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Emerging Kidney Technologies: Kidney-on-a-Chip, Genomics, and 3D Bioprinting

B. Salihu[1,2], M. R. Garba[1], H. Liman[1], M.B. Salihu[1], A. B. Yakubu[1], I. S. Ahmed[1,2]
[1] Biomedical Engineering Department, Abubakar Tafawa Balewa University Teaching Hospital (ATBUTH), Bauchi, Nigeria
[2] Federal University of Technology, Owerri, Imo, Nigeria

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Abstract: *Kidney diseases remain a major global health challenge affecting millions of people worldwide. Contemporary kidney care is evolving through advances in dialysis delivery, microphysiological modeling, genomics, bioengineering, and digital support systems. This review examines current hemodialysis and hemodiafiltration technology, clarifies that the existing dialyser already functions as an artificial kidney in a limited extracorporeal sense, and distinguishes it from emerging implantable or bioartificial systems intended to provide more continuous and biologically integrated support. Kidney-on-a-chip platforms are increasingly useful for segment-specific physiology, transporter studies, disease modeling, and nephrotoxicity assessment. Genomic testing is becoming more relevant for diagnosis, prognostic stratification, family screening, and precision-nephrology pathways in inherited disorders involving genes such as PKD1, PKD2, PKHD1, and COL4A3-5. Telemedicine and home dialysis are established models of care rather than entirely new technologies, whereas portable and wearable dialysis remain largely investigational. Future progress in kidney care will depend on combining scientific innovation with affordability, implementation science, equitable access, and careful translational validation.*

Keywords: Kidney technology, dialysis innovation, artificial kidney, nephrology, kidney-on-a-chip, digital health in kidney care.

INTRODUCTION

Kidney disease is a major global health challenge that affects millions of people and places a heavy burden on patients, families, and health systems. CKD affects roughly one in ten people worldwide, and the burden is especially severe in low-resource settings where diagnosis, specialist care, and kidney replacement therapy remain limited. Hypertension, diabetes, and cardiovascular disease continue to accelerate CKD progression and contribute to rising rates of end-stage kidney failure (ESKF). [1,2]

The economic impact is also substantial. Dialysis and kidney transplantation require major healthcare expenditure, and patients with end-stage kidney failure (ESKF) account for a disproportionate share of spending in many health systems. For patients and families, the burden extends beyond direct cost

to include loss of work, caregiver strain, and reduced quality of life. These realities explain why kidney technology is judged not only by technical performance, but also by accessibility, sustainability, and patient-centered design. [3,4]

This paper reviews contemporary kidney technology with emphasis on dialysis innovation, artificial kidney development, digital health, and genomics-based care. It also clarifies important terminology: the current dialyser already functions as an artificial kidney in a limited extracorporeal sense, while next-generation "bioartificial" or implantable kidney projects aim to provide a more continuous, integrated, and biologically informed replacement of kidney function. [4,7,17]

Advances in Kidney Technology

Dialysis Innovations

The main kidney replacement therapies remain hemodialysis (HD), hemodiafiltration (HDF), and peritoneal dialysis (PD). These modalities are established treatments for kidney failure, especially end-stage kidney failure (ESKF), rather than recent inventions. Innovation today is more accurately described as refinement of delivery, monitoring, and biocompatibility. High-volume HDF may improve middle-molecule clearance in selected settings, while modern HD programs increasingly emphasize personalization, home training, self-care, and remote support. [4,7]

Portable and wearable dialysis are best viewed as investigational or emerging platforms rather than routine clinical care. By contrast, home dialysis is already well established in several healthcare systems. In the United Kingdom, longstanding home hemodialysis services include major programs in Manchester, illustrating that home treatment is a mature service model rather than a new technology. [5,6]

The discussion of PD also requires precision. HD does not "avoid" PD; rather, PD is a distinct home-based kidney replacement therapy that uses the peritoneal membrane for solute and fluid exchange. What is genuinely newer in PD is the refinement of delivery and monitoring: automated PD cyclers, remote patient management, software-supported prescription review, and efforts to improve dialysate biocompatibility. Remote monitoring can strengthen adherence, identify mechanical problems earlier, and reduce avoidable visits. Examples of more biocompatible osmotic strategies include icodextrin-based solutions, along with other efforts to improve buffers and protective additives, although many advances remain selective rather than universal standards of care. [4,7,16]

Artificial Kidney, Kidney-on-a-Chip, and Bioengineering

The term "artificial kidney" can be confusing and should be defined carefully. The current dialyser already functions as an artificial kidney in a limited extracorporeal sense because it replaces part of glomerular clearance during intermittent hemodialysis or hemodiafiltration. However, it does not reproduce the full spectrum of native kidney function, particularly continuous homeostasis, tubular transport, endocrine activity, and metabolic regulation. For that reason, current research on implantable or bioartificial kidneys focuses on miniaturized systems that seek to move beyond the present dialyser by combining filtration membranes, sorbent or fluid-management engineering, and, in some concepts, living renal cells. The key distinction is therefore between the existing artificial kidney used in clinical

dialysis and next-generation bioartificial or implantable platforms that aim for more continuous, integrated, and biologically informed kidney support. [4,7,17]

Kidney-on-a-chip technology is not a replacement therapy but a microphysiological research platform. More specifically, it can model glomerular filtration interfaces, proximal-tubular transport, distal-nephron segments, endothelial-epithelial crosstalk, fluid shear stress, and selected disease mechanisms using human cells in microfluidic systems. Here, endothelial-epithelial crosstalk refers to the two-way structural and biochemical communication between tubular epithelial cells and adjacent microvascular endothelial cells across a membrane or matrix under flow. This interaction influences barrier integrity, solute transport, inflammatory signaling, oxygen delivery, and injury responses. Its major strengths are nephrotoxicity testing, transporter biology, disease modeling, and potentially patient-specific drug testing. Its current limitations include incomplete representation of whole-kidney physiology, variable reproducibility, limited standardization across platforms, and the need for stronger translational validation before broad regulatory use. [10,20]

Kidney-on-a-chip is most useful when the question is mechanistic and segment-specific rather than whole-organ replacement. Depending on the design, a chip may model the glomerular barrier, proximal-tubular secretion and reabsorption, endothelial-epithelial interaction, inflammatory injury, diabetic stress, or nephrotoxic drug exposure under controlled flow conditions. Here, endothelial-epithelial interaction refers to bidirectional signaling between tubular epithelial cells and neighboring endothelial cells across a membrane under flow, which helps regulate barrier behavior, solute transport, inflammation, and injury responses. Its translational value lies in linking human-cell biology to measurable functional readouts, but standardization and regulatory qualification are still evolving. The overall workflow is illustrated in Figure 1, and the main applications, strengths, and limitations are summarized in Table 1. A representative platform image is also shown in Figure 1A. [10,20]

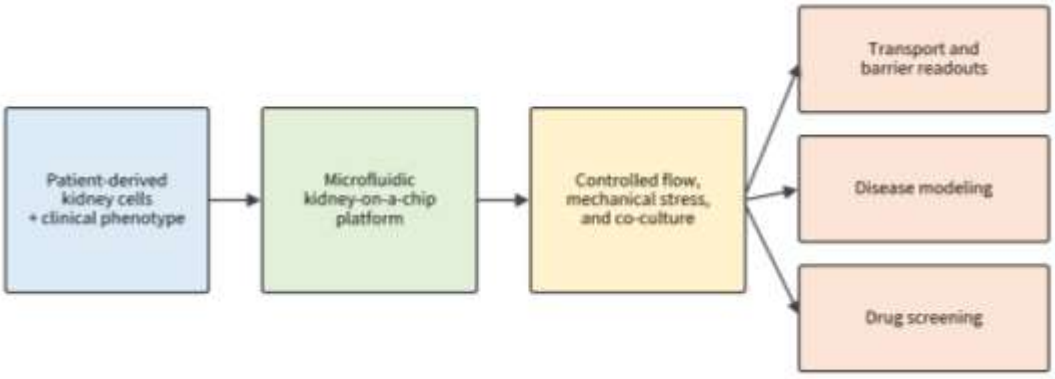

Figure 1. Workflow of a kidney-on-a-chip platform showing how patient-derived kidney cells can be integrated with microfluidic systems to support disease modeling, transporter studies, and nephrotoxicity testing.

Table 1. Kidney-on-a-chip applications, strengths, and current limitations.

Platform focus	Main application	Strength	Current limitation	Readiness
Glomerulus-on-chip	Barrier and filtration modeling	Captures podocyte-endothelial interaction under flow	Does not reproduce the whole organ	Preclinical research
Tubule-on-chip	Transport and nephrotoxicity testing	Supports physiologic shear stress and transporter studies	Assay standardization remains limited	Preclinical research
Multi-compartment kidney chip	Disease modeling across interfaces	Improved biologic complexity	Lower scalability and higher fabrication complexity	Early translational
Patient-specific chip	Personalized drug testing	Potential for precision nephrology	Cell sourcing, reproducibility, and regulatory validation	Experimental

Bioengineering and 3D bioprinting remain promising but should be described realistically. Current work is directed mainly at organoids, tissue constructs, scaffolds, vascularization strategies, disease-model platforms, and cell-patterned test systems rather than full transplantable kidneys. It is also helpful to distinguish ordinary 3D printing from bioprinting: conventional 3D printing already has practical value for anatomical modeling, surgical planning, and training, whereas renal bioprinting is still largely experimental and focused on tubules, organoid support, and microtissue organization. These technologies are valuable for regenerative research and disease modeling, but they have not yet solved the problems of scale, vascular integration, immune compatibility, nephron-level organization, and long-term function required for routine organ replacement. [7,10,17,19,20]

Additional recent reviews further support the distinction between practical anatomic 3D printing and experimental kidney bioprinting: current near-term uses include surgical planning, education, and in vitro tissue modeling, whereas functional implantable kidney fabrication remains investigational because vascularization, maturation, and nephron-scale organization remain unresolved challenges. [19,20]

Three-dimensional printing in nephrology already has practical applications in anatomical reconstruction, preoperative planning, simulation, and education. By contrast, kidney bioprinting remains experimental and is currently more credible as a platform for disease modeling, organoid support, scaffold design, and microtissue fabrication than as a near-term route to a transplantable whole kidney. The main bottlenecks remain vascularization, maturation, nephron-scale architecture, immune compatibility, and durable function. A schematic overview is shown in Figure 2, a representative printed or bioprinted kidney image is shown in Figure 2A, additional images of kidney-printing demonstrations and a printed kidney-shaped construct are shown in Figures 2B and 2C, and the current applications and translational challenges are summarized in Table 2. [19,20]

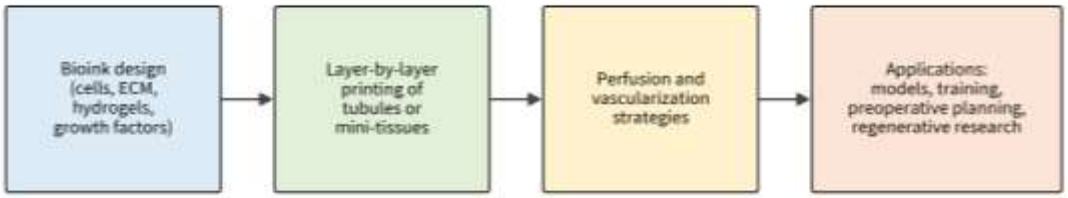

Figure 2. Development pipeline for kidney 3D printing and bioprinting, highlighting bioink design, layer-by-layer construction, perfusion strategies, and major translational bottlenecks.

Table 2. Current applications and translational challenges of kidney 3D printing and bioprinting.

Technology	Primary purpose	Strength	Main challenge	Current maturity
Anatomic 3D Printing	Surgical planning and education	Patient-specific anatomy and communication	Needs high-quality imaging and workflow time.	Clinically applicable
Bioprinted tubule models	Transport studies and nephrotoxicity testing	More realistic cell architecture than static culture	Limited complexity and long-term maturation	Preclinical research
Organoid-assisted bioprinting	Developmental modeling and screening	Combines stem-cell biology with controlled patterning	Batch variability and incomplete maturation	Experimental
Regenerative bioprinting	Future tissue replacement concepts	Long-term potential for personalized repair	Vascularization, scale-up, immune, and regulatory barriers	Investigational

Digital Health in Nephrology

Telemedicine is not a new technology. It is an established model of care delivery that has expanded in nephrology through better video platforms, remote monitoring, and integration with electronic health records. Its value lies in improving access, follow-up, education, and continuity of care, especially for patients with CKD, home dialysis, and post-discharge needs. [8,16] At the same time, telemedicine should not be described uncritically. In resource-poor settings, it is often bedeviled by device cost, unstable telecommunications infrastructure, limited bandwidth, digital literacy gaps, reimbursement uncertainty, and concerns about privacy and governance. Its role is especially relevant in home PD, where regular communication between patients, caregivers, and kidney teams can improve adherence, identify technique problems early, and support timely intervention. AI-enabled risk prediction and web-based decision tools may add value, but they depend on reliable data capture and implementation capacity. Telemedicine is therefore best framed as an important support technology whose success depends on context, not as a universally new solution. [1,8,9,15,16,18]

Genomics, Precision Medicine, and Gene Therapy

Genetic and genomic profiling are increasingly relevant in nephrology because they can refine diagnosis, clarify prognosis, and support more individualized care pathways. This is particularly important in hereditary kidney disorders, where molecular diagnosis can distinguish related phenotypes and true phenocopies. In this context, a phenotype is the observable clinical pattern, whereas a phenocopy is a different genetic disease that mimics a familiar syndrome, such as classical PKD1- or PKD2-related ADPKD. In practice, genomic evaluation may involve cystic-kidney genes such as PKD1, PKD2, PKHD1, GANAB, and DNAJB11; basement membrane genes such as COL4A3, COL4A4, and COL4A5; and other monogenic causes of steroid-resistant nephrotic syndrome, tubulopathies, complement-mediated disease, or syndromic CKD. DNAJB11-related disease is best viewed as a specific atypical ADPKD-spectrum disorder with phenotypic overlap with ADTKD, rather than simply being labeled a generic phenocopy. [11-13,22]

Gene therapy in kidney disease must also be described specifically rather than generically. In ADPKD, the principal genes are PKD1 and PKD2; in ARPKD, PKHD1 is central; and in Alport syndrome, COL4A3, COL4A4, and COL4A5 are key targets. The practical strategies differ by disease. For ADPKD, experimental examples include re-expression of Pkd1 or Pkd2 in mouse models, synthetic PKD1 transgene delivery, anti-miR-17 oligonucleotide approaches to restore polycystin expression and reduce cyst growth, and base-editing or prime-editing concepts for selected pathogenic variants. For Alport syndrome, antisense exon-skipping approaches have been explored preclinically to improve collagen IV expression. PKD1 deserves special mention because it is large and polymorphic, making vector packaging, delivery efficiency, variant interpretation, and precise editing technically difficult. These examples show why kidney gene therapy must be discussed as disease-specific and still largely preclinical, rather than as a single generic platform already ready for routine care. [11,23]

Precision nephrology requires disease-specific rather than generic genomic language. In cystic-kidney disease, DNAJB11 should be treated as a specific genetic diagnosis within the atypical ADPKD spectrum, not casually grouped as a “DNAJB11 phenocopy.” More broadly, a phenocopy refers to a different disorder that mimics the clinical appearance of classical PKD1- or PKD2-related ADPKD. Thus cystic-kidney evaluation may involve PKD1, PKD2, PKHD1, GANAB, DNAJB11, HNF1B, ALG5, ALG8, ALG9, and IFT140; basement-membrane disease may implicate COL4A3, COL4A4, and COL4A5; and other pathways are relevant in nephrotic syndromes, tubulopathies, or complement-mediated disorders. The practical value of testing lies in refining diagnosis, prognosis, family screening, and selection for research or targeted therapy, as outlined in Figure 3 and Table 3. [11-13,22]

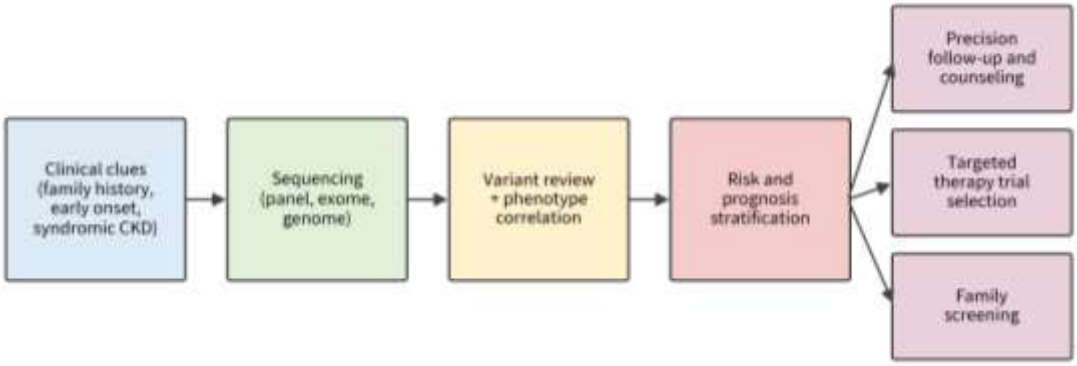

Figure 3. Precision nephrology pathway enabled by genomic testing, from clinical suspicion and sequencing to variant interpretation, family screening, and individualized care planning.

Table 3. Key genomic tools and their clinical value in nephrology.

Genomic approach	Example use	Clinical value	Key limitation	Near-term priority
Targeted gene panel	PKD1/PKD2, PKHD1, COL4A3-5, NPHS1/2, complement genes.	Focused high-yield testing in selected phenotypes.	May miss unexpected or non-panel variants.	Routine use in selected cases.
Whole-exome sequencing	Undiagnosed familial CKD	Broader diagnostic reach	Interpretation burden and incidental findings	Specialist referral pathways
Whole-genome sequencing	Complex rare disease	Captures coding and non-coding variation	Cost and bioinformatics complexity	Tertiary-center implementation
Risk-informed genomic models	Risk refinement in common kidney disease	Potential population stratification	Validation across ancestries remains limited	Careful equitable evaluation
Gene-based therapy research	Disease-specific programs such as PKD or Alport pathways	Future disease-modifying potential	Delivery, safety, and durability challenges	Translational trials

Clinical Implications

The clinical importance of kidney technology lies in its potential to improve survival, symptom control, treatment flexibility, and patient autonomy. Better dialysis design, broader home-care pathways, and more responsive digital follow-up can reduce the travel burden and support individualized therapy. Research tools such as kidney-on-a-chip and genomic profiling may also accelerate safer drug development and more accurate disease classification. [4,7,10,12,13]

However, benefit is uneven unless implementation is realistic. A technically sophisticated therapy has limited clinical value if it cannot be financed, maintained, or integrated into routine care. The most useful advances are therefore often those that combine sound engineering with usability, training pathways, and service redesign. [4,14,15]

Challenges in Implementing Kidney Technology

Major barriers to implementation include cost, infrastructure, interoperability, regulation, and workforce training. New devices must compete not only on efficacy but also on reliability, maintenance burden, data compatibility, and reimbursement logic. These issues are particularly visible in low-resource settings, where the shortage of specialists and fragile supply chains make even proven therapies difficult to scale. [1,14,15]

Ethical and governance questions are equally important. Gene editing, AI-assisted prediction, and increasingly data-rich remote monitoring all raise concerns about consent, privacy, bias, and equitable access. For kidney technology to improve care rather than widen disparities, implementation must be accompanied by transparent oversight and deliberate equity planning. [11,13-15,18]

Future Directions

Future progress in kidney technology will likely come from convergence rather than from a single breakthrough. The most promising direction is the combination of patient-centered dialysis delivery, improved remote monitoring, smarter AI-assisted triage, more robust kidney-on-a-chip platforms, and progressively more precise genomic classification of kidney disease. Even so, not every promising technology will become routine practice. Fully wearable dialysis, implantable artificial kidneys, and gene-correction strategies must still overcome major technical, regulatory, and manufacturing hurdles. The key policy challenge is to ensure that innovation is matched by affordability and access so that future gains are not restricted to a small number of well-resourced centers.

CONCLUSION

Kidney technology is evolving rapidly, but the field benefits from precise language and realistic expectations. Home dialysis and telemedicine are established care models, not entirely new inventions; wearable dialysis, implantable kidney systems, and advanced bioengineering remain promising but still developmental. The conventional dialyser is already an artificial kidney in a narrow functional sense, whereas next-generation bioartificial kidney systems aim to reproduce a wider range of kidney functions. Similarly, kidney-on-a-chip platforms, genomic profiling, and gene-therapy research are opening important new directions, but their present role is mainly to refine research, risk stratification, and future therapeutic design. The next phase of progress in kidney care will depend as much on implementation, equity, and cost control as on engineering sophistication.

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