









Pioneering green surgery: exploring current positions, advances, challenges, and pragmatic solutions for resource-inadequate settings-a scoping review

 Patrick Ashinze^{*1},  Gabriel Adedoyin²,  Peter Ayodele¹,  Eniola Akande¹,  Bethrand Chukwu¹,
 Alexander Entonu¹,  Ambrose Ogbue³,  Mayowa Olagoke⁴,  Aishat Mahmoud⁵,  Adeshina Azeez¹,
 Oluwatosin Afolabi¹,  Eniola Obafemi¹,  Godwin Chiazor⁶,  Adeshina Ahmed⁷

¹Department of Clinical Sciences, Faculty of Medicine, University of Ilorin Teaching Hospital, Ilorin, Nigeria

²Department of Orthopedics and Traumatology, Mid Yorkshire Teaching NHS Trust, England, United Kingdom

³Department of Orthopedics and Traumatology, Irrua Specialist Teaching Hospital, Irrua, Edo, Nigeria

⁴Department of Medical Oncology, National Health Service, England, United Kingdom

⁵Department of Rheumatology, Betsi Cadwaladr University Health Board, Wales, United Kingdom

⁶Department of Internal Medicine, University of Benin Teaching Hospital, Benin, Edo, Nigeria

⁷Department of General Surgery, Federal Medical Centre, Ebute Metta, Lagos, Nigeria

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ABSTRACT

Aims: Surgery is a major contributor to greenhouse gas emissions, especially through anesthetic gases, energy use from machines, and disposable materials. In low- and middle-income countries (LMICs) like Nigeria with limited access to surgery, its environmental impact further challenges already strained systems. This scoping review aims to map the current evidence on the feasibility, strategies, and future directions for implementing environmentally sustainable (green) surgical practices in resource-constrained settings. It also examines its potential role in promoting equity, reducing costs, and supporting ecological conservation.

Methods: We conducted a scoping review following methodological guidance for this study type. A structured search of peer-reviewed articles, global health reports, and case studies was performed using PubMed, Google Scholar, and Scopus. Key concepts and evidence were charted and synthesized thematically. Tools such as the PIPES instrument and Green Surgery Checklist were analyzed for their applicability in LMICs.

Results: Green surgical practices, which include reuse models, solar-powered theatres, digital health, and waste segregation, have been shown to reduce costs, improve outcomes, and cut emissions by up to 97%. The green channel model demonstrated reduced postoperative complications without compromising care. Tools like the PIPES assessment and 5Rs-based checklists support implementation. Climate-resilient infrastructure, ethical frameworks, and global collaborations, including WHO's three-bin waste system, further strengthen sustainability in surgical care.

Conclusion: Green surgery is both feasible and beneficial in LMICs. It aligns environmental goals with surgical equity, cost-effectiveness, and quality care. Embedding sustainable practices into health systems through innovation, policy, and global cooperation is essential for building climate-resilient surgical services and mitigating healthcare's environmental footprint.

Keywords: Green surgery, surgical applications, environmental health, environmental sustainability, health systems, surgery

INTRODUCTION

Conceptual Framework

Green surgery is a concept that aims to ensure surgical practices done in healthcare settings are safe for the environment, thereby minimizing or nullifying the negative, eco-inflammatory impact of surgery on climate.¹ As healthcare systems globally confront the urgent challenge of climate change, green surgery emerges as a model for responsible clinical care that aligns with environmental stewardship. It consists of strategies aimed at waste reductions, energy conservations, and utilization of resources responsibly. The

ultimate goal is to decarbonize surgical pathways without compromising quality, safety, or equity, thereby making a positive impact on climate.

Environmental Burden

Surgical care contributes significantly to the environmental impact of healthcare systems. It is interesting to note that studies have estimated that the healthcare sector is responsible for 4.4% of global net emissions,² which include carbon

Corresponding Author: Patrick Ashinze, patrickashinze@yahoo.com



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dioxide, methane, and ozone, among others; and that if the healthcare sector were a country, it would be the fifth largest emitter. The National Health Service (NHS) in England generates an estimated 25 million tons of carbon dioxide per year,³ responsible for around 4% of national greenhouse gas emissions.⁴ Operating rooms (ORs), in particular, are among the most energy-intensive areas in hospitals, consuming three to six times more energy per square foot than other hospital areas.⁵ Healthcare is expected to increasingly contribute to exacerbating climate change and its negative impacts, with increasing demand for care worldwide, unless actions are rapidly put in place.

Equity Imperative

A glaring paradox exists in the global distribution of surgical care and its environmental impacts. Low- and middle-income countries (LMICs) represent approximately 70% of the world's population, yet 93% of individuals living in these regions lack access to safe, timely, and affordable surgical care.⁶ This contrasts sharply with high-income countries (HICs), where surgical care is more readily available. For example, surgical procedures in HICs often generate 10 to 20 times more waste per case than those performed in LMICs, primarily due to the use of single-use instruments, high rates of over-packaging, and more energy-intensive infrastructure.⁷ This disparity highlights a crucial double burden: LMICs face a severe lack of access, while HICs contribute disproportionately to environmental damage from surgical waste.⁸

Review Scope and Objectives

This review sets out to evaluate recent innovations and adaptations in green surgery, with a particular focus on resource-constrained settings. It critically examines systemic barriers to implementation—such as financing, infrastructure, and workforce limitations—and proposes context-specific, pragmatic solutions. The review also explores future directions, including the integration of sustainability metrics into surgical system strengthening. The overarching goal is to inform strategies that expand surgical capacity in LMICs in a manner that is climate-resilient and equitable. The article also aims to critically examine the barriers to implementation. These may include limited financial investment, regulatory restrictions, lack of awareness among healthcare professionals, and cultural preferences for single-use items. The main goal is to ensure that as global surgical capacity expands, it does so in a disposition that aligns with climate resilience and global health equity.

PRINCIPLES AND CURRENT STATE

Core Principles: the 5R Framework

The pursuit of sustainable surgery is anchored in the 5R framework; reduce, reuse, recycle, rethink, and research.

This framework was originally adapted from waste reduction models and the principles have become instrumental in identifying actionable strategies to mitigate the environmental burden of surgical care without compromising safety or access.⁹

Reduce strategies focus on minimizing unnecessary consumption of energy, materials, and pharmaceuticals. Operating theatres consume 3-6 times more energy per square meter than other hospital environments.⁴ Transitioning to

low-flow anaesthesia, avoiding high-global warming potential agents like desflurane, and optimizing surgical tray content can significantly reduce carbon output.¹⁰

Reuse involves substituting single-use consumables with validated reusable alternatives, such as autoclavable laparoscopic instruments, surgical drapes, and gowns. When adequately sterilized, these can reduce waste generation by over 50% and lower costs over time.^{11,12}

Recycle initiatives require structured segregation of theatre waste streams such as metals, plastics, and paper, supported by staff education and administrative commitment. Although recycling uptake varies globally, targeted interventions in surgical suites have shown recovery of up to 30% of perioperative waste.¹³

Rethink compels re-evaluation of standard protocols. Substituting general anaesthesia with spinal or local techniques, where clinically appropriate, can lower emissions and reduce resource intensity. Similarly, increased use of day-case surgery and enhanced recovery programs may lessen hospital stays and environmental footprint.

Research remains essential to scale sustainable practices. Although robust data exists from HICs, evidence from LMICs is limited. Investment in implementation science and carbon accounting is needed to inform policy and innovation in diverse contexts.¹⁴

Global Initiatives

Momentum toward green surgery has been propelled by coordinated global initiatives and institutional commitments. In 2020, NHS England became the world's first national health system to commit to net-zero emissions, with a 2040 target for direct care and 2045 for the entire supply chain.⁴ Within this framework, the Green Surgery Challenge 2021 catalyzed hospital-led innovations, including eliminating desflurane, optimizing reusable theatre kits, and reducing single-use plastics. Collectively, the five finalist projects projected savings of over 130 tonnes of CO₂ equivalent yearly.¹⁵

In LMICs, sustainability is gaining traction through the platform of National surgical, obstetric, and anaesthesia plans (NSOAPs). These national blueprints, adopted in more than a dozen countries, emphasize infrastructure resilience and systems strengthening. Zambia has piloted solar-powered sterilization in district theatres, while Tanzania has explored modular, energy-efficient facility design.¹⁶ Global alliances like the global green and healthy hospitals (GGHH) network support cross-border collaboration. Examples include reusable medical kits in India and hospital waste minimization in the Philippines, demonstrating that green solutions can be locally led and globally informed.¹⁷

HICs vs. LMICs: Contrasting Priorities and Implementation Landscapes

Disparities between HICs and LMICs shape the green surgery frontier. HICs benefit from established infrastructure, enabling sustainability efforts to focus on emission tracking, green procurement, and policy mandates. For instance, several UK and European centres have integrated carbon tracking tools into operating room audits, and are also trialing “carbon budgets” for procedures.¹⁸ In contrast, many LMICs operate with foundational deficits: limited electricity,

water scarcity, supply chain fragility, and under-resourced workforces. Here, the immediate imperative is often access, not emissions. Nevertheless, green practices have emerged organically. Examples such as reprocessed mosquito nets used as hernia mesh in Uganda, or gasless laparoscopy systems deployed in rural India, exemplify low-waste, high-ingenuity interventions.^{16,17}

A critical challenge remains the misalignment of incentives. Reusables often carry higher upfront costs, which are not reimbursed in fee-for-service models. Furthermore, global funding mechanisms rarely prioritize sustainability metrics in surgical investments. To bridge this divide, financing strategies, capacity building, and context-adapted innovation pipelines are vital (Table).

TECHNOLOGICAL ADVANCES

Energy-Efficient Technologies

Improving access to safe and affordable surgical care in LMICs is associated with notable health and economic benefits across a range of patient groups.¹⁴ Several established methods exist to facilitate these improvements. As sustainability initiatives progress in LMICs and other resource-limited settings, policymakers should focus on adopting technological and energy-efficient approaches within surgical care to enhance outcomes.

For example, the LigaSure™ energy haemostatic device has been shown to reduce operative times, minimise blood loss, and improve results compared to traditional diathermy in low-resource environments.²⁰ Lighting contributes significantly to direct energy consumption in operating rooms; thus, introducing LED lighting in LMICs’ operating theatres may both improve provider comfort and lower overall energy expenditure.²¹ Additionally, energy-efficient technologies can contribute to the development of minimally invasive surgery in resource-constrained contexts. A randomised trial determined that gasless laparoscopy was not inferior to conventional laparoscopy, suggesting its suitability in these settings.²² The TARGET study addressed issues related to sustainability and skills transfer in LMICs, concluding that structured training programmes in complex procedures increase knowledge and surgical skill acquisition in rural areas.¹⁹

Waste Reduction Innovations

Recent studies indicate that reusable instrument systems have certain benefits compared to single-use alternatives, such as reduced costs and more environmentally sustainable

outcomes.^{23,24} By adopting these models, LMICs may achieve economic efficiencies by utilising reusable equipment, which is estimated to cost between 47-83% of comparable single-use options.²³ It is important to note that disposing of reusable equipment before the end of its recommended lifespan can lead to increased overall costs.²⁵

The use of biodegradable polymers in LMICs could help limit surgical waste and promote sustainable healthcare practices. Their biocompatibility supports tissue regeneration, and both synthetic and natural variants allow for specific adaptation in terms of mechanical properties, degradation rates, and antimicrobial profiles.²⁶ Unlike metal implants, biodegradable polymers do not require removal procedures, potentially reducing patient burden.²⁶ Thereby, offering better medical, financial, and psychological sustainable advantages when compared to conventional solid materials.

Resource-Optimizing Diagnostic Tools

Available data indicate that patients living in rural areas of HICs are offered fewer surgical options for certain treatable cancers compared to those in urban locations.²⁷ A similar disparity is observed as a significant concern in LMICs as well.²⁸ Addressing this challenge involves improving diagnostic tools to better allocate resources and potentially improve surgical outcomes in LMICs, especially where resources are limited. Techniques such as fluorescence-guided surgery have been proposed as possible strategies. Evidence suggests their usefulness across multiple surgical specialties, with growing support for their role in enhancing patient safety and surgical efficiency.^{29,30} A recent study investigated the practicality of introducing new point-of-care imaging devices in LMICs. The research described the advantages of both basic technologies, such as point-of-care ultrasound, and advanced equipment, including portable ultra-low field MRI, for strengthening diagnostic capacity in these settings.³¹ Considerations such as energy consumption, maintenance, and training-needs should be regularly evaluated over time to determine long-term viability as a model for sustainability for LMICs.

Digital Solutions

LMICs continue to encounter significant healthcare challenges, including workforce shortages and inadequate infrastructure. Telemedicine and Artificial Intelligence (AI) offer potential solutions for remote consultations, recordkeeping, diagnostics, and treatment monitoring; however, their implementation necessitates the development of robust ethical and data privacy frameworks.³² In the

Domain	HICs	LMICs
Infrastructure	Reliable electricity, sterilization, and waste management systems	Unreliable electricity and water supply; limited sterilization and waste disposal capacity
Sustainability focus	Emission tracking, procurement reform, and surgical carbon budgeting ⁴	Expanding access, minimizing waste, and maximizing equipment reuse
Examples of innovations	Carbon footprint calculators integrated into OR audits ⁴	Mosquito nets used as low-cost hernia mesh in Uganda; gasless laparoscopy in rural India ¹⁹
Economic barriers	Upfront costs of sustainable tools often supported by reimbursement or central funding	High capital costs for reusables rarely reimbursed; local systems lack fiscal incentives
Policy environment	Sustainability embedded in national strategy (e.g., NHS Net Zero) ⁴	NSOAPs rarely incorporate environmental sustainability metrics
Innovation model	Top-down, institutionally funded green R&D pipelines	Grassroots, frugal innovations tailored to local limitations

HICs: High-income countries, LMICs: Low- and middle-income countries, OR: Operating room, NSOAPs: National surgical, obstetric, and anaesthesia plans, NHS: National health service

aftermath of the COVID-19 pandemic, telemedicine has been increasingly adopted to improve healthcare access, sustain continuity of services, and mitigate disparities in resource-limited environments.³³ Additionally, these technologies have improved access to specialist care, resulting in reduced travel costs and shorter wait times, particularly in the context of postoperative management.³⁴ Nonetheless, there remain unmet needs that could be addressed through broader adoption of these innovations across LMICs.

Furthermore, telemedicine has proven effective for skills transfer in low-resource settings, facilitating complex procedures as well as evaluation and peer mentoring during skill acquisition, even when trainers are located remotely from trainees.¹⁹

LMIC-Specific Adaptations

One example is the use of sterilized mosquito net mesh (MNM) as an alternative to the more costly commercial synthetic mesh (CSM). A systematic review study reported no statistically significant difference in overall post-operative complication rates between the two methods.³⁵ Furthermore, MNM has demonstrated patient-friendliness, clinical effectiveness, and cost efficiency, making it a promising option for adoption in resource-limited settings across LMICs.³⁶ Another adaptation that could benefit LMICs is the use of medicinal maggots in surgical care, as several studies have shown their superior benefits for treating complex surgical wounds.^{36,37} Though these innovations enhance efficiency and are sustainable, challenges like ethico-cultural acceptance, training gaps, and uneven regulation must be addressed for broader use.

IMPLEMENTATION CHALLENGES IN RESOURCE-CONSTRAINED SETTINGS FOR GREEN SURGERY

Systemic Barriers

Implementing green surgery in resource-constrained settings, particularly in LMICs, faces significant systemic barriers that hinder sustainable surgical practices. A 2016 study highlighted that 31% of hospitals in low-income countries lack consistent electricity, severely limiting the feasibility of energy-efficient technologies like solar-powered systems for green surgery, while water scarcity and inadequate sterilization facilities, often reliant on outdated autoclaves, increase infection risks and force dependence on single-use items that elevate waste and carbon footprints.³⁸ The dependency on imported surgical supplies in LMICs creates vulnerabilities in green surgery implementation. Stockouts of essential materials, such as reusable surgical instruments, are common due to disrupted supply chains, leading to delays in care and reliance on less sustainable alternatives.¹⁴ Stockpiles of broken or outdated donated medical devices are a well-documented issue in Sub-Saharan Africa, with 70% of donated equipment non-functional due to lack of maintenance or compatibility with local infrastructure.³⁹ These supply chain inefficiencies hinder the adoption of reusable, eco-friendly surgical tools. Furthermore, limited budgets in LMICs make it hard to invest in sustainable infrastructure, such as energy-efficient operating rooms or reusable instruments. Fee-for-service payment models, widespread in Sub-Saharan Africa, favor cheaper disposable supplies over pricier reusable ones, as the high upfront costs of solutions like solar-powered sterilizers are out of reach without external funding.⁴⁰

Workforce Limitations

The shortage of trained surgeons is another major hurdle. LMICs, especially in Sub-Saharan Africa, have fewer than one surgeon per 100,000 people, compared to 29 in high-income countries, leaving little capacity to train staff in sustainable practices like maintaining reusable equipment.⁴¹ Task-shifting, where non-physician clinicians (NPCs) perform surgical procedures, is a common strategy in Sub-Saharan countries to address workforce shortages. However, its sustainability is compromised without adequate supervision and training. A 2020 review found that NPCs in 25 sub-Saharan countries face barriers like insufficient training and lack of regulatory support, which hinder their ability to adopt green surgery practices effectively.⁴²

Four Delays Framework Application

The four delays framework, originally developed to address barriers in maternal healthcare,⁴³ provides a lens to analyze obstacles to implementing green surgery in resource-constrained settings. Lack of awareness about surgical needs and cultural stigmas in rural sub-Saharan Africa often deter patients from seeking care, leading to delayed interventions that increase the environmental burden due to advanced diseases requiring resource-intensive procedures.⁴⁴ Geographic inaccessibility and transportation challenges further exacerbate delays, with poor road infrastructure and reliance on carbon-intensive diesel-powered ambulances increasing emissions, countering green surgery goals; a 2018 study estimated that 92.5% of sub-Saharan Africa's population lives within two hours of a surgical facility, but this assumes functional transport, which is often unavailable in rural areas.⁴⁵ Inadequate equipment and frequent power outages disrupt surgical procedures, as evidenced by a 2023 study in Malawi, Tanzania, and Zambia, which found that only 60% of district hospitals had reliable surgical tools, with power outages forcing reliance on diesel generators that undermine sustainability efforts by increasing carbon emissions.⁴⁶ Post-operative care is compromised by poor sanitation and infection control, with 22% of sub-Saharan African hospitals lacking running water, increasing infection risks and necessitating additional resource-intensive interventions that further strain environmental sustainability.³⁸

Data and Metrics Gaps

Data gaps make things worse. Unlike high-income countries, LMICs lack standard ways to measure surgical carbon emissions, with less than 5% of global surgical sustainability studies focusing on LMICs, leaving little evidence to shape policy.⁴¹

Data on waste generation, energy use, and supply chain emissions are rarely collected, hindering the ability to design targeted interventions. For example, the carbon footprint of single-use versus reusable instruments in Sub-Saharan hospitals remains unquantified, making it difficult to advocate for sustainable alternatives.

Case Studies: Surgical Capacity in Sub-Saharan Africa District Hospitals

The PIPES (Personnel, Infrastructure, Procedures, Equipment, Supplies) Index is a standardized tool used to assess surgical capacity in healthcare facilities, particularly in low-resource settings, by evaluating five key components: personnel (availability of trained surgical staff), infrastructure (access

to reliable electricity, water, and facilities), procedures (types of surgeries performed), equipment (availability of functional surgical tools), and supplies (access to consumables like sutures and anesthetics).⁴⁷ The PediPIPES Index is a specialized adaptation of the PIPES tool, specifically designed to assess pediatric surgical capacity, focusing on the unique needs of children, such as age-appropriate equipment and specialized procedures. A 2023 study across 67 district hospitals in Malawi, Tanzania, and Zambia reported low PediPIPES scores, highlighting critical shortages, including no specialist surgeons or anesthesiologists, inconsistent electricity and water supply, and poor availability of pediatric surgical equipment and supplies, with Malawi showing the most severe deficits and Tanzania slightly better capacity.⁴⁷ In Sudan, Djibouti, and the Central African Republic, an efficiency-productivity paradox is evident: despite high surgical demand, limited resources result in low surgical output, with only 295 surgeries performed per 100,000 population annually compared to 11,110 in high-income countries, exacerbating environmental impacts due to reliance on disposable supplies and carbon-intensive diesel generators.⁴⁸

FEASIBILITY AND SUSTAINABILITY STRATEGIES

The concept of green surgery might sound outlandish, especially in the context of low-income countries still grappling with basic health problems like brain drain, poor infrastructure and healthcare access. However, sustainable strategies exist to make it feasible, taking advantage of preexisting systems and simple innovations to enable efficient, effective change in process and practices.

Context-Adapted Models

- **SURG-Africa's specialist supervision:** SURG-Africa, Scaling up Safe Surgery for District and Rural Populations in Africa is a tested intervention that has trained and supervised non-physician clinicians to deliver essential and emergency surgery using remote training and in person visits to support delivery of surgical services.⁴⁹ Green surgery initiatives, now a routine practice in HICs can be included in these programs, enabling effective inclusion using preexisting processes.
- **Surgathons:** The Surgathon model focuses on local medical students and healthcare provider communities, building teams to troubleshoot and solve local health challenges with support and mentorship,⁵⁰ enabling local problems to be solved with local solutions and also creating a local innovation system focused on peculiar challenges. This model can be particularly useful in finding solutions specific to an environment to tackle challenges in establishing green initiatives.

5R Framework in LMICs

Reduce: Blood test rationalization involves the development and implementation of quality improvement interventions to reduce the unnecessary abuse of laboratory testing. This has been shown to significantly reduce the cost laboratory procedures and consumption of laboratory resources.⁵² Streamlining surgical trays to exclude infrequently used or excess instruments, with preference cards for suture requirements and estimated suture use has also been found to improve operating efficiency, save time, reduce sterilization costs and reduce wastage across board.⁵³

Reuse: Reusable surgical linens and instruments are considered to be environmentally friendly. Preferring reusable materials will lead to less waste generation and reduce landfill and incineration costs.⁵⁴ Using reusable gowns in operating theaters could lead to a 70% final waste reduction. Currently, reusable gowns are preferred by surgeons and operating theatre technicians, but disposable ones are still broadly used.⁵⁵ Establishing reusable surgical linen systems in LMICs, using supply nodes, dissemination, tracking and return is both economical and environmentally friendly.

Recycle: Recycling in the health-care setting presents several challenges, however concerns like contamination and infection control can be mitigated with education on waste handling and clear protocols. Materials like paper, cardboard and metal products can be easily collected for recycling in the operating room. A cohort study that evaluated the waste generated by 237 operations concluded that recycling is not associated with additional costs and has several advantages if the practice is expanded.⁵⁶ Establishing formalized regional waste segregation programs makes this more feasible and effective.

Rethink: Rethinking involves selecting the most sustainable choice of intervention and equipment to treat patients without causing any harm. While patient outcomes remain the main focus, sustainability should become a part of practice. Choices like anesthesia type, with the American Society of Anesthesiologists Task Force on the Environment recommending using regional and total intravenous anesthesia as the most sustainable option compared to inhalational agents⁵⁷ with an 80% atmospheric loss and global warming potential 2000 times that of carbon dioxide,⁵⁸ or an increase in the creation and use of reusable medical devices compared to more expensive but profitable single use devices. Telementoring and Telemedicine, new and emerging solutions, can help reduce pressure on saturated health systems, reduce patient travel and vehicle emissions and also enable international networking in surgical training through virtual conferences, eliminating unnecessary travel.⁵⁷

Research: Environmentally protective choices are typically economical, and promoting more sustainable surgical practice would help improve environmental protection and financial saving. This is especially important in LMICs with struggling economies. There remains a wide gap in sustainable healthcare research, and an even wider gap in sustainable healthcare research specific to developing countries. Research partnerships are necessary to bridge this gap, leveraging preexisting mutually beneficial relationships in vaccine research and tropical disease eradication to drive collaborative efforts. Although the motivation of practitioners and researchers is crucial, the support of national and international entities is needed to address this issue adequately (Figure).⁵⁷

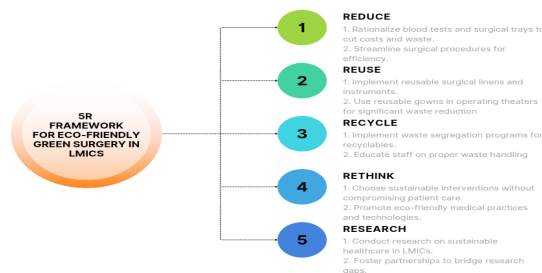


Figure. A process flow chart of the 5R eco-friendly framework for green surgery in LMICs like Sub-Saharan Africa

5R: Reduce, reuse, recycle, rethink, and research, LMICs: Low- and middle-income countries

Workforce Development

Implementing these changes requires a mental shift, with increasing priority being given to sustainable surgical care at the educational level to retrain and remodel actions and thought processes using mentorship pyramids and curriculum changes.

Surgical mentorship pyramids: This framework is a hierarchical structure where senior surgeons guide junior surgeons and they in turn guide medical officers and students below them, creating a repeating model of improving skills, academic, professional, and technical development. Incorporating sustainable health models, where innovative ideas at the level of surgathons are moved up the pyramid and tested by the seniors, while rethinking choices, new protocols and research focus are subsequently mentored down the pyramid will be an important part of redeveloping the healthcare workforce with a focus on sustainable health.

Green surgery curriculum integration: Also, the integration of environmentally sustainable practices into surgical training, clinical settings and medical school curriculum will stimulate the continued interest in sustainable health research and practices as found in the Green Surgery report.¹⁶

Policy and Financing

In countries with poor access to surgical care, the approach to sustainable surgical practice is twofold, first to identify and eliminate delays in accessing surgical care like the South Africa's Four Delays prioritization framework,⁵⁹ and then establishing National work plans like NSOAPs to implement identified changes on a bedrock of sustainable health practices in a progressively scalable manner.

Integrating green principles into NSOAPs: NSOAPs are strategic efforts embedded in a countries' national health plan to scale up surgical obstetric and anesthesia care. They provide country specific blueprints for building surgical systems that are contextually adapted to the local healthcare system and policies. Meeting the projected need for an additional 143 million surgeries in LMICs and fulfilling the goal of a NSOAP would mean that total emissions could reach 858.0 million to 116.4 billion kg of emitted CO₂.⁶⁰ Of the eight NSOAPs launched in 2023, only two reported consideration for environmental sustainability and no guidelines regarding indicators for assessing or improving environmentally sustainable surgical capacity building exist. Sustainable health practices and policies must be designed to mitigate the effects of climate change and optimize resource preservation,⁶¹ and NSOAPs created with sustainable surgical care in consideration, provide the most effective pathway to implementation of green surgery in LMICs.

Results-based financing for sustainable practices: By linking financial rewards to the achievement of predetermined sustainable practice targets, results-based financing helps to improve efficiency, accountability and effectiveness of efforts in sustainable health development.

Business Models

Moving towards green surgery is economically beneficial, and embracing the principles of resource optimization, reuse and cost efficiency helps reduce the financial burden of healthcare on low-income populations. Business models exist to take

advantage of this, leveraging green initiatives to deliver increasingly affordable surgical goods and services.

Circular economy approaches for device reprocessing: In an era of electronics-driven healthcare, the disposability of many medical devices raises environmental concerns. Transitioning these devices towards a circular economy, extending their lifecycle, involving practices like reuse, remanufacturing, and recycling, holds promise.⁶² These approaches involve collecting, cleaning, decontaminating, and potentially repairing or replacing parts of used devices to make them safe and functional for further use (reuse, refurbishment, remanufacturing, recycling, redesign, repair, recover).

Another model to consider is Cross-subsidization, which is a situation where profits from one type of surgical service are used to offset the losses incurred from another, often less profitable, surgical service. This can be a crucial mechanism to ensure continued access to essential but less profitable services for low-income populations. Reducing wastage in high income services helps improve profit margins, providing crucial funds for running low-income essential services.

METRICS AND EVALUATION

Several metrics and evaluation tools can be used to standardize and improve the guidelines for green surgery transformation, especially for low-resource settings. They include environmental impact assessment, clinical outcome measures, equity metrics, and other standardized tools.

Environmental Impact Assessment

Carbon footprint quantification and life-cycle analysis (LCA) are important metrics for this assessment. A study documented the carbon footprints of surgical procedures performed in hospitals around the globe, pointing out carbon hotspots related to surgery and identifying discrepancies in reported carbon footprints.⁶³ The carbon dioxide equivalents (CO₂e) of the estimated carbon footprint varied from 28.49 kg to 505.1 kg CO₂e. Emissions from medical equipment and consumables were the highest, with the majority of this carbon hotspot coming from material production and manufacturing. This suggests that sustainability initiatives should be targeted at medical devices and consumables.

Furthermore, according to life cycle studies, the bulk (74%) of total emissions from medical plastic manufacture are caused by items like surgical piping or Polypropylene Random Pipe (PP-R), which have a significant negative impact on the environment.⁶⁴ Therefore, the key to reducing the carbon emissions of PP-R pipe by an estimated 50% is the use of more recovered materials and novel technologies for PP-R raw material production.⁶⁴

Clinical Outcome Measures

Emerging novel techniques for anastomotic leak reduction through perfusion assessment, like indocyanine green fluorescence angiography (ICG-FA) for increasing surgical perfusion accuracy, are seen as tech-enabled green methods to stop leaks and cut reoperation rates, hence reducing resource consumption and carbon footprint.⁶⁵ Additionally, while considering the rate of surgical site infections between reusable and disposable items, Tevlin et al.⁶⁶ in their study, found that a high-volume tertiary referral hand surgery division implemented a three-stage "green case" strategy over one year

to proactively minimize waste and expense associated with routine ambulatory hand treatments. The findings showed that following greening, waste and expenses decreased by 64% and 75%, respectively. Following the use of greening, no rise in surgical site infections or problems was noted.⁶⁶ Surgeons can effectively use green measures to cut expenses and waste while maintaining asepsis of surgical sites.

Equity Metrics

Green surgery at low-resource institutions significantly expanded access and decreased delays in surgery without sacrificing results. According to Wang et al.,⁶⁷ Green channel surgery's short-term effectiveness in treating hip fractures in older individuals was investigated in their study, comparing the green with the non-green group, and there was no significant difference between the two groups. Additionally, surgical complications were drastically reduced in the green group.⁶⁷ The frequency of postoperative problems can be considerably decreased by establishing green channel surgery and collaborating with multidisciplinary teams.

Furthermore, the adoption of green surgery practices is resource-efficient; that is involving the use of less equipment and reuse models, which reduces the overall cost of surgery, which usually contributes to catastrophic expenditure.⁶⁸

Standardized Tools

A verified and trustworthy metric for evaluating surgical capability in environments with limited resources is the PIPES tool (personnel, infrastructure, procedures, equipment, supplies). To evaluate the inter-rater reliability of the PIPES tool, the tool evaluated the infrastructure and processes, equipment, and supply sections. The PIPES instrument is a useful indicator of surgical capability, according to the results.⁶⁹

Another standardized tool used as a metric is the Green Surgery Checklist, which was developed by the 3 UK surgical colleges and distributed among their members. It includes 16 primary suggestions for addressing recognized carbon hotspots in surgery that are focused on the "5 Rs" (reduce, reuse, recycle, rethink, research).⁷⁰ Action on the climate catastrophe must be taken immediately. The NHS will be able to meet its NetZero goal by using the Green Theatre checklist to encourage frontline surgical teams to adopt more sustainable practices.⁷⁰ The Green Surgery Checklist can, following a conditioning, be adapted and modified for use in low-resource settings.

PROSPECTS

Priority Research Areas

According to a study, they reported that the surgical system in low- and middle-income countries (LMICs) consist of the public and private sectors.¹⁴ The private sector consists of all sorts of qualified doctors, quacks and traditional medical professionals. In some countries under LMICs, the private surgical system controls about ninety percent (90%) of surgical practices.⁷¹ Most patients in LMICs patronize the private sector especially the quacks and traditional medical professionals due to the easy accessibility and affordability.⁷²

Additionally, in order to reduce the threats to the surgical system and to promote safe surgical practice, it is important to have climate resilient surgical infrastructure. An example of

the climate resilient surgical technique used in some countries is the digestive endoscopic system.⁵⁷ This system promotes the 'reduce, reuse, renew and recycle' techniques which help to improve the deleterious effect of surgical processes like anesthetic gases such as desflurane on climate change.⁷³

Technological Opportunities

In LMICs, there is an important course to maintain a carbon-free surgical system because of its negative impact on climate change such as harsh weather conditions and emergency of various health conditions.⁷⁴

Therefore, approaches such as use of solar powered surgical suites have been employed in some LMICs such as Rwanda in Butaro District Hospital thereby reducing the use of carbon emitting materials such as generators.⁷⁵

Additionally, the application of the digital technique can also help to promote better green surgical practices in LMICs. For example, in Rwanda, mobile health is now used to practice primary health care services.⁷⁶

Ethical Frameworks

The implementation of ethical guidelines for sustainable green surgical practices requires a robust multidisciplinary team consisting of healthcare providers, researchers and policy makers in order to provide a functional policy change.⁷⁷

Global Collaboration

In the Global North, most of the equipment in the surgical systems are usually used once, while in the Global South, reuse is still very common. This helps to reduce financial and environmental impact of surgical practices, thereby creating a gap for South North learning.⁷⁸

Globally, in order to mitigate the risk associated with surgical practices, the WHO advocates for the introduction of a three-bin system. This system entails separating waste into non-infectious, general and infectious or sharp waste bins. The waste should be collected regularly and rightly labelled.⁷⁹

THE ROLE OF GREEN SURGERY IN ECO-CONSERVATION; A FOCUSED UPDATE

Climate change is the greatest threat to human health in the 21st century. Healthcare provision contributes to 4.4% of total global greenhouse gas emission.⁸⁰ This has various effects of extreme weather conditions such as heatwaves, flooding, droughts and storms. Hospital worldwide are responsible for considerable amount of hazardous emission and toxic waste product into base climate.⁸⁰

Healthcare systems, particularly operating theatres are among the foremost causes of environmental pollution due to high energy procedures, anaesthetic gas, and single use surgical instruments. Green surgery practice highlights the need to minimize the use of disposable instruments and promote recycling. This has a significant role in conserving the ecosystem by; reducing emissions, conserving energy, and reducing waste. The potential reduction in carbon emission from adoption of sustainable practices in operating theatre is substantial. In the United Kingdom this has been effective in reducing carbon footprints of surgery by about 50-97%.⁸¹ Also, the endoscopic project in Würzburg reduced carbon emission by 20.1%.⁸¹ The health sector consumes a significant amount of fossil fuels, and contributes to considerable greenhouse

gas emission. Placing solar panels in operating theatres and hospitals reduced fossil fuels consumption and power vital appliances and equipment.⁸² The use of biodegradable plastic materials and diversion of uncontaminated plastic waste from recycling help minimize the waste sent to the land fills.⁸¹

Limitations

This review has several inherent methodological constraints. As a scoping review, its synthesis is descriptive and did not include a formal quality assessment of the included literature. While this allowed for broad mapping of a nascent field, it means the findings represent a spectrum of evidence that varies in robustness. The highly heterogeneous nature of the evidence also prevented quantitative synthesis or direct comparison of outcomes. Finally, despite a comprehensive search, the broad scope may have introduced selection bias, with potential underrepresentation of local grey literature from LMICs.

CONCLUSION

This scoping review affirms that green surgery is not a luxury but a necessary and feasible evolution of surgical care in LMICs. It is underpinned by pragmatic frameworks like the 5Rs, enabled by context-adapted technologies and frugal innovations, and measurable through evolving metrics. The path forward requires integrated action:

- **Embed sustainability in foundational plans:** Environmental considerations must be explicitly integrated into national surgical plans (NSOAPs) and health infrastructure projects.
- **Invest in context-specific evidence:** Funding must support research partnerships that generate LMIC-focused data on the environmental and economic impacts of surgical practices.
- **Empower the workforce:** Sustainability must be core to surgical education and training, fostering leadership from within clinical teams.
- **Foster equitable collaboration:** Global partnerships must value and integrate knowledge from LMICs, moving beyond a donor-recipient model to shared innovation. By championing green surgery, the global health community can simultaneously advance two urgent agendas: ensuring universal access to safe, timely surgical care and protecting the planetary systems upon which human health depends.

ETHICAL DECLARATIONS

Peer Review Process

This review was externally peer-reviewed.

Conflict of Interest

The authors declare no conflicts of interest.

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