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Healing Beyond Humans: Biomedical Engineering for Environmental Sustainability

Dr. P. Jamuna Rani*, Afrin.N, Agaliya Dheborah.U**, Arthi.SR****

Associate Professor, Department of Chemistry, Mahendra Institute of Technology, (Autonomous) Namakkal, Tamil Nadu India*

UG Student, Department of Bio Medical and Engineering, Mahendra Institute of Technology, (Autonomous) Namakkal, Tamil Nadu India**

ABSTRACT: Biomedical engineering (BME) is widely recognized for advancing human health through diagnostics, therapeutics, and assistive technologies. Less explored—but rapidly gaining urgency—is its role in protecting ecosystems and enabling low-carbon, circular health systems. This article synthesizes how BME can drive environmental sustainability beyond the clinic by (i) integrating life-cycle assessment (LCA) into medical device design, (ii) replacing persistent plastics and electronics with bio-based and bioresorsable alternatives, (iii) deploying paper-based and synthetic-biology biosensors for decentralized water and air quality monitoring, (iv) translating biomimetic membranes and microbial fuel cells into greener water and waste management, and (v) mitigating high-impact emissions in peri-operative and hospital practice (e.g., anaesthetic gases). We present recent case studies—including the NHS England phase-out of desflurane, LCA-backed shifts from single-use to reusables, and sharps recycling—and propose a pragmatic HEALING blueprint (Holistic LCA, Eco-design & energy efficiency, Avoid-and-substitute toxins, Localize supply, Integrate One Health, Nature-inspired materials, Governance & standards). We conclude with an implementation roadmap for resource-constrained settings and research priorities that align human care with planetary health.

KEYWORDS: One Health; life-cycle assessment; bioresorbable electronics; biodegradable polymers; paper-based microfluidics; microbial fuel cells; aquaporin membranes; anaesthetic gases; circular economy; environmental biosensors

I. INTRODUCTION: FROM PATIENT HEALTH TO PLANETARY HEALTH

The global health sector carries a sizable environmental footprint through energy use, supply chains, pharmaceuticals, single-use devices, and waste management. According to Health Care Without Harm (2019), healthcare contributes nearly 4.4% of net global greenhouse gas (GHG) emissions—equivalent to the world's fifth largest emitter if considered as a country. A large share comes from energy-intensive hospitals, medical supply chains, and high-impact clinical practices such as anaesthesia and sterilization.

For countries like India, where healthcare access is expanding rapidly, this footprint will only grow unless sustainability principles are integrated early. India already faces dual challenges of environmental degradation (air pollution, water contamination, biomedical waste) and resource constraints (limited clean energy, high patient load). Biomedical engineering therefore plays a pivotal role: it can reduce the ecological cost of care while supporting equitable access to health technologies in low- and middle-income countries (LMICs).

Aligning health gains with ecological integrity is a central aim of the One Health approach, which seeks to optimize human, animal, and ecosystem health together. Biomedical engineers occupy a strategic position in this transition: they design the materials, sensors, and systems that determine resource flows and emissions across the health continuum—from manufacturing and use to end-of-life.

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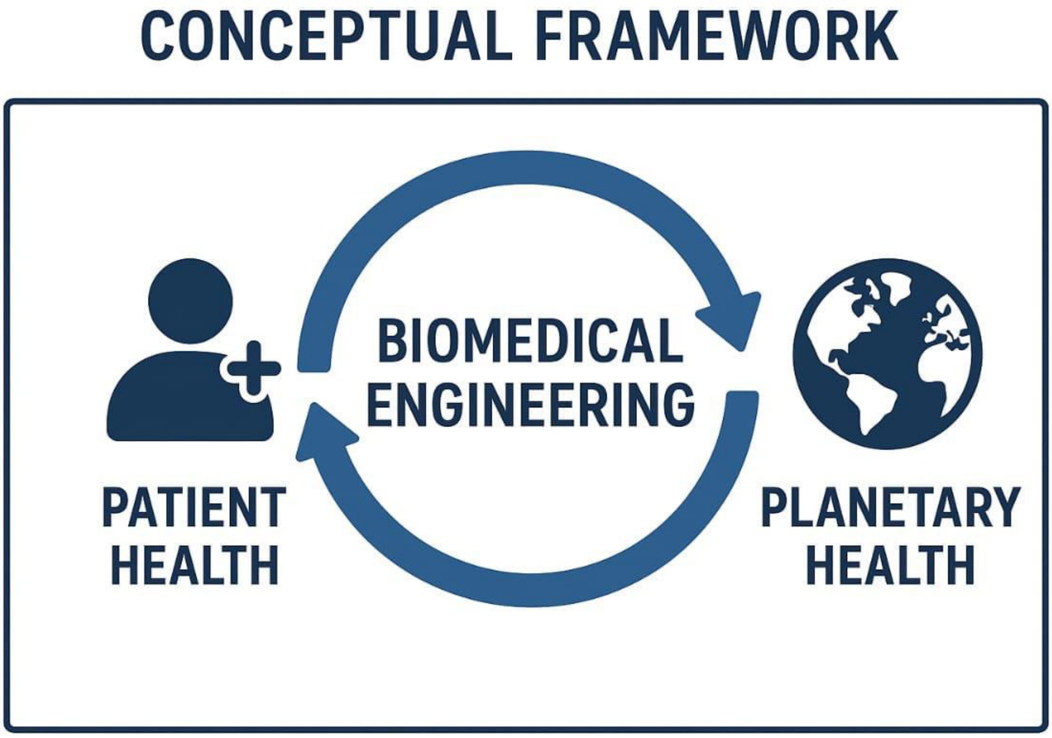

Figure 1: Conceptual framework

This paper positions BME as a lever for environmental sustainability in three arenas:

1. inside healthcare (low-carbon devices and practices),
2. at the human–environment interface (biosurveillance and remediation), and
3. upstream in design (materials, architectures, and standards that enable circularity and low energy).

We draw on recent evidence and illustrate actionable pathways for practitioners, students, and policymakers.

II. ENGINEERING LEVERS FOR SUSTAINABILITY

2.1 Life-Cycle Assessment (LCA) as a Design Tool

LCA quantifies environmental impacts (e.g., climate change, water use, toxicity) across a product's life—from raw materials to disposal. Integrating LCA early in design helps teams avoid burden shifting (e.g., lower energy but higher toxicity) and compare single-use vs. reusable options under realistic sterilization and logistics. Recent LCAs of instrument sets and reprocessed devices show that well-managed reusables

Design checklist: modular assemblies; disassembly for repair; low-temperature sterilizable materials; minimized packaging; compatibility with remanufacture/reprocessing; digital twins to simulate impacts.

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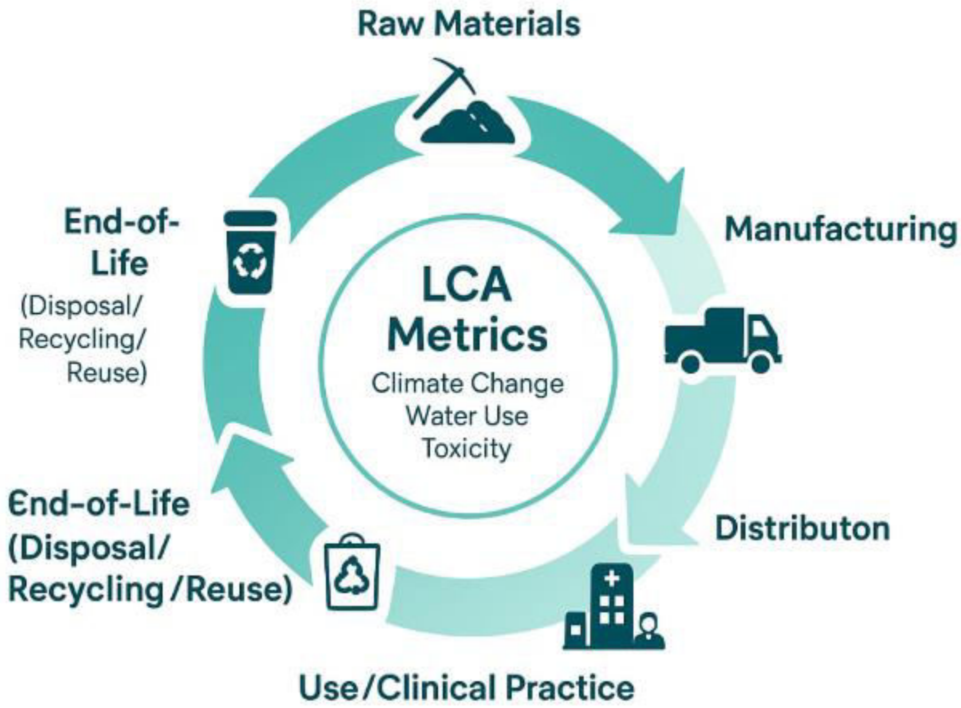

Figure 2: Life-Cycle Assessment

2.2 Materials: From Persistent to Biocompatible and Biodegradable

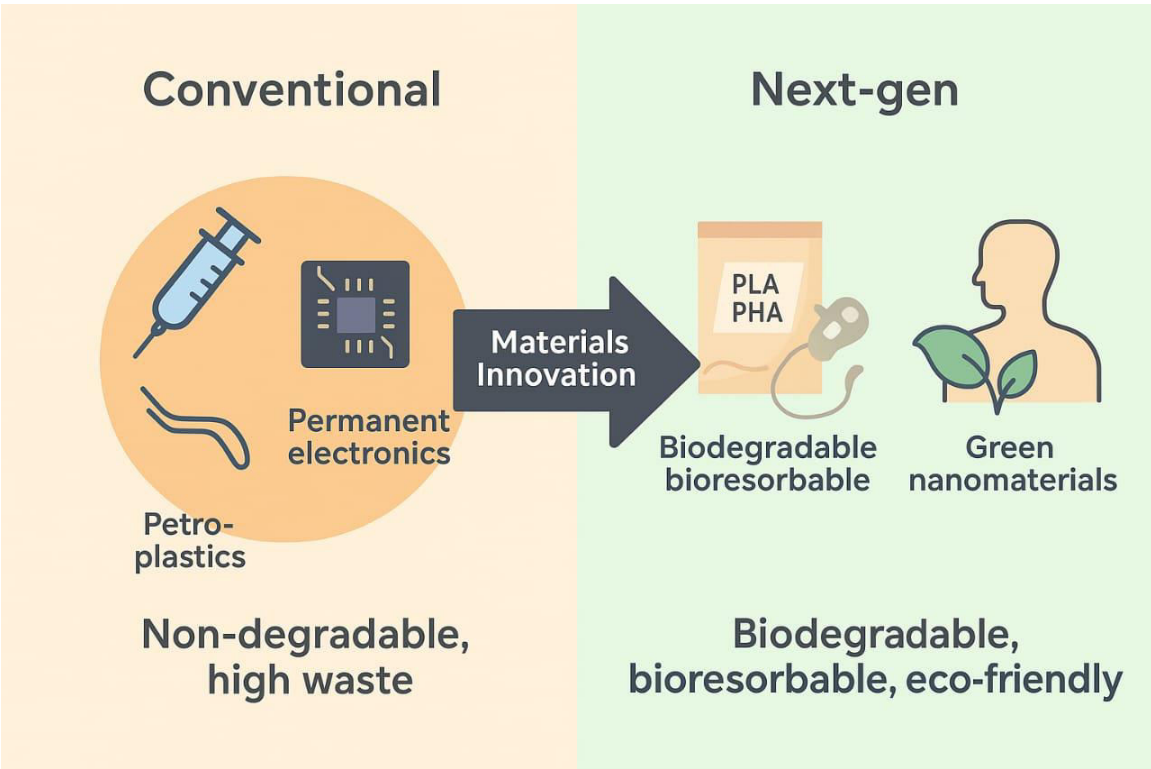

Figure 3: Materials

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- Biomedical devices have historically relied on durable petro-plastics and permanent electronics that accumulate as waste. A new materials toolbox offers alternatives:
- Biodegradable polymers (e.g., PLA, PHA and blends) for disposables, dressings, and some device housings; advances address brittleness and processing constraints.
- Bioresorbable/transient electronics enable sensors and stimulators that dissolve harmlessly after use, reducing explant surgeries and e-waste in the body and the hospital supply chain.
- Green nanomaterials synthesized via plant or microbe routes can reduce solvent and energy footprints for biosensors and drug-delivery platforms.
- Trade-offs: bioplastics may require industrial composting, can shed micro-particles if poorly managed, and may use agricultural feedstocks—necessitating full LCA and end-of-life planning.

2.3 Environmental Biosensors: Paper, Microfluidics, and Synthetic Biology

Paper-based microfluidics (µPADs) and low-cost electrochemical strips deliver point-of-need tests for pathogens, metals, PFAS, and nutrients with minimal reagents, capillary flow (no pumps), and incinerable substrates. Whole-cell and cell-free biosensors engineered via synthetic biology detect bioavailable toxins (e.g., arsenic, mercury) and fecal contamination, enabling community monitoring frameworks. The key is translating lab sensitivity/specificity into robust field kits (stable reagents, low background, clear readouts) and safe containment/disposal of biological components.
Design checklist: cold-chain-free reagents; shelf-stable lyophilized components; clear colorimetric outputs; validated detection limits vs. regulatory thresholds; safe containment.

2.4 Nature-Inspired Water Technologies

Aquaporin-based biomimetic membranes emulate cellular water channels to improve selectivity and permeability, offering pathways to lower-energy desalination and removal of trace contaminants. Microbial fuel cells (MFCs) pair wastewater treatment with electricity generation and can also serve as self-powered sensors; while not yet mainstream for large plants, MFCs are promising for decentralized sanitation and remote monitoring.

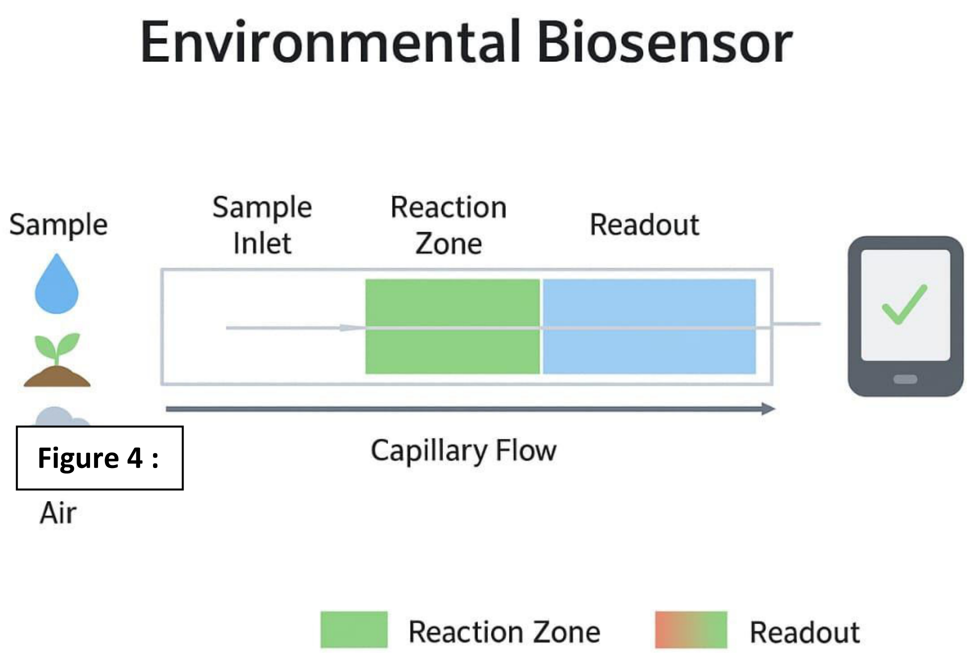

FIG:4

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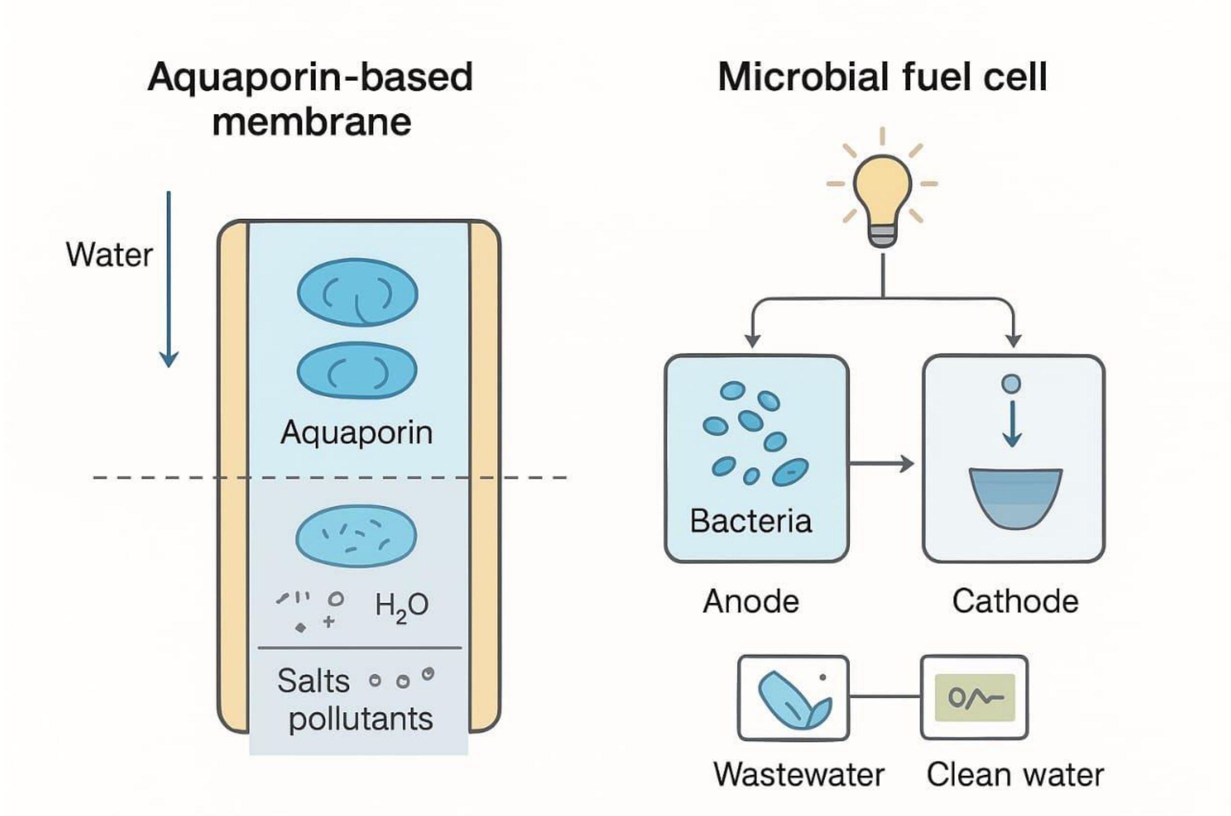

FIG: 5

2.5 High-Impact Hotspots in Care Delivery

Peri-operative care and anaesthesia are prominent hotspots. Desflurane, a volatile anaesthetic, has an exceptionally high global warming potential; health systems that have eliminated or strictly limited it (shifting to sevoflurane at low flows or to total intravenous anaesthesia where clinically appropriate) have achieved rapid emissions reductions without compromising patient outcomes. Similarly, device reprocessing, optimized sterilization cycles, and sharps recycling programs can cut waste and procurement impacts.

III. CASE STUDIES AND EVIDENCE SNAPSHOTS

Case 1: National phase-out of desflurane (UK). NHS England decommissioned routine use of desflurane in 2024, projecting savings of ~40 kilotonnes CO_2-e per year—illustrating how a single agent switch can deliver system-level gains when backed by clinical guidance and procurement policy.

Case 2: Single-use vs. reusable instrument sets. LCAs comparing reusable instrument sets (with validated reprocessing) to equivalent single-use sets show lower climate and resource impacts for reusables under typical utilization (hundreds of cycles), while flagging the importance of efficient washer-disinfectors and loading practices.

Case 3: Reprocessing & remanufacturing. For certain devices, regulated reprocessing (third-party or in-house) reduces impacts relative to single-use, when transport and sterilization are optimized. Transparent LCA plus post-market surveillance is essential to maintain safety and quality.

Case 4: Sharps recycling. Closed-loop programs reclaim plastic from sharps collectors and select components, diverting waste from incineration/landfill and reducing virgin resin use—demonstrating circular solutions even in regulated waste streams.

Case 5: Paper-based water tests & WCBs. Paper microfluidics and whole-cell biosensors have matured from lab prototypes to field pilots detecting arsenic and mercury below WHO limits, supporting village-level water safety monitoring with minimal equipment.

Case 6: Aquaporin membranes. Pilot-to-commercial biomimetic membranes report high salt rejection with improved water flux; ongoing work targets durability, fouling resistance, and scalable, low-cost fabrication for municipal adoption.

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IV. THE HEALING BLUEPRINT FOR SUSTAINABLE BIOMED DESIGN

H— Holistic LCA at concept stage: require screening LCAs during feasibility; set carbon, water, and toxicity budgets per function (e.g., per dose, per procedure).
E— Eco-design & energy efficiency: low-temperature sterilization compatibility; low-power electronics; energy-aware firmware; enable low-flow anaesthesia and idle-mode cutoffs.
A— Avoid and substitute toxics: phase out high-GWP anaesthetics and nitrous oxide leakage; minimize PFAS-containing coatings; design out halogenated solvents.
L — Localize & dematerialize supply: regional manufacturing where safe; lighter packaging; digital instructions; repair hubs; shared fleets of high-value equipment.
I — Integrate One Health & equity: design environmental biosensors and sanitation tech with communities; ensure affordability and accessibility in LMICs.
N — Nature-inspired materials/systems: aquaporin membranes, bio-based polymers, green-synthesized nanomaterials, and bioresorbable circuits.
G — Governance, standards & data: EPDs, eco-labels for devices, procurement specifications that weight LCA results, and open datasets for benchmarking.

V. IMPLEMENTATION ROADMAP (WITH LMIC & INDIA-RELEVANT NOTES)

1. Policy & procurement:mandate LCA/EPDs for tenders; include anaesthetic gas metrics; reward reusables/reprocessed devices where safe; set targets for nitrous oxide abatement.
2. Clinical practice:adopt low-flow anaesthesia protocols; retire desflurane; deploy capture/abatement for N_2O where still used; build green-OT playbooks.
3. Materials & manufacturing:co-develop PLA/PHA blends suitable for device housings and trays; pilot controlled composting or chemical recycling partnerships.
4. Waste & circularity:roll out sharps and tray take-back schemes; track waste diversion and carbon savings; train biomedical equipment technicians (BMETs) for repair/refurbishment.
5.Water & sanitation tech:pilot µPADs and biosensors for arsenic/fluoride/heavy metals with district labs; integrate with state water quality dashboards; evaluate aquaporin-based modules in decentralized plants.
6. Capacity & curricula:embed LCA, One Health, and eco-design in biomedical engineering courses; fund student projects on self-powered sensors and low-resource diagnostics.
7. Measurement & reporting:define functional units (per bed-day, per surgery, per test); publish annual sustainability reports with device-level indicators.
Risks & safeguards:avoid greenwashing; validate biodegradation claims in realistic end-of-life contexts; ensure biosensor safety/containment; protect environmental data privacy for communities; keep patient safety non-negotiable.

6. Research Gaps and Opportunities

- Durable, low-cost bioresorbable electronics with predictable dissolution and stable performance windows.
- Scalable fabrication of aquaporin membranes with anti-fouling surfaces and long service life in variable water chemistries.
- High-selectivity, field-robust biosensors (cell-based and cell-free) with smartphone-enabled quantification and local manufacturing.
- Validated LCAs for common devices in Indian contexts, including real energy mixes, transport, and reprocessing infrastructure.
- Sterilization innovations (e.g., plasma, low-temperature H_2O_2) optimized for energy/water while maintaining sterile assurance levels.

VII. DISCUSSSION

The evidence reviewed shows that biomedical engineering can act as a powerful driver of environmental sustainability, but translating these innovations into practice requires careful balancing of benefits, risks, and context-specific realities. Globally, high-income countries (HICs) are leading with policies such as the UK NHS net-zero roadmap and the phase-out of desflurane. These demonstrate that regulatory guidance, procurement standards, and strong clinical buy-in can accelerate rapid emissions reductions. However, in low- and middle-income countries (LMICs) such as India, adoption is complicated by resource limitations, infrastructure gaps, and the need to prioritize affordability alongside sustainability. For example, reusable devices may offer large climate benefits but require sterilization systems and logistics that are not yet reliable in all Indian hospitals.

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Another key trade-off lies in materials innovation. Biodegradable polymers and bioresorbable electronics hold promise, but they may demand industrial composting or specialized recycling streams. Without these, such materials could generate new waste challenges instead of solving old ones. Similarly, microbial fuel cells and aquaporin membranes show potential for water and sanitation, but their scalability, durability, and cost remain barriers to deployment outside of research pilots.

The social dimension is equally important. Technologies such as paper-based biosensors can empower communities to monitor water quality, yet success depends on local training, cultural acceptance, and safe disposal practices. Biomedical engineers must therefore work closely with public health experts, policymakers, and local communities to co-design solutions that are technically sound and socially equitable.

In sum, while the innovations described in this paper present exciting opportunities, their success hinges on building enabling ecosystems: policy support, clinical guidelines, circular waste management, and global knowledge exchange. Without these, sustainability may remain a niche feature rather than a systemic shift in biomedical engineering.

VIII. CONCLUSION

Healing beyond humans requires biomedical engineering to design with the biosphere in mind. By embedding LCA, shifting to bio-based and bioresorbable materials, deploying environmental biosensors, translating biomimetic water technologies, and tackling clinical hotspots like anaesthetic gases, the field can deliver care that is safer for patients and kinder to the planet. The HEALING blueprint offers a practical scaffold to accelerate this transition across design studios, operating theatres, and community water projects alike.

IX. FUTURE VISION

Looking ahead, biomedical engineering has the capacity to transform healthcare into a sector that not only heals patients but also regenerates ecosystems. Over the next decade, three trends are likely to define this transformation:

1. Smart, Circular Medical Devices – Devices will be designed for reuse, repair, and remanufacture by default, supported by digital twins and AI-driven life-cycle simulations to minimize waste and optimize resource use.
2. Community-Embedded Biosensors – Paper-based, synthetic-biology, and smartphone-linked sensors will become standard tools for local environmental monitoring, allowing citizens to safeguard water and air quality in real time.
3. Nature-Inspired Infrastructure – Aquaporin membranes, microbial fuel cells, and biodegradable polymers will expand from pilot studies to mainstream infrastructure, powering hospitals and sanitation systems in both urban and rural contexts.

For countries like India, where healthcare expansion and sustainability must advance together, biomedical engineers of the present generation will play a decisive role. By embedding eco-design, One Health principles, and circular economy thinking into curricula and practice, they can ensure that growth in health access does not come at the cost of environmental degradation.

Ultimately, the vision is a future where hospitals are carbon-neutral healing hubs, diagnostics are low-cost and self-powered, and biomedical waste streams are reabsorbed by nature rather than accumulating in landfills. Achieving this future will require bold innovation, cross-disciplinary collaboration, and the leadership of young biomedical engineers ready to design not just for patients, but for the planet.

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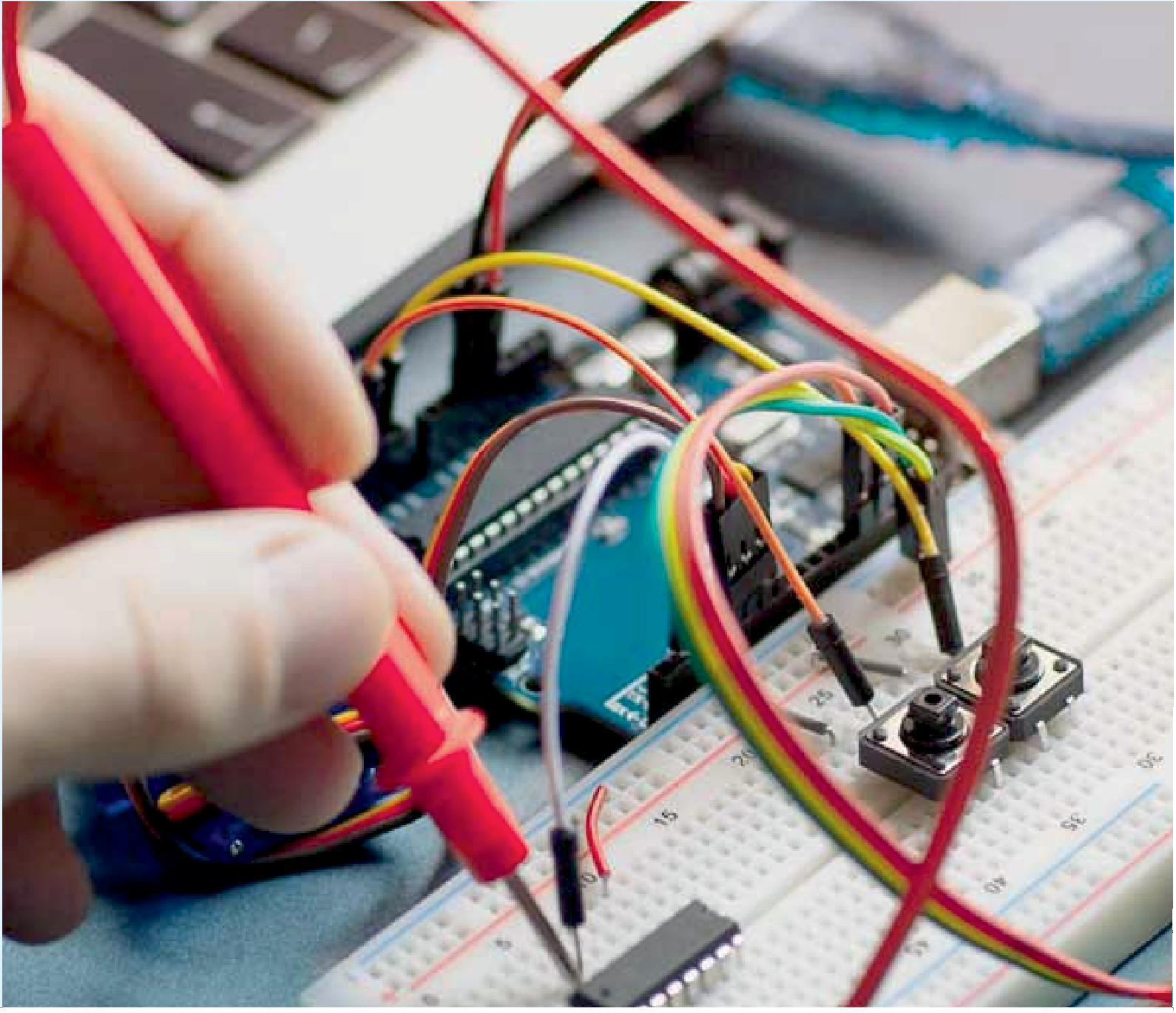

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