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Digital Transformation in Nephrology as a Strategy for Reducing the Carbon Footprint of Kidney Care: A Systems Engineering Perspective

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ABSTRACT

Healthcare and dialysis services have substantial environmental footprints because of repeated patient travel, intensive water and energy use, and high consumption of medical materials. This study examines how Information and Communication Technologies (ICT) can support lower-carbon kidney care through telemedicine, remote patient monitoring, interoperable electronic health records, artificial intelligence, connected devices, and digitally enabled home care. Evidence from structured literature reviews, an exploratory survey of healthcare professionals in Portugal and Spain, and an integrated systems-engineering analysis was synthesized. The findings indicate that ICT contributes to sustainability mainly indirectly: digital tools improve information exchange and multidisciplinary coordination, enabling organizational integration, workflow redesign, more efficient resource use, decentralized care, and reduced patient mobility. Interoperability and organizational readiness emerged as critical implementation conditions. A Digital Carbon-Smart Nephrology Framework is proposed in which organizational integration mediates the pathway from ICT adoption to clinical, operational, and environmental outcomes. Digital transformation should therefore be treated as a socio-technical and organizational strategy, rather than as technology deployment alone, within future low-carbon nephrology policies.

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Introduction

Climate change and the environmental footprint of healthcare have increased pressure on health systems to deliver high-quality care with lower resource consumption and greenhouse-gas emissions. Nephrology is particularly relevant because Chronic Kidney Disease (CKD) management and kidney replacement therapies depend on repeated healthcare encounters, specialized infrastructure, water, electricity, consumables, and patient transportation [1]. The growing prevalence of CKD further strengthens the need for care models that are clinically effective, economically efficient, and environmentally sustainable [2].

Digital transformation offers a potential route to redesign kidney care. Telemedicine can replace selected face-to-face visits; Remote Patient Monitoring (RPM) can support continuous follow-up and home therapies; interoperable Electronic Health Records (EHRs) can reduce fragmented information and duplicated activity; Artificial Intelligence (AI) can support risk prediction and resource allocation; and connected medical devices can enable decentralized care [3]. Their sustainability value, however, does not arise automatically from the technologies themselves. Benefits depend on how effectively digital tools are integrated into clinical workflows, professional roles, information systems, and organizational structures [4].

This study therefore examines digital transformation from a systems-engineering perspective. It integrates literature evidence with exploratory survey findings from healthcare professionals to explain the mechanisms through which ICT may contribute to lower-carbon nephrology. The central proposition is that organizational integration mediates the relationship between technology and sustainability: ICT enables interoperability and information sharing; these capabilities improve coordination and workflows; optimized workflows reduce unnecessary activity, resource use, and patient mobility; and these changes can ultimately lower the environmental footprint of kidney care [5-7]. The objectives of this study are to characterize the environmental pressures associated with kidney care, evaluate the sustainability pathways enabled by key digital technologies, identify the organizational barriers and enablers influencing their implementation, and propose an integrated Digital Carbon-Smart Nephrology Framework.

Environmental Burden and the Opportunity for Digital Transformation

Kidney care generates environmental impacts across the full care pathway. In-center hemodialysis combines frequent patient transportation with intensive water and electricity consumption and substantial volumes of single-use materials [8]. Additional impacts arise from hospital infrastructure, water purification, control of thermal comfort, procurement, waste treatment, and fragmented service delivery. Repeated diagnostic procedures, avoidable appointments, delayed referrals, and duplicated documentation also represent organizational inefficiencies with environmental consequences [9].

Geography modifies this burden. Rural and remote populations may travel long distances for specialist consultations and dialysis, while urban systems face congestion and high demand for centralized outpatient services. Digitally enabled decentralization can address both problems. Teleconsultation and electronic referral may reduce unnecessary travel; Remote Patient Monetarization (RPM) can shift appropriate monitoring to the home; and home dialysis supported by connected technologies can reduce dependence on facility-based care [10].

Digital transformation should, therefore, be viewed as an enabling strategy for low-carbon care rather than a direct carbon-reduction intervention. The relevant causal pathway is organizational: digital tools change where care occurs, how information moves, how professionals collaborate, and how resources are allocated. Environmental evaluation should consequently consider avoided travel and visits, reduced duplication, resource efficiency, and the footprint of the digital infrastructure itself [11].

Digital Technologies Enabling Sustainable Kidney Care

Telemedicine and virtual care are among the most mature digital interventions in nephrology. When clinically appropriate, virtual consultations and electronic multidisciplinary meetings can reduce travel and improve access, particularly for geographically dispersed populations [12]. Their implementation requires reliable infrastructure, digital literacy, appropriate patient selection, reimbursement, and integration with conventional care [13].

RPM extends decentralized care by transmitting clinical and treatment data from connected devices, wearables, mobile applications, or home dialysis equipment [14]. It can support earlier recognition of deterioration, treatment adherence, and timely intervention while reducing selected hospital visits. In home dialysis, remote supervision may strengthen confidence in decentralized treatment and facilitate efficient clinical oversight [15].

Interoperable EHRs are foundational because digital services generate limited system-level value when information remains fragmented [16]. Standards-based exchange can improve continuity between primary care, nephrology, laboratories, hospitals, and dialysis services, reducing repeated investigations and administrative duplication [17]. AI and clinical decision support may add value through risk stratification, prediction of CKD progression or acute deterioration, and more efficient scheduling and resource allocation. Internet of Medical Things (IoMT) technologies connect dialysis machines, sensors, and monitoring equipment with clinical platforms, enabling automated data transmission, alerts, and predictive maintenance [18].

Across these technologies, the key sustainability mechanisms are reduced patient mobility, prevention of avoidable deterioration, fewer unnecessary encounters and investigations, improved capacity utilization, and support for home-based care [19]. These benefits require governance, cybersecurity, privacy protection, data quality, and organizational change.

Systems Engineering and Organizational Integration

Healthcare is a complex socio-technical system in which patients, professionals, technologies, workflows, organizations, and regulation interact. Systems engineering provides a useful perspective because it focuses on interfaces and interactions rather than isolated components. In digital nephrology, its core principles include interoperability, standardized information exchange, workflow integration, continuous monitoring and feedback, resilience, automation, and data-driven decision support.

A data integration platform can function as the interoperability layer connecting EHRs, laboratory and imaging systems, dialysis equipment, telemedicine, RPM, pharmacy systems, mobile applications, and analytics. Such platforms also require identity management, cybersecurity, auditability, governance, and regulatory compliance [20].

Figure 1 shows that the central proposition of this study is that organizational integration is the mediator between ICT and sustainable outcomes. Technology enables information sharing; information sharing improves multidisciplinary communication and aligned decision-making; organizational integration supports workflow optimization; and optimized workflows improve clinical and operational performance. Environmental benefits then emerge through lower resource consumption, reduced duplication, and less patient travel [21]. This pathway shifts attention from technology acquisition to the redesign of the overall care system.

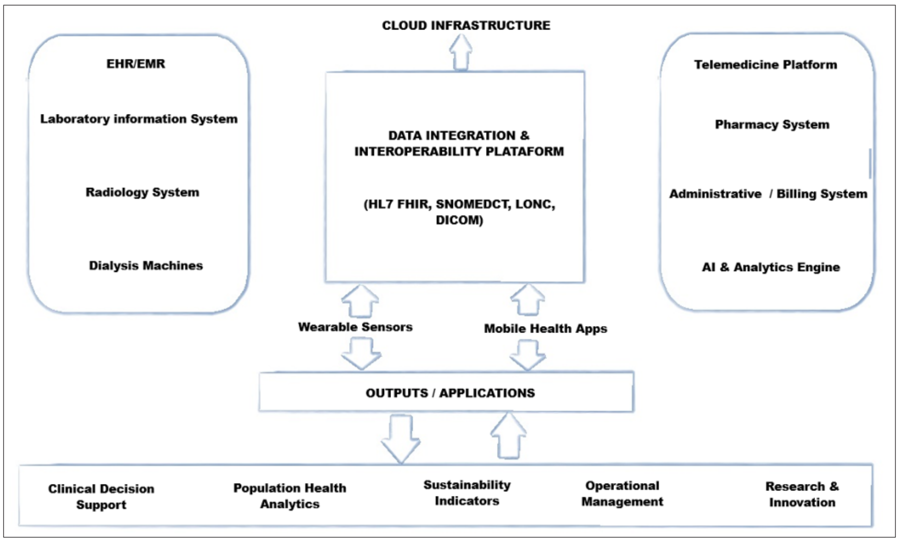

Figure 1: Data Integration Platform for Digital Nephrology (Hub-and Spoke Architecture)

Materials and Methods

A mixed-methods approach integrating structured literature reviews, exploratory cross-sectional survey research, and systems-engineering synthesis was adopted. Literature searches addressed tele-nephrology, RPM, EHR interoperability, AI, green nephrology, and systems integration using major bibliographic databases (e.g. Web of Science, Scopus). Eligible peer-reviewed studies concerned ICT relevant to CKD or kidney replacement therapy and reported clinical, organizational, operational, or sustainability outcomes. Study selection followed structured screening principles and methodological quality was considered according to study design [22-23]. The empirical component consisted of an electronic survey of healthcare professionals working in primary care and nephrology in Portugal and Spain. Questions addressed CKD screening, ICT adoption, primary care–nephrology coordination, organizational integration, sustainability, and implementation barriers. Distribution through professional organizations preserved data-protection requirements but prevented calculation of a precise response rate. Participation was voluntary and anonymous [24-25].

Quantitative results were analyzed descriptively using frequencies, percentages, and exploratory country comparisons because of the small sample. Open-ended responses underwent thematic analysis. Literature and survey findings were subsequently integrated using systems-engineering reasoning to identify relationships among technological infrastructure, information flow, organizational processes, workflows, resource utilization, patient mobility, and environmental outcomes. The study followed applicable ethical and General Data Protection Regulation (GDPR) requirements [24-27].

Results

Five themes emerged from the integrated analysis. First, early CKD detection was consistently viewed as essential to sustainable nephrology. EHR alerts, laboratory integration, and decision-support systems can strengthen systematic screening and timely referral; prevention or delayed progression may reduce future demand for resource-intensive kidney replacement therapy [28].

Second, participants perceived telemedicine, RPM, EHRs, mobile health, and AI positively, while emphasizing those digital tools should complement clinical practice. Organizational readiness and integration into routine workflows were repeatedly identified as determinants of success (see table 1).

Table 1: Key Digital Technologies in Nephrology and Their Contributions to Sustainability

Digital Technology	Primary Functions in Nephrology	Sustainability Contributions	Environmental Aspects
Telemedicine and Virtual Care	Remote consultations, tele-nephrology, virtual multidisciplinary meetings	Reduces travel, optimizes clinic capacity, improves access	Lower transportation emissions, less time off work, fewer visits
Remote Patient Monitoring	Home monitoring of vital signs, weight, BP, dialysis parameters	Early detection, fewer hospitalizations, less emergency care	Fewer hospital visits, reduced emissions and resource use
Electronic Health Records & Interoperability	Shared records, integrated laboratory & imaging data	Less duplication, better coordination, continuity of care	Reduced unnecessary tests, lower paper and energy use
Artificial Intelligence & Decision Support	Risk prediction, treatment optimization clinical alerts	Improved decision-making, personalized care, efficient resource allocation	Optimized resource use, less waste and overuse
Home Dialysis with Digital Support	Home HD/PD, remote supervision, patient education	Decentralized care, improved quality of life, less facility use	Reduced travel, energy savings, less consumables transport
Mobile Health & Patient Apps	Medication reminders, education, symptom tracking	Empowered patients, better adherence, self-management	Fewer visits, digital (paperless) communication
Cloud Platform and Big Data	Data storage, analytics, population health management	Better planning, predictive analytics, optimized operations	Energy-efficient data centers, smart resource allocation

Third, coordination between primary care and nephrology emerged as a major systems challenge. Fragmented information, incomplete referrals, and limited interoperability can produce delays, repeated investigations, and inefficient use of resources. Shared records, electronic referrals, and teleconsultation were identified as mechanisms for improving coordination.

Fourth, sustainability benefits were associated mainly with reduced travel, decentralized care, fewer unnecessary hospital encounters, improved scheduling, and better resource allocation [29]. The evidence supports an indirect pathway from digitalization to carbon reduction rather than a simple direct effect [30].

Fifth, barriers include interoperability limitations, fragmented processes, insufficient training and digital competencies, resistance to change, financial constraints, cybersecurity, and regulatory complexity. Many barriers were organizational rather than purely technical. Taken together, the findings support a transformation pathway from ICT infrastructure and interoperability through organizational integration and workflow optimization to clinical improvement, resource efficiency, reduced mobility, and potentially lower carbon emissions (see Table 2) [31].

Table 2: Carbon Reduction Opportunities

ICT	Positive Environmental Aspect
Telemedicine	Reduced Travel
Home Dialysis	Reduced Transport
Remote monitoring	Fewer Hospital Visits
AI	Better Resource Allocation
EHR	Less Paper
Decision Support	Reduced Duplication

Discussion

The principal implication is that sustainable digital nephrology requires organizational transformation, not merely implementation of digital tools. Telemedicine, RPM, EHRs, AI, and connected devices become valuable when embedded in coordinated workflows and interoperable systems. This interpretation is consistent with socio-technical theory and systems engineering, both of which emphasize joint optimization of people, technology, and organizational processes [32].

Organizational integration is proposed as the central mediating mechanism. This proposition helps explain why similar technologies may produce different outcomes across institutions: the effect depends on information exchange, professional collaboration, governance, and workflow redesign. It also suggests that evaluations of digital health should extend beyond technology adoption and clinical endpoints to include process measures, avoided travel, duplication, resource utilization, and environmental indicators [33].

The carbon-reduction potential of ICT is likely to be context dependent. Rural populations may gain substantially from avoided long-distance travel, whereas urban services may benefit from reduced congestion and more efficient capacity use [35]. Digital services themselves also consume energy and infrastructure; therefore, future studies should use life-cycle and carbon-accounting approaches rather than assuming that digitalization is inherently low carbon [36].

For policy, investment priorities should include interoperability, standardized data exchange, workforce capability, cybersecurity, governance, and change management. Environmental metrics should be incorporated into digital-health evaluation alongside clinical, economic, equity, and patient-experience outcomes [37-39].

The proposed Digital Carbon-Smart Nephrology Framework can be summarized in the figure 2 below.

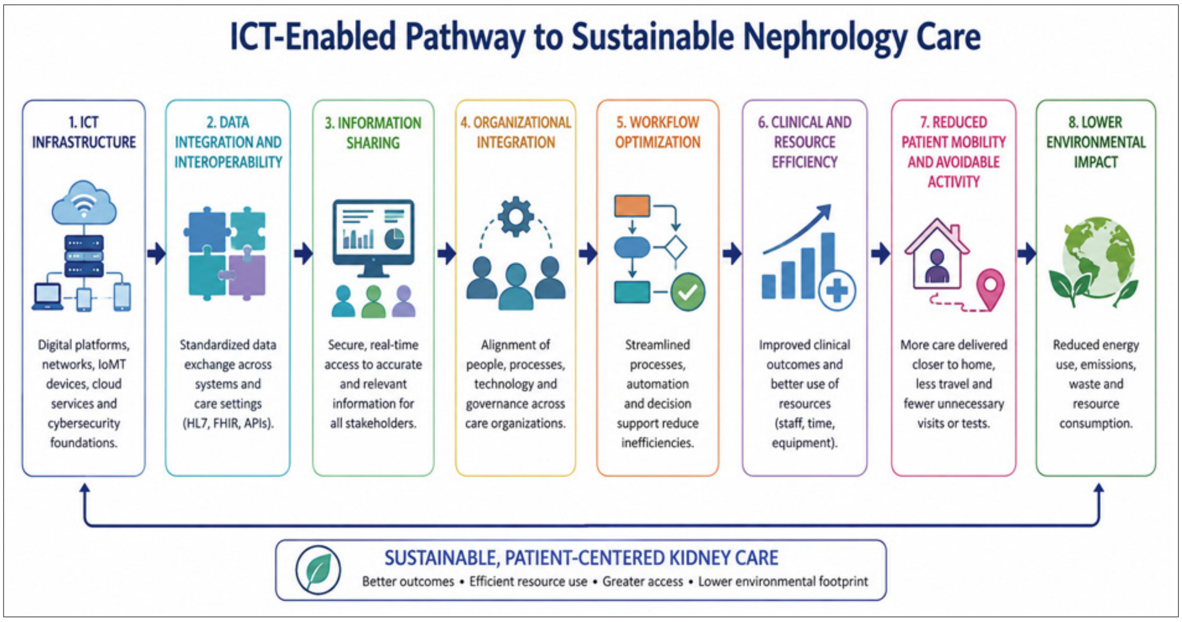

Figure 2: Digital Carbon-Smart Nephrology Framework. (Systems Engineering Pathway from ICT to Sustainable Nephrology)

Continuous monitoring and feedback should connect outcomes back to system design.
The study is limited by the exploratory survey sample, heterogeneity of the literature, and the absence of direct carbon measurements. Its contribution is therefore conceptual and hypothesis-generating.

Future multicenter research should quantify travel avoided, emissions, energy and water use, waste, and rebound effects for specific digital interventions and test whether organizational integration statistically mediates sustainability outcomes [40-43].

Conclusions
ICT can support the transition toward more sustainable kidney care, but its environmental significance depends on the organizational changes it enables. Telemedicine, RPM, interoperable EHRs, AI, and connected devices can improve information exchange, coordination, decentralized care, and resource efficiency. These changes may reduce unnecessary patient mobility and healthcare activity and thereby contribute to a lower carbon footprint.

The Framework for Digital and Carbon-Efficient Nephrology identifies organizational integration and workflow optimization as the cornerstone of technology implementation and sustainability outcomes.This systems-engineering perspective provides a more realistic basis for implementation and evaluation than technology-centered approaches alone. Future low-carbon nephrology strategies should integrate digital infrastructure with interoperability, governance, workforce development, process redesign, and standardized environmental measurement.

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