Editorial

Sustainable anaesthesia: beyond carbon and towards system-level change

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The environmental cost of anaesthesia is increasingly recognised, yet efforts to quantify it remain fragmented, inconsistent, and narrowly focused on carbon-equivalent metrics of individual practice [1-3]. This emphasis risks prioritising what is easily measurable over broader ecological harms, including upstream and downstream impacts on peri-operative care [4].

Despite growing interest, sustainable anaesthesia remains a nascent field characterised by inconsistent system boundaries, variable methodologies, and incompatible functional units, leaving comparisons between techniques incomplete. In this editorial, we outline the limitations of the current evidence and its underlying methods and highlight the need for standardised, comprehensive approaches that assess environmental impacts on a more comprehensive basis. We also identify where sustainability efforts are likely to deliver the greatest gains - particularly upstream decisions, infrastructure, and system-level contributors - rather than unidimensional comparisons between anaesthetic agents. Finally, we set out priorities for future research, including broader environmental accounting and consequential, system-wide analyses to guide practice.

Where current environmental assessments fall short

The past decade has seen a rise in life-cycle assessments of peri-operative practice, reflecting growing interest in quantifying the environmental burden of practice; yet, findings remain inconsistent. Systematic reviews highlight the lack of cradle-to-grave analyses, variable boundary definitions, and incomplete emissions inventories, all of which hinder meaningful comparisons between inhaled anaesthesia, total intravenous anaesthesia (TIVA), and wider surgical practice [5, 6]. Rizan et al. identified eight studies labelled as ‘carbon footprinting’ that used widely differing inventory boundaries [6].

Minor boundary variation may have limited impact, but many studies differ substantially in scope. Most life-cycle assessments omit upstream and downstream processes such as drug disposal or the energy-intensive sterilisation and packaging of equipment, and fewer still consider clinical consequences [5]. For instance, a cradle-to-grave life-cycle assessment of morphine traced emissions back to opium farming and found sterilisation and packaging contributed 90% of its carbon footprint [7]. Even when production emissions are low - as with propofol - sterilisation, packaging, and transport are often excluded [8]. As a result, carbon estimates for similar surgical procedures range over orders of magnitude, reflecting both methodological divergence and the absence of standardised reporting [6].

Comparisons of TIVA and volatile anaesthesia generally fall into three categories: life-cycle assessments, modelling studies, and retrospective record reviews. Most life-cycle assessments and life cycle emission analyses struggle to account for the complexity of real-world systems and practices regarding drug waste [9]. Well-documented examples of drug wastes that may fall outside study system boundaries include unused propofol and systemic waste from piped nitrous oxide delivery systems [10]. Recent observational studies report around 16% of drawn-up propofol is wasted, and while incineration incurs carbon cost, improper disposal leads to biosphere pollution [11]. Some studies clarify they are not full life-cycle assessments, for example by using ‘cradle-to-gate’ boundaries for the production of active pharmaceutical ingredients rather than the traditional 'cradle-to-grave' for the production, use and disposal of prepared medications [8].

Retrospective reviews typically compare pharmacy procurement data from TIVA-predominant centres with mixed-use centres [3]. Drug consumption is converted to kilograms of carbon dioxide equivalent ($kgCO_2e$), occasionally incorporating associated equipment like syringes. Some analyses consider airway devices and induction agents, but omit major contributors like glass ampoule packaging, despite these potentially representing greater emissions than the drug itself [12]. These studies offer valuable estimates of emissions, but are constrained by their retrospective design and incomplete scope of data.

Modelling studies often focus on drug emissions alone, excluding sterilisation and packaging, which may contribute up to 90% of a medication's carbon footprint [7]. However, more recent models are beginning to include auxiliary anaesthetic equipment such as processed EEG monitors [13]. Reported metrics vary widely; while $kgCO_2e$ is commonly reported, alternatives like MAC-hours limit comparability and synthesis of data. Contributions of anaesthetic drugs and equipment to total peri-operative emissions are said to range from 5% to 67%, reflecting both contextual variation and methodological inconsistency [14, 15].

Perhaps more important than the inconsistencies outlined above is that studies tend to focus on comparing versions of the same intervention, incorporating a tacit assumption that the intervention needs to be done. In the context of advancing technology and an ageing population, peri-operative physicians have been encouraged to ask "just because we can, does it mean we should?" While the avoidance of low-value or harmful care is generally (and appropriately) framed in patient-centred terms, there are likely to be sustainability co-benefits to optimising resource allocation. In other words, sustainability is unlikely to depend on selecting the 'greenest' anaesthetic agent, but on the bigger picture: considering *why* we are performing anaesthesia and surgery, and what can be done to prevent people from becoming patients in the first place.

Risks of carbon tunnel vision

Focusing narrowly on carbon emissions limits our understanding of anaesthesia's broader environmental impact, which spans into less visible (but no less consequential) planetary boundaries beyond the troposphere — including acidification, eutrophication, freshwater ecotoxicity, ozone depletion, photochemical oxidation, and water use.

Volatile agents like sevoflurane and desflurane are not only potent greenhouse gases but degrade into per- and polyfluoroalkyl substances (PFAS): synthetic compounds notoriously resistant to environmental degradation [16]. While a small fraction of sevoflurane is metabolised in vivo to hexafluoroisopropanol, most is vented into the atmosphere and oxidises over two years to trifluoroacetic acid – both of these substances are PFAS compounds that accumulate in soil, water, and the food chain. Anaesthetic maintenance using sevoflurane requires 20–120 times more active pharmaceutical ingredients per hour than TIVA, amplifying its environmental burden. Desflurane use emits yet more pharmaceutical product due to its low potency. Despite this, most analyses focus on greenhouse effects, neglecting chemical ecotoxicity. Drawing on this approach, narratives have tended to dichotomise intravenous drugs as ecological toxins and inhalational drugs as greenhouse gases, without acknowledging that both types of medication have impacts on both planetary boundaries.

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Despite its low production footprint, propofol has been reported to be the most wasted intravenous anaesthetic drug by volume and is often discarded in ways that allow it to enter aquatic ecosystems [11]. Although the chemical breakdown pathways of sevoflurane and propofol are reasonably well characterised, the long-term ecological effects of their byproducts remain largely unknown and are inferred from chemical stability rather than observed impacts. This highlights that current assessments of anaesthetic ecotoxicity are provisional, and both TIVA and volatile agents may have unquantified long-term consequences.

Non-carbon effects are rarely captured in conventional life-cycle assessments. The concept of 'carbon tunnel vision' (Fig. 1) illustrates how focusing solely on greenhouse gas emissions overlooks resource depletion, water scarcity, and material toxicity, all of which have long-term health and equity implications [2]. Volatile anaesthetics exemplify this complexity; the high global warming potential of desflurane positions it as a prime target for mitigation and this is supported by national and international guidance. While some climate scientists support this approach, others caution against equating its short atmospheric lifetime with the multi-generational persistence of CO_2 [17]. This debate illustrates the limitations of CO_2e as a 'chosen metric.

The Intercollegiate Green Theatre Checklist suggests multi-speciality modifications to practice, to optimise environmental gains once in theatre [18]. However, the greatest environmental harms from healthcare are unlikely to be dictated by the differences between TIVA and volatile anaesthesia, but by upstream systems, including resource allocation, service organisation, and the justification for interventions. As the World Federation of Societies of Anaesthesiologists emphasises, sustainable anaesthesia must extend beyond individual choices to include education, quality improvement, and institutional leadership [19].

Building sustainable structures for future practice

A case study demonstrated dramatic reductions in peri-operative emissions through system-level interventions: a 'net zero' laparoscopic bowel resection under TIVA, with reduced theatre energy use, reusable textiles, and surgical equipment recycling, resulted in a footprint of 417 $kgCO_2e$ — far below the high-end estimate of 1,948 $kgCO_2e$ [20]. This was offset by staff commuting sustainably and planting a tree. While not scalable across the health service, it serves as a commentary on the impact of system-level change.

Reuse and recycling are often promoted as sustainable strategies, but their environmental benefit depends on energy sources. In the UK, where the energy mix includes a high proportion of renewables, reuse is advantageous from a greenhouse gas perspective [21]. In contrast in Australia, coal-derived electricity makes reusable equipment potentially 10% more carbon-intensive than single use. However, as we outline above, reuse remains beneficial in terms of waste reduction and the stewardship of other resources.

Recycling is the least effective circular strategy - the high energy cost of material recovery frequently outweighs environmental returns [21]. Hence, sustainability depends on 'reduction'. Leasing models for medical equipment support sustainability by incentivising manufacturers to design durable, repairable products, unlike the planned obsolescence of single-use items. In low-resource settings circular practices are common: a cataract operation in India using mostly reusable equipment emits under 5% of the carbon of a comparable UK procedure, with similar outcomes [22].

Intervention-based studies show that anaesthetic emissions can be meaningfully reduced. Systematic reviews of 'green' anaesthesia report carbon savings of up to 25%, but highlight institutional culture and staff engagement as key barriers [1]. Broader peri-operative reviews show that up to 99% of theatre energy use comes from heating, ventilation, and air conditioning systems, with less than 10% from electronic equipment [21]. If regional and intravenous anaesthesia were the default, scavenging systems could be eliminated entirely - a potentially impactful system redesign, but one which would depend on systemwide practice change.

These examples highlight that environmental harms often stem from upstream system design rather than individual clinician choices. Nowhere is this clearer than with nitrous oxide, whose footprint is driven primarily by delivery infrastructure. Piped delivery systems are associated with pre-utilisation waste of up to 99% because procurement is effectively decoupled from clinical use [21]. In cases like this, individual behaviour has little impact and effective mitigation has relied on system-level interventions such as decommissioning pipelines, and moving to point of care cylinders where needed. Given their potential for impact, system level opportunities to identify and reduce waste should be identified and prioritised.

Addressing determinants of demand, not just delivery

A decision to operate often reflects a failure of preventive care; as peri-operative physicians, we should help re-engineer pathways that strengthen prevention, reduce avoidable disease, and limit reliance on surgical intervention. Overtreatment can result from mismatched expectations, defensive medicine, and misinterpretation of clinical evidence. The Choosing Wisely campaign aims to reduce low-value interventions and is developing a "Top 5" list for each specialty [4]. Enhanced recovery and prehabilitation programmes can also reduce resource use during hospital stay and post-discharge and may, therefore, offer sustainability co-benefits [23].

Regional anaesthesia reduces resource use by minimising ventilator dependence, anaesthetic gas use, and postoperative monitoring, while also shortening operating room occupancy and recovery time compared with general anaesthesia [24]. It is also associated with far lower pharmaceutical emissions: an ampoule of bupivacaine contains just 20 mg of active drug - orders of magnitude less than any type of general anaesthesia, where a 50 ml ampoule of 2% propofol contains 1 g, and an hour of inhalational anaesthesia at 1 MAC with 0.5 $l \cdot min^{-1}$ fresh-gas flow emits 2 g of isoflurane, 5 g of sevoflurane, or 12 g of desflurane. Spinal anaesthetic drugs have an estimated footprint of 0.07 $kgCO_2e$, versus 4.7 $kgCO_2e$ for general anaesthesia in comparable orthopaedic cases [25]. Though regional techniques still use agents like chlorhexidine and levobupivacaine, their environmental release is limited compared to the broader array of inhalational and intravenous agents. System-level changes including expanding regional anaesthesia, promoting day-case pathways, and reinforcing the importance of public health have the potential to offer far greater environmental returns than focusing on drug-level emissions alone [21].

Sustainable anaesthesia research remains rooted in attributional analysis: measuring carbon footprints without modelling the broader consequences of change. We currently lack consequential studies assessing system-wide impacts. Improving efficiency may clear waiting lists and enhance patient justice, but it also increases institutional emissions as more surgery is performed. We need to think in terms of environmental ‘optimisation of care’: maximising patient benefit for each additional unit of environmental and financial cost. Stopping medical interventions would cut emissions, but our goal should be to deliver healthcare in the most clinically *and* environmentally efficient way possible, while remaining with the financial limits of the healthcare system. Achieving this means focusing on macro-level public health initiatives and meso-level interventions such as decommissioning nitrous oxide manifolds.

Practical, system-level, and research-focused actions to advance sustainable anaesthesia are presented in Figure 2. There remains scope in redesigning perioperative pathways to minimise unnecessary treatment, such as the Choosing Wisely initiative [4]. Future research should focus on outcomes beyond carbon; furthermore, we are lacking standardised, comprehensive assessment methods and robust consequential studies that evaluate the system-wide impacts of practice change.

Clinicians can reduce impact by favouring regional anaesthesia, as it uses far less pharmaceutical product, and reduces perioperative resource demand. Drug waste should be minimised by drawing up only what is required and using pre-filled syringes for infrequently administered yet frequently discarded emergency drugs. Disproportionately high-polluting agents such as nitrous oxide should be eliminated, given that most emissions arise not from use but from systemic loss through pipelines.

Although we have presented some key critiques of the current evidence base for more sustainable anaesthesia, waiting for ‘perfect’ evidence before acting is irresponsible; we must act now, but also be ready to adapt as knowledge evolves. If anaesthesia is to contribute meaningfully to planetary health, we must move beyond carbon metrics, beyond individual preference, and towards a discipline that interrogates *why* and *how* we deliver care - and acts decisively on what is already within our control.

Figures

Figure 1: Carbon tunnel vision. Graphic reproduced with permission from the artist, Jan Konietzko.

Figure 2: Practical, system-level, and research-focused actions to advance sustainable anaesthesia

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