be directly generalized to Mid-Atlantic urban environments for several reasons. First, travel substitution effects differ in high-density cities where public transportation use alters emission baselines. Second, broadband access reliability and digital literacy vary across neighborhoods, affecting telehealth participation rates. Third, regional climate policies and carbon accounting methodologies may differ from those used in international studies [16–18].

The limited representation of Mid-Atlantic-specific research therefore constitutes both a gap and an opportunity. While existing studies provide methodological building blocks, localized empirical calibration is required to ensure accurate environmental accounting and economic valuation within regional planning frameworks [12,33].

5.4 Toward an Integrated Evaluation Framework

From an engineering education perspective, the evidence synthesis and framework structure support curricular emphasis on systems thinking, transparent emissions accounting, and benefit–cost reasoning as applied to digital infrastructure-enabled public services [27–28]. Embedding telehealth as a case context can help students connect transportation demand, carbon estimation standards, and equity constraints within a single evaluative problem structure, consistent with calls for rigorous, reproducible synthesis methods and applied decision analysis in engineering education research [12,27–28].

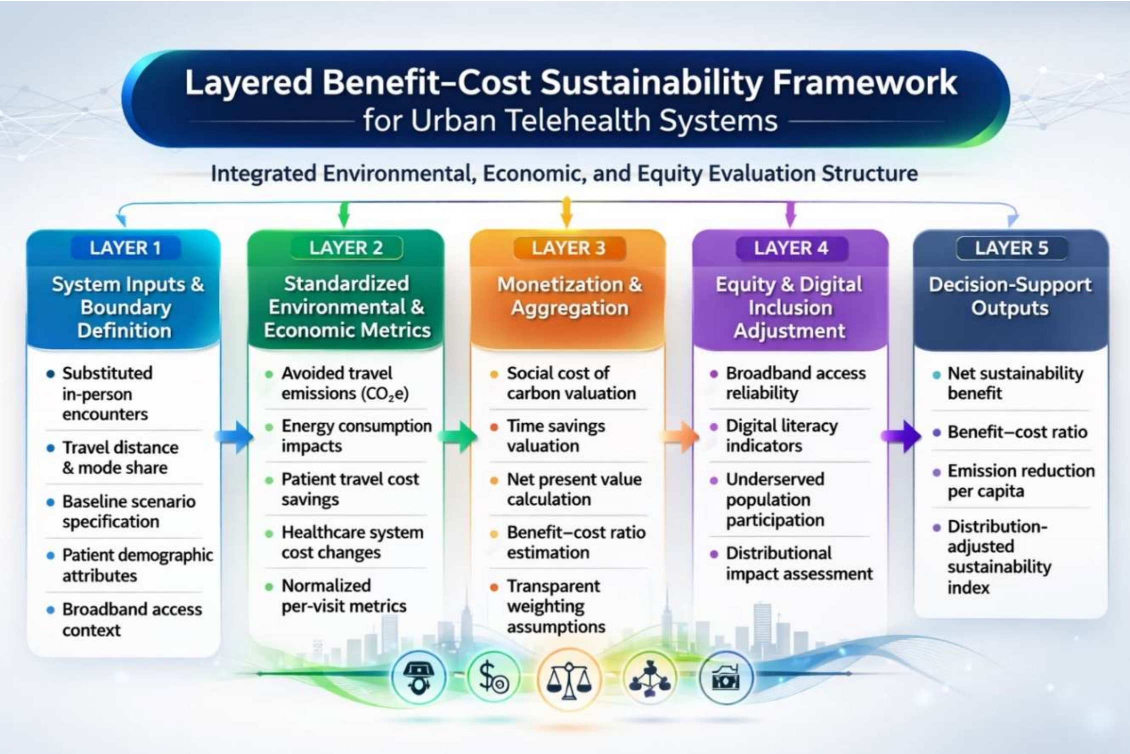
The synthesis indicates that telehealth sustainability assessment requires integration across environmental metrics, economic valuation, and digital equity indicators. Current studies frequently treat these dimensions separately, limiting their collective policy relevance [32,35].
An integrated evaluation structure must establish consistent system boundaries, harmonized emission factors, and transparent monetization procedures while accounting for digital access constraints [16–18,33].

Such integration is particularly relevant for municipalities seeking to align telehealth expansion with climate action plans and transportation demand management strategies. By translating patient travel substitution into standardized carbon and cost metrics, telehealth can be evaluated alongside infrastructure investments using comparable analytical criteria [33–34].

6. Integrated Benefit–Cost Sustainability Framework for Urban Telehealth Systems

The synthesis of the reviewed literature reveals persistent fragmentation in telehealth sustainability assessment. Environmental metrics, cost outcomes, and equity considerations are frequently evaluated independently, limiting their utility for infrastructure-level decision-making [32,35]. To address this structural gap, Figure 8 presents a layered benefit–cost sustainability framework designed to integrate these dimensions within a unified analytic structure suitable for urban policy contexts [12,33].

The framework is organized as a sequential systems architecture progressing from boundary definition to decision output. Each layer corresponds to methodological deficiencies identified in the review and provides a structured mechanism for harmonization [12,33–34].



6.1 System Definition and Boundary Specification

The first layer establishes explicit analytical boundaries. Telehealth encounters are defined relative to substituted in-person visits within a specified geographic region. Travel distance assumptions, transportation mode shares, baseline healthcare delivery scenarios, and population characteristics are specified at this stage. Clear boundary definition corrects inconsistencies observed across prior studies, particularly regarding counterfactual assumptions and system scope [12,33–34].

6.2 Standardized Environmental and Economic Metrics

The second layer translates system inputs into normalized quantitative indicators. Avoided travel emissions, energy consumption impacts, patient cost savings, and healthcare system cost changes are expressed in consistent per-visit or per-capita units. Emission factors are derived from recognized technical standards to improve comparability across jurisdictions [16–18]. This layer directly addresses the emission-unit variability and normalization gaps identified in the literature [15].

6.3 Monetization and Aggregation

The third layer converts environmental and economic indicators into a unified valuation structure. Avoided emissions may be monetized using an appropriate social cost of carbon [26], while time savings are valued using standardized opportunity-cost assumptions [33–34]. Net present value and benefit–cost ratio calculations are then derived under transparent discounting parameters [34]. This aggregation stage transforms descriptive metrics into decision-relevant indicators [33].

6.4 Equity and Digital Inclusion Adjustment

The fourth layer incorporates digital access conditions and distributional impacts. Broadband reliability, digital literacy constraints, and participation rates among underserved populations are treated as structural adjustment parameters rather than peripheral considerations [2–3,21–22]. This enables evaluation of both aggregate sustainability gains and their distribution across demographic groups. The operationalization of equity addresses a recurring limitation identified in prior research [32,35].

6.5 Decision-Support Outputs

The final layer produces interpretable outputs for planners and municipal decision-makers. These outputs may include net sustainability benefit, benefit–cost ratio, emission reduction per capita, and distribution-adjusted sustainability indices. By structuring telehealth assessment within this layered architecture, the framework enables integration with transportation demand management strategies, climate action planning, and public health budgeting [12,33].

7. Limitations and Future Research Directions

This review is subject to methodological constraints inherent in systematic literature synthesis. Although the search process followed PRISMA guidelines and applied structured screening criteria, variability in emission reporting standards, cost valuation methods, and baseline scenario definitions limited direct cross-study comparability. Many studies reported environmental or economic indicators without standardized normalization or monetization procedures. In addition, database selection may not fully capture grey literature or municipal pilot evaluations, potentially underrepresenting practice-based telehealth sustainability initiatives.

Geographic representation within the included studies was uneven, with limited concentration in Mid-Atlantic metropolitan contexts. Urban systems such as North Central Maryland and Washington, D.C. exhibit transportation, broadband, and demographic characteristics that may alter travel substitution dynamics and digital participation patterns relative to rural or globally aggregated cases [2–3,29–30]. Accordingly, the proposed framework requires empirical calibration using region-specific travel behavior, emission factors, and digital inclusion data before operational deployment [16–18,33]. Future research should prioritize integrated empirical application of the framework within a defined urban boundary to validate aggregation procedures and equity adjustment mechanisms.

8. Conclusion

This study synthesized 124 peer-reviewed and academic sources to evaluate how telehealth sustainability has been assessed across environmental, economic, and equity dimensions. The findings show that while telehealth-related emission reductions and patient cost savings are frequently reported, methodological integration remains limited. Formal benefit–cost analysis was conducted in a minority of studies [33–34], emission standards were inconsistently cited [16–18], and digital inclusion factors were often discussed without quantitative operationalization [2–3,21–22]. These patterns reveal structural fragmentation that constrains comparative evaluation and limits direct applicability to municipal planning contexts [12,32].

To address these gaps, this paper proposed a layered benefit–cost sustainability framework that integrates boundary definition, standardized metrics, monetization, and equity adjustment into a unified evaluation structure. The framework is designed to support urban decision-making, particularly within Mid-Atlantic metropolitan systems where transportation behavior, broadband reliability, and demographic diversity influence telehealth outcomes. By translating telehealth substitution effects into comparable environmental and economic indicators while incorporating digital access considerations, the framework offers a structured pathway for integrating telehealth into broader infrastructure and sustainability planning [33–34]. Future empirical calibration within defined urban regions will further strengthen its operational utility.

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