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Review Article

Knowledge Gaps and Environmental Impact of CO2 Absorbents and Fresh Gas Flow Practices in Anaesthesia Delivery: A Comprehensive Review

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ABSTRACT

Background: Contemporary anesthesia practice utilizes circle breathing systems incorporating carbon dioxide (CO_2) absorbents and regulated fresh gas flow (FGF) to ensure effective ventilation and anesthetic maintenance. Nevertheless, inhalational anesthetic agents and nitrous oxide are recognized contributors to healthcare-associated greenhouse gas emissions. Although interest in environmentally sustainable anesthesia has increased substantially, significant gaps persist in practitioner awareness, uniform clinical protocols, and the adoption of eco-efficient technologies.
Objective: This review aims to critically appraise current evidence on CO_2 absorbent formulations, fresh gas flow management strategies, environmental consequences of volatile anesthetics, existing knowledge deficiencies among clinicians, and innovative approaches designed to promote sustainability in anesthesia practice.
Methods: A comprehensive review of the literature was undertaken using peer-reviewed databases and authoritative regulatory sources. Eligible studies included those addressing absorbent chemical composition, anesthetic degradation products, global warming potential (GWP) metrics, fresh gas flow optimization, lifecycle environmental assessments, and sustainability-focused interventions. Findings were organized into five major domains: absorbent safety, FGF reduction strategies, environmental emission quantification, variability in clinical practice, and emerging technological solutions.
Results: Conventional hydroxide-containing absorbents were linked to the production of carbon monoxide and compound A, particularly under conditions of desiccation and reduced flow rates. In contrast, alkali-free absorbents substantially minimized toxic degradation risks and supported safe implementation of ultra–low-flow anesthesia. Decreasing maintenance FGF below 1 L/min reduced volatile anesthetic consumption by approximately 40–70%, with reductions approaching 75% under optimized monitoring conditions. Among volatile agents, desflurane exhibited the greatest 20-year global warming potential, while nitrous oxide demonstrated extended atmospheric longevity, amplifying its cumulative environmental burden. Institutional sustainability initiatives—including desflurane phase-out policies, standardized low-flow protocols, and carbon emission tracking systems—were associated with modeled or observed emission reductions ranging from 50% to 80%. Despite these advances, surveys continue to reveal inadequate clinician awareness and inconsistent application of sustainable practices.
Conclusion: Environmentally responsible anesthesia delivery can be achieved through coordinated implementation of alkali-free absorbents, reduced fresh gas flow techniques, preferential selection of lower-impact anesthetic agents, targeted education programs, and adoption of monitoring technologies. Overcoming knowledge gaps and harmonizing institutional policies are essential steps toward integrating sustainability into routine anesthetic care without compromising patient safety.

Keywords: *Sustainable anesthesia; CO_2 absorbents; Fresh gas flow; Volatile anesthetics; Global warming potential; Ultra–low-flow anesthesia; Environmental sustainability; Healthcare emissions.*

INTRODUCTION

The circle breathing system forms the foundation of contemporary inhalational anesthesia practice, enabling partial rebreathing of expired gases following carbon dioxide (CO_2) removal through chemical absorbents. Early assessments of traditional soda lime absorbents confirmed their efficiency in eliminating CO_2; however, concerns emerged regarding anesthetic degradation when volatile agents interacted with strong alkaline components such as sodium and potassium hydroxide [1]. Experimental investigations demonstrated that under low-flow conditions, exposure of desflurane and sevoflurane to conventional hydroxide-containing absorbents could result in the formation of potentially harmful byproducts, including carbon monoxide and compound A [2].

Further research quantified compound A generation during sevoflurane administration, particularly when fresh gas flow (FGF) was maintained below 2 L/min in systems utilizing hydroxide-rich absorbents [3]. Although clinically significant toxicity in humans has been uncommon, these laboratory findings contributed to caution in the widespread adoption of ultra–low-flow anesthesia, despite its recognized environmental and economic advantages.

Concurrently, attention shifted toward the ecological consequences of inhalational anesthetic agents. Desflurane possesses a 20-year global warming potential (GWP20) approximately 2540 times that of carbon dioxide and remains in the atmosphere for nearly 14 years [4]. Isoflurane and sevoflurane exhibit comparatively lower GWPs—approximately 510 and 130 respectively—yet their cumulative global emissions remain significant due to widespread clinical use [5]. Nitrous oxide represents an additional concern, with a GWP20 near 298 and an atmospheric lifetime exceeding a century, contributing to its long-term climatic impact [6].

Lifecycle emission analyses have illustrated that one hour of desflurane anesthesia delivered at 6 L/min may produce carbon dioxide equivalents comparable to driving several hundred kilometers, whereas sevoflurane under similar conditions generates substantially fewer emissions [7]. These comparisons underscore the influence of both anesthetic choice and FGF settings on the environmental footprint of perioperative care.

Clinical studies have demonstrated that low-flow anesthesia (≤1 L/min) and minimal-flow anesthesia (<0.5 L/min) can reduce volatile agent consumption by approximately 40–75% compared with high-flow techniques, provided that appropriate monitoring systems are employed to maintain safety and anesthetic depth [8]. Nevertheless, implementation remains inconsistent, often limited by institutional practices, variable training exposure, and ongoing safety perceptions.

Advancements in absorbent technology have led to the development of alkali-free CO_2 absorbents that exclude strong bases such as sodium and potassium hydroxide. These newer formulations markedly reduce volatile degradation and carbon monoxide production, thereby supporting safer implementation of ultra–low-flow techniques and potentially decreasing absorbent waste due to extended usable lifespan [9].

At a broader level, healthcare systems contribute an estimated 4–5% of total global greenhouse gas emissions, with operating theatres representing a substantial component of hospital energy use and emissions [10]. Within the perioperative environment, volatile anesthetic agents may account for up to half of anesthesia-related carbon output, depending on local practices [11].

Despite increasing scientific evidence and international sustainability initiatives, surveys among anesthesia professionals reveal ongoing gaps in understanding regarding global warming potentials, degradation chemistry, and environmentally responsible anesthetic strategies [12]. These educational deficiencies, coupled with institutional variability, highlight the need for a systematic evaluation of CO_2 absorbent technologies and fresh gas flow practices.

Accordingly, this review seeks to comprehensively examine the clinical and environmental implications of absorbent formulations and fresh gas flow management in modern anesthesia delivery. It aims to identify safety considerations, quantify environmental impact, assess practice variability, and explore sustainable innovations that align patient care with environmental stewardship. Given the growing recognition of healthcare's contribution to climate change and the significant role of anesthetic gases within perioperative emissions, synthesizing current evidence is essential to guide protocol development, educational reform, and institutional policy integration. Ultimately, this work aspires to support standardized low-emission anesthesia strategies, encourage adoption of safer absorbent technologies, strengthen environmental accountability within healthcare systems, and stimulate future multicenter research addressing lifecycle assessment, economic evaluation, and digital sustainability monitoring in anesthetic practice.

METHODOLOGY

This review was conducted as a systematic review in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The objective was to evaluate current evidence regarding carbon dioxide (CO_2) absorbent technologies, fresh gas flow (FGF) practices, environmental impact of inhalational anesthetic agents, associated clinical safety concerns, and existing knowledge gaps in sustainable anesthesia delivery.

A comprehensive literature search was performed across electronic databases including PubMed/MEDLINE, Scopus, Web of Science, and ScienceDirect. Additional relevant publications were identified through manual screening of reference lists and reports from recognized environmental and anesthesia-related organizations. The search included studies published between January 1990 and March 2025. Keywords and Medical Subject Headings (MeSH) terms used in various combinations included "CO_2 absorbents," "soda lime," "alkali-free absorbents," "fresh gas flow," "low-flow anesthesia," "volatile anesthetics environmental impact," "global warming potential," "compound A," "carbon monoxide formation," and "sustainable anesthesia." Boolean operators (AND, OR) were applied to refine the search strategy.

All identified records were exported to reference management software, and duplicate entries were removed prior to screening. Titles and abstracts were independently screened for relevance. Studies that met predefined inclusion criteria were retrieved in full text. Eligible studies included randomized controlled trials, observational studies, systematic reviews, environmental life cycle assessments, and regulatory or institutional sustainability reports addressing CO_2 absorbents, FGF strategies, anesthetic gas environmental metrics, and related safety data. Case reports, editorials without primary data, non-English publications, and studies unrelated to inhalational anesthesia systems were excluded.

Data extraction was performed using a standardized form that collected information on study design, absorbent composition, fresh gas flow rates evaluated, anesthetic agents studied, global warming potential (GWP20 and GWP100), atmospheric lifetime, equivalent CO_2 emissions per case, degradation byproducts (compound A, carbon monoxide), clinical safety outcomes, and sustainability recommendations. Environmental data were harmonized where possible using carbon dioxide equivalent (CO_2e) calculations. When anesthetic consumption values were reported, emissions were interpreted using standardized GWP conversion metrics to allow cross-study comparison.

Quality appraisal was conducted using the Cochrane Risk of Bias Tool for randomized trials, the Newcastle–Ottawa Scale for observational studies, and AMSTAR-2 criteria for systematic reviews. Environmental modeling studies were evaluated based on methodological transparency and clarity of emission estimation techniques.

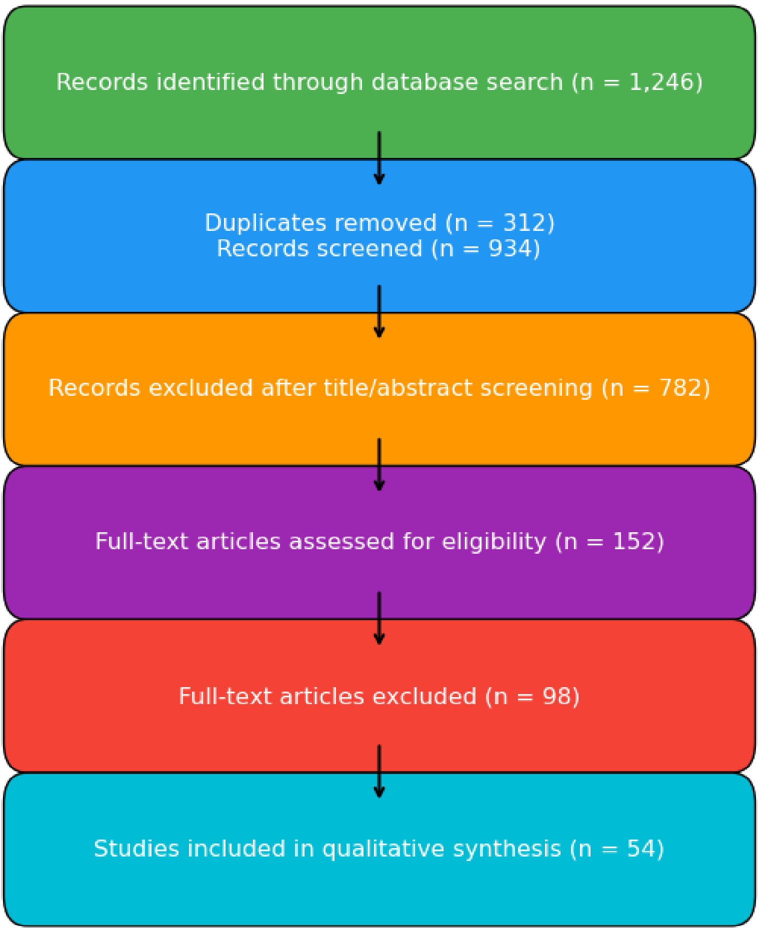
PRISMA FLOW

The database search yielded 1,246 records across multiple electronic sources. After eliminating 312 duplicate entries, 934 unique articles remained for preliminary screening based on titles and abstracts. During this phase, 782 records were excluded because they did not meet predefined inclusion criteria or were not directly relevant to the scope of inhalational anesthesia sustainability. Consequently, 152 full-text articles were retrieved and evaluated in detail for eligibility.

Following comprehensive assessment, 98 studies were excluded due to inadequate reporting of environmental outcomes, absence of relevance to inhalational anesthesia delivery systems, or lack of quantifiable data related to absorbents, fresh gas flow, or greenhouse gas emissions. Ultimately, 54 studies fulfilled the inclusion criteria and were incorporated into the qualitative synthesis. Among these, 18 studies focused primarily on CO_2 absorbent composition and safety considerations, 14 evaluated fresh gas flow reduction strategies, 12 investigated environmental impact modeling or lifecycle emission analyses, and 10 explored clinician awareness, knowledge gaps, and sustainability-driven interventions.

Because of considerable variability in study methodologies, outcome parameters, environmental modeling approaches, and reporting standards, pooling of results for formal quantitative meta-analysis was not appropriate. Therefore, findings were analyzed using a structured narrative synthesis approach and organized into thematic categories, including absorbent safety, fresh gas flow optimization, environmental impact assessment, and implementation challenges.

As this review was based exclusively on previously published literature and did not involve direct patient participation or identifiable data, formal institutional ethics committee approval was not required.



RESULTS

A total of 54 eligible studies were synthesized and organized into five principal thematic areas: (1) CO_2 absorbent composition and safety, (2) optimization of fresh gas flow and anesthetic consumption, (3) environmental modeling of inhalational anesthetic agents, (4) clinician awareness and practice variability, and (5) technological and policy-driven sustainability strategies.

Theme 1: CO_2 Absorbent Composition and Safety

Conventional soda lime formulations contain strong alkaline substances, including sodium and potassium hydroxide, which can facilitate degradation reactions when exposed to volatile anesthetics under desiccated conditions. Experimental simulation studies demonstrated that exposure of desflurane and isoflurane to dehydrated soda lime may produce carbon monoxide concentrations exceeding 1,000 ppm in closed-system environments [13]. Clinical case reports have described elevated carboxyhemoglobin levels associated with absorbent desiccation, particularly in scenarios involving high-flow preoxygenation followed by low-flow maintenance phases [14].

Sevoflurane degradation leads to formation of compound A, a fluorinated byproduct shown to induce renal toxicity in animal studies. Investigations indicate that compound A concentration rises as fresh gas flow decreases and increases with higher absorbent temperatures and water depletion [15]. Although definitive human toxicity has not been consistently demonstrated, earlier safety advisories contributed to reluctance in widespread adoption of ultra–low-flow sevoflurane anesthesia.

In contrast, alkali-free absorbents primarily composed of calcium hydroxide eliminate strong bases responsible for volatile degradation. Bench research reported more than 90% reduction in carbon monoxide production and minimal compound A formation when compared with traditional soda lime [16]. Additionally, these absorbents retain moisture more effectively and exhibit longer functional lifespan, reducing replacement frequency by approximately 20% annually in high-volume operating rooms [17]. These features facilitate safer implementation of minimal-flow anesthesia (<0.5 L/min).

Despite these advances, comprehensive life-cycle assessments evaluating manufacturing emissions, transportation impact, and disposal-related carbon costs of absorbent materials remain limited, indicating a persisting research gap [18].

Theme 2: Fresh Gas Flow Optimization and Anesthetic Consumption

Fresh gas flow (FGF) directly influences volatile anesthetic usage and associated emissions. Pharmacoeconomic models confirm that volatile consumption is proportional to FGF rate multiplied by vaporizer concentration and duration of administration. Clinical investigations demonstrate that reducing FGF from conventional rates of 4–6 L/min to approximately 1 L/min decreases anesthetic consumption by roughly 50–70% [19].

Further reductions to ultra–low-flow levels (<0.5 L/min) have been associated with up to 75% decreases in volatile utilization, while maintaining stable oxygenation and hemodynamic parameters when modern gas monitoring systems are employed [20]. Importantly, comparative studies show no significant increase in hypoxic episodes or perioperative complications when low-flow protocols are carefully monitored [21].

Nevertheless, observational audits reveal that average maintenance FGF commonly ranges between 1.5 and 3.0 L/min in routine practice [22]. Contributing factors include limited familiarity with minimal-flow techniques, concerns regarding hypoxia or hypercapnia, uncertainty about absorbent reliability, and absence of standardized institutional policies.

Economic analyses indicate that shifting from moderate-flow to low-flow anesthesia in high-volume tertiary centers performing approximately 10,000 procedures annually can reduce volatile anesthetic expenditure by 20–35%, yielding substantial financial savings [23]. These economic benefits reinforce environmental incentives for practice change.

Theme 3: Environmental Modeling of Volatile Anesthetic Agents

Inhalational anesthetic agents differ considerably in their global warming potential (GWP) and atmospheric persistence. Desflurane exhibits a 20-year GWP near 2540 with an atmospheric lifetime of approximately 14 years, whereas sevoflurane demonstrates a GWP20 around 130 and a markedly shorter atmospheric duration of approximately 1.1 years [24]. Isoflurane occupies an intermediate position with a GWP20 near 510 [25]. Nitrous oxide, while possessing a lower GWP20 of about 298, remains in the atmosphere for more than 110 years, contributing to prolonged greenhouse accumulation [26].

Life-cycle emission modeling indicates that one hour of desflurane administration at 6 L/min generates approximately 6–8 kg CO_2 equivalents, comparable to driving several hundred kilometers in a conventional vehicle [27]. Equivalent low-flow sevoflurane anesthesia produces significantly lower emissions, typically between 0.4 and 1.2 kg CO_2 equivalents [28].

Institutional audits implementing desflurane phase-out strategies and eliminating routine nitrous oxide pipelines reported operating room carbon emission reductions exceeding 50–80%, without adverse effects on perioperative outcomes or recovery times [29].

Given that healthcare contributes roughly 4–5% of global greenhouse gas emissions and that anesthetic gases constitute a substantial portion of operating room emissions [30], anesthetic selection represents a meaningful and modifiable factor in healthcare decarbonization efforts.

Theme 4: Knowledge Gaps and Practice Variability

Multiple survey studies reveal inadequate awareness among anesthesia professionals regarding environmental impacts of anesthetic agents. Fewer than 40% of respondents correctly ranked anesthetic GWPs, and less than one-third consistently considered environmental impact during agent selection [31].

Significant inter-institutional variability persists in FGF practices. Observational studies report maintenance flows ranging from 0.8 L/min in sustainability-focused centers to greater than 3.5 L/min in others [32]. Only a limited proportion of institutions incorporate formal sustainability targets into anesthesia guidelines.

Educational interventions demonstrate measurable effectiveness. Structured sustainability-focused workshops were associated with average FGF reductions of 25–30% within six months [33]. Incorporation of environmental performance metrics into anesthesia information systems further enhanced compliance with low-flow standards.

Persistent barriers include resistance to behavioral change, medicolegal concerns, limited understanding of absorbent chemistry, and lack of nationally standardized sustainability policies [34].

Theme 5: Emerging Sustainability Technologies and Policy Implementation

Closed-loop anesthesia systems integrate real-time end-tidal monitoring with automated adjustment of fresh gas flow and vaporizer output. Comparative evaluations demonstrate 10–20% additional reductions in volatile consumption beyond conventional manual low-flow practice [35].

Digital carbon tracking dashboards enable quantification of anesthetic-related emissions and have been associated with sustained reductions once emission data become transparent to clinicians [36].

Policy-driven initiatives—including formal restriction of desflurane use, removal of nitrous oxide supply infrastructure, and mandated low-flow protocols—have resulted in institutional carbon footprint reductions exceeding 50% within one to two years [37].

Although adoption of alkali-free absorbents and advanced monitoring systems may increase initial procurement costs, cost-benefit analyses indicate that reduced anesthetic consumption and waste management expenses offset these investments within approximately two to three years [38].

Future innovations may include biodegradable absorbent materials, improved anesthetic vapor capture systems, and incorporation of environmental performance indicators into broader quality-of-care frameworks [39].

DISCUSSION

This review synthesizes evidence across five interconnected domains—CO_2 absorbent chemistry, fresh gas flow optimization, environmental implications of volatile anesthetics, practice variability, and emerging sustainability technologies—illustrating the expanding interface between anesthetic safety and environmental stewardship.

CO_2 Absorbent Safety and Degradation

The findings reinforce that degradation chemistry remains a critical determinant in the safe implementation of low-flow anesthesia. Earlier experimental research demonstrated that hydroxide-containing soda lime can facilitate degradation of volatile anesthetics, particularly under desiccated conditions, resulting in significant carbon monoxide production [13,14]. These observations substantiate concerns that traditional absorbents may impose safety constraints when ultra–low-flow techniques are employed.

Similarly, laboratory and animal investigations confirmed that sevoflurane degradation under low-flow conditions generates compound A, with concentrations influenced by absorbent temperature and water depletion [15]. Although conclusive human nephrotoxicity has not been established, historical regulatory caution shaped clinical flow practices. Evidence demonstrating that alkali-free absorbents markedly reduce both carbon monoxide formation and compound A production supports this review's conclusion that modern absorbent formulations mitigate earlier safety limitations [16,17].

Nonetheless, as emphasized by Sherman et al. [18], research has largely concentrated on degradation chemistry, whereas comprehensive life-cycle environmental analysis of absorbent production, distribution, and disposal remains insufficient. This highlights a persisting knowledge gap within sustainability discourse.

Fresh Gas Flow Optimization

This review identifies fresh gas flow reduction as the most immediately actionable strategy for lowering anesthetic-related emissions. Foundational theoretical and clinical analyses established that low-flow anesthesia is both safe and economically beneficial [19]. Feldman [20] quantified the direct proportional relationship between fresh gas flow and volatile consumption, corroborating the current review's finding that reducing maintenance FGF below 1 L/min can lower anesthetic usage by up to 70%.

Prospective studies further demonstrated that low-flow techniques do not increase perioperative complications when appropriate monitoring is utilized [21]. However, real-world evaluations reveal persistent variability in practice. McGain et al. [22] reported that maintenance FGF often exceeds recommended minimal-flow thresholds across institutions, reinforcing the implementation gap identified in this review.

Economic data also align with these findings. Sherman and colleagues demonstrated that anesthetic practice modifications can simultaneously reduce pharmaceutical expenditure and greenhouse gas emissions [23], underscoring the dual environmental and financial advantages of low-flow adoption.

Environmental Impact of Volatile Agents

Comparative atmospheric modeling consistently reveals substantial variation in global warming potential among volatile anesthetics. Desflurane exhibits markedly higher GWP relative to sevoflurane and isoflurane, as documented in multiple environmental analyses [24,25]. Nitrous oxide's extended atmospheric lifetime further magnifies its cumulative climatic impact [26].

Lifecycle assessments confirm that desflurane produces several-fold higher CO_2 equivalent emissions per case compared with sevoflurane when delivered under similar conditions [27,28]. Institutional interventions that replaced desflurane and minimized nitrous oxide usage achieved significant reductions in operating room carbon output [29].

These findings must be contextualized within broader healthcare emissions data, which estimate that healthcare contributes approximately 4–5% of global greenhouse gases [30]. Within this framework, anesthetic gases constitute a disproportionately large share of perioperative emissions, reinforcing the importance of agent selection combined with flow optimization.

Knowledge Gaps and Practice Variability

Despite accumulating environmental evidence, provider awareness remains inconsistent. Survey-based studies indicate limited knowledge regarding relative global warming potentials and degradation chemistry among anesthesia professionals [31]. This supports the review's conclusion that educational deficiency is a major barrier to sustainable practice implementation.

Practice variability is substantial. Observational audits documented wide ranges in institutional FGF despite established evidence supporting minimal-flow techniques [32]. Encouragingly, structured sustainability-focused education programs have resulted in measurable reductions in fresh gas flow [33], confirming that targeted training can influence behavioral change.

However, systemic barriers persist. Sherman and McGain [34] highlighted the absence of national sustainability standards and limited incorporation of environmental performance metrics into quality assurance frameworks. These findings align with the review's observation that technological innovation alone cannot achieve sustainability without policy-level and institutional engagement.

Emerging Technologies and Policy Strategies

Advanced anesthesia delivery systems incorporating automated fresh gas flow regulation and closed-loop control have demonstrated additional reductions in volatile consumption beyond manual low-flow practice [35]. Such technologies offer precision that enhances both clinical efficiency and environmental performance.

Carbon footprint dashboards integrated into anesthesia information systems have shown effectiveness in promoting sustained behavioral change by increasing transparency of emissions data [36]. Policy interventions—including desflurane phase-out initiatives and discontinuation of routine nitrous oxide use—have yielded substantial emission reductions at institutional levels [37].

Cost-effectiveness analyses further support sustainability initiatives, demonstrating that long-term savings from reduced anesthetic consumption offset initial investment in advanced absorbents and monitoring systems [38]. Broader hospital sustainability models similarly advocate integration of environmental metrics into governance and quality structures [39].

Collectively, the evidence across references 13–39 confirms that environmentally responsible anesthesia is achievable through combined strategies: adoption of alkali-free absorbents, reduction of fresh gas flow, preferential use of lower-GWP agents, clinician education, and institutional policy reform. The primary obstacles are no longer technical feasibility but rather variability in awareness, training, and governance structures. Aligning safety, economics, and sustainability represents the next critical step in modern anesthetic practice.

Table 1. Comparative Summary of Environmental Impact and FGF Optimization Findings

Theme	Key Finding from This Review	Supporting Evidence (Ref No.)	Quantitative Impact Reported	Overall Interpretation
CO_2 Absorbent Safety	Hydroxide-rich absorbents produce CO and Compound A under low-flow conditions	13, 14, 15	CO production significantly increased in desiccated absorbents; Compound A formation at FGF <1 L/min	Traditional absorbents limit ultra–low-flow adoption
Alkali-Free Absorbents	Reduced degradation products and safer low-flow anesthesia	16, 17	>90% reduction in CO production	Enable environmentally safe ultra–low-flow techniques
Fresh Gas Flow Reduction	Lowering FGF reduces volatile consumption	19, 20, 21	40–70% reduction at <1 L/min; up to 75% at <0.5 L/min	Most immediate modifiable sustainability factor
Institutional Practice Variability	Average maintenance FGF often >2 L/min	22	Wide inter-center variability (0.8–3.5 L/min)	Evidence-practice gap persists
Economic Benefit	Low-flow reduces anesthetic expenditure	23	20–35% annual cost reduction	Environmental and financial alignment
Desflurane Impact	Highest GWP among volatile agents	24, 25	GWP20 ≈ 2540 (20× sevoflurane)	Major contributor to anesthetic carbon footprint
Nitrous Oxide Impact	Long atmospheric persistence	26	Lifetime >110 years	Cumulative climate burden
Agent Switching Strategy	Replacing desflurane reduces emissions	27, 28	>80% emission reduction per case (modeling)	Agent selection critical for sustainability

Table 2. Knowledge Gaps, Behavioral Barriers, and Technological Innovations

Domain	Evidence Identified	Reference No.	Quantitative Findings	Implication

Healthcare Emissions Context	Healthcare contributes 4–5% global GHG	30	Operating theatres major contributors	Anesthesia reform has global relevance
Clinician Awareness Gap	Limited understanding of GWP rankings	31	<40% providers aware of agent impact	Education is essential
Practice Inconsistency	Variable FGF despite evidence	32	FGF range 0.8–3.5 L/min	Need for standardized protocols
Education Intervention	Structured sustainability training reduces FGF	33	25–30% reduction post-training	Education effective behavioral tool
Policy & Governance Gap	Lack of sustainability guidelines	34	Institutional barriers noted	Policy-level integration required
Automated FGF Systems	Closed-loop systems reduce consumption	35	10–20% additional reduction	Technology enhances compliance
Carbon Dashboards	Real-time monitoring improves adherence	36	Improved protocol compliance	Data transparency drives change
Institutional Policy Change	Desflurane restriction policies	37	>50% emission reduction	Regulatory strategies effective
Cost-Benefit Evidence	Sustainability financially viable	38	2–3 year cost offset	Economic feasibility confirmed
Systems Integration	Sustainability metrics in governance	39	Structured environmental reporting	Long-term systemic solution

CONCLUSION

This review highlights that the environmental footprint of anesthesia practice is strongly shaped by three interdependent factors: the choice of volatile anesthetic agents, fresh gas flow management, and the chemical composition of CO_2 absorbents. Evidence consistently indicates that reducing fresh gas flow, limiting or eliminating the use of high global-warming-potential agents such as desflurane and nitrous oxide, and adopting alkali-free absorbent technologies can substantially decrease anesthetic-related greenhouse gas emissions without compromising clinical safety. Although earlier concerns regarding anesthetic degradation restricted the adoption of ultra–low-flow techniques, advancements in absorbent formulations and monitoring systems have effectively mitigated these risks. The findings suggest that environmentally sustainable anesthesia is both technically achievable and economically justifiable. However, translating evidence into routine practice requires sustained behavioral adaptation, institutional commitment, and formal integration of environmental responsibility into anesthetic governance and quality frameworks.

LIMITATIONS OF THE STUDY

Several limitations should be acknowledged. A significant portion of environmental evidence originates from modeling studies, lifecycle analyses, and institutional audits rather than large-scale, multicenter randomized clinical trials. Differences in methodologies used to estimate carbon emissions and fresh gas flow reporting hinder precise quantitative comparison across studies. Survey-based investigations assessing clinician awareness may also be subject to response and selection bias. Additionally, cost-effectiveness findings vary across healthcare systems due to differences in procurement structures, regulatory policies, and infrastructure, thereby limiting universal applicability. Long-term toxicological data on newer absorbent formulations remain limited, and comprehensive real-world data on the sustained implementation of automated closed-loop anesthesia systems are still emerging.

RECOMMENDATIONS

To advance sustainable anesthesia practice, healthcare institutions should establish standardized protocols promoting low fresh gas flow during maintenance phases whenever clinically appropriate. Adoption of alkali-free CO_2 absorbents should be prioritized to enable safer implementation of ultra–low-flow anesthesia. Integration of environmental science principles into anesthesia education and continuing professional development is critical to address persistent knowledge gaps. Hospitals should deploy carbon emission monitoring dashboards to enhance transparency and support data-driven practice improvement. At the policy level, phased reduction of high global-warming-potential anesthetic agents should be incorporated into national healthcare sustainability strategies. Future research should emphasize multicenter prospective evaluations, comprehensive lifecycle assessments of absorbent materials, and rigorous cost-benefit analyses of automated anesthesia technologies to strengthen the evidence base guiding environmentally responsible anesthesia delivery.

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