Submitted: 04 April, 2025 Accepted: 20 June, 2025 Published: 08 September, 2025 DOI:10.22514/sv.2025.123

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REVIEW

Carbon footprint and sustainable development in anesthesia: a narrative review

Xiaofeng Chen[1], Han Huang[1,*]

[1]Department of Anesthesiology, West China Second University Hospital, Key Laboratory of Birth Defects and Related Diseases of Women and Children, Sichuan University, Ministry of Education and Children's Medicine Key Laboratory of Sichuan Province, 610041 Chengdu, Sichuan, China

***Correspondence**
han.huang@scu.edu.cn
(Han Huang)

Abstract

Global climate change poses a significant threat to human health. While healthcare services can offer protection, they also contribute to this threat through indirect environmental impacts. Projections indicate that greenhouse gas emissions from medical services will continue to rise in the foreseeable future. Within the healthcare sector, anesthesia represents a substantial contributor to the overall carbon footprint. Given the persistent increase in the volume of anesthesia cases, anesthesiologists have a pivotal role in promoting sustainable anesthesia and enhancing environmental sustainability in healthcare. Life Cycle Assessment (LCA) serves as an analytical tool that quantifies the environmental impact of products, processes, and activities throughout their life cycles. Its application is gradually gaining acceptance in the medical field and can assist physicians in comparing the environmental impacts of various diagnostic and treatment approaches in clinical practice. The primary objective of applying LCA to anesthesiology is to assess the carbon footprint and environmental impact of different anesthesia modalities under the guidance of anesthesia providers. This review highlights the advantages of reducing high-Global Warming Potential (GWP) inhalational anesthetics and minimizing drug waste, implementing low-flow anesthesia, carefully evaluating the benefits and drawbacks of reusable versus disposable materials, and optimizing energy consumption to mitigate the carbon footprint associated with anesthesia. Furthermore, this review examines potential sources of carbon footprint in anesthesia practices and discusses strategies to achieve net-zero emissions in anesthesia, offering a valuable reference to foster sustainable anesthesia practices.

Keywords

Climate change; Life cycle assessment; Anesthesia; Carbon footprint; Waste reduction

1. Introduction

The health implications of climate change are becoming increasingly severe. In *The Lancet*'s 200 Years publication, climate change and health were identified as one of the five major issues to be addressed [1]. Scientific evidence demonstrates that global temperatures are rising, and if they surpass 1.5 °C above pre-industrial levels, the consequences for life on earth will be catastrophic [2]. Furthermore, the surge in extreme weather events resulting from climate change will exacerbate existing crises such as the spread of infectious diseases, habitat destruction, increased economic losses, and negative impacts on mental health. This will further strain healthcare systems worldwide [3]. It is important to note that healthcare services themselves contribute to greenhouse gas emissions, either directly or indirectly [4]. As a result, all healthcare professionals should aim to minimize the carbon footprint of their clinical practice. Globally, the healthcare sector contributes about 4.6% to greenhouse gas emissions [5]. In China, it accounts for 2.7%, making it the largest contributor among all sectors [6].

The operating room represents the most resource-intensive environment within a hospital, necessitating significant energy consumption, extensive medical equipment, a variety of consumables, pharmaceuticals, and generating substantial exhaust emissions and medical waste. Additionally, it requires multidisciplinary collaboration among various healthcare teams, making it an optimal starting point for the medical industry's efforts to achieve net-zero carbon emissions [5]. The National Institute for Health and Care Research Global Health Research Unit on Global Surgery has established strategies aimed at mitigating the environmental impact of surgical practices on a global scale. The three primary priorities identified include (1) the implementation of reusable devices, (2) a reduction in the use of consumables, and (3) a decrease in the reliance on general anesthesia in favor of local or regional anesthesia [6]. Current research has examined the carbon emissions associated with various surgical procedures, including cardiac surgery [7, 8], gastrointestinal endoscopy [9], and hysterectomy [10]. However, the carbon emissions attributed to anesthesia should not be overlooked. MacNeill *et al.* [11] found that anesthesia may generate more carbon emissions than surgical procedures themselves, primarily due to the emissions produced by anesthetic gases such as desflurane [11]. Furthermore, the carbon emissions associated with disposable consumables, the washing and sterilization of reusable items, anesthesia drugs, and medical waste also contribute to the overall carbon footprint of the operating room, with emission levels varying depending on the anesthesia method used [12].

There are over 200 million anesthesia procedures conducted globally each year. Given this substantial potential source of carbon emissions, anesthesia providers must consider strategies to mitigate their carbon footprint and promote sustainable healthcare practice within their professional domains [13]. In this context, the present review elucidates the relationship between healthcare and climate change, summarizes the potential sources of carbon emissions associated with anesthesia activities, and compares these with other medical interventions, such as surgery and radiotherapy. Furthermore, it discusses feasible measures to minimize the carbon footprint of anesthesia and offers a reference for fostering a positive feedback loop between health and climate change.

2. Literature review

2.1 Carbon footprint

It is essential to acknowledge that every product or service utilized in our daily life carries a carbon footprint. In recent years, medical professionals have increasingly recognized the environmental impact of various medical activities (Table 1, Ref. [12, 14–20]), including those associated with operating rooms [7–10, 14–16], modes of delivery [17], radiation therapy [21], pathology testing [18], COVID-19 [19], clinical trials [22], conferences [23], and telemedicine [20, 24]. One of the most pressing concerns relates to the carbon footprint generated by these activities. The term "carbon footprint" refers to the total amount of greenhouse gases (GHGs) emitted by an individual, organization, event, or product, typically measured in kilograms of carbon dioxide equivalent produced over a specified time frame. This measurement is generally obtained through life cycle assessment (LCA), which serve as a means to evaluate the impact of human activities on the environment and climate change. Life cycle assessment is an environmental management tool that analyzes the environmental impact of a product, process, or activity across various life cycle stages, including the extraction of raw materials, production, transportation, sale, use, recycling, maintenance, and final disposal. For instance, LCA can be employed to assess the environmental impact associated with the production and subsequent disposal of anesthetic drug trays [25]. According to International Organization for Standardization (ISO) and its ISO-14040 series of standards, LCA encompasses goal and scope definition, inventory analysis, impact assessment, and interpretation of results (Fig. 1) [26]. A detailed explanation of each stage of the LCA process is provided in Table 2.

2.2 Inhalation anesthetics

2.2.1 The nature and current status of inhalation anesthetics

Inhalation anesthesia administers volatile agents with oxygen through a ventilator, allowing gradual inhalation. This method effectively suppresses cerebral activity, leading to a gradual onset of unconsciousness. As the concentration of inhaled anesthetics increases, the patient progressively loses consciousness, ceases spontaneous respiration, experiences analgesia, and achieves muscular relaxation, thus attaining an appropriate state for surgical intervention. Currently, the inhalation anesthetics employed in clinical settings can be broadly categorized into two groups: nitrous oxide (N_2O) and halogenated compounds, including sevoflurane, desflurane, isoflurane, and methoxyflurane. Inhaled anesthetics offer several advantageous characteristics, such as ease of titration, real-time monitoring of alveolar concentrations, broad pharmacological effects, and minimal metabolic processing within the body. In addition, the potential for topical application is emerging [27]. However, the limited metabolic transformation of inhaled anesthetics within the body raises significant concerns from an environmental perspective. This phenomenon occurs because inhaled anesthetics are predominantly eliminated via respiration in their unchanged state [28], leading to their direct release into the atmosphere without any post-use treatment. The inhaled anesthetic gases currently employed in clinical practice are recognized as greenhouse gases [29, 30], with estimates of their contribution to climate change ranging from 0.01% to 0.1% of total global greenhouse gas emissions [31–33]. Furthermore, direct emissions from these anesthetics account for approximately 3% of the healthcare-related climate footprint in high-income countries, as well as over half of the emissions associated with perioperative services [34–37]. To illustrate the environmental impact, this is analogous to the carbon dioxide emissions produced by driving between 235 to 470 miles for desflurane, 18 miles for sevoflurane, or 20 to 40 miles for isoflurane per hour, respectively, based on average carbon dioxide emissions per mile in the United States [38].

2.2.2 Environmental and occupational impact of inhaled anesthetics

Nitrous oxide (N_2O) and chloro-halogenated compounds, specifically isoflurane and methoxyflurane, are classified as ozone-depleting substances [31]. The Ozone Depleting Potential (ODP) serves as a metric used to quantify the extent of ozone destruction attributable to these substances, relative to chlorofluorocarbon-11 (CFC-11) [39]. N_2O possesses an ODP value of 0.015, while isoflurane and methoxyflurane exhibit ODP values of 0.03 and 0.001, respectively [28]. Among these compounds, N_2O emerges as the primary contributor to ozone layer depletion [40], accounting for approximately 6% of anthropogenic global warming. Furthermore, studies indicate that N_2O emissions are poised to increase in the future across all conceivable emission scenarios [39, 41]. Non-chlorinated halogenated anesthetics, namely sevoflurane and desflurane, also significantly contribute to climate change despite their negligible potential for ozone layer depletion. This is largely due to their robust infrared absorption bands, which coincide with the outgoing radiation within the atmospheric window,

TABLE 1. Comparison of carbon emissions from different medical activities.

Authors (yr)	Study type	Study focus	Functional unit	Conclusions	Limitations	Practical guidance
Thiel *et al.* [14] (2015)	Single center Real-world data Prospective	Hysterectomy (a) Vaginal (b) Abdominal (c) Laparoscopic (d) Robotic	One hysterectomy Patient enters the OR to leaves	(1) Abdominal and vaginal hysterectomies emit significantly less greenhouse gases than laparoscopic and robotic hysterectomies without anesthetics; (2) The major sources of environmental emissions: (a) The production of disposable materials and single-use surgical devices; (b) Energy used for HVAC; (c) Anesthetic gases	Do not account for the length of stay and postsurgical resource use, which may result in different emissions profiles.	Effective management of HAVC systems can effectively reduce energy consumption and thus reduce carbon footprint.
Wang *et al.* [15] (2022)	Single center Real-world data Retrospective	Transforaminal Lumbar Interbody Fusions (a) Spinal anesthesia (b) General anesthesia	Nil*	(1) The dramatic carbon footprint reduction associated with using spinal anesthesia compared with general anesthesia; (2) The desflurane use in general anesthesia patients resulted in a sizeable increase in CO_2e	(1) The carbon footprint calculations only consider the anesthetic agents that are used in the surgery. (2) The GWP100 of anesthetic agents downplays the worse near-term environmental impact.	The environmental friendliness and potential cost-benefit of spinal anesthesia in lumbar surgery may be underestimated.
Rizan *et al.* [16] (2023)	Multi-center Mixed methods (real-world data combined with models) Prospective	Surgical operations (a) Carpal tunnel Decompression (b) Inguinal hernia Repair (c) Knee arthroplasty (d) Laparoscopic Cholecystectomy (e) Tonsillectomy	One operation "Cradle to factory gate" activity	The production of single-use items, decontamination of reusable instruments, and waste disposal were the largest contributors to the carbon footprint	The result was affected by differences in emission factors and system boundaries in the database and may not be generalizable to other contexts.	Identifying the largest sources of carbon footprint and eliminating or replacing them with low-carbon products is the most feasible strategy.
McGain *et al.* [12] (2021)	Single center Real-world data Prospective	Knee Replacements (a) Spinal anesthesia (b) General anesthesia	All anesthesia for a total knee Replacement	(1) All anesthetic approaches had similar carbon footprints; (2) Several choices determine the final carbon footprint: (a) Low-flow anesthesia (b) Total intravenous anesthesia (c) Reducing single-use plastics (d) Reducing oxygen flows (e) Collaborating with engineers (f) Renewable electricity	Comparisons between the anesthetic groups and between countries are uncertain because it is a small, single-center, prospective, nonrandomized, observational, unblinded study.	The choice of anesthesia has little impact on the carbon footprint, and choices (a–f) determine the final carbon footprint.

TABLE 1. Continued.

Authors (yr)	Study type	Study focus	Functional unit	Conclusions	Limitations	Practical guidance
McAlister *et al.* [18] (2020)	Multi-center Real-world data Prospective	Pathology testing (a) Full blood Examination (b) Coagulation profile (c) U&E (d) CRP (e) ABG	One pathology testing Collection to analysis	Full blood examination produced the highest CO_2e emissions and some unnecessary testing should be reduced	Primary data for the manufacture of phlebotomy equipment and reagents were unavailable and conservative estimates were made.	Reducing and avoiding unnecessary pathogen testing is even more important to reduce the carbon footprint.
Morooka *et al.* [19] (2022)	Single center Real-world data Retrospective	Influence of COVID-19 on the 10-year carbon footprint	Direct and indirect carbon emission sources	(1) The overall carbon footprint increases and it decreased slightly during the COVID-19 epidemic; (2) Carbon footprint per person per admission has increased.	This study did not include the carbon footprint generated by the education, outpatient clinics, and scientific research institutes.	It is relatively easy to conduct an overall longitudinal carbon footprint study of health care institutions and can help address the climate crisis.
Sillcox *et al.* [20] (2023)	Single center Real-world data Retrospective	The Bariatric Surgery Telemedicine Use	One bariatric Surgery Initial clinic visit to the operation date	Implementation of telemedicine for bariatric preoperative evaluations reduced patient travel, and carbon emissions, and improved the attrition rate	(1) The study is limited to preoperative clinic visits. (2) Only one standard mode of transportation modality (gasoline-burning car) was considered. (3) The actual starting point of the patient was not confirmed.	For patients who need repeated outpatient evaluation over a long period of time, telemedicine may increase patient compliance and bring environmental benefits.
Spil NA *et al.* [17] (2024)	Multi-center Real-world data Retrospective	Different modes of birth (a) Planned caesarean birth (b) Uncomplicated vaginal birth in hospital (c) Uncomplicated vaginal birth at home	The birth of a live baby	(1) The carbon footprint of cesarean section is higher than that of vaginal delivery without regard for anesthesia/analgesia, the main contributors to carbon footprint come from disposables, energy, and instruments. (2) The use of N_2O/O_2 for analgesia increased the carbon footprint of vaginal delivery by 25 times, more than that of a cesarean section.	(1) This study only considers the ideal pregnancy with low risk, ignoring the complexity of the actual situation, such as the change of delivery mode or delivery place. (2) The duration of labor and the use of analgesia were basically averaged, ignoring the differences among clinical individuals. Individualized observation and analysis should be strengthened in the future.	Relieving maternal pain or capturing N_2O to catalytic lysis would significantly reduce the carbon footprint of childbirth.

**The authors did not define or mention.*

GWP: Global Warming Potential; U&E: Urea and electrolytes; CRP: C-reactive protein; ABG: Arterial blood gases; COVID-19: Coronavirus disease 2019; HVAC: heating, ventilation, and air conditioning systems; CO_2e: Carbon dioxide equivalent; N_2O: Nitrous oxide.

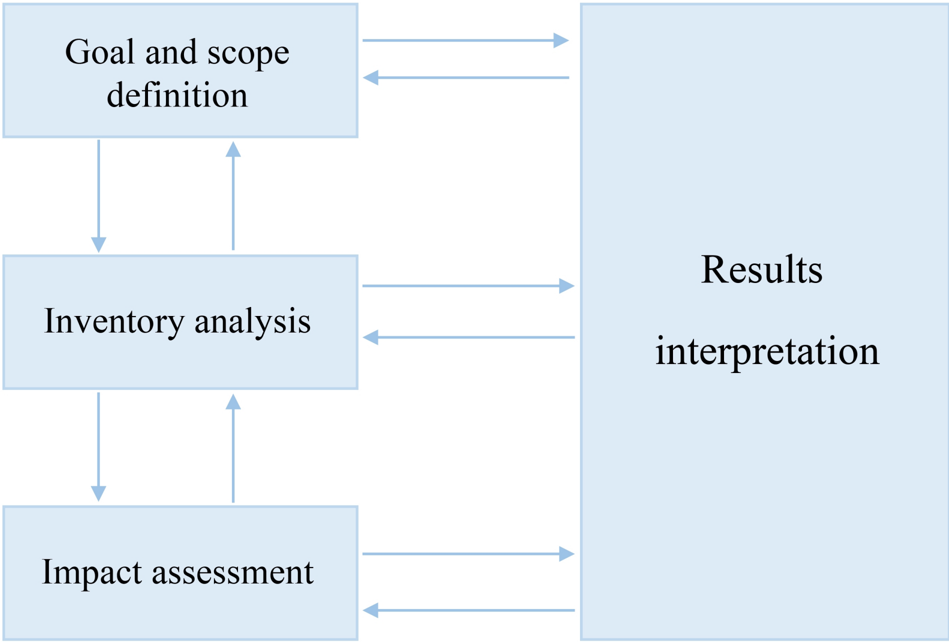

FIGURE 1. Life cycle assessment framework. The four stages of the life cycle assessment, where the arrows represent the underlying information flow, and each arrow is required to interpret the results.

thereby diminishing the emission of infrared heat energy [28]. Additionally, the prolonged atmospheric persistence of these agents further exacerbates their environmental impact on the climate system.

As articulated by the Intergovernmental Panel on Climate Change (IPCC), the Global Warming Potential (GWP) quantifies the cumulative radiative forcing produced by the instantaneous release of a gas per unit mass. This metric serves as a critical tool for assessing the potential impact of greenhouse gases on climate change, with carbon dioxide (CO_2) designated as the reference gas [38]. The GWP of a specific gas is primarily influenced by its infrared absorption spectrum and atmospheric lifetime [42, 43]. Furthermore, the infrared absorption spectra of anesthetic gases can be measured with high precision in laboratory settings [40]. Anesthetic gases exhibit significant infrared absorption characteristics, particularly within the atmospheric window, a spectral region where infrared radiation typically escapes into space. Halogenated anesthetic agents—such as isoflurane, desflurane, sevoflurane, and methoxyflurane demonstrate pronounced absorption in this region. In contrast, nitrous oxide (N_2O) is situated outside this region, thereby impeding the efficient escape of infrared radiation to higher altitudes. This phenomenon has implications for the radiation balance of the Earth, contributing to its warming [31, 39]. Anesthetic gases remain in the atmosphere based on how quickly they break down. These compounds are predominantly removed from the atmosphere through reactions *involving* hydroxyl (OH) radicals, with N_2O also susceptible to direct photolysis in the stratosphere. The atmospheric lifetimes of these anesthetic gases vary, reflecting the strength of their chemical bonds [28]. Among the commonly utilized anesthetic gases, their atmospheric lifetimes, ranked from shortest to longest, are as follows: methoxyflurane (0.15 years), sevoflurane (1–2 years), isoflurane (3.5 years), desflurane (14 years), and N_2O (109 years) [44, 45].

In general, the difference in the GWP of anesthetic gases mainly comes from the difference in atmospheric lifetime rather than the infrared absorption band [46]. The GWP100 values, from lowest to highest, are methoxyflurane (4), sevoflurane (195), N_2O (273), isoflurane (539), and desflurane (2590), which is roughly the same as the order of atmospheric lifetime [45]. Notably, desflurane accounts for approximately 80% of the greenhouse effect associated with volatile anesthetic gases [47]. This significant contribution may be linked to desflurane's GWP, which is, on average, ten times greater than that of the other anesthetic gases, coupled with its higher Minimum Alveolar Concentration (MAC) compared to sevoflurane and isoflurane. We provide a summary of the atmospheric parameters and minimum effective concentrations of clinically utilized volatile anesthetics in Table 3 (Ref. [45, 48]). This information may contribute to minimizing clinical waste and prioritizing volatile anesthetics with a reduced potential for carbon emissions.

Another significant yet often overlooked environmental impact of anesthetic gases is aquatic ecotoxicity [49]. Volatile anesthetic gases and their degradation products, which contain at least one fully fluorinated methyl or methylene carbon atom, are classified as per- and polyfluoroalkyl substances (PFAS). Upon their release into the atmosphere, these compounds do not simply "dissipate"; rather, they are eventually deposited through precipitation or directly enter surface water bodies, leading to gradual accumulation and persistent water pollution. In comparison to Total Intravenous Anesthesia (TIVA), PFAS, commonly referred to as "forever chemicals", pose greater ecological risks due to their extreme environmental persistence and toxicity. Given their potential hazards, there is an urgent need for comprehensive ecological impact assessments and effective regulatory oversight to manage their environmental footprint.

TABLE 2. Life cycle assessment (LCA) stages and application of LCA to a general anesthesia example.

LCA stage	Interpretation	General anesthesia example
Goal and scope definition	LCA aims to compare the environmental impact of multiple products or activities (*e.g.*, endoscopy, traditional laparotomy, robotic surgery, or different inhalation anesthetics). Research objectives, research objects, functional units, system boundaries, and related constraints determine the scope.	Environmental impact assessment of general anesthesia in the operating room for the following surgical procedures: general surgery, obstetrics and gynecology surgery, eye surgery, cardiac surgery, joint replacement, neurosurgery.
Functional unit	An object or process of particular interest is known as a functional unit. Such as the functional unit of the refrigerator is “kg-MJ”, and the functional unit of health care is “one treatment or one operation”.	The functional unit is a general anesthetic for one patient.
System boundaries	System boundaries define the scope of the study, *i.e.*, which inputs, outputs, and life cycle phases to include, with a focus on high-emitting sources.	Time: The system boundaries encompass the entire process from the moment the patient enters the operating room to the completion of general anesthesia and the final exit from the operating room. The boundaries include the use of anesthetic drugs and gases, disposable or reusable items, energy utilized in operating room-related equipment (capital equipment, computers, lighting, heating, ventilation, and air conditioning systems), and the production and disposal of these resources for all patients undergoing general anesthesia during this period.
Life cycle inventory	Life cycle inventory is the data collection stage, including the input energy, output products or processes, and emissions to the atmosphere, water, and soil, which is the basis for the next impact assessment.	Record and specify consumption, service life, and material composition of items used. Energy usage can be determined either by taking measurements or by performing calculations. Carbon emissions from the production and disposal of supplies should also be recorded.
Impact assessment	Impact assessment *involves* quantifying the environmental load impact identified in inventory analysis through impact classification, characterization, and quantitative assessment.	Convert data to environmental impact units according to certain rules for easy comparison, (*e.g.*, $kgCO_2e/kg$ or $kgCO_2e/L$ or $kgCO_2e/h$). CO_2e = carbon dioxide equivalents
Interpretation	This stage *involves* analyzing, interpreting, and discussing research results to identify high-emission aspects of products or processes, and providing recommendations for ecological optimization.	Identify the high carbon emission links of general anesthesia, discuss the influence of relevant restrictions on the results, and put forward suggestions on the realization of ecological sustainability of general anesthesia.

TABLE 3. Atmospheric parameters and MAC of anesthetic gases.

Anesthetic	Atmospheric Lifetime (yr)	Atmospheric infrared radiation spectral wavelength (8–14 μm)	The 100-year Global warming potential	Minimum alveolar concentration
Nitrous oxide N_2O	109.00	Nonoverlapping	273	105.00
Isoflurane $CF_3CHClOCHF_2$	3.50	Overlapping	539	1.15
Desflurane $CF_3CHFOCHF_2$	14.10	Overlapping	2590	6.00
Sevoflurane $(CF_3)_2CHOCH_2F$	1.00–2.00	Overlapping	195	1.71
Methoxyflurane $CHCl_2CF_2OCH_3$	0.15	Overlapping	4	0.16

Data were derived from IPCC Report 31 [45] (AR6-chapter-7) and Aranake et al. [48]. MAC: Minimum Alveolar Concentration.

The effects of anesthetic gases extend beyond environmental degradation, such as the greenhouse effect and ozone depletion; they may also pose significant health risks to individuals with chronic occupational exposure, particularly in settings with inadequate exhaust ventilation [50]. Early investigations have indicated that medical personnel working in environments with insufficient clearance of inhaled anesthetics may encounter health complications such as liver disease, kidney disease, neurological disorders, cancer, spontaneous abortion, reduced fertility, and congenital anomalies [51–54]. Therefore, many countries have proposed legislation to establish occupational exposure limits for anesthetic gas emissions in order to reduce the associated health risks [55–58]. However, clinical observations [59, 60] have demonstrated that, in certain instances, occupational exposure to anesthetic gas emissions exceeds the established legislative thresholds. With the implementation of gas extraction systems (scavenging systems) and appropriate ventilation in operating rooms, the majority of anesthesia exhaust can be effectively removed, thus maintaining levels within the recommended exposure limits. As a result, health risks related to immunosuppression, mutagenicity, and oxidative stress from anesthetic gas emissions can be substantially mitigated [61]. A systematic review conducted in 2023 revealed that existing evidence linking occupational exposure to anesthesia gases with spontaneous abortion or teratogenicity remains limited, due to methodological variability and heterogeneity across studies [62]. Indeed, adherence to guidelines for occupational exposure to inhaled anesthetics, along with controlling exposure duration and the volume of anesthetic exhaust, and utilizing appropriate scavenging and ventilation systems to maintain environmental anesthetic gas levels below recommended thresholds, have not resulted in significant adverse effects [59, 61–63]. Nonetheless, it is important to acknowledge that some reports suggest that occupational exposure to anesthetic exhaust gases may induce genotoxicity, mutagenicity, and oxidative stress-related injuries, particularly in low-resource or developing countries where clearance and ventilation systems are inadequate, access to low-flow anesthesia technology is limited, and older, more toxic anesthetic agents are still in use [64, 65]. Therefore, routine monitoring of anesthetic gas concentrations in operating rooms, advocacy for governmental regulation and legislation concerning occupational exposure limits, and improvements to scavenging and ventilation infrastructure are essential strategies for reducing the risk of chronic exposure to anesthetic gas emissions in healthcare settings.

2.3 Measures and new technologies

Anesthetic exhaust gases are discharged directly into the external environment, undergo minimal metabolic processing, and are not subjected to treatment. This situation contributes to environmental degradation and poses a risk of occupational exposure risk to residual anesthetic gases. Nitrous oxide (N_2O), classified as both an ozone-depleting substance (ODP 0.015) and a potent greenhouse gas (GWP 100253), should be minimized whenever possible. Nevertheless, in obstetrics, N_2O is frequently utilized as one of the primary analgesics, resulting in significant carbon emission [66], thereby increasing the carbon footprint of vaginal delivery by 25 times, much higher than cesarean section [17]. Catalytic lysis *involves* employing a catalyst within a purification system to decompose the exhaled N_2O from patients into nitrogen (N_2) and oxygen (O_2). The efficacy of this process is contingent upon the volume of the patient's exhaled breath that is expelled through the face mask or endotracheal tube, directed to the scavenging system and subsequently routed to the catalytic device [67, 68]. This innovative technology minimizes both environmental impact and occupational exposure in medical settings where N_2O is indispensable and is already in routine use [68]. Additionally, research is actively being conducted on technologies that adapt the catalyst type or concentration based on the composition of anesthesia exhaust gases to enhance the efficiency of emissions capture.

Desflurane exhibits a significantly greater GWP compared to other commonly utilized anesthetic agents, attributable to its prolonged atmospheric lifespan and elevated alveolar effective concentration. Furthermore, desflurane contributes the highest carbon emissions associated with non-anesthetic exhaust factors when evaluating the upstream environmental impact, which encompasses manufacturing, transportation, packaging, and drug delivery throughout the lifecycle of inhaled anesthetics [38]. Consequently, it is advisable to avoid the routine use of desflurane when clinically appropriate, in order to mitigate the environmental harm associated with inhalation anesthesia without compromising patient outcomes [69]. In 13 January 2023, the impending complete ban on desflurane in the United Kingdom, scheduled for 2024 [70], along with a proposal within the European Union [71] to prohibit or at least impose stringent restrictions on the use of desflurane by 2026, underscore the compelling arguments against its utilization in clinical practice.

Notably, the prohibition and substantial restriction of desflurane could result in a reduction of approximately 80% in the carbon footprint associated with volatile anesthetic gas. However, this should not diminish the importance of considering other effective interventions [72], such as minimization of fresh gas flow (FGF) anesthesia. This approach is among the most recent strategies recommended by the American Society of Anesthesiologists and other experts for reducing anesthetic emissions [73, 74]. Implementing reduced FGF can lead to decreased drug consumption, waste, and environmental impact in a straightforward, safe, and effective manner. Ryan *et al.* [38] suggested utilizing sevoflurane with an FGF reduction of 2 L/min, while recommending desflurane and isoflurane with a reduction to FGF levels of 0.5 to 1 L/min, which may represent an optimal approximation of the ideal FGF. Through the utilization of a closed respiratory system and a quantitative anesthesia delivery system based on a modern anesthesia workstation, Feldman *et al.* [75] demonstrated that employing balanced anesthesia with low or minimal fresh gas flow ($\leq$1 L/min) during irrigation, and a metabolic fresh gas flow (0.35 L/min) during steady-state maintenance, resulted in a reduction of CO_2 emissions and costs by approximately 50%. Among the various methods for controlling the end-tidal concentration of anesthetic gases at the end of expiration [76], the electronic control mode (including automatic control, tidal end control, and automatic gas control) has shown significant potential in reducing inhalation anesthetic consumption and greenhouse gas emissions compared to traditional fresh gas flow techniques.

The strategies outlined above not only reduces the risk of occupational exposure and adverse environmental impacts but also respond to societal demands for immediate climate action. Furthermore, the development of novel technologies that prevent the release of anesthetics into the atmosphere and facilitate gas capture for reuse represents the most perspective means of achieving sustainable anesthesia and mitigating the carbon footprint.

Numerous capturing technologies have been patented:

(1) Charcoal particles or molecular sieve adsorption [77]. Activated carbon, which possesses favorable adsorption properties, can be utilized to capture volatile anesthetics and is commonly employed in intensive care settings where liquid volatile agents are directly introduced into the respiratory circuit. However, the advantages of this system are short lived, as volatile anesthetics are quickly desorbed and released into the atmosphere during the disposal of carbon-based devices. Currently, various technologies, such as SageTech medical (http://www.sagetechmedical.com/), Bluezone anesthetic collection service (https://www.blue-zone.com/), and CONTR Afluran [78] (https://www.baxter.be/en/node/3766), have been developed to capture volatile anesthetics and subsequently enable their potential reuse through a purification process. Silicate (zeolite) materials, which offer precise pore size control, can serve as an alternative to activated carbon for capturing volatile anesthetics. Doyle *et al.* [79] reported the effective removal of 1% isoflurane from exhaled air within eight hours using a silica-zeolite hydrophobic molecular sieve adsorbent. Additionally, volatile silicates can desorb and condense, allowing for purification or destruction to prevent the release of volatile anesthetics into the atmosphere, followed by the recovery of anesthetics through the purification process to achieve potentially sustainable inhalation anesthesia [74].

(2) Gas-phase photochemistry. This refers to the chemical reactions that occur in the gas phase as a result of light exposure. A photochemical waste gas destruction system, based on this principle, represents a novel method for eliminating anesthetic waste gas. This system offers high removal efficiency, cost-effectiveness, and eliminates the need for secondary treatment. The gas-phase photochemical reactor currently under development can be tailored to the chemical properties and concentration of anesthetics, thereby enhancing removal efficiency and effectively limiting the release of anesthetic waste gas into the atmosphere [80].

(3) Polymerized membrane technology. This filters CO_2, O_2, and N_2 to the surface of the removal membrane while retaining anesthetic vapor, thus reducing the fresh gas flow and preventing volatile anesthetic gas from escaping into the exhaust air stream, thereby minimizing anesthetic waste gas. It is important to note that the efficiency of these techniques diminishes with an increase in the fresh gas flow (FGF); therefore, utilizing low-flow anesthesia can maximize the environmental benefits of these technologies while considering the ecological and environmental impacts inherent to the techniques themselves. This warrants further research and development [81]. The recycling of anesthetics that are not officially approved for clinical reuse also poses a challenge, as improper storage may exacerbate emissions. Overall, however, these technologies hold considerable promise and have the potential to reduce greenhouse gas emissions significantly.

Two life cycle assessment studies of volatile anesthetic gas capture and recycling technologies illustrate that CO_2 equivalent emissions can be diminished by over 85% through the processes of gas capture, recycling, and reuse [82]. Nevertheless, it is important to acknowledge that any volatile anesthetics (VA) capture or destruction technology is inherently constrained by the fact that half of the volatile anesthetic administrated in the operating room may not be effectively captured, due to patient uptake, exhalation, and leaks within the circuit. The recycling of anesthetics that have not received official approval for clinical reuse presents a significant challenge, as inadequate storage practices may exacerbate emissions. Consequently, only a limited number of countries have sanctioned their reuse to date. Existing data indicate that capture efficiency within a clinical environment ranges from 25% to 70% [77], which is substantially lower than the efficiencies observed in computer simulations or laboratory settings. Furthermore, the actual effectiveness, cost-effectiveness, and standards for implementation reuse require further evaluation. Nonetheless, these technologies demonstrate considerable promise and possess the potential to mitigate greenhouse gas emissions significantly [83].

In addition to leveraging technology to address emissions-related challenges, it can also be employed to tackle issues associated with generated waste anesthetic gases. The advancement of novel climate-friendly anesthetics represents a promising avenue of research. Xenon is the sole inert gas with anesthetic properties that exists in the atmosphere under standard pressure [84]. Notably, the xenon released during medical procedures is returned to the atmosphere in its original form, thereby avoiding environmental pollution but increasing medical costs. With the increasing adoption of low-flow inhalation anesthesia techniques and the emergence of innovative equipment and technologies, xenon inhalation anesthesia may offer new perspectives for developing environmentally sustainable anesthetic practices.

While inhalation anesthesia has a significant atmospheric impact, there are numerous strategies available to mitigate its effects. The straightforward approach is to identify and reduce the use of high-carbon-emission anesthetic gases and implement low FGF anesthesia. Beyond these immediate measures, the development and application of various gas-capture technologies offer promising solutions. Additionally, ongoing research and development efforts are focused on creating environmentally friendly anesthetic gases that have a lower carbon footprint and reduced atmospheric impact.

2.4 Intravenous anesthetics

Intravenous anesthesia refers to the administration of non-volatile general anesthetics via intravenous injection, facilitating their entry into the central nervous system through the systemic circulation. This method does not contribute to the greenhouse effect or pose occupational exposure risks associated with inhalation anesthetics, and it is considered an effective approach to minimizing the consumption of volatile anesthetics [85]. In a study aimed at reducing greenhouse gas emissions from laparoscopic surgery, Thiel *et al*. [86] found that substituting inhaled anesthetics with propofol resulted in a significant reduction in greenhouse gas emissions (28%), while maintaining clinical safety and also showed advantages in transcatheter aortic valve replacement (TAVR) [87] and weight loss surgery [88]. TIVA also reduces greenhouse gas emissions by more than 20 times compared to mixed anesthesia [89]. A simulation study in pediatric anesthesia also indicated that intravenous anesthesia presents a climatic advantage over inhaled anesthetics [90]; however, real-world data are necessary for validation. Sherman *et al*. [91] employed life cycle assessment (LCA) to evaluate the environmental impact of anesthetic drugs on climate change and discovered that the greenhouse gas emissions associated with propofol were four orders of magnitude lower than those of desflurane or nitrous oxide, primarily due to the minimal energy required to operate the syringe pumps. During intravenous anesthesia, the most substantial contributions to the carbon footprint were related to anesthesia-associated electricity usage (20%), disposable plastic syringes (19%), and bottle handling (4%) [12]. Nonetheless, intravenous anesthetics also exhibit adverse environmental effects [92]. Research indicates that more than 45% of intraoperative propofol is either unused or discarded, with direct environmental release posing toxicity risks to aquatic organisms and detectable levels in drinking water and fish, thus necessitating incineration for safe disposal [93]. It is noteworthy that not all medical institutions have implemented formal incineration protocols for excess propofol, and the disposal process may generate varying amounts of greenhouse gases. Improper disposal practices could further exacerbate the environmental impact of intravenous anesthesia [94].

To mitigate carbon dioxide emissions, the adoption of intravenous anesthesia as a substitute for inhalational anesthesia must carefully weigh the environmental benefits and drawbacks of both modalities. Intravenous anesthesia represents a viable strategy towards achieving net-zero carbon anesthesia [66], and addressing the challenge of managing intravenous anesthesia waste may serve as a significant solution for promoting sustainable and cost-effective anesthesia practice [95].

2.5 Regional anesthetics

Regional anesthesia *involves* the localized injection of anesthetic agents, which can temporarily inhibit nerve conduction within specific regions of the body. The procedures associated with regional anesthesia generally have a lower carbon footprint compared to general anesthesia (including intravenous and inhalation methods), due to the simplicity of the drugs utilized and the absence of routine airway management equipment. In the context of transforaminal lumbar interbody fusion, spinal anesthesia offers several advantages over general anesthesia, including reduced surgical duration and postoperative pain [96], as well as a significant decrease in the carbon footprint associated with its use [15], consistent with findings from Olmos *et al*. [97]. The carbon footprint of regional anesthesia primarily arises from activities such as instrument washing, disinfection, oxygen inhalation, and plastic packaging, rather than from the anesthetic agents themselves. This carbon footprint is also evident in other anesthesia techniques. Consequently, the use of regional anesthesia, either as a primary method or in place of general anesthesia, is increasingly recommended to mitigate emissions of volatile substances and reduce the consumption of intravenous anesthetics [98]. However, a recent study assessing the carbon footprint of various anesthesia techniques used in total knee replacements revealed that the carbon footprint associated with spinal anesthesia was not significantly reduced when considering the entire lifecycle of the anesthesia process. This may be attributable to the additional requirements for instrument washing and disinfecting instruments, puncture packaging, plastic usage, and oxygen flow, which may offset the environmental advantages of spinal anesthesia, particularly as the use of desflurane and nitrous oxide was avoided in general anesthesia. A recent editorial in “Anesthesiology” further emphasized that the carbon footprint associated with anesthetics is not solely linked to the anesthetic agents themselves; rather, the replacement or adoption of multiple anesthesia techniques aimed at reducing the consumption of respective drugs does not necessarily result in lower overall carbon emissions [99]. Thus, multiple strategies are required to effectively reduce carbon emissions.

Current research on the carbon footprint of regional anesthesia predominantly focuses on spinal anesthesia, with limited consideration given to the environmental impact of other local or regional anesthesia techniques, such as nerve blocks or peripheral nerve blocks. This focus may stem from the broader clinical application of spinal anesthesia, indicating a need for further exploration in future studies.

Table 4 presents a summary and comparison of the primary carbon emission associated with the three clinical anesthesia methods: inhalational, intravenous and regional anesthesia. Additionally, we propose potential targeted measures for reduction of these emissions. However, it is essential that the principal criterion guiding the selection of anesthesia methods is patient-centered, with environmental considerations being a secondary factor. Consequently, we provide a summary and comparative analysis of the advantages and disadvantages of the three modalities of anesthesia concerning clinical application and environmental impact, thereby offering a valuable reference for practitioners in the field (see Table 5).

2.6 Single-use and reusable equipment in anesthesia practice

Most anesthesia equipment utilized during surgical procedures is disposable, including items such as laryngoscopes, monitoring electrodes, finger pulse oximeters, masks, tracheal tubes, breathing circuits, syringes, and various types of puncture kits. The trend towards replacing reusable anesthesia equipment with disposable alternatives [100], may be attributed to the prevailing belief that disposable items are more hygienic and better at preventing infections [101]. However, contrary to theoretical assumptions, studies have shown that disposable laryngoscope handles do not demonstrate a significant advantage in minimizing infection risk [102], while the use of reusable sheets can actually help minimizes the spread of

TABLE 4. Comparison of the carbon footprints for the different anesthesia modalities.

The possible sources of the carbon footprint	Inhalation anesthesia	Intravenous anesthesia	Regional anesthesia*
Anesthesia exhaust gas	√√	×	×
Oxygen	√	√	√√
Wastage of anesthesia drugs	√	√√	√
Disposable devices	√	√√	√
Reusable devices	√	√	√
Energy (a) HVAC (b) anesthesia machine (c) electricity for washing, disinfecting, sterilizing (d) patient air warmer	√	√	√√
Targeted measures	No high GWP inhalation anesthetics and develop new technologies to recover and dispose of anesthetic waste gas	Reduce drug waste and PVC product use	Lower flow rates
Common measures	(1) Promote energy optimization (2) Minimize fresh gas flow (FGF) anesthesia (3) Weigh the economic and environmental benefit ratio between disposables and reusables (4) Strengthen education and publicity (5) Multi-disciplinary cooperation		

*"√" represents the carbon footprint source component, "×" represents that there is no or little about the carbon footprint source component, "√√" indicates that this carbon footprint source component is more prominent under anesthesia. *Take spinal anesthesia as an example.*
GWP: Global Warming Potential; PVC: polyvinyl chloride; HVAC: heating, ventilation, and air conditioning systems.

TABLE 5. Pros/cons of each modality (inhalation, intravenous and regional) in terms of clinical and environmental effects.

Pros and cons	Inhalation anesthesia	Intravenous anesthesia	Regional anesthesia
Clinical advantages	(1) Fast onset, easy to adjust the depth of anesthesia (2) Less negative impact on the cardiovascular system (3) Some muscle relaxation effect (4) Less metabolic activity in the body	(1) The implementation is relatively simple and does not require complex equipment (2) Fast onset, strong efficacy (3) Multiple drugs can be reasonably selected according to the need (4) Specific antagonist that can reverse the anesthetic effect	(1) The patient is conscious, and the airway safety is high (2) Little effect on physiological function and patients recover quickly after operation (3) Easy to operate, no need for complex equipment
Clinical drawbacks	(1) Special equipment and personnel such as volatile vaporizers and anesthesia machines (2) May cause postoperative nausea and vomiting (3) Airway irritation	(1) Most intravenous anesthetics depend on liver and kidney function of the patient (2) Injection pain (3) Difficult to implement for obese or poor vascular conditions (4) Drug concentrations cannot be monitored in real-time	(1) Potential risk of local anesthetic allergy or poisoning (2) The range of blockage is limited and not suitable for large areas or complex surgery (3) The patient is conscious and may be overly anxious or uncomfortable

TABLE 5. Continued.

Pros and cons	Inhalation anesthesia	Intravenous anesthesia	Regional anesthesia
Environmental advantages	(1) Less drug waste occurs which can effectively control the waste of drugs	(1) No aerosols or volatile anesthetic gases will be produced (2) Reduce the risk of operating room contamination and explosion	(1) No aerosols or volatile anesthetic gases will be produced
Environmental drawbacks	(1) Large carbon emission potential and obvious impact on the atmospheric environment (2) Ozone layer destruction (3) Accumulation and deposition in the atmosphere may also cause aquatic ecological pollution	(1) The phenomenon of drug waste is obvious and needs to be treated by incineration and other special treatments (2) Direct discharge may lead to aquatic ecological pollution (3) Disposable syringes, infusion bags and so on are used more	(1) The phenomenon of drug waste is obvious and needs to be treated by incineration and other special treatment (2) The use of disposable items, such as puncture bags and syringes, has increased (3) Oxygen flow increased

particulate matter [103]. Therefore, it is not reasonable to use disposable devices for all patients as a means of mitigating any potential infection risks. In Germany, the validity period for reusing anesthetic breathing circuits is one week, while in the United States, it is limited to a single use [74]. Evidence has indicated that the reuse of respiratory circuits may be safe [104], thus, further research is necessary to determine whether disposable anesthesia devices are superior to reusable options in controlling infection rates. A comparative analysis of cost-effectiveness and environmental benefits between reusable and disposable equipment reveals a degree of complexity, influenced by various environmental factors [105]. A study by McGain *et al.* [106] found that converting anesthesia equipment in Australian operating rooms from single-use items (such as masks, laryngoscopes, and respiratory circuits) to reusable alternatives resulted in an average annual savings of $30,000; however, this change also led to a 10% increase in carbon dioxide emissions. In contrast, using the British/European energy mix could potentially reduce carbon emissions by 84%, considering that the energy required for cleaning, disinfection, and sterilization of reusable equipment is sourced from renewable resources. Rizan C *et al.* [16] who analyzed the carbon footprint of products used in five common surgical operations in the UK health system, found that eliminating single-use items or switching to reusable ones when feasible could significantly reduce the carbon footprint. Eckelman *et al.* [101] assessed the carbon footprint of disposable and reusable laryngeal masks using life cycle assessment methods and found that the carbon dioxide emissions associated with reusable masks (primarily stemming from gas production and combustion for washing and sterilization) were approximately half those of disposable masks (where emissions primarily resulted from polyvinyl chloride (PVC) plastic production, packaging, and waste disposal). Improvements in sterilization technologies, enhancements in energy-efficient autoclaves, strategic procurement, and reductions in the use of PVC products represent viable avenues for decreasing carbon dioxide emissions throughout the entire life cycle of medical equipment. Reusable blood pressure cuffs exhibit superior cost-effectiveness and environmental benefits compared to disposable cuffs [107], making them one of the current strategies for carbon reduction routinely adopted by anesthesia providers. McGain *et al.* [12] quantified the carbon footprint associated with each component in knee replacement procedures, revealing that the carbon footprint for general anesthesia disposable equipment compared to 5% for reusable equipment. In the case of spinal anesthesia, however, reusable equipment had a higher carbon footprint (30%) compared to disposable equipment (22%). These findings suggest that the choice of anesthesia technique may influence the selection of related equipment (disposable versus reusable) and consequently result in different carbon footprints. In practice, hospitals can optimize environmental benefits from equipment usage by fostering collaboration between finance, procurement, logistics, and suppliers. Overall, the comparison between reusables and disposables indicates that reusable equipment is generally more advantageous in terms of cost control and environmental impact, depending on the number of reuses, sterilization methods, and the energy sources employed (coal, gas, or renewable energy) [13]. When renewable energy constitutes the majority of electricity generation, reusable equipment can be utilized more frequently when clinically appropriate. Conversely, when electricity is derived from high carbon footprint sources such as coal, there is potential to explore improvements in energy composition and enhance the efficiency of equipment transportation and manufacturing [108]. Furthermore, waste generated from the use of either disposable or reusable equipment should adhere to the 3R principle (reduce, recycle, reuse): plastics, paper, medical PVC—including intravenous bags and oxygen masks/tubings—and metals (such as blades and surgical utensils) should be recycled to minimize solid medical waste treatment and subsequently reduce the overall carbon footprint [109].

Reusable equipment in anesthesia practice generally outperforms single-use items in terms of cost control and environmental impact. However, their superiority must be evaluated comprehensively, considering clinical conditions, sterilization techniques, and the local energy mix. Adhering to the 3R principle in clinical practice can significantly minimize the carbon footprint associated with device use. Moreover, collaborative efforts among healthcare providers, administrators, suppliers, and policymakers can further maximize the environmental benefits derived from equipment usage.

2.7 Drug wastage

Drug wastage is a widespread issue in anesthesia practice [95]. For instance, propofol commonly used in total intravenous anesthesia, is often discarded after partial use and a significant portion of nitrous oxide supplied in inhalation anesthesia is also lost due to leaks in cylinders and pipelines or underutilization [41]. Additionally, considerable waste is associated with muscle relaxants, sedatives, vasoactive agents, and even normal saline [110]. These unused drugs are typically discarded as medical waste, significantly contributing to environmental pollution [111]. Additionally, the disposal of syringes utilized for diluting these wasted drugs exacerbates economic costs and undermines environmental sustainability. Barbariol *et al*. [95] estimated that drug wastage during general anesthesia could result in an increase in medical waste by 4986 kg annually, a finding corroborated by a survey conducted by Peker *et al*. [110]. Addressing drug wastage during anesthesia and implementing better management practices could mitigate anesthesia-related environmental issues. Strategies such as transitioning to prefilled sterile syringes to reduce costs [112], and avoiding the over-preparation of drugs "just in case" are potential approaches for achieving net-zero carbon anesthesia [66]. However, it is noteworthy that there is currently no reported data on the wastage of local anesthetics. This absence of data does not imply that such wastage does not occur; for example, the volume of local anesthetic solutions or iodine used for disinfection often exceeds actual demand. While the recycling of anesthetic drugs may appear beneficial, it raises concerns regarding the increased risk of nosocomial infections and the challenges associated with improper drug storage.

Drug waste is a pressing issue that cannot be overlooked. Once discarded as medical waste, it has a particularly significant impact on the environment. Since there are limited feasible measures for treatment after disposal, reducing waste at the source is essential. Strategies such as optimizing procurement and management processes, preparing drug dosages more reasonably, and using environmentally friendly alternatives can all effectively alleviate the environmental pressure caused by drug waste.

2.8 Energy

The operating room represents the most resource-intensive area within a hospital, with the energy consumption throughout the entire perioperative period being the highest. This contributes significantly to the overall carbon footprint of hospital operations. A survey assessing the carbon footprint of operating rooms across three healthcare systems revealed that energy requirements associated with operating rooms (including heating, air conditioning, and ventilation) ranked second only to those of anesthesia, with the HVAC (heating, air conditioning, and ventilation) system accounting for approximately 90% of the energy consumption within the operating room [11]. Thiel *et al*. [14] further identified that over 70% of the energy consumption in operating rooms is attributed to heating, ventilation, and air conditioning, indicating that effective management of the HVAC system may serve as a critical target for reducing overall energy consumption.

Occupancy-based ventilation strategies for instance, can help reduce or mitigate unnecessary air convection, thereby lowering energy use [113]. In addition to HVAC systems, substantial energy is consumed by operating room lighting, anesthesia machines, maintenance infusion pumps, monitors, and computers. McGain *et al*. [12] reported that during the administration of anesthesia, energy consumption related to anesthesia (including the anesthesia machine and patient air warmer) accounted for approximately 20% of the total carbon dioxide emissions. Additionally, the energy expended on cleaning, disinfecting, and sterilizing reusable equipment within the operating room constitutes another important source of carbon footprint [109]. Addressing this issue necessitates optimizing the energy mix, which includes reducing energy wastage, enhancing energy efficiency, and transitioning to renewable energy sources. Such advancements will require ongoing collaboration among engineers and developers [80]. Anesthesia providers can significantly contribute to reducing energy consumption and minimizing the carbon footprint throughout the lifecycle of anesthesia [13]. Actions that can be undertaken include: (1) minimizing standby time, balancing the use of disposable versus reusable equipment, and fostering institutional coordination to diminish energy consumption and environmental emissions; and (2) collaborating with professionals in industry, construction, and environmental fields to facilitate the achievement of net-zero carbon anesthesia and promote sustainable anesthesia practices.

In summary, the carbon footprint of energy consumption, second only to anesthesia, mainly arises from HVAC system, anesthetic devices, lighting, monitors, computers, and infusion pumps. The sterilization of reusable instruments also adds substantially to emissions. Reducing energy waste and consumption represents a practical and impactful strategy for environmental improvement in healthcare.

3. Limitations

This review utilizes the 100-year GWP value to compare the atmospheric effects of different anesthetic gases. However, the validity of GWP100 has recently been questioned. Some atmospheric scientists argue that GWP100 can be misleading when applied to gases with short atmospheric lifetimes, such as those examined in this study. Simply converting them into CO_2 equivalent emission overlooks the complexities of the climate system [114] and may result in an underestimation of their short-term climatic environmental impacts. Nevertheless, current greenhouse gas accounting frameworks as recommended by the United States and United Nations continue to endorse the use of GWP100 for consistency and comparability in emissions reporting [115].

4. Conclusions

A reciprocal relationship exists between climate change and healthcare. A comprehensive examination of the carbon footprint and environmental impact associated with medical practices has revealed that the ecological consequences of anesthesia cannot be overlooked. This issue is gaining increasing recognition within the medical and broader scientific community. Over the past decade, healthcare professionals have begun using carbon footprint assessment tools to evaluate anesthesia-related products and activities, as evidenced by relevant literature on life cycle assessment (LCA). Furthermore, various strategies [66, 74] and consensus guidelines [13] have been developed to achieve net-zero carbon anesthesia. The feasible but influential measures taken by individuals are shown in Fig. 2. Specific measures can be implemented, including (Table 4), including (1) reducing or eliminating the use of anesthetic gases with significant global warming potential, such as nitrous oxide and desflurane; (2) using the low fresh gas flow anesthesia while ensuring clinical safety [38, 116]; (3) mastering intravenous anesthesia and regional anesthesia techniques to reduce reliance on volatile agents [85]; (4) minimizing waste associated with intravenous anesthesia; (5) incorporating the principles of environmental sustainability into anesthesia education to enhance awareness among individuals, institutions and governments [117]; (6) promoting energy optimization; (7) developing quantitative software for the calculation and real-time monitoring of personal carbon footprints, akin to radiation metering cards [118]. It is important to emphasize that these measures are not intended to create a dichotomy between healthcare provision and environmental responsibility. Instead, they aim to achieve net-zero carbon anesthesia while prioritizing clinical safety and supporting the broader goal of environmental sustainability. Looking ahead, multidisciplinary collaboration and the establishment of sustainable healthcare teams will be essential in mitigating the contribution of medical activities to climate change. Additionally, attention must be paid to other environmental impacts of healthcare such as ozone layer depletion or aquatic biotoxicity, as we strive toward truly green and sustainable healthcare systems.

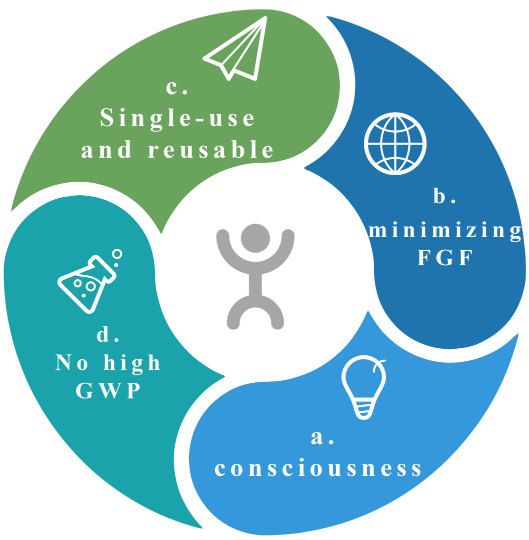

FIGURE 2. The most feasible but most impactful measures for anesthesia providers. (a) Reduce waste and cultivate awareness of emission reduction. (b) Minimizing fresh gas flow (FGF) anesthesia. (c) Weigh Single-use and Reusable Equipment. (d) No high global warming potential (GWP) inhalation anesthetics and preferred total intravenous anesthesia or regional anesthesia.

ABBREVIATIONS

FGF, fresh gas flow; GHGs, greenhouse gases; GWP, global warming potential; HVAC, heating, ventilation, and air conditioning systems; LCA, life cycle assessment; MAC, minimum alveolar concentration; ODP, ozone depleting potential; PVC, polyvinyl chloride; PFAS, per- and polyfluoroalkyl substance; ISO, International Organization for Standardization; N_2O, nitrous oxide; CFC-11, chlorofluorocarbon-11; IPCC, Intergovernmental Panel on Climate Change; OH, hydroxyl radicals; TIVA, Total Intravenous Anesthesia; N_2, nitrogen; VA, Volatile anaesthetics; TAVR, transcatheter aortic valve replacement; COVID-19, Coronavirus disease 2019.

AVAILABILITY OF DATA AND MATERIALS

Not applicable.

AUTHOR CONTRIBUTIONS

HH—designed the research study. XFC and HH—performed the research; wrote the manuscript. XFC—analyzed the data. Both authors contributed to editorial changes in the manuscript. Both authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

ACKNOWLEDGMENT

Not applicable.

FUNDING

This research was funded by Science and Technology Department of Sichuan Province, grant number 2024YFFK0252 to Han Huang and Committee of Healthy Care of Sichuan Province, grant number 2024-1702 to Han Huang.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] The Lancet. The Lancet's 200 years: much more to do. The Lancet. 2023; 402: 1199.

[2] Hoegh-Guldberg O, D Jacob, M Taylor, M Bindi, S Brown, I Camilloni, *et al.* 2018: impacts of 1.5 ºC global warming on natural and human systems. 2018. Available at: https://www.ipcc.ch/sr15/chapter/chapter-3/ (Accessed: 31 March 2025).

[3] Romanello M, Di Napoli C, Drummond P, Green C, Kennard H, Lampard P, *et al.* The 2022 report of The Lancet countdown on health and climate change: health at the mercy of fossil fuels. The Lancet. 2022; 400: 1619–1654.

[4] Lenzen M, Malik A, Li M, Fry J, Weisz H, Pichler PP, *et al.* The

environmental footprint of health care: a global assessment. The Lancet Planetary Health. 2020; 4: e271–e279.

[5] Bhangu A, Frankling C, Glasbey J, Kamarajah S, Li E, Nepogodiev D, *et al*. Net zero surgery: proof of concept and uncertainties. The Bulletin of the Royal College of Surgeons of England. 2022; 104: 326–331.

[6] National Institute for Health and Care Research Global Health Research Unit on Global Surgery. Reducing the environmental impact of surgery on a global scale: systematic review and co-prioritization with healthcare workers in 132 countries. The British Journal of Surgery. 2023; 110: 804–817.

[7] Hubert J, Gonzalez-Ciccarelli LF, Wang AW, Toledo E, Ferrufino R, Smalls K, *et al*. Carbon emissions during elective coronary artery bypass surgery, a single center experience. Journal of Clinical Anesthesia. 2022; 80: 110850.

[8] Ditac G, Cottinet PJ, Quyen Le M, Grinberg D, Duchateau J, Gardey K, *et al*. Carbon footprint of atrial fibrillation catheter ablation. Europace. 2023; 25: 331–340.

[9] Henniger D, Windsheimer M, Beck H, Brand M, Lux T, Hann A, *et al*. Assessment of the yearly carbon emission of a gastrointestinal endoscopy unit. Gut. 2023; 72: 1816–1818.

[10] Ramani S, Hartnett J, Karki S, Gallousis SM, Clark M, Andikyan V. Carbon dioxide emissions and environmental impact of different surgical modalities of hysterectomies. JSLS: Journal of the Society of Laparoendoscopic Surgeons. 2023; 27: e2023.00021.

[11] MacNeill AJ, Lillywhite R, Brown CJ. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. The Lancet Planetary Health. 2017; 1: e381–e388.

[12] McGain F, Sheridan N, Wickramarachchi K, Yates S, Chan B, McAlister S. Carbon footprint of general, regional, and combined anesthesia for total knee replacements. Anesthesiology. 2021; 135: 976–991.

[13] White SM, Shelton CL, Gelb AW, Lawson C, McGain F, Muret J, *et al*. Principles of environmentally-sustainable anaesthesia: a global consensus statement from the World Federation of Societies of Anaesthesiologists. Anaesthesia. 2022; 77: 201–212.

[14] Thiel CL, Eckelman M, Guido R, Huddleston M, Landis AE, Sherman J, *et al*. Environmental impacts of surgical procedures: life cycle assessment of hysterectomy in the United States. Environmental Science & Technology. 2015; 49: 1779–1786.

[15] Wang AY, Ahsan T, Kosarchuk JJ, Liu P, Riesenburger RI, Kryzanski J. Assessing the environmental carbon footprint of spinal versus general anesthesia in single-level transforaminal lumbar interbody fusions. World Neurosurgery. 2022; 163: e199–e206.

[16] Rizan C, Lillywhite R, Reed M, Bhutta MF. The carbon footprint of products used in five common surgical operations: identifying contributing products and processes. Journal of the Royal Society of Medicine. 2023; 116: 199–213.

[17] Spil NA, van Nieuwenhuizen KE, Rowe R, Thornton JG, Murphy E, Verheijen E, *et al*. The carbon footprint of different modes of birth in the UK and the Netherlands: an exploratory study using life cycle assessment. BJOG: An International Journal of Obstetrics & Gynaecology. 2024; 131: 568–578.

[18] McAlister S, Barratt AL, Bell KJ, McGain F. The carbon footprint of pathology testing. Medical Journal of Australia. 2020; 212: 377–382.

[19] Morooka H, Yamamoto T, Tanaka A, Furuhashi K, Miyagawa Y, Maruyama S. Influence of COVID-19 on the 10-year carbon footprint of the Nagoya University Hospital and medical research centre. Globalization and Health. 2022; 18: 92.

[20] Sillcox R, Blaustein M, Khandelwal S, Bryant MK, Zhu J, Chen JY. Telemedicine use decreases the carbon footprint of the bariatric surgery preoperative evaluation. Obesity Surgery. 2023; 33: 2527–2532.

[21] Lichter KE, Charbonneau K, Sabbagh A, Witztum A, Chuter R, Anand C, *et al*. Evaluating the environmental impact of radiation therapy using life cycle assessments: a critical review. International Journal of Radiation Oncology, Biology, Physics. 2023; 117: 554–567.

[22] Adshead F, Al-Shahi Salman R, Aumonier S, Collins M, Hood K, McNamara C, *et al*. A strategy to reduce the carbon footprint of clinical trials. The Lancet. 2021; 398: 281–282.

[23] Roberts I, Godlee F. Reducing the carbon footprint of medical conferences. The BMJ. 2007; 334: 324–325.

[24] Cockrell HC, Maine RG, Hansen EE, Mehta K, Salazar DR, Stewart BT, *et al*. Environmental impact of telehealth use for pediatric surgery. Journal of Pediatric Surgery. 2022; 57: 865–869.

[25] McGinnis S, Johnson-Privitera C, Nunziato JD, Wohlford S. Environmental life cycle assessment in medical practice: a user's guide. Obstetrical & Gynecological Survey. 2021; 76: 417–428.

[26] Finkbeiner M, Inaba A, Tan R, Christiansen K, Klüppel HJ. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. The International Journal of Life Cycle Assessment. 2006; 11: 80–85.

[27] Xu W, Bing H, Tian W, Wang L, Xia Z, Chu Q. Topical sevoflurane in the treatment of complex wounds: new application perspectives. Anesthesiology and Perioperative Science. 2025; 3: 15.

[28] Sulbaek Andersen MP, Nielsen OJ, Sherman JD. Assessing the potential climate impact of anaesthetic gases. The Lancet Planetary Health. 2023; 7: e622–e629.

[29] Hu X, Pierce JT, Taylor T, Morrissey K. The carbon footprint of general anaesthetics: a case study in the UK. Resources, Conservation and Recycling. 2021; 167: 105411.

[30] Samad K, Yousuf MS, Ullah H, Ahmed SS, Siddiqui KM, Latif A. Anesthesia and its environmental impact: approaches to minimize exposure to anesthetic gases and reduce waste. Medical Gas Research. 2025; 15: 101.

[31] Sulbaek Andersen MP, Nielsen OJ, Wallington TJ, Karpichev B, Sander SP. Medical intelligence article: assessing the impact on global climate from general anesthetic gases. Anesthesia and Analgesia. 2012; 114: 1081–1085.

[32] Mychaskiw G, Eger EI. A different perspective on anesthetics and climate change. Anesthesia and Analgesia. 2013; 116: 734.

[33] Devlin-Hegedus JA, McGain F, Harris RD, Sherman JD. Action guidance for addressing pollution from inhalational anaesthetics. Anaesthesia. 2022; 77: 1023–1029.

[34] Tennison I, Roschnik S, Ashby B, Boyd R, Hamilton I, Oreszczyn T, *et al*. Health care's response to climate change: a carbon footprint assessment of the NHS in England. The Lancet Planetary Health. 2021; 5: e84–e92.

[35] Kampman JM, Sperna Weiland NH. Anaesthesia and environment: impact of a green anaesthesia on economics. Current Opinion in Anesthesiology. 2023; 36: 188.

[36] Eckelman MJ, Sherman JD. Estimated global disease burden from US health care sector greenhouse gas emissions. American Journal of Public Health. 2018; 108: S120–S122.

[37] Weisz U, Pichler PP, Jaccard IS, Haas W, Matej S, Bachner F, *et al*. Carbon emission trends and sustainability options in Austrian health care. Resources, Conservation and Recycling. 2020; 160: 104862.

[38] Ryan SM, Nielsen CJ. Global warming potential of inhaled anesthetics: application to clinical use. Anesthesia and Analgesia. 2010; 111: 92–98.

[39] NOAA Chemical Sciences Laboratory (CSL). Scientific assessment of ozone depletion: 2010. 2011. Available at: https://csl.noaa.gov/assessments/ozone/2010/ (Accessed: 31 March 2025).

[40] Buhre W, Disma N, Hendrickx J, DeHert S, Hollmann MW, Huhn R, *et al*. European Society of Anaesthesiology Task Force on Nitrous Oxide: a narrative review of its role in clinical practice. British Journal of Anaesthesia. 2019; 122: 587–604.

[41] Seglenieks R, Wong A, Pearson F, McGain F. Discrepancy between procurement and clinical use of nitrous oxide: waste not, want not. British Journal of Anaesthesia. 2022; 128: e32–e34.

[42] Drew J, Christie SD, Tyedmers P, Smith-Forrester J, Rainham D. Operating in a climate crisis: a state-of-the-science review of life cycle assessment within surgical and anesthetic care. Environmental Health Perspectives. 2021; 129: 76001.

[43] Van Norman GA, Jackson S. The anesthesiologist and global climate change: an ethical obligation to act. Current Opinion in Anaesthesiology. 2020; 33: 577–583.

[44] Andersen MPS, Nielsen OJ, Sherman JD. The global warming potentials for anesthetic gas sevoflurane need significant corrections. Environmental Science & Technology. 2021; 55: 10189–10191.

[45] Forster P, T Storelvmo, K Armour, W Collins, J-L Dufresne, D Frame, *et al*. Chapter 7: the earth's energy budget, climate feedbacks, and climate sensitivity. 2021. Available at: https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-7/ (Accessed: 31 March 2025).

[46] O'Brien O, Conlon N. Anaesthetic gases and the environment: is it time

for a rethink? The Surgeon. 2024; 22: 200–202.
[47] Lehmann F, Mader J, Koch C, Markmann M, Leicht D, Sander M. Minimising the usage of desflurane only by education and removal of the vaporisers—a before-and-after-trial. BMC Anesthesiology. 2025; 25: 108.
[48] Aranake A, Mashour GA, Avidan MS. Minimum alveolar concentration: ongoing relevance and clinical utility. Anaesthesia. 2013; 68: 512–522.
[49] Kalmar AF, Groffen T, Vereecke H, Teunkens A, Dewinter G, Mulier H, *et al*. Volatile anaesthetics and PFAS forever chemicals: a critical gap in environmental impact assessments. Best Practice & Research Clinical Anaesthesiology. 2024; 38: 342–348.
[50] Silva MAP, Carvalho LIM, Destro MV, Braz LG, Braz MG. From indoors to outdoors: impact of waste anesthetic gases on occupationally exposed professionals and related environmental hazards—a narrative review and update. Environmental Toxicology and Pharmacology. 2025; 113: 104624.
[51] Vaĭsman AI. Working conditions in the operating room and their effect on the health of anesthetists. Experimental Surgery and Anesthesiology. 1967; 12: 44–49.
[52] Boivin JF. Risk of spontaneous abortion in women occupationally exposed to anaesthetic gases: a meta-analysis. Occupational and Environmental Medicine. 1997; 54: 541–548.
[53] Occupational disease among operating room personnel: a national study. Report of an ad hoc committee on the effect of trace anesthetics on the health of operating room personnel, American Society of Anesthesiologists. Anesthesiology. 1974; 41: 321–340.
[54] Cohen EN, Gift HC, Brown BW, Greenfield W, Wu ML, Jones TW, *et al*. Occupational disease in dentistry and chronic exposure to trace anesthetic gases. Journal of the American Dental Association (1939). 1980; 101: 21–31.
[55] Woebkenberg ML, Doemeny LJ. NIOSH's criteria for a recommended standard—occupational exposure to waste anesthetic gases and vapors. American Industrial Hygiene Association Journal. 1978; 39: 598–600.
[56] Henderson KA, Matthews IP. An environmental survey of compliance with Occupational Exposure Standards (OES) for anaesthetic gases. Anaesthesia. 1999; 54: 941–947.
[57] Marx T. Pollution of the work environment by volatile anesthetics and nitrous oxide. Anesthesiology, Intensive Care Medicine, Emergency Medicine, Pain Therapy. 1997; 32: 532–540. (In German)
[58] Unceta-Barrenechea Orúe B, Vicinay Pinedo S, Garrán Sabando B, Serna de Andrés A, Seoane de Lucas A. Occupational exposure of the anesthesiologist to nitrous oxide and halothane. Control measures. Spanish Journal of Anesthesiology and Resuscitation. 1989; 36: 267–275. (In Spanish)
[59] Keller M, Cattaneo A, Spinazzè A, Carrozzo L, Campagnolo D, Rovelli S, *et al*. Occupational exposure to halogenated anaesthetic gases in hospitals: a systematic review of methods and techniques to assess air concentration levels. International Journal of Environmental Research and Public Health. 2022; 20: 514.
[60] Braz LG, Braz JRC, Cavalcante GAS, Souza KM, Lucio LM de C, Braz MG. Comparison of waste anesthetic gases in operating rooms with or without an scavenging system in a Brazilian University Hospital. Brazilian Journal of Anesthesiology. 2017; 67: 516–520.
[61] Braz MG, Carvalho LIM, Chen CYO, Blumberg JB, Souza KM, Arruda NM, *et al*. High concentrations of waste anesthetic gases induce genetic damage and inflammation in physicians exposed for three years: a cross-sectional study. Indoor Air. 2020; 30: 512–520.
[62] García-Álvarez JM, Escribano-Sánchez G, Osuna E, Molina-Rodríguez A, Díaz-Agea JL, García-Sánchez A. Occupational exposure to inhalational anesthetics and teratogenic effects: a systematic review. Healthcare. 2023; 11: 883.
[63] Allweiler SI, Kogan LR. Inhalation anesthetics and the reproductive risk associated with occupational exposure among women working in veterinary anesthesia. Veterinary Anaesthesia and Analgesia. 2013; 40: 285–289.
[64] Amma RO, Ravindran S, Koshy RC, Jagathnath Krishna KM. A survey on the use of low flow anaesthesia and the choice of inhalational anaesthetic agents among anaesthesiologists of India. Indian Journal of Anaesthesia. 2016; 60: 751–756.
[65] Oliveira LA, P El Dib R, Figueiredo DBS, Braz LG, Braz MG. Spontaneous abortion in women occupationally exposed to inhalational anesthetics: a critical systematic review. Environmental Science and Pollution Research International. 2021; 28: 10436–10449.
[66] Shelton CL, Knagg R, Sondekoppam RV, McGain F. Towards zero carbon healthcare: anaesthesia. The BMJ. 2022; 379: e069030.
[67] Khan-Perez J, MacCarrick T, Martin F. The use of nitrous oxide "cracking" technology in the labour ward: a case report and patient account. Anaesthesia Reports. 2022; 10: e12182.
[68] Pinder A, Fang L, Fieldhouse A, Goddard A, Lovett R, Khan-Perez J, *et al*. Implementing nitrous oxide cracking technology in the labour ward to reduce occupational exposure and environmental emissions: a quality improvement study. Anaesthesia. 2022; 77: 1228–1236.
[69] Hendrickx JFA, Nielsen OJ, De Hert S, De Wolf AM. The science behind banning desflurane: a narrative review. European Journal of Anaesthesiology. 2022; 39: 818–824.
[70] Kmietowicz Z. Desflurane: use of carbon emitting anaesthetic to end in England. The BMJ. 2023; 380: 102.
[71] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014. 2022. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0150 (Accessed: 31 March 2025).
[72] Skowno J, Weatherall A. Lighting a candle, or cursing the darkness? Delivering a climate friendly anaesthetic. Journal of Paediatrics and Child Health. 2021; 57: 1781–1784.
[73] American Society of Anesthesiologists. Inhaled anesthetic 2023 challenge. 2025. Available at: https://www.asahq.org/about-asa/governance-and-committees/asa-committees/environmental-sustainability/inhaled-anesthetic-challenge (Accessed: 31 March 2025).
[74] McGain F, Muret J, Lawson C, Sherman JD. Environmental sustainability in anaesthesia and critical care. British Journal of Anaesthesia. 2020; 125: 680–692.
[75] Feldman JM. Managing fresh gas flow to reduce environmental contamination. Anesthesia & Analgesia. 2012; 114: 1093–1101.
[76] Kalmar AF, Van Der Vekens N, De Rydt F, Allaert S, Van De Velde M, Mulier J. Minimizing sevoflurane wastage by sensible use of automated gas control technology in the flow-I workstation: an economic and ecological assessment. Journal of Clinical Monitoring and Computing. 2022; 36: 1601–1610.
[77] Gandhi J, Barker K, Cross S, Goddard A, Vaghela M, Cooper A. Volatile capture technology in sustainable anaesthetic practice: a narrative review. Anaesthesia. 2024; 79: 261–269.
[78] Mulier H, Struys MMRF, Vereecke H, Rex S, Teunkens A, Kalmar AF. Efficiency of CONTRAfluran^{TM} in reducing sevoflurane pollution from maintenance anaesthesia in minimal flow end-tidal control mode for laparoscopic surgery. Anaesthesia. 2024; 79: 849–855.
[79] Doyle DJ, Byrick R, Filipovic D, Cashin F. Silica zeolite scavenging of exhaled isoflurane: a preliminary report. Canadian Journal of Anaesthesia. 2002; 49: 799–804.
[80] Rauchenwald V, Rollins MD, Ryan SM, Voronov A, Feiner JR, Šarka K, *et al*. New method of destroying waste anesthetic gases using gas-phase photochemistry. Anesthesia and Analgesia. 2020; 131: 288–297.
[81] Feldman JM, Lo C, Hendrickx J. Estimating the impact of carbon dioxide absorbent performance differences on absorbent cost during low-flow anesthesia. Anesthesia and Analgesia. 2020; 130: 374–381.
[82] Soulliere K. Blue zone technologies: prevented emissions LCA project. 2023. Available at: https://www.blue-zone.com/wp-content/uploads/2022/09/Blue-Zone-Technologies-Prevented-Emissions-LCA-Project-021723.pdf (Accessed: 31 March 2025).
[83] Müller-Wirtz LM, Volk T, Meiser A. Towards sustainability of volatile anaesthetics: capture and beyond. British Journal of Anaesthesia. 2024; 133: 1363–1366.
[84] McGuigan S, Abrahams BF, Scott DA. A narrative review of gas separation and conservation technologies during xenon anesthesia. Medical Gas Research. 2025; 15: 93.
[85] Bernat M, Colombini N, Bouvet L, Castro P, Remacle A, Poirier M, *et al*. Skills in total intravenous anaesthesia facilitate reduced volatile

anaesthetic consumption. British Journal of Anaesthesia. 2023; 133: 1374–1376.

[86] Thiel CL, Woods NC, Bilec MM. Strategies to reduce greenhouse gas emissions from laparoscopic surgery. American Journal of Public Health. 2018; 108: S158–S164.

[87] Yang L, Hubert J, Gitundu S, Brovman E, Cobey F. Carbon footprint of total intravenous and inhalation anesthesia in the transcatheter aortic valve replacement procedure. Journal of Cardiothoracic and Vascular Anesthesia. 2024; 38: 1314–1321.

[88] Dargent J. Reducing greenhouse gas emissions in a bariatric surgical unit is a complex but feasible project. Scientific Reports. 2024; 14: 1252.

[89] Bernat M, Boyer A, Roche M, Richard C, Bouvet L, Remacle A, *et al*. Reducing the carbon footprint of general anaesthesia: a comparison of total intravenous anaesthesia *vs.* a mixed anaesthetic strategy in 47,157 adult patients. Anaesthesia. 2024; 79: 309–317.

[90] Narayanan H, Raistrick C, Tom Pierce JM, Shelton C. Carbon footprint of inhalational and total intravenous anaesthesia for paediatric anaesthesia: a modelling study. British Journal of Anaesthesia. 2022; 129: 231–243.

[91] Sherman J, Le C, Lamers V, Eckelman M. Life cycle greenhouse gas emissions of anesthetic drugs. Anesthesia and Analgesia. 2012; 114: 1086–1090.

[92] Kalmar AF, Rex S, Groffen T, Vereecke H, Teunkens A, Dewinter G, *et al*. Environmental impact of propofol: a critical review of ecotoxicity and greenhouse effects. Best Practice & Research Clinical Anaesthesiology. 2024; 38: 332–341.

[93] Lane SF. The environmental sustainability of propofol use in daily practice. British Journal of Anaesthesia. 2020; 124: e221–e222.

[94] Waspe J, Orr T. Environmental risk assessment of propofol in wastewater: a narrative review of regulatory guidelines. Anaesthesia. 2023; 78: 337–342.

[95] Barbariol F, Deana C, Lucchese F, Cataldi G, Bassi F, Bove T, *et al*. Evaluation of drug wastage in the operating rooms and intensive care units of a regional health service. Anesthesia and Analgesia. 2021; 132: 1450–1456.

[96] De Biase G, Gruenbaum SE, West JL, Chen S, Bojaxhi E, Kryzanski J, *et al*. Spinal versus general anesthesia for minimally invasive transforaminal lumbar interbody fusion: implications on operating room time, pain, and ambulation. Neurosurgical Focus. 2021; 51: E3.

[97] Olmos M, Patel J, Kanter M, Karimi H, Kryzanski J. Evaluating the potential impact of spinal anesthesia use in lumbar surgery on global healthcare cost and climate change. Brain & Spine. 2023; 3: 101754.

[98] Petre MA, Malherbe S. Environmentally sustainable perioperative medicine: simple strategies for anesthetic practice. Canadian Journal of Anaesthesia. 2020; 67: 1044–1063.

[99] Struys MMRF, Eckelman MJ. Environmental footprint of anesthesia: more than inhaled anesthetics! Anesthesiology. 2021; 135: 937–939.

[100] Sherman JD, Raibley LA, Eckelman MJ. Life cycle assessment and costing methods for device procurement: comparing reusable and single-use disposable laryngoscopes. Anesthesia and Analgesia. 2018; 127: 434–443.

[101] Eckelman M, Mosher M, Gonzalez A, Sherman J. Comparative life cycle assessment of disposable and reusable laryngeal mask airways. Anesthesia and Analgesia. 2012; 114: 1067–1072.

[102] Sherman JD, Hopf HW. Balancing infection control and environmental protection as a matter of patient safety: the case of laryngoscope handles. Anesthesia and Analgesia. 2018; 127: 576–579.

[103] Stålfelt F, Tenghamn J, Malchau H, Malchau KS. Deployment of real-time particle detection monitoring system in operating theatres for airborne contamination assessments: a methodological evaluation. Bone & Joint Open. 2025; 6: 499–505.

[104] Dhane M, Gobert Q, Dernis L. Reusable breathing circuits: an environmentally sustainable alternative. Canadian Journal of Anesthesia. 2024; 71: 1433–1435.

[105] Hemberg L, Wessberg N, Leire C, Bentzer P. Environmental impact of single-use and reusable items in central venous catheter insertion kits: a life cycle assessment. Intensive Care Medicine. 2023; 49: 662–664.

[106] McGain F, Story D, Lim T, McAlister S. Financial and environmental costs of reusable and single-use anaesthetic equipment. British Journal of Anaesthesia. 2017; 118: 862–869.

[107] Sanchez SA, Eckelman MJ, Sherman JD. Environmental and economic comparison of reusable and disposable blood pressure cuffs in multiple clinical settings. Resources, Conservation and Recycling. 2020; 155: 104643.

[108] MacNeill AJ, Hopf H, Khanuja A, Alizamir S, Bilec M, Eckelman MJ, *et al*. Transforming the medical device industry: road map to a circular economy. Health Affairs (Project Hope). 2020; 39: 2088–2097.

[109] Pillay L, Winkel KD, Kariotis T. Developing the green operating room: exploring barriers and opportunities to reducing operating room waste. Medical Journal of Australia. 2024; 221: 279–284.

[110] Peker K. The wastage and economic effects of anaesthetic drugs and consumables in the operating room. Turkish Journal of Anaesthesiology and Reanimation. 2020; 48: 321–327.

[111] Salgueirinho C, Pereira H. The anesthesiologist and global climate change: an ethical obligation to act and being scientifically rigorous. European Journal of Anaesthesiology. 2022; 39: 840.

[112] Atcheson CLH, Spivack J, Williams R, Bryson EO. Preventable drug waste among anesthesia providers: opportunities for efficiency. Journal of Clinical Anesthesia. 2016; 30: 24–32.

[113] Stauning MT, Bediako-Bowan A, Andersen LP, Opintan JA, Labi AK, Kurtzhals JAL, *et al*. Traffic flow and microbial air contamination in operating rooms at a major teaching hospital in Ghana. The Journal of Hospital Infection. 2018; 99: 263–270.

[114] Slingo JM, Slingo ME. The science of climate change and the effect of anaesthetic gas emissions. Anaesthesia. 2024; 79: 252–260.

[115] Nielsen OJ, Sulbaek Andersen MP. Inhalational volatile anaesthetic agents: the atmospheric scientists' viewpoint. Anaesthesia. 2024; 79: 246–251.

[116] Rübsam ML, Kruse P, Dietzler Y, Kropf M, Bette B, Zarbock A, *et al*. A call for immediate climate action in anesthesiology: routine use of minimal or metabolic fresh gas flow reduces our ecological footprint. Canadian Journal of Anesthesia. 2023; 70: 301–312.

[117] Chambrin C, de Souza S, Gariel C, Chassard D, Bouvet L. Association between anesthesia provider education and carbon footprint related to the use of inhaled halogenated anesthetics. Anesthesia and Analgesia. 2023; 136: 101–110.

[118] Hansen EE, Chiem JL, Righter-Foss K, Zha Y, Cockrell HC, Greenberg SLM, *et al*. Project SPRUCE: saving our planet by reducing carbon emissions, a pediatric anesthesia sustainability quality improvement initiative. Anesthesia & Analgesia. 2023; 137: 98–107.

How to cite this article: Xiaofeng Chen, Han Huang. Carbon footprint and sustainable development in anesthesia: a narrative review. Signa Vitae. 2025; 21(9): 4-19. doi: 10.22514/sv.2025.123.