Al-Nahrain Journal for Engineering Sciences

Al-Nahrain J. Eng. Sci. 29(2) 364-370, 2026
Original Article

A Digital Systems and Infrastructure Assessment for Resilient Primary Healthcare Delivery in Paschim Bardhaman, India

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DOI: https://www.doi.org/10.29194/NJES.29020364

Received: March 20, 2026 **Revised:** April 16, 2026 **Accepted:** April 20, 2026 **Published:** June 20, 2026

Abstract

Primary healthcare institutions are highly important socio-technical systems, where infrastructure, digital technologies, and service delivery processes collaborate to establish service resilience and performance. Digital systems and sustainable infrastructure may not be integrated as well in a limited environment with resources, which may lead to reduced system robustness and efficiency. This paper is a systematic digital systems and infrastructure evaluation of the process of providing primary healthcare in Paschim Bardhaman District, India, through an engineering-based, multi-criteria analysis framework.
Cross-sectional engineering analysis was carried out on 25 Primary Health Centers (PHCs) chosen based on the rural and semi-urban settings. They have developed a composite system performance index by incorporating five domains of engineering, namely infrastructure robustness, operational workflow efficiency, outcome performance, digital systems readiness (ICT), and environmental sustainability systems. Information was gathered based on formal auditing of facilities, check of readiness of ICT equipment and software, field observation of operations and review of documents. Domain-specific scores were also summed up to create a Composite Quality and Resilience Index (CQRI). Statistical analyses were made to provide measures of description, correlation analysis and comparative testing between rural and semi-urban facilities.
Findings showed that there was moderate system performance (mean CQRI = 1.21 ± 0.24) and there was high inter-facility difference. The positive correlation of infrastructure robustness and the efficiency of operational workflow were found to be strong with composite system performance ($r = 0.67$ and $r = 0.74$, respectively). The readiness to digital systems, and environmental sustainability scored relatively low, which points out to the underutilization of ICT infrastructure, lack of telemedicine adoption, and the integration of renewable energy sources. The composite performance of semi-urban PHCs was much better than that of rural facilities ($p < 0.05$), which highlights the importance of infrastructure accessibility and digital connectivity to system resilience.
The results show that integration of digital systems and infrastructure design that is sustainable are important engineering determinants of resilient primary healthcare delivery. The suggested composite assessment framework can be used as a scalable engineering-based tool to estimate and optimize the performance of low-resource healthcare infrastructure in supporting the resilience of the system and its long-term sustainability and efficiency in delivering the services.

Keywords: *Digital Systems Assessment, Healthcare Infrastructure, System Resilience, ICT Readiness, Sustainability Engineering, Primary Healthcare Systems*

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1. Introduction

Primary healthcare facilities constitute essential service infrastructures in the national healthcare systems, and they are systems of integrated socio-technical systems with physical infrastructures, digital technologies, operational processes and environmental systems collaboratively defining how well the system performs and how resilient the system is. Engineering-wise, the reliability and efficiency of such facilities is not only reliant on the availability of clinical services, but also on the strength of the infrastructure systems, integration of information and communication technology (ICT), and a facility design that is sustainable [1], [2].

The new digital health technologies that have emerged over recent years such as electronic health records (EHRs), telemedicine platforms, and health information management systems have created new engineering challenges to primary healthcare infrastructure. These technologies demand that they have a constant power supply, network connectivity, and interoperable hardware-software environment and trained human-machine interface. The lack of digital infrastructure and systems integration in most of the low- and middle-income environments restricts the successful use of such technologies, decreasing the overall system resiliency and efficiency

[3], [4]. Accordingly, digital systems preparedness has become a crucial engineering characteristic of healthcare infrastructure systems.
Simultaneously, healthcare facilities are becoming more and more known as a contributor to environmental stress, both in terms of energy consumption, production of biomedical waste, and inefficient water and sanitation services. The sustainability interventions which are engineering based, including renewable energy integration, energy efficient building design and structured waste management systems are vital in reduction of environmental impact and enhancement of long-term operations reliability [5], [6]. Yet, there is a tendency to have the sustainability issues loosely integrated into primary healthcare infrastructure planning and assessment, especially in the ones that belong to the public sector [7].
Although the problem has increasingly gained importance in the literature, much of the current measurement of primary healthcare facilities focuses on clinical quality measures or service coverage measures, and very little on engineering-level measures of infrastructure systems, digital connectivity, and environmental sustainability. This disconnect prevents the policymakers and system designers to detect any technical bottlenecks that undermine service resiliency [2], [8]. There is thus a necessity of multi-criteria engineering appraisal models which can achieve or experience the connections between the robustness of infrastructure, the working processes, ICT preparedness and sustainability frameworks in healthcare premises.
The main healthcare system in India provides a good background to such an assessment which is engineering based. PHCs are the backbone to healthcare provision, specifically in the rural and semi-urban areas. Although national efforts have enhanced the upgrades in infrastructure and the expansion of digital health, the disparities are witnessed through unequal allocation of resources, unequal connectivity, and outdated physical infrastructure [9], [10]. The systems engineering perspective of PHCs allows revealing any performance gaps that cannot be observed with the help of the traditional health indicators only.
Paschim Bardhaman District in West Bengal is a heterogeneous operational environment comprising of industrial semi-urban areas and rural areas that are limited in resources. This spatial diversity enables a comparative evaluation of the impact of infrastructure accessibility, ICT connectedness, and systems of sustainability on primary healthcare performance across different conditions [11]. This kind of analysis is critical in coming up with scalable engineering solutions that can be applied in different regional situations.
This paper, therefore, carries out a systematic digital systems and infrastructure audit of primary healthcare systems in Paschim Bardhaman District, through a multi-criteria analysis system based on engineering. A composite index of system performance is built by integrating five system performance dimensions that include the robustness of infrastructure, the efficiency of operational workflow, the outcome performance, the readiness of digital systems, and the environmental sustainability. The study will determine major engineering determinants of resilience in the primary healthcare service provision by quantitatively analyzing and comparatively assessing the rural and semi-urban PHCs.
The results also add to the body of knowledge in the engineering sciences since the researchers have come up with a model of network infrastructure and digital systems evaluation of healthcare centers. The study connects ICT readiness and sustainability engineering to the performance outcomes on a system level, which allows the evidence-based planning of infrastructures and optimization of digital system performance to support resilient healthcare delivery in resource limited environments.

2. Review of Literature

2.1 Quality Lapses in Primary Healthcare Systems in India and West Bengal

Primary healthcare (PHC) infrastructure in India has been widely understood to be a low performing yet critical constituent of the Indian national health system. Even though the PHCs are set up to deliver equitable, accessible and comprehensive care at the initial contact, various reports have revealed that gaps in service capacity, infrastructure strength, and human resource supply persistently [1]. The national-level evaluations show that about 30% of PHCs do not have a full-time medical officer, and more than 40% of the PHCs do not have the necessary paramedical staff members including laboratory technicians and pharmacists, which leads to the lack of an integrated service provision and operational efficiency in these institutions [2].
The Donabedian model, that frames the concept of quality in healthcare regarding the structural, process, and outcome levels of quality, continues to be a cornerstone of a model of quality evaluation on a system level [3]. In the Indian scenario, there has been reported inadequacy in the structure, like the lack of diagnostic equipment, intermittent supplies of medicine and staff shortages among various states [4]. Inefficiencies in processes involve management of clinical documentation, lack of consistency in adhering to protocols and lack of supervisory mechanisms that together compromise on the reliability of the services [5].
The same patterns have been observed in state-level analysis of West Bengal, especially in the rural PHCs. Although advancements have been made in the coverage indicators of some of the services selected including immunization and institutional deliveries, the infrastructural preparedness and management capacity of the system is still suboptimal [6]. These results indicate that there is a need to implement assessment works that cannot be reduced to mere basic infrastructure auditing, but operational and system level performance evaluation.

2.2 Health Systems Digital Resilience.

Digital transformation has proven to be a major provider of resilience, effectiveness and flexibility of healthcare systems. Digital resilience is the ability of health systems to provide fundamental services, adjust to disruptions, and preserve data integrity with the help of effective utilization of digital technologies [7]. The COVID-19 crisis greatly enhanced the usage of telemedicine, electronic health records (EHRs), e-prescriptions, and mobile health platforms and supports the concept of ICT infrastructure as a central system element [8].
Efforts in India, including the National Digital Health Mission (NDHM) and the eSanjeevani telemedicine platform, have increased

the possibilities of digitally enabled primary care. Nevertheless, empirical research shows that there are significant digital disparities in PHC level, especially regarding the internet connectivity, hardware accessibility, the system interoperability, and staff digital skills [9]. A national evaluation estimated that less than 35 percent of rural PHCs had a working computer with dependable internet connectivity and less than 20 percent regularly used electronic data management systems to provide service delivery or reporting [10].

Digital projects run by the West Bengal state, such as telemedicine centers and citizen service portals, have been found to be promising at higher administrative levels, but have been unevenly implemented in peripheral facilities. Minimal digitalization limits the capacity of PHCs to utilize information-based decisions, optimization of supply chains, and remote services delivery, which limits the overall system resilience.

2.3 Healthcare Infrastructure Sustainability

The healthcare infrastructure sustainability is an aspect that involves effective resource use, environmental care, and sustainability in operation. The healthcare sector produces about 4.4 percent of the total greenhouse gas emissions in the world, and thus there is an urgency to design and operate infrastructure that is environmentally friendly [11].

Regulatory authorities in India, including Biomedical waste management rules (2016) and national green hospital guidelines, enable green practices, like the use of renewable energy, energy-consuming equipment, water management, and waste segregation. Nonetheless, the PHC level of implementation is still underdeveloped because of the financial, technical, and managerial limitation [12].

Empirical research has shown that incorporation of solar energy systems, rainwater harvesting systems, and structured waste disposal systems into the rural healthcare facilities can lead to a reduction in the operational cost, better service delivery and trust by the community [13]. But indications of the West Bengal region reveal that there have been long-standing problems in the biomedical waste management and little use of renewable energy sources, so there is a distance between the policy intention and the on-ground enforcement [14].

The introduction of the sustainability indicators into the healthcare quality assessment frameworks will allow focusing the goals of service delivery on the objectives of the environment and climate in general and SDG 3 (Health) and SDG 13 (Climate Action) in particular.

2.4 Quality, Digital, and Sustainability Dimension Integration

Current literature mostly considers the healthcare quality, digital transformation and environmental sustainability as relatively independent research areas. There have been few studies which have suggested combined assessment models that can simultaneously describe structural soundness, efficiency in operations, ICT preparedness as well as sustainability performance on the primary care level [5], [15].

Systems engineering viewpoint: These dimensions are essential in the interaction to have resilience, responsiveness, and sustainability in healthcare infrastructure. Online systems increase the efficiency and transparency of the processes and the sustainable infrastructure can guarantee the stability of operation during a long period of time and save resources [16]. Nevertheless, there is little empirical implementation of this type of integrated models, especially in low and middle-income countries.

2.5 Identified Research Gap

Although much has been written on the subject of healthcare quality and new studies on the topic of digital health and sustainability have been reported, the gap data that is missing in the literature is the systematic, multi-domain assessments that combine service quality, digital resilience, and environmental sustainability at the PHC level in India. None of the published studies used a composite engineering-based assessment model including structural, process, digital, and ecological indicators in Paschim Bardhaman District, West Bengal.

This gap offers the justification of the current study aiming at producing the empirical data on the impact of digital systems integration and sustainable infrastructure on primary healthcare performance. The study will support the infrastructure planning, digital optimization of systems, and policy formulation based on sustainability development goals because it will apply a cohesive systems assessment.

3. Methodology

3.1 Study Design

The research took a quantitative systems evaluation design that was cross-sectional and facility based to determine the performance of Primary Health Centres (PHCs) in terms of service quality, digital resilience, and infrastructure sustainability. Cross-sectional approach allows to measure a number of indicators of infrastructure and operational performance at a single point in time, which is appropriate when the system-level performance needs to be evaluated [1].

The evaluation framework was developed on the basis of the Donabedian Structure Process outcome (SPO) model [2] with an addition of the digital systems readiness and environmental sustainability engineering indicators to accommodate the multidimensional nature of healthcare infrastructure systems [3], [4].

3.2 Study Area

The data analysis was performed in Paschim Bardhaman District (West Burdwan), which is a district in the western part of West Bengal, India. The district is a heterogeneous healthcare setting of industrialized semi-urban municipalities (e.g. Asansol, Durgapur) and predominantly rural and resource-limited administrative blocks (e.g. Jamuria, Kanksa, and Andal) [5].

There is apparently 27 operational Primary Health Centers and 146 subcenters within Paschim Bardhaman, which serves a population of 2.9 million [6], [7]. By its heterogeneity in infrastructures and disparities in digital connectivity across the district, the district is suitable to be evaluated in terms of comparative infrastructure and systems performance.

3.3 Sampling Design and Sample Size

The multi-stage purposive sampling technique was used so as to bring both the rural and semi-urban healthcare infrastructure systems into the picture.
Stage 1: Block Selection
Five administrative blocks were randomly chosen according to the coverage of the population, accessibility, and indicators of healthcare use, and variability of the infrastructure [8]. These were two semi-urban blocks and three rural blocks.
Stage 2: Facility Selection
From the selected blocks, 25 PHCs were included in the study:
- 15 rural PHCs
- 10 semi-urban PHCs

Stage 3: Respondent Selection
System-level data in each PHC were gathered in various categories of respondents to be triangulated:
- Medical Officers-in-Charge (MOICs): 25
- Healthcare staff (nurses, laboratory technicians, health assistants): 55
- Patients/beneficiaries attending outpatient departments: 125

Total respondents = 205
This triangulation of respondents provided an opportunity to cross-validate managerial, operational and user-interface outlooks [9].

3.4 Study Variables and Performance Domains

A structured assessment checklist was used to gather data and this was structured into five engineered performance domains, as summarized in Table 1.:

Table 1. Domains & Key Variables. Source: Developed by authors

Domain	Key Variable
Infrastructure Robustness	building condition, power supply reliability, equipment availability, and staffing adequacy
Operational Workflow Efficiency	patient flow management, documentation practices, SOP adherence, and infection control
Outcome Performance	service continuity, patient satisfaction, and referral effectiveness
Digital Systems Readiness	ICT availability, internet connectivity, digital reporting, and telemedicine utilization
Environmental Sustainability Systems	biomedical waste management, energy efficiency measures, and renewable energy integration

Each indicator was scored on a three-point ordinal scale:
- 0 = Non-functional
- 1 = Partially functional
- 2 = Fully functional

This scoring approach has been widely used in facility-level systems assessments [10].

3.5 Data Collection Tools and Procedures

Data were collected between January and June 2025 using the following standardized tools:
- Facility Infrastructure and ICT Checklist: Developed using Indian Public Health Standards (IPHS) and Primary Health Care Performance Initiative (PHCPI) indicators [11], [12].
- Key Informant Interviews: Semi-structured interviews with MOICs and senior staff to document managerial and operational system challenges.
- Staff Questionnaires: Structured instruments capturing process-level indicators such as SOP compliance, digital data entry, infection prevention, and waste segregation.
- Patient Exit Interviews: Utilized in measuring the service satisfaction, waiting time, cleanliness and access to digital services.
- Document Review: The outpatient registers, stock records, maintenance records, digital reporting systems, including HMIS [13].

3.6 Composite Index Construction and Interpretation

Each PHC had domain-specific scores, which were averaged to produce a Composite Quality Index (CQI). The composite index for evaluating system performance was calculated using eq. (1).

CQI = (Structure + Process + Outcome + Digital + Sustainability)/5 .... (1)

CQI values were interpreted as follows:
- Low system performance: CQI < 1.0
- Moderate system performance: CQI = 1.0–1.49
- High system performance: CQI ≥ 1.5

This is a composite measure that makes it possible to compare with IPHS standards and SDG 3 service delivery targets [11], [14].

3.7 Study Hypotheses

In accordance with the conceptual framework and available literature, the hypothesis was developed as follows:
H1: The performance of the composite systems in semi-urban PHCs is much better than the rural PHCs.
H2: Composite quality performance has a positive correlation with the infrastructure robustness.
H3: Digital systems preparedness is positively related to operational workflow efficiency.
H4: PHCs that have a better sustainability system score have better outcome performance.
H5: Infrastructure, digital and sustainability-focused performance are important predictors of resilience in the healthcare system.

4. Results and Discussion

4.1 System Evaluation Overview

On Paschim Bardhaman 25 PHCs (15 rural, 10 semi-urban) were assessed. The 205 respondents (25 MOICs, 55 healthcare staff, and 125 patients) were used to collect the data. An organized socio-technical systems audit was conducted in accordance with the SPO model of Donabedian with the addition of the ICT-resilience and sustainability engineering indicators [2], [3], [4].

4.2 Facility Load and Service Demand Profile

Rural PHCs had a median population of 10,724 people and semi-urban PHCs had 12, 983 people. The median OPD attendance was 2,054 (rural) and 1,823 (semi-urban), which showed a heterogeneous demand of services that are dependent on the spatial accessibility and population clustering [1], [6], [9].

4.3 Composite Quality and Resilience Index (CQRI) Performance

The CQRI scores as presented in Fig.1., were between 0.72 to 1.76 with the mean of 1.21 + 0.24. Categorization of performance indicated:

- 52% moderate performance (CQRI 1.0–1.49)
- 20% high performance (≥1.5)
- 28% low performance (<1.0)

These limits were similar to national PHC performance scales [10], [14].

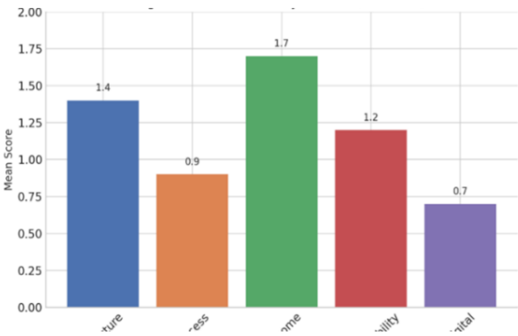

Figure1. Histogram of CQRI Distribution. (Source: Developed by authors)

4.4 Domain-Wise System Performance

Mean domain scores were summarized in Table 2. (n = 25):

Table 2. Domain-wise performance of PHCs . (Source: Developed by authors)

Domain	Mean Score ± SD
Infrastructure Robustness	1.32 ± 0.28
Operational Workflow Efficiency	1.15 ± 0.22
Outcome Performance	1.34 ± 0.26
Digital Systems Readiness	1.02 ± 0.31
Environmental Sustainability	1.22 ± 0.25

As shown in Fig.2, the lowest means were process compliance and digital resilience which describe bottlenecks of the system in documentation governance, ICT adoption, and interoperability readiness [5], [9], [11].

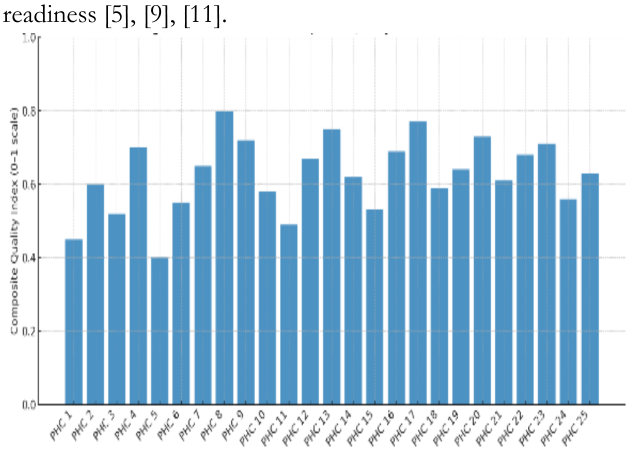

Figure 2. Mean Scores by Domain (Bar Chart). (Source: Developed by authors)

As shown in Fig.2, the lowest means were process compliance and digital resilience which describe bottlenecks of the system in documentation governance, ICT adoption, and interoperability readiness [5], [9], [11].

4.5 Rural vs Semi-Urban System Performance Comparison

The comparison of composite system performance between rural and semi-urban PHCs is presented in Fig.3. The mean CQRI in semi-urban PHCs (1.34 +- 0.20) was more than that of the rural PHCs (1.12 +- 0.23). The difference was statistically significant ($t(23) = 2.42$, $p = 0.023$) in the independent samples t-test, which supported the hypothesis that semi-urban PHCs had better engineered system performance [7], [9].

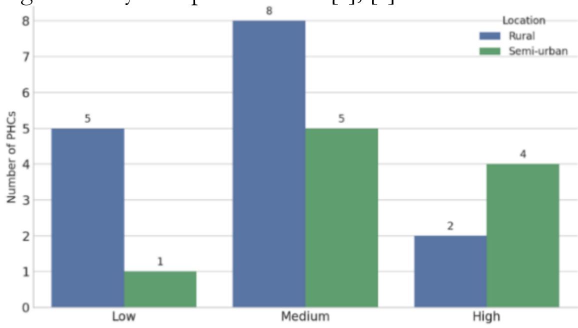

Figure 3. Boxplot: CQRI by Location (Rural vs Semi-Urban). (Source: Developed by authors)

4.6 Inter-Domain Dependency and System Correlation

Correlation analysis identified significant positive associations. The results of the correlation analysis are presented in Table 3.

Table 3. Correlation between domain scores and Composite Quality Index (n = 25). Source: Developed by authors

Correlated Domains	r value	Significance
Structure Score-CQRI	r = 0.67	p < 0.01
Process Score-CQRI	r = 0.74	p < 0.01
Digital Readiness-Process Efficiency	r = 0.59	p = 0.002
Sustainability Score-Outcome Reliability	r = 0.42	p = 0.037

The most predictive of composite system performance were infrastructure robustness and process reliability which aligns with the infrastructure-led system quality theory [2], [4], [7]. Process reliability was moderately coupled with digital readiness, which is transitional system maturity, as presented in Fig.4 [9], [11], [12].

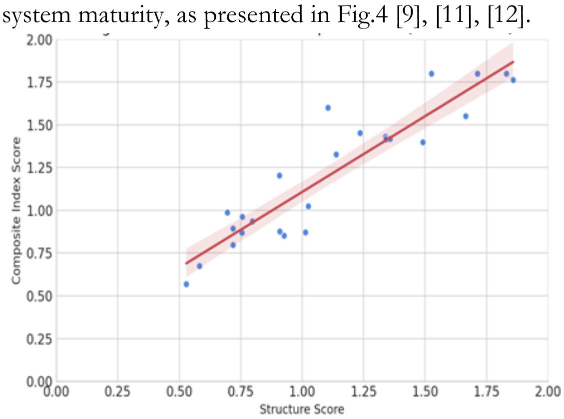

Figure 4. Scatter Plot: Structure Score vs CQRI (with regression trend line). (Source: Developed by authors)

4.7 Interpretation

4.7.1 Infrastructure Preparedness and System Quality

PHCs with stable power systems, well-equipped systems and trained staff rated better in the outcome reliability, confirming the engineering claim that structural robustness comes before process reliability [2], [4].

4.7.2 Workflow and Governance Inefficiencies

A lack of clinical records, stock records, and irregularity in monitoring infection-control practices were found as governance weaknesses. This was in line with national data in which quality gains were largely hardware-oriented with poorer governance of processes [1], [5], [10].

4.7.3 ICT Resilience and Digital System Gaps

Only 35% rural PHCs possessed stable computers with internet access and 20% were actively using telemedicine or EHR. This limited real time exchange of data and reliability of remote services, which embodies weaknesses in the ICT- continuity layers [9], [11], [12].

4.7.4 Sustainability Systems Adoption Status

Most PHCs (80% and 68% respectively) took waste segregation and the use of autoclave, although a small portion (16%), implemented solar power. This showed that the sustainability subsystems were being adopted prematurely with semi-penetration in the energy-resilience architecture [5], [13], [3].

4.7.5 Rural–Semi-Urban System Disparity

Semi-urban PHCs were characterized by smaller CQRI variation, more median, and better ICT and energy stability, which represent space inequity in the resource flow of systems as well as infrastructure distribution [8], [9].

4.8 Policy System Implications

The findings indicated that engineered PHC resilience required:

- baseline ICT infrastructure and telemedicine pilots [9], [12]
- dashboard-driven compliance audits [10], [13]
- renewable energy retrofitting [5], [13]
- peer mentoring for low-performing system nodes [7], [9]

5. Limitations

5.1 Restricted Infrastructure Geography

The research focused on 25 PHCs within a single district, which restricted the ability to generalize it to other socio-ecological territories [6], [9].

5.2 Temporal System Snapshot

Cross-sectional design did not allow causal inference among digital and sustainability subsystems because of time-series behavior absence [1], [4].

5.3 Respondent-Layer Bias Risk

Social-desirability and recall deviations might have been caused by managerial and staff interviews. Other conditions of the system like OPD load, availability of resources and ICT uptime can also change according to the inspection day [5], [10].

5.4 Proxy-Level Digital and Sustainability Indicators

Digital resilience and sustainability were assessed with the help of proxy indicators (internet access, computers, telemedicine use, solar energy, waste segregation). They failed to capture some of the deeper layers of the system like cybersecurity, carbon load, or EHR interoperability maturity [11], [5].

5.5 Small System Sample Constraint

The sample size of the facility reduced multivariate modeling power, inhibiting the complex system reliability inference [10], [14].

5.6 Missing Community Qualitative System Signals

The measure of patient satisfaction was carried out, but what were not obtained were community-level qualitative signals of the system (e.g., FGD, household narrative) [1], [9].

5.7 Cost-System Exclusion

The subsystem performance of cost-effectiveness and financial performance was not considered, and it restricted the inference on the scalability of the digital and sustainability interventions [2], [13].

6. Conclusion

6.1 Engineered System Performance Summary

The mean of CQRI of 1.21 +- 0.24 was moderate in terms of performance of the composite system. Structural and outcome domains scored better, whereas process reliability and ICT resilience had lower scores, which demonstrate that there are bottlenecks in governance and layers of digital infrastructure [2], [4], [7].

6.2 Spatial System Disparity

Semi-urban PHCs had a significant difference in CQRI between the rural PHCs ($p = 0.023$), which demonstrates the spatial inequity in infrastructure, staffing, and the availability of ICTs [7], [9].

6.3 System Inter-Dependencies

The expectation that infrastructure robustness and process governance are key determinants of engineered system performance was again confirmed by strong correlation of structure ($r = 0.67$) and process ($r = 0.74$) with CQRI [2], [4].

6.4 Digital and Sustainability System Maturity

Only the domains of digital resilience and sustainability were partially merged, which was indicative of immature continuity and green-energy subsystems in ICT continuity, [5], [11], [13].

6.5 Engineering Implications

The paper has demonstrated the necessity of integrating digital-ecological PHC infrastructure design that could empower PHCs to become resilient, data-driven and environmentally adaptive care nodes, in accordance with SDG 3 targets (3.1, 3.2, 3.8) [14], [10], [13], [9].

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