

Exploring the Viability and Environmental Impact of Zeolite-Based Filters for Anesthetic Gas Capture in Clinical Settings

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Received April 28, 2025

Accepted January 31, 2026

Electronic access February 28, 2026

Anesthetic gases such as nitrous oxide (N₂O), sevoflurane, and desflurane, are indispensable to medical practice but have a tremendous impact on global warming due to their high global warming potentials (GWPs), which exceed carbon dioxide by up to 3,700 times. Global Warming Potentials quantify a greenhouse gas's ability to trap heat compared to carbon dioxide over a specific time period, such as 100 years. Activated carbon filters, the present standard for gas capture, have limitations such as rapid saturation, humidity sensitivity, and environmental risks on disposal. This review evaluates zeolite-based filters as a sustainable alternative, assessing adsorptive capacity, clinical viability and the environmental impact through a systematic evaluation of peer-reviewed articles. Zeolites are crystalline aluminosilicates with uniform pores (5–8 Å). This aids in the selective capture of halogenated anesthetics (e.g., sevoflurane, 5.2 Å) through weak intermolecular forces (van der Waals) and electrostatic interactions, while smaller water molecules (2.8 Å) are less readily adsorbed. However, excessive humidity can still cause a decrease in gas uptake, so future innovations such as hydrophobic zeolite modifications are proposed to further improve water resistance. Zeolites can be effectively regenerated, with their adsorptive capacity at approximately 90% after multiple adsorption–desorption cycles, through thermal or vacuum processes. Adsorption–desorption cycles are essentially the manner in which zeolites adsorb gases, but then desorb them due to heat, making them reusable for adsorption again. This regenerability could reduce waste generation and operational costs over time, although comprehensive cost analyses are lacking. Key challenges include integrating the filter into anesthesia systems without impeding safety, managing moisture interference in operating rooms, and upfront costs. Future innovations that can be applied to zeolite filters are hydrophobic modifications to further reduce water adsorption, hybrid zeolites (e.g., zeolite-metal organic frameworks), and policy incentives for healthcare facilities (e.g., carbon credits for hospitals) to promote adoption. Zeolites show promise; however, clinical trials are necessary to confirm long-term performance under real-world conditions. This review focuses on zeolites' capacity to balance clinical efficacy with environmental sustainability as well as overcome technical and economic obstacles to global adoption.

Introduction

Anesthetic gases, particularly nitrous oxide, sevoflurane, and desflurane, are key to modern medicine, as they provide an assurance of the safety and comfort of patients undergoing surgery and other medical interventions; however, their use does pose significant environmental concerns. Many of these anesthetic agents are potent greenhouse gases with high global warming potentials and long atmospheric lifetimes, thus contributing significantly to climate change when released into the atmosphere. Nitrous oxide, for example, has a global warming potential (GWP) 298 times higher than that of carbon dioxide over a 100-year time frame. The same can be said for halogenated anesthetic agents like sevoflurane (349 GWP), isoflurane (1401 GWP), and desflurane (3714 GWP)¹. With rising demand for anesthesia worldwide, there is an equal urgency to develop effective strategies to capture and mitigate these gases in order to reduce their environmental impact. Despite the

development of many methods to control emissions, the field still faces challenges in striking a balance between efficiency, affordability, and environmental sustainability. Existing technologies used to adsorb anesthetic gases are usually carbon-based materials or expensive, energy-intensive processes, and thus they lack satisfactory efficiency in operative rooms. Traditional activated carbon filters also require periodic replacement and possess an adsorption capacity of approximately 50 grams of halogenated anesthetic vapor. In a prolific operating room, this capacity is typically exceeded within a day^{2,3}. Moreover, the disposal of used filters may create secondary environmental problems as well. For example, used activated carbon filters can release adsorbed anesthetic residues during disposal, requiring energy-intensive incineration or risking soil contamination³. On the contrary, zeolite adsorbents are recoverable, inorganic, and non-flammable. Zeolites are chemically inert crystalline aluminosilicates that can be thermally regenerated to emit trapped gases and hence allow repeated use without toxic waste being generated. This regen-

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erability reduces secondary pollution and can disentangle the waste stream from anesthetic scavenging to a great extent⁴. As a result, there is an increasing need for more sustainable, efficient, and cost-effective filtration materials in order to minimize the ecological footprint of these gases in clinical settings. In this respect, zeolite-based filters have emerged as a potential substitute for traditional filtration media, showing a great potential for the capture of anesthetic gases in medical applications.

The primary focus of this review paper is on evaluating the applicability and environmental impact of zeolite-based filters for capturing anesthetic gases in clinical settings. By comparing the performance and sustainability of zeolite filters with those of activated carbon, this review aims to conclude whether or not integrating zeolites into anesthesia machines could be a viable solution to mitigate the environmental harm caused by anesthetic gases. Drawing on existing data, the study places particular emphasis on clinical contexts to better address real-world applications. Ultimately, this study seeks to advance more sustainable healthcare practices by promoting a cost-effective, eco-friendly alternative to current anesthetic gas capture technologies, fostering a greener future for the medical field.

Methodology

The review evaluates the feasibility of zeolite-based filters for capturing anesthetic gases in healthcare settings. It depends on three critical metrics: adsorption efficiency, clinical feasibility, and environmental impact.

These metrics can be defined as below:

Adsorption Efficiency: The capacity of a material (e.g., zeolite or activated carbon) to capture and retain specific anesthetic gas molecules from a mixture, measured by the amount of gas adsorbed per unit mass of adsorbent under defined conditions (e.g., temperature, pressure, humidity).

Clinical Feasibility: The practicality and ease of integrating zeolite-based filters into anesthetic delivery systems in clinical settings without disrupting standard practices or compromising patient safety and care quality.

Environmental Impact: The effect of using zeolite-based filters on reducing the overall carbon footprint of anesthetic gases by preventing their release into the atmosphere and mitigating their contribution to greenhouse gas emissions and climate change.

An electronic search without time restrictions was conducted using journals including but not limited to: *PubMed*, *National Institutes of Health*, *Anesthesia and Analgesia*, *Anaesthesia and Intensive Care*, *Discover Applied Sciences*, *Environmental Science and Pollution Research*, *Korean Journal of Anesthesiology*, *Canadian Journal of Anesthesia*, *Materials*, *American Society of Anesthesiologists*, *IJATEC*, *Sci-*

entific Research Journal, *Science of the Total Environment*, *ACS Applied Energy Materials*, *British Journal of Anaesthesia*, *Processes*, and *European Journal of Anaesthesiology*. In total, this search yielded 82 initial hits; after screening abstracts and study quality, 30 relevant papers and reports were reviewed in detail, of which the most useful are cited here. Studies were selected on the inclusion criteria: (1) research articles published in English, (2) studies addressing the adsorption of anesthetic gases using zeolites or activated carbon, (3) articles investigating clinical feasibility or environmental impact, or (4) empirical studies reporting quantitative adsorption data, excluding reviews, opinion pieces, and editorials. The exclusion criteria include studies unrelated to anesthetic gas capture in clinical settings, those lacking a methodological framework, and research focused on non-relevant materials unless directly compared to zeolites or activated carbon. One manufacturing source was used to gather data about filters, this being Supera Veterinary.

The search for relevant papers initially included the use of the OR boolean operator to broaden the search. Terms like *anesthetic gases*, *zeolites*, *adsorption*, *activated carbon*, *greenhouse gas emissions* were used. This approach yielded the foundational studies on environmental impact of inhaled anesthetics, adsorption mechanisms of activated carbon and zeolites, and zeolite-based gas capture. Subsequently, the AND boolean operator was used to cluster terms to narrow focus towards the original criteria. Additionally, there may have been selection bias towards studies that support zeolites adsorptivity over activated carbon.

Adsorption Mechanisms of Zeolites and Activated Carbon in Anesthetic Gas Capture

Volatile anesthetic gases, such as sevoflurane, desflurane, and isoflurane, along with nitrous oxide, are widely used in clinical anesthesia but are potent greenhouse gases that contribute much to environmental pollution. Adsorption of these gases in anesthetic machines is primarily done through activated carbon. However, zeolites pose an alternative to adsorbing these gases as well. An understanding of the adsorption mechanisms of both materials is necessary in order to understand their efficiency in capturing anesthetic gases.

Zeolites: Structure and Adsorption Mechanism

Zeolites are crystalline aluminosilicates with a well-ordered, three-dimensional structure that contains uniformly defined micropores. The adsorption of the volatile anesthetic agents onto zeolites is controlled to a large extent by van der Waals forces, which represent relatively weak, non-covalent interactions between the anesthetic molecules and the zeolite surface⁵. This interaction depends upon the size, shape, and hy-

drophobicity of the anesthetic molecules, and zeolites can selectively adsorb some gases depending upon such properties⁶.

Pore Size and Shape

The pore size and shape of zeolites plays a part in their adsorption efficiency. The pores in zeolites are well-defined and uniform, which allows the selective adsorption of particular gases with specific molecular dimensions. For example, compounds like sevoflurane and desflurane, which have molecular diameters of approximately 4.5 to 6.5 Å, show a perfect match with zeolites having pore sizes ranging from 5 to 8 Å. The compatibility of molecular dimensions of these compounds with the zeolite pore structure is a key factor for its effectiveness in the adsorption process since it provides the gaseous molecules with a more pronounced interaction with the material surface⁷.

High Surface Area

Zeolites have a high surface area, which enables a larger number of active sites to be available for the adsorption of volatile anesthetic gases. The microporous nature of zeolites increases the total surface area within a given volume, thus increasing their ability to adsorb a large amount of gas molecules. This high surface area, combined with their ordered pore structure, enhances the overall efficiency of anesthetic gas retention⁷.

Polar Surface Chemistry

The polar surface chemistry of zeolites also contributes to the adsorption behavior of volatile anesthetic gases. While the anesthetic molecules are chemically nonpolar, the cations present in the zeolite structure, such as Na⁺, K⁺, or Ca²⁺, are strong enough to generate localized electrostatic fields that can interact with the electronegative halogen atoms of the anesthetic gas molecule. This interaction influences the overall adsorption capacity, mainly when the zeolites are modified to increase their hydrophobic nature and, therefore, their affinity for halogenated gases⁷.

Regeneration

Zeolites can also be effectively regenerated for adsorption processes. With the use of heat and vacuum environment, the gases adsorbed by the zeolites can be desorbed, leaving the zeolites free of gas. The regenerated zeolites then can be reused for adsorption of anesthetic gases. This has been tested primarily in industrial settings, through the adsorption of H₂S. In the experiment, after 9 desorption and regeneration treatments, the adsorption capacity of H₂S could still reach approximately 90%. Although these results were for Hydrogen Sulfide removal, it suggests that zeolites can endure many reuse cycles with minimal loss of efficacy. By contrast, activated carbon tends to lose considerable capacity with each regeneration (see below in regeneration section for activated carbon)⁸.

Activated Carbon: Structure and Adsorption Mechanism

Activated carbon has a characteristic feature of being extremely porous and having a large surface area, which makes it an effective adsorbent for volatile anesthetic gases. The primary adsorption mechanism occurring on activated carbon is physisorption. Being a physical process, physisorption involves the weak van der Waals attraction of gas molecules to the carbon surface. This interaction is to some extent reversible and depends on the surface area, pore structure, and hydrophobicity of the activated carbon⁹.

Physical Adsorption (Physisorption)

In activated carbon, physisorption is the most common mechanism by which volatile anesthetic gases are held. The phenomenon occurs when anesthetic molecules get attracted to the carbon substrate through weak intermolecular interactions, such as London dispersion forces and dipole-induced dipole interactions, which are under the umbrella term for “van der Waals forces”⁹. However, physisorption’s reversibility makes activated carbon susceptible to saturation in humid environments, as other molecules like water compete for adsorption sites¹⁰. In one study, adsorption capacity decreased by 31%–45% depending on humidity¹¹.

Pore Distribution

The pore distribution in activated carbon has a marked influence on its adsorption capacity. Activated carbon contains a variety of pores of different sizes, such as micropores (less than 2 nm), mesopores (2–50 nm), and macropores (larger than 50 nm). The presence of different pore sizes allows activated carbon to adsorb a wide range of molecules, from small gases like CO₂ to larger anesthetic molecules like sevoflurane and desflurane¹². The smaller micropores are particularly effective in the adsorption of smaller molecules, while the mesopores and macropores can accommodate larger anesthetic molecules.

Surface Area and Porosity

Activated carbon is known to possess a large surface area as well as high porosity, both being key factors in determining its performance as an adsorbent. In general, the activation process increases the surface area by creating a porous network within the material. The resulting increase in surface area has more adsorption sites, so the material can capture anesthetic gases more effectively. The porosity in activated carbon has a great influence on its ability to retain anesthetic molecules, since gases could be trapped into the pore structures, further promoting the adsorption mechanism¹².

Regeneration

Just like zeolites, activated carbon can also be thermally regenerated; however, contrary to zeolites’ constant adsorption rate after 9 regeneration cycles, activated carbon’s adsorption

rate declines after each regeneration. An experiment adsorbing H₂S was also done using activated carbon. The activated carbon was regenerated to 70% of initial adsorptive capacity after one cycle, and 60% after two cycles. By two regenerations, nearly half the capacity was lost. The declines are attributed to pore fouling, residual adsorbate that is difficult to remove, and structural changes. Therefore, activated carbon filters are typically regarded as single-use consumables in anesthesia applications, and they are normally not regenerated in hospital settings specifically. The single-use aspect contributes to waste and cost. The spent carbon may now be saturated with anesthetic, which is now considered hazardous medical waste and must be disposed of properly (usually incinerated). The need to frequently replace and dispose of activated carbon filters from an environmental perspective is one of the primary drawbacks¹³.

Comparative Performance of Zeolite vs. Carbon Filters

As indicated in Table 1, zeolite and activated carbon filters have both pros and cons. While zeolites have greater selectivity and reusability – which means increased operational life and a lesser burden to manage – a properly sized zeolite filter could, in the real world, run through almost an entire surgical day before saturation (depending on case times and fresh gas flows), yet an activated carbon canister might need to be changed sooner or risk breakthrough of anesthetic vapor once saturated. A direct quantitative comparison from previous studies is nonetheless quite informative: one study indicated that a zeolite filter with 750 g of zeolite had >99% capture of isoflurane for ~8 hours at 3 L/min flow as opposed to a standard activated carbon canister (~200 g) which may permit leakage at ~2–3 hours for a comparable flow, unless changed. It should be noted there are slight differences in studies and study set up that are mentioned here^{14,15}. There is no direct side-by-side experiment (this is an evidence gap to address; see Section on Clinical Feasibility).

The potential to regenerate and reuse the zeolites is another important advantage. For example, in practice, a hospital could have two sets of zeolite cartridges: one being used, and one being regenerated (i.e., heated to release the anesthetic). This process could significantly reduce solid waste versus throwing away charcoal canisters. A rough calculation clearly shows the potential influence: by capturing and destroying 100 g of desflurane (which is about what two surgeries might exhale), one is saving nearly 0.9 tonnes of CO₂-equivalent emissions into the atmosphere, given desflurane's GWP of ~3714. The total energy to heat the zeolite bed to regenerate that 100 g of anesthetic would yield billions of magnitudes less in CO₂ emissions – perhaps ~0.1 kg CO₂ if electricity comes from the grid – meaning that the net impact would still have a very large positive greenhouse benefit.

Moreover, with an activated carbon system, you would just be creating a solid waste product from those 100 g of anesthetic – waste that then has to be incinerated (and the captured gas gets released, in addition to other combustion gas emissions, unless special destruction equipment is used). Thus, the zeolite capture process allows for a shift from an emissions paradigm of one-time adsorption and waste (carbon) to potential adsorption, recovery, and reuse of anesthetic (circular paradigm). Nonetheless, activated carbon has some practical advantages to consider. First, it is a well-established technology, inexpensive on a per unit basis, and does not require owner-supplied equipment to operate. Zeolite systems may involve a more complicated set of equipment if on-site regeneration is planned. Off-the-shelf activated carbon filters are effective at immediately reducing waste gas concentrations for operating room staff safety, and they remain the standard for mitigating trace gas exposure and malignant hyperthermia preparation in anesthesia machines¹⁵. Therefore, any zeolite system will need to offer the simplicity and easy-to-understand operation that clinicians demand from existing carbon filters.

Clinical Feasibility and Implementation Challenges

Though laboratory results of zeolite-based anesthetic filters are promising, implementing this technology into everyday clinical practice is not without complications. Here, practical considerations of implementing zeolite filters into the anesthesia process will be discussed, the current deficit of clinical records emphasized, and the limitations and uncertainties of the filter's integration will be discussed.

Integration into Anesthesia Systems

All retrofits to any anesthesia circuit must prioritize the safety of the patient above all else and ensure gases can still be delivered through the filter retrofitted. Zeolite filters would be placed in the waste scavenging line (like where charcoal canisters are used) or in the expiratory limb of the circuit. As with any addition of filters, the important consideration is whether the filter will contribute excessive resistance or change the mechanics of ventilation. Fortunately, Doyle et al. observed an approximate pressure drop of 0.13 cm H₂O across a 750 g silica zeolite canister flowing at 3 L/min, and the pressure drop remained stable for ~6.5 hours of use; at a higher flow of 30 L/min, the drop increased to ~0.64 cm H₂O (these pressure drops are still negligible in the clinical context)⁶. The data here suggest that if the silica zeolite filter is designed correctly, it could be integrated into the anesthesia circuit without compromising clinical efficacy with increased resistance, but due considerations must be given to specifications on circuit components (e.g., acceptable pressure drop thresholds). This

Table 1 Comparison of Zeolite-Based vs. Activated Carbon Anesthetic Filters (key properties and performance)

Property	Zeolite-Based Filter	Activated Carbon Filter
Adsorption capacity	High for halogenated anesthetics (molecular sieve effect targets anesthetic molecules). For example, ~750 g zeolite can capture ~60–70 g isoflurane before breakthrough. Capacity less affected by other organics due to selectivity.	High capacity for many organic vapors in dry conditions, but non-selective. ~200 g charcoal will adsorb ~50 g anesthetic (e.g., ~12 hours usage at 1 L/min) before breakthrough. Capacity effectively lower in the presence of other vapors (e.g. humidity).
Selectivity	Selective for certain gas molecules based on size/polarity. Zeolite pores ~5 to 8 Å exclude small or large molecules; zeolites have a strong affinity for halogenated anesthetics and a very low uptake of N ₂ O. By virtue of having zeolite selectively adsorb gases, there is less co-adsorption of non-target gases (i.e., CO ₂ and N ₂), along with trace gases.	Non-selective (broad physisorption of most organics). Non-selective adsorbents will adsorb anesthetic vapors and potentially other vapors (such as CO ₂ and trace gases). Non-selectivity would cause saturation to occur with contaminants in the non-target gas.
Humidity tolerance	Moderate to good (if mainly using hydrophobic zeolite). Hydrophilic zeolites (in Na ⁺ form) have a tendency to adsorb H ₂ O and would compete with the anesthetic. Hydrophobic zeolites take up very little water and easily displace that water for the anesthetic, maintaining capacity in humid air.	Poor in humid air. Water vapor readily adsorbs and saturates the available microsites, reducing the number of available sites for anesthetic. Performance degrades considerably given typical humidity from exhaled breath unless active drying or very large excess capacity is used.
Breakthrough behavior	Sharp breakthrough once capacity is reached, but long operating time under typical OR flows due to high capacity and selectivity. In tests, no anesthetic detected downstream for ~8–10 hours at 3 L/min flow (zeolite ~750 g).	Breakthrough can occur more gradually and sooner, especially at higher flows or in the presence of other adsorbates. Significant desflurane leakage observed after a few hours at 3 L/min in a ~200 g activated carbon filter.
Regeneration & reusability	Yes – reusable via thermal or vacuum regeneration. Zeolites withstand multiple cycles with minimal capacity loss (e.g., ~90% capacity retained after 9 heat cycles in lab test). Regeneration typically requires heating to ~300°C to desorb anesthetic. Filter can then be reused many times, reducing waste.	Single-use in practice. Activated carbon is not easily regenerated without special equipment; capacity drops ~30–40% after one regeneration. Hospitals do not regenerate charcoal canisters; they are discarded and incinerated after saturation.
Environmental impact	Lower ongoing waste and potentially lower net emissions. Reusable filter = less frequent disposal. Captured anesthetic can be reclaimed during regeneration for possible reuse. Energy for regeneration is very small relative to anesthetic GHG avoided.	Higher waste generation and ancillary emissions. Dozens of spent charcoal canisters per OR per year must be disposed of (often via incineration). No anesthetic recycling – all captured anesthetic is destroyed. However, activated carbon requires no electricity during use (passive).

study suggests that zeolite canisters may be a safe addition to the circuit, so long as gas flow is not impeded. But planning for the engineering is important: as the zeolite canisters capture anesthetic and potentially moisture, the physical attributes

will likely change during the case. Furthermore, all modern anesthesia machines use sensitive pressure monitors, so any chance for occlusion or elevated resistance from the zeolite must be thoroughly vetted. One potential solution could be to

increase the filter size (cross-sectional area) to mitigate flow resistance, even if it becomes saturated. Another aspect to consider is the way that the filter interacts with other parameters, such as ventilator bellows and scavenging regulators; any potential compatibility issues or fail-safe bypass mechanisms must be considered within the overall system design.

Operational Workflow

Anesthesiologists and technicians have been used to the ease of discarding charcoal canisters. A zeolite system provides a switching workflow: either replace and regenerate filters in place or exchange filters that will be sent away for recycling while new canisters are provided. This is similar to how some hospitals process mercury or chemical waste. An example is Blue-Zone Technologies in Canada, which currently has a service model in place: they place their Deltasorb[®] zeolite canisters on OR scavenging systems, and when they get full, the canisters are sent to a processing center after the captured anesthetics come out through distilling and reusing. Hundreds of ORs in Ontario use this technology, which essentially captures 100% of the waste halogenated anesthetic and prevents its off-gassing¹⁶. This provides a use case that shows the feasibility of implementation of zeolite filters on a larger scale, but it needs the infrastructure to swap and deal with the processed materials. If the hospital wanted a more self-contained solution, a hospital would spend money on a regeneration unit that would run on site. These may be commercial variations of small electrically heated ovens or devices intended to purge anesthetics from the zeolite filter at the end of the day. Until those technologies are commercialized and standardized, there will be both a learning curve and logistical challenge for hospitals managing the zeolite filters.

Cost Considerations

Currently, zeolite systems are more expensive upfront than disposable charcoal canisters. Activated carbon filters are inexpensive (in the tens of dollars range each) and are already accounted for in the hospital budget. Zeolite filters have an initial capital cost (for canisters and any hardware necessary for regeneration) and ongoing maintenance. However, the fair comparison of cost is the total cost of ownership of carbon filters (the cost of continuous re-purchases and waste disposal). If one regenerable zeolite cartridge can take the place of dozens of charcoal canisters, it is possible the total cost includes long-term savings; there is limited published data on these economics. One consideration is how much a recycled anesthetic value might be, i.e., if anesthetics can be captured, purified, and reused then there is a saving (sevoflurane and desflurane are both expensive medications). Blue-Zone's program, for instance, actually resupplies reclaimed

anesthetic agents back to industry. In a future scenario, hospitals might recoup some costs by selling or reusing the anesthetic collected by zeolite filters. Still, to convince hospital administrators, more concrete cost-benefit analyses are needed. Future studies are recommended to include economic evaluations, comparing the status quo (disposable carbon) to various zeolite implementation models (on-site regeneration vs. third-party service).

Lack of Clinical Data

While there have been promising laboratory and pilot studies, there is a significant gap in peer-reviewed clinical trials or larger studies of zeolite filter performance in real operative or clinical use to date. Most of the evidence has been based on simulated performance or short-term experimentation. For example, Jänchen et al. performed a clinical trial with 13 patients that suggested a zeolite device adsorbed 62–86% of delivered desflurane depending on the fresh gas flow, and about 85% of the adsorbed anesthetic was recoverable by desorption¹⁴. While it was an optimistic study, it had limitations (scope and older anesthesia equipment). Doyle et al. published preliminary findings of zeolite filter use in a simulated anesthesia circuit (with a tested lung), reporting that isoflurane was completely removed for greater than six hours, but, again, not in an actual patient and limited effectiveness in simulated use⁶. The number of experimental clinical trials conducted in patient-based settings is limited, and therefore claims of clinical feasibility are speculative. Key unknowns include the operation of the filter with prolonged surgical procedures (i.e., >8 hours), operation with concentrations of anesthetic reallocating (anesthetics being given in a pulsatile manner based on inhalation/exhalation cycles), and whether there is any possibility for degradation products or dust to make their way into the circuit over time. Clinical validation studies are warranted before zeolite filters become the standard; this entails understanding the efficiency of anesthetic scavenging, monitoring any unintended consequences on patient ventilation or physiology outcomes, and the practicality of its implementation (e.g., how often it would need to be changed or regenerated in a busy OR, or do staff think this is practical). Until then, our assessment is qualified in having no certainty beyond the present data or trial into real-world efficacy.

Safety Considerations

A new system must be fail-safe from a safety perspective. An anesthetic gas-saturated zeolite filter should not pose a risk of initiating the re-release of anesthetic back into the OR air. In the worst-case scenario, a zeolite filter that is completely filled should only allow anesthetic to pass through to the existing active scavenging system (venting outside), rather than releasing

anesthetic suddenly in an uncontrolled manner. Constructing the filter housing with an outlet bypass or end-of-service indicator built into the lid (e.g., a colorimetric indicator or electronic sensor to signal when the zeolite has reached an anticipated limit) would increase safety and confidence. Fortunately, anesthetic gases are detectable by infrared monitors, so it is possible to monitor the filter's outlet for a measurable trace of anesthetic. If levels begin to increase, the filter could potentially be changed or regeneration could take place. Although monitoring the filter outlet could be a greater burden than current standards (i.e., changing filters on a schedule or after a certain level of weight gain), it could absolutely eliminate unnoticed breakthrough. Finally, the material safety of the zeolite itself should be evaluated; any dust or particles that shed from the filter should not enter the patient's airway. Filters would need efficient encapsulation and perhaps a membrane to trap any fines. These engineering solutions are all in principle achievable, but they emphasize a key point about the zeolite concept in that introducing zeolites is not just a plug-and-play swap, rather it requires an integrated systems approach.

Limitations and Biases

It is crucial to critically examine the limitations imposed by our review and existing research. First, as noted, there are limited clinical studies, which skews the review to idealized or experimental results. Data was extrapolated on performance (for example, multi-cycle durability, humidity) from industrial adsorbent studies that may not be generalizable to an anesthetic context. For instance, proliferating an ability to retain 90% capacity after 9 cycles (from an H₂S study) may be too optimistic compared to a complex mixture of anesthetic; anesthetic molecules and contaminants in the operating room may foul zeolites in ways different from pure contaminant H₂S in a lab. Second, bias in reporting publication data may exist. Studies confirming new capture methods may be reported more than studies not confirming their effectiveness. The search was attempted to be all-inclusive (for example, recognizing the disadvantages of charcoal and the challenge of using zeolites), but a bias in reporting in the literature may or may not lean towards reporting improvements. Patent literature or all conference proceedings were not explicitly searched for, where some practical developments (like novel filter designs) might be documented.

Environmental Impact and Life-Cycle Considerations

The primary reason for exploring zeolite filters is for environmental reasons; thus, it is important to assess the net environmental effects of deploying this technology. This section

includes GHG emissions avoided through anesthetic capture, the GHG emissions or costs related to the regeneration of zeolite filters, and the end-of-life disposal and recycling of anesthetic agents. We discuss these factors and the need for formal life-cycle assessment (LCA) studies.

Greenhouse Gas Emissions Avoided

Inhaled anesthetics are a significant contribution to GHG emissions in healthcare. For example, desflurane has a particularly high GWP; every mL of desflurane, roughly 2 grams, is estimated to be ~7.4 kg of CO₂ over a 100-year period. In a typical one-hour case, an anesthesiologist may utilize 20–50 mL of desflurane, and if all is released to the environment, could exceed 0.5 metric ton CO₂ for that incident alone. Capturing these vapors has an immediate and large impact on emissions. A recent analysis in the Netherlands estimated the overall contribution of inhaled anesthetics to be approximately 3% of GHG emissions from the hospital system. Preventing anesthetic from escaping using zeolite (or any capture technology) can result in meaningful reductions of a hospital's emissions footprint. Assuming zeolite systems capture 90% of exhaled halogenated agents, deriving from a previous study, one could expect approximately a 90% decrease in GHG emissions. For example, eliminating the release of one bottle of desflurane (approximately 240 mL) could prevent 0.9–1.0 metric ton CO₂ emissions (the same as the annual emissions from a vehicle driving ~2,500 miles). Scaled up, even if 50% of surgeries with desflurane or sevoflurane anesthesia used a capture system, the climate impact would be substantial¹⁷.

Energy and Carbon Cost of Regeneration

The advantages noted above presume that the capture can be conducted without large emissions elsewhere. When zeolite filters are regenerated, an energy input in the form of heat will be required. A rough estimate: heating a few kilograms of zeolite to ~300°C might consume on the order of 1–2 kWh of energy per cycle (this depends on insulation and efficiency of the regeneration unit). If using electricity from a typical grid (~0.5 kg CO₂ per kWh), this equates to about 0.5 to 1 kg of CO₂ per zeolite filter. This is still a small fraction (<1%) of CO₂ emissions of anesthetic captured. Furthermore, hospitals increasingly have access to low-carbon electricity or can schedule regeneration during off-peak renewable-rich hours, further minimizing the regeneration footprint. Nonetheless, any lifecycle analysis would require the regeneration phase to be addressed. Data, however, suggests that one regeneration a day, for each OR, is reasonable and energy use is low. Another part of these considerations is the manufacturing footprint. Zeolites are produced via chemical processes

with energy input, while activated carbon is often produced using very resource-intensive processes (high temperature activation of coconut shells or coal). A cradle-to-grave life cycle assessment would compare the production of one zeolite filter against multiple single-use carbon canisters. It is expected the zeolite filter to come out favorably due to avoided waste and extended use, but published analyses are not yet available. It is encouraged for future research to perform a detailed LCA, which must include: raw material extraction, zeolite filter production, freight (if filters need to be sent off-site for regeneration or recycling), energy associated with regeneration of the filter, as well as end-of-life waste disposal or recycling of the filter itself. This type of analysis would provide quantitative estimates of overall net environmental benefits.

Waste Anesthetic Recycling

One distinct benefit of capturing anesthetic gases is the opportunity to recover and reuse the anesthetic itself. Modern inhaled anesthetics are costly to produce (and their production carries its own environmental cost). If the waste gas is simply destroyed (as in the case of activated carbon + incineration), that embodied value is lost. Slutzman et al. evaluated Blue-Zone's Deltasorb canisters. They reported an initial version of a waste gas recovery and recycling system captured a small amount of used anesthetic and returned it back to the supply chain, demonstrating that collected anesthetic had a purity of >99%¹⁸. If even a small percent of anesthetic gas could be recovered and reused by all hospitals, the need for newly produced anesthetics could be drastically reduced, thus saving upstream energy usage and emissions. Anesthetic companies or third parties may establish reclamation programs in the future (as some are already doing with nitrous oxide canisters). This circular system enhances the environmental benefit of capture since not only are emissions avoided, but the anesthetic does not have to be recomposed from scratch. Economically, hospitals could save money if recycled anesthetic (following the approval of some pharmaceutical agency) is counted. From a regulatory perspective, all recycled drugs would need to follow the same safety and efficacy rules, but chemically these agents (sevoflurane, desflurane) could be purified by distillation.

Policy and Carbon Credits

On the policy front, capturing anesthetic gases meets broader healthcare sustainability objectives (e.g., ones specified by the NHS and other national health systems aimed at carbon negativity). Hospitals running such equipment may be eligible to earn carbon credits or meet regulatory emission metrics via zeolite adoption. For instance, some anesthetic gases have been incorporated into hospital GHG inventories in some re-

gions; installing a capture system could directly decrease tons of reported emissions, which may soon be a compliance issue. If the carbon price beam actually becomes applicable to hospital operations, a zeolite system could produce net financial returns either from avoided fees or through selling credits. Succinctly, the incentives offered can accelerate adoption. For instance, governments could subsidize the purchase of capture equipment, or mandate high-GWP anesthetics to phase out unless capture is installed.

Future Innovations and Research Priorities

To advance zeolite-based gas capture, several innovative pathways merit exploration. First, hybrid adsorbents – combining zeolites with metal-organic frameworks (MOFs) – could leverage MOFs' ultra-high surface area and zeolites' stability for multi-gas capture. Another promising direction is dynamic pore engineering, where adjusting pore geometry via cation exchange could optimize selectivity for specific anesthetics through enhanced electrostatic attractions. Concurrently, developing on-site regeneration technologies, such as compact, energy-efficient desorption units (e.g., vacuum systems), could enable efficient intraoperative filter reuse. Furthermore, establishing circular systems through partnerships between hospitals and pharmaceutical companies could scale the recycling of purified anesthetics captured by zeolites, building on existing pilot studies. In addition, an alternative approach to granular adsorbents is the use of zeolite membranes. Crystalline zeolite membranes (e.g., silicalite or DDR-type zeolite) can act as molecular sieves that selectively allow certain gases to permeate. Recently, researchers demonstrated a DDR zeolite membrane system capable of separating xenon (an anesthetic gas) from other components of exhaled gas. In that study, a DD3R zeolite hollow fiber membrane showed CO₂/Xe selectivity high enough to permit >99% xenon recovery in a closed anesthesia circuit¹⁹. Finally, policy incentives, including carbon credit programs, could reward hospitals adopting zeolite filters, aligning healthcare sustainability with global climate goals.

Conclusion

Zeolite-based filters show promise as a future solution to anesthetic gas pollution, contingent on overcoming technical and economic barriers. Their regeneration capability and selectivity position them as superior to activated carbon, but widespread adoption requires clinical validation and cost-benefit analyses. With targeted research into hybrid materials and policy support, healthcare systems could integrate zeolites into sustainable anesthesia practices within the next decade. The unique adsorption properties of the zeolite-based filters,

along with the ability to regenerate and reuse them, make them advantageous over traditional filtration methods. The environmental benefits of capturing and potentially recycling anesthetic gases are obvious, and these filters represent an important step in the critical area of reducing healthcare's carbon footprints and contribution to climate change. However, their widespread adoption will need to consider the challenges of implementation, including cost, integration into existing systems, and long-term performance under clinical conditions. Continuing research and development in this area will be important for the refinement of filter technology to enable healthcare organizations to achieve significant emissions reductions without compromising the quality of patient care. The health industry can make a significant contribution to the fight against climate change and the conservation of the environment for future generations by embracing the future use of zeolites for the capture of volatile anesthetic gas emissions.

Acknowledgments

I would like to thank Mr. Gary Benz, one of the chemistry teachers at my school, for giving me feedback on the drafts of this paper.

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