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Sustainable healthcare practices: Pathways to a carbon-neutral future for the medical industry

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ABSTRACT

The healthcare sector is essential for public health but contributes substantially to environmental pollution and carbon emissions, largely through energy-intensive operations, extensive waste generation, and resource-heavy pharmaceutical production. As climate change intensifies, there is a growing imperative for healthcare to adopt carbon-neutral practices that align with global sustainability goals. This narrative review explores the pathways through which healthcare can transition toward carbon neutrality, focusing on energy-efficient hospital designs, eco-friendly medical supplies, sustainable waste management, and low-carbon pharmaceutical manufacturing. Energy-efficient hospital design utilizes renewable energy, sustainable architecture, and AI-driven energy optimization to lower operational emissions. Environmentally sustainable medical supplies reduce single-use plastics by incorporating biodegradable and reusable materials, as well as sustainable procurement practices. Waste management strategies, including waste segregation, recycling, and energy recovery systems, help reduce healthcare's environmental footprint, while green chemistry and renewable energy integration in pharmaceutical manufacturing further mitigate emissions. Although financial, regulatory, and operational challenges remain, advances in green technology and increasing awareness provide new opportunities for healthcare organizations to adopt sustainable practices. By prioritizing both environmental responsibility and patient care, the healthcare sector can contribute significantly to global climate objectives. This review highlights the importance of collaboration, policy support, and investment in sustainable healthcare to ensure a resilient, low-carbon future.

1. Introduction

The healthcare sector is inherently committed to preserving human health, yet the operational and infrastructural demands of healthcare systems worldwide significantly impact the environment. Healthcare operations—including hospitals, pharmaceutical manufacturing, specialist clinics, family practices, long-term care facilities, and the production and use of medical equipment and supplies—are energy-intensive and generate substantial waste, collectively contributing to a significant carbon footprint, defined as the total emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), measured in carbon dioxide equivalents (CO_2e). These facilities use substantial amounts of energy to operate intricate machinery, HVAC and water-heating systems, maintain strict air quality and temperature controls, and ensure patient safety and comfort [1]. Furthermore, single-use medical supplies, waste management requirements, and transportation needs for pharmaceuticals and medical products collectively amplify this environmental toll. The production, delivery, and disposal of goods and services acquired by healthcare facilities, including pharmaceuticals, hospital equipment, instruments, and medical devices, constitute about 70 % of healthcare emissions [2,3]. As healthcare's impact on the environment becomes clearer, the sector

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faces a pressing need to reconcile its role as a protector of human health with its responsibilities toward planetary health.

The environmental burden imposed by healthcare systems is an unintended but severe consequence that is increasingly difficult to ignore. Studies have shown that healthcare systems contribute a significant share of global carbon emissions, with some estimates indicating that the sector is associated directly and indirectly with approximately 4–5 % of global emissions, including those generated across its supply chains and energy use [4–6]. While healthcare systems are essential for population well-being, the adverse environmental effects of their activities present a paradox: in their pursuit to treat and prevent illness, they inadvertently contribute to pollution and climate change—factors that exacerbate public health challenges [7]. For instance, emissions from healthcare facilities and their energy sources contribute to poor air quality, which is directly linked to respiratory illnesses and other chronic conditions, especially among vulnerable populations [8]. This irony underscores the importance of identifying sustainable (i.e. continuous) solutions that allow healthcare systems to reduce their environmental impact without compromising patient care.

Recognizing these challenges, the World Health Organization (WHO) and other global health bodies have called for a transformation in healthcare practices, emphasizing sustainability as a cornerstone of future health systems. The WHO has stated that environmental health is fundamental to achieving global health goals and has advocated for "greener" healthcare approaches to mitigate climate-related health risks. These include promoting energy-efficient infrastructure, sustainable procurement policies, waste reduction strategies, and the adoption of low-carbon technologies [9,10]. In response to this call, numerous healthcare organizations and governments are beginning to set ambitious carbon-neutral goals and implement practices that reduce their environmental impact. For example, fourteen nations have committed to establishing carbon-neutral health systems, which entails minimizing emissions from facilities, infrastructure, public transportation, hospital waste, and procuring ecologically sustainable medical equipment and supplies [11]. By committing to these changes, the healthcare sector not only works to mitigate climate change but also aligns its mission more closely with a holistic view of health that encompasses environmental wellness as integral to human well-being [12].

This shift toward sustainability in healthcare is not without its challenges. Implementing carbon-neutral practices requires a rethinking of long-established processes and infrastructures, often accompanied by considerable upfront costs [13]. However, while initial investments in sustainability can be significant, research indicates that the vast majority of interventions to decarbonize healthcare generate substantial cost savings in the medium and long term [14,15]. For instance, energy-efficient hospital retrofits, waste reduction initiatives, and renewable energy transitions not only lower carbon emissions but also reduce operational expenses over time, making sustainability financially viable for healthcare institutions [16]. For example, transitioning to renewable energy sources or retrofitting hospital buildings with energy-efficient technologies involves significant initial cost and logistical complexity but ultimately leads to reduced energy expenditure and enhanced financial sustainability [15]. Additionally, the healthcare sector is subject to strict regulatory standards that prioritize patient safety, which can make it difficult to incorporate sustainable alternatives without rigorous testing and compliance measures [17]. Notwithstanding these challenges, the growing acknowledgment of healthcare's environmental impacts has stimulated innovative strategies and partnerships aimed at achieving a balance between the amount of carbon emitted and the amount of carbon removed i.e. carbon neutrality, as green process innovation and environmental orientation are essential for enhancing environmental performance across multiple sectors, including manufacturing [18]. Companies specializing in green technology (emission reduction innovations), energy management, and sustainable materials are increasingly collaborating with healthcare providers to explore new pathways for reducing emissions and resource consumption while also improving financial efficiency through long-term cost reductions [19].

This narrative review aims to analyze the current state of sustainability in healthcare and identify key pathways through which the sector can transition to a carbon-neutral model. Drawing from recent literature, it will explore four critical areas where healthcare can make a significant environmental impact: energy-efficient hospital design, sustainable medical supply chains, waste management practices, and low-carbon pharmaceutical manufacturing. While previous reviews have examined sustainability in healthcare, this review differentiates itself by integrating a cross-sectoral approach that synthesizes evidence-based strategies from multiple disciplines, providing a more holistic framework for achieving carbon neutrality. It further highlights the economic feasibility of these interventions, addressing both the financial barriers and long-term cost savings associated with sustainable healthcare transformations, an aspect often overlooked in existing literature.

Through examining these pathways, this review seeks to provide a comprehensive overview of practical strategies for reducing healthcare's carbon footprint. The goal is not only to highlight opportunities for sustainable practices but also to address the broader implications of carbon-neutral healthcare for global health and environmental justice. By bridging the gap between environmental responsibility and healthcare resilience, this review presents a forward-looking perspective that aligns decarbonization efforts with the evolving demands of healthcare systems in the face of climate change.

2. Energy-Efficient hospital design

Hospitals play a vital role in public health; however, they rank among the most energy-intensive facilities due to their specific operational requirements, intricate building functions, and high concentration of electrical equipment [20]. Hospitals operate 24/7, requiring continuous energy to support complex medical equipment, HVAC systems, lighting, and other essential functions that ensure patient safety and comfort. As a result, hospitals consume significantly more energy per square meter than most other types of buildings, contributing to high carbon emissions [21]. The drive toward energy-efficient hospital design is, therefore, a priority in the healthcare industry's sustainability journey. By integrating renewable energy such as a grid-connected hybrid renewable energy system (HRES), sustainable architecture, and advanced energy optimization technologies, hospitals can reduce their reliance on fossil fuels, cut operational costs, and move closer to carbon-neutral goals [22].

2.1. Renewable energy integration

The transition to renewable energy sources is a cornerstone of sustainable hospital design. Many hospitals worldwide are adopting on-site renewable energy solutions, including solar panels, wind turbines, and geothermal systems, to offset their dependence on conventional power grids [23]. Solar panels, for instance, can be installed on hospital rooftops and open areas, converting sunlight into electricity that can power various hospital functions. Recent studies indicate that solar panel installations can potentially meet a substantial portion of a hospital's energy requirements, contingent upon factors such as location, climate, and available space [24]. This shift not only reduces greenhouse gas emissions but also shields healthcare facilities from fluctuations in energy costs, fostering long-term operational savings [25].

In addition to solar, hospitals are exploring wind energy where feasible, particularly in regions with high average wind speeds. On-site wind turbines can generate considerable power, especially when paired with battery storage systems that allow for energy use during low-wind periods [26]. Ground source heat pumps provide another renewable alternative, utilizing the Earth's stable underground temperatures to heat and cool hospital buildings efficiently [27]. Presently, there are 66 projects in Serbia that utilise geothermal energy directly. Approximately

1005 geothermal heat pump units exist. Their power ranges from 10 kW to 40 kW, operating for 2860 full load hours annually [28]. Renewable energy not only helps hospitals reduce carbon emissions but also enhances their resilience to power outages and other disruptions, a critical factor for facilities that cannot afford downtime.

2.2. Sustainable architecture

Sustainable architecture is essential in designing energy-efficient hospitals, utilizing diverse design principles, materials, and construction methods to minimize environmental impact. This approach emphasizes material recycling and reuse, waste reduction, and energy optimization, thereby fostering a healthier environment. Sustainable architecture in healthcare facilities encompasses building programming, operational efficiency, and effective management practices, which collectively improve air quality and foster ecological balance [29]. One widely adopted framework for sustainable hospital construction is the Leadership in Energy and Environmental Design (LEED) certification, which sets stringent standards for environmentally responsible building design [30]. LEED-certified hospitals incorporate features such as energy-efficient windows, optimal insulation, and advanced ventilation systems, all of which help maintain stable indoor temperatures with minimal energy input [31].

For example, the Cleveland Clinic in Ohio achieved LEED certification for several of its buildings by using materials that improve insulation and reduce heat loss, significantly lowering heating and cooling demands [32]. Energy-efficient windows and natural lighting design are also central to sustainable hospital architecture. By maximizing natural daylight, hospitals can reduce the need for artificial lighting, which can account for a large share of energy use. Additionally, exposure to natural light has been shown to benefit patient recovery times and staff well-being, creating a dual impact of environmental and human health benefits [33].

Hospitals are also incorporating green roofing systems, which involve planting vegetation on rooftops to reduce rainwater runoff, mitigate urban heat island effects, and provide aesthetic and psychological benefits for patients and staff. While green roofs offer natural cooling effects by shading roof surfaces and lowering ambient temperatures, they do not significantly improve insulation compared to conventional thermal insulation materials. Nonetheless, when used alongside high-performance building envelopes and other sustainable materials, green roofs can contribute to an overall reduction in cooling loads and enhance the hospital environment. Sustainable architecture in hospital design, therefore, supports not only environmental goals but also improved patient outcomes and a more comfortable experience for staff and visitors [34,35].

2.3. Energy optimization through smart technologies

While renewable energy and sustainable architecture lay the groundwork for energy-efficient hospitals, energy optimization technologies take these efforts to the next level by managing energy use in real time. Smart energy management systems use artificial intelligence (AI) and machine learning (ML) algorithms to monitor, analyze, and adjust energy consumption based on various factors such as occupancy levels, weather patterns, and time of day [36]. These systems can automatically adjust lighting, temperature, and ventilation, optimizing energy use to minimize waste without sacrificing patient comfort or safety [37]. Hospitals equipped with smart energy systems can reduce energy consumption by 30–50 %, a substantial savings given the sector's high energy demand [38].

For instance, a hospital in The Netherlands, Amsterdam UMC, integrated a smart energy management system that leverages AI to monitor and control its heating, ventilation, and air conditioning (HVAC) systems [39]. By dynamically adjusting settings based on real-time data, the system reduces energy use during off-peak hours, cutting costs and emissions. Moreover, predictive maintenance algorithms can identify inefficiencies or potential failures in equipment, enabling preventive measures that further optimize energy use and prevent costly breakdowns [40]. Fig. 1 outlines the essential elements involved in designing energy-efficient hospitals. The figure highlights the integration of renewable energy sources, sustainable architecture practices, and energy optimization through smart technologies to achieve reduced carbon emissions and operational costs.

Beyond smart energy management, optimizing HVAC settings in surgical suites offers an actionable approach to energy reduction that does not require full-scale smart hospital infrastructure. Operating rooms (ORs) are among the most energy-intensive areas of hospitals due to stringent air exchange rates, temperature regulation, and continuous ventilation requirements to maintain sterility [41]. Studies have shown that adjusting HVAC systems based on OR occupancy and procedural needs can lead to significant energy savings without compromising air quality or patient safety [42]. A hospital implementing occupancy-based HVAC adjustments in its surgical suites achieved up to a 40 % reduction in energy use, demonstrating the efficiency of such an approach [38]. Modulating air changes per hour (ACH) during unoccupied periods, or tailoring airflow to match real-time surgical demands, has been identified as a cost-effective intervention for reducing carbon emissions in surgical services [43].

The integration of these intelligent systems aligns with the concept of a "smart hospital," a facility that leverages data and technology to improve efficiency and sustainability. Smart hospitals are gaining traction as they not only lower energy usage but also improve overall patient care by ensuring an optimal environment [41]. These systems can enhance air quality management, for example, by controlling filtration rates according to occupancy and air quality needs, a feature critical during times of infectious disease outbreaks. By tailoring energy usage precisely to hospital needs, including surgical spaces, smart technologies reduce both environmental impact and operational expenses, contributing to the goal of net-zero emissions.

Table 1 presents essential energy-efficient design features that healthcare facilities may implement to reduce carbon emissions. The integration of renewable energy systems, high-efficiency equipment, and smart building technologies enables hospitals to significantly lower operational energy use and associated greenhouse gas emissions. The "energy savings" figures shown are based on comparisons with baseline consumption levels prior to the implementation of each intervention. In most cases, this baseline refers to the average energy consumption of conventional healthcare facilities—typically hospitals or clinicsoperating without the specified energy-efficient features at the time of design, construction, or retrofit. Although exact baselines may vary by study, region, and building type, the values represent commonly reported savings relative to standard practice or pre-retrofit energy profiles. Every design element in the table contributes toward a more sustainable healthcare environment and supports the broader goal of carbon neutrality within the sector.

2.4. Adapting healthcare to climate-driven health challenges

As the healthcare sector strives to reduce its carbon footprint, it must also adapt to the evolving health challenges posed by climate change. Climate change, driven by greenhouse gas emissions from fossil fuel consumption, has been identified as the foremost public health challenge of the 21st century. Approximately 150,000 fatalities occur each year globally as a result of health risks associated with climate change. It is anticipated that climate change will result in an additional loss of 250,000 lives per year between 2030 and 2050 [52]. Rising global temperatures, increased frequency of extreme weather events, and shifting disease patterns are placing new demands on healthcare systems, necessitating strategic adaptations to ensure resilience and continuity of care [53]. Climate change exacerbates health conditions such as heat-related illnesses, respiratory diseases due to worsening air

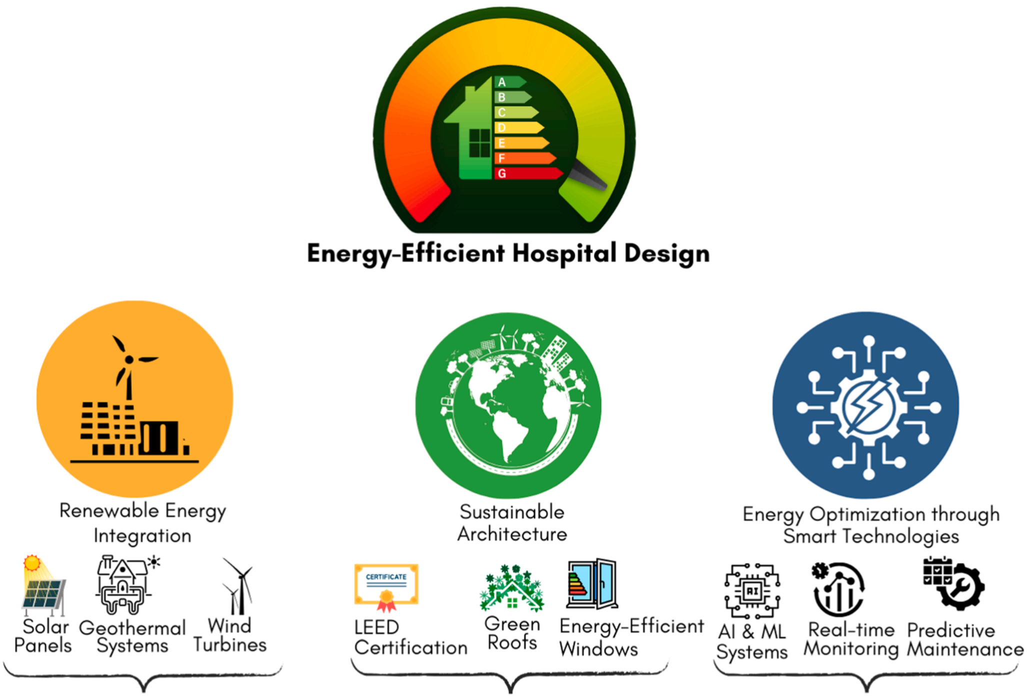

Fig. 1. Diagram illustrating the key components of energy-efficient hospital design.

Table 1
Energy-efficient design features for healthcare facilities, including estimated energy savings relative to baseline consumption observed in conventional buildings prior to the implementation of each intervention.

Energy-Efficient Design Feature	Description	Key Benefits	Energy Savings relative to the building initial consumption	Reference
Green Building Certification (LEED)	Design and construction meeting energy and environmental standards	Improves energy efficiency, enhances indoor environment	30–50 % reduction in total building energy use compared to non-certified buildings	[44]
Renewable Energy Integration	Use of solar panels, wind turbines, or geothermal energy sources	Reduces reliance on fossil fuels, cuts energy costs	20–40 % of total energy supplied from renewable sources, displacing conventional grid use	[45]
High-Efficiency HVAC Systems	Advanced heating, ventilation, and air conditioning systems	Lowers energy consumption, improves air quality	30–40 % reduction in HVAC energy use compared to standard systems	[46]
LED Lighting and Smart Controls	Energy-efficient lighting with motion sensors and daylight controls	Cuts electricity use, reduces maintenance needs	40–60 % reduction in lighting energy use relative to traditional lighting systems	[47]
Natural Ventilation and Lighting	Building design optimized for daylight and airflow	Reduces lighting and cooling demands, enhances comfort	15–20 % reduction in lighting and cooling loads compared to fully mechanical systems	[48]
Efficient Water Heating Systems	Solar water heaters, heat pump water heaters	Decreases electricity use, reduces greenhouse gases	25–35 % reduction in water heating energy compared to electric resistance systems	[49]
Insulation and Window Glazing	High-performance insulation and double-glazed windows	Maintains indoor temperatures, lowers heating/cooling	20–30 % reduction in heating and cooling energy use compared to standard envelopes	[50]
Building Automation Systems (BAS)	Automated energy management for lighting, HVAC, and security systems	Optimizes energy use, minimizes waste	10–20 % reduction in total building energy consumption compared to manual control systems	[51]

quality, and the spread of vector-borne diseases into previously unaffected regions [54]. The existing literature on healthcare sustainability has primarily focused on efforts to mitigate greenhouse gas emissions associated with healthcare activities, while comparatively less attention has been given to understanding how climate change including its impacts such as extreme weather events and rising heat-related health risks affects healthcare systems themselves [55]. These evolving health threats require structural and operational adjustments in healthcare infrastructure, workforce training, and public health planning [56]. However, even within mitigation-focused research, our collective understanding of healthcare's total carbon footprint and its key emission "hotspots" remains limited, especially when compared to sectors like building construction or automotive manufacturing, which have more established sustainability frameworks.

Healthcare facilities must strengthen their resilience to extreme weather events by integrating smart design and construction techniques, including flood-resistant structures, heat-resistant materials, and modern air filtration systems. Enhancing infrastructure through decentralised renewable energy and flexible architectural solutions can ensure hospitals maintain functionality during climate catastrophes, hence minimising disruptions and decreasing evacuation requirements [57]. For instance, in July 2019, Mount Auburn Hospital in Massachusetts experienced a power failure, necessitating the evacuation of patients from overheated rooms during a heatwave, highlighting the need for resilient infrastructure [58]. Hospitals in vulnerable regions must also integrate climate-responsive designs that ensure continuity of care during extreme weather conditions.

Climate change is also influencing the spread of infectious diseases, necessitating enhanced disease surveillance and response systems [59]. Bangladesh faced a severe dengue outbreak in 2023, with over 400 deaths and >78,595 hospital admissions, attributed to rising temperatures and prolonged monsoon seasons that created ideal conditions for mosquito breeding [60]. Similarly, Malawi experienced increased cases of cholera and malaria following extreme weather events like Cyclone

Freddy, underscoring the need for robust public health interventions [61]. The rise in climate-sensitive diseases demands stronger epidemiological monitoring, early warning systems, and climate-informed healthcare planning to ensure adequate preparedness and response.

Preparing healthcare professionals to address climate-induced health issues is crucial in building resilience within healthcare systems. In Uganda, the National Health Adaptation Plan includes climate training for healthcare workers, ensuring that medical personnel can manage climate-related health hazards effectively [62]. Integrating climate adaptation into medical education and disaster response training will help healthcare professionals anticipate and mitigate the health impacts of environmental changes [63]. Increased collaboration between medical institutions, governments, and global health organizations can enhance the capacity of healthcare systems to respond to the growing burden of climate-driven illnesses.

Engaging communities in climate adaptation strategies is equally vital for public health. Initiatives like "My Green Doctor" provide healthcare professionals with tools to integrate environmental sustainability into their practices while educating communities on climate-related health risks [64]. Raising public awareness about the health consequences of climate change and promoting climate-conscious behaviors, such as heatwave preparedness and water conservation, can improve resilience at both individual and community levels. Strengthening primary healthcare systems and improving access to preventative care in high-risk areas can further reduce the health burden of climate-related illnesses.

Developing and implementing policies that integrate climate and health data are essential for ensuring healthcare systems remain responsive to changing health needs. A report from the Rockefeller Foundation emphasizes the urgent need for increased funding for climate-health adaptation, noting that current global commitments fall short of the estimated $11 billion required annually. Between 2009 and 2019, 0.39 % of global climate adaptation money was allocated to health-related initiatives, with the most vulnerable nations receiving the least investment per project [65]. The Lancet commission as at 2015, recommended that governments and international organizations must scale up investments in healthcare resilience, providing funding for infrastructure upgrades, climate-resilient supply chains, and research into the health impacts of climate change, to ensure a better understanding of the adaptation needs and the potential health co-benefits of climate mitigation at the local and national level [14]. Strengthening global health systems through climate-conscious policies and sustainable funding mechanisms will be critical in safeguarding public health in an increasingly unstable climate.

While efforts to decarbonize healthcare are essential, adapting to climate-related health challenges must occur in parallel to ensure that healthcare systems remain effective and responsive in a changing world [66]. A dual approach that integrates both mitigation and adaptation strategies will be crucial in advancing sustainability goals while protecting communities from the growing health risks associated with climate change [67].

3. Eco-Friendly medical supplies

The healthcare sector's dependency on single-use medical supplies has historically been driven by a priority for sterility and convenience. Environmentally sustainable medical supplies are healthcare products designed to reduce negative environmental impacts across their entire life cycle—from production and distribution to use and end-of-life disposal. Single-use items such as gloves, syringes, and gowns are essential for infection prevention, yet their extensive use contributes significantly to healthcare-related waste and carbon emissions [68]. The manufacturing, transportation, and disposal of these products consume considerable energy and resources, reinforcing a cycle of resource depletion and environmental degradation. Transitioning to more sustainable alternatives—such as biodegradable or reusable supplies—along with implementing sustainable procurement policies and adopting low-emission manufacturing practices, represents a vital step in reducing the healthcare sector's overall ecological footprint [69].

3.1. Biodegradable and reusable supplies

One of the most promising areas for reducing healthcare waste is the development and adoption of biodegradable and reusable medical supplies. Conventional plastics, derived from fossil fuels, are widely used for single-use medical items due to their durability, low cost, and ability to maintain sterility. However, they are non-biodegradable and contribute to pollution when disposed of in landfills or incinerated [70,71]. In response, biodegradable alternatives made from plant-based plastics, such as polylactic acid (PLA) derived from corn starch, have gained traction as potential substitutes. These materials degrade more easily than traditional plastics, reducing long-term waste accumulation and environmental pollution [72,73]. However, the environmental benefits of plant-based plastics depend on multiple factors, including production emissions, energy-intensive processing, and end-of-life treatment. While PLA and similar materials offer a reduction in fossil fuel dependency, their true sustainability must be evaluated using comprehensive Life Cycle Assessment (LCAs) to determine their comparative advantage over traditional plastics [74]. Life Cycle Assessment (LCA) is a standardized and methodical approach used to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle—from raw material extraction and manufacturing to use and end-of-life disposal. Governed by international standards such as ISO 14,040:2006 and ISO 14,044:2006, LCA helps identify sustainability challenges, quantify environmental burdens, and support improvements in resource efficiency.

Biodegradable syringes and disposable gloves, constructed from materials such as natural rubber or PLA, present viable alternatives to conventional petroleum-based products. Although their adoption is still in preliminary phases, research suggests that these biodegradable options can uphold essential sterility standards while reducing environmental impacts associated with disposal. However, their effectiveness is contingent on proper disposal infrastructure, as many biodegradable plastics require industrial composting conditions rather than breaking down naturally in landfill environments [73]. Furthermore, sterilization techniques like electron beam processing can improve the transparency, yellow index, dimensional stability, and mechanical properties of PLA and its blends, rendering them appropriate for single-use medical devices [74].

The introduction of reusable supplies, particularly for non-sterile applications such as trays, basins, and certain surgical instruments, offers another avenue for waste reduction. A study evaluated the comparative climatic impacts of reusable and disposable objects, revealing that, in relation to the most significant case study, reusable items were predominantly more environmentally sustainable than their disposable counterparts [75]. Reusable items designed for durability can withstand multiple cycles of sterilization, making them both cost-effective and environmentally sustainable over the long term [76]. However, the sustainability of reusable medical supplies depends on several factors, including the energy and water consumption required for sterilization, the durability of the materials, and the number of reuses before degradation. While some reusable devices have been shown to generate fewer emissions over their lifecycle compared to disposable alternatives, others may require substantial energy inputs for repeated sterilization, potentially offsetting their environmental benefits [77].

Challenges persist in adopting reusable items on a large scale due to the labor and infrastructure required for thorough cleaning and sterilization. Nevertheless, advancements in sterilization technologies, including heat, radiation, filtration, chemicals, plasma, pulsed-light systems, microwaves, and supercritical carbon dioxide, are improving the efficiency of reprocessing medical devices, making reusable options more viable across diverse healthcare applications [77]. Ultimately, the choice between biodegradable, reusable, and single-use medical supplies must be informed by rigorous life cycle assessments, considering factors such as manufacturing emissions, resource use, durability, and disposal impact. While these innovations hold potential for waste reduction and cost savings, decision-making in sustainable healthcare procurement must be evidence-based rather than prescriptive, ensuring that environmental benefits are realized in practice rather than assumed.

3.2. Sustainable procurement policies

A critical driver of eco-friendly practices in healthcare is sustainable procurement, where hospitals and healthcare organizations commit to sourcing supplies from manufacturers that are conscious of the environment [78]. Sustainable procurement policies prioritize eco-friendly suppliers who offer products made from recycled or sustainably sourced materials and aim to minimize the carbon footprint of the entire supply chain. These policies also encourage the use of suppliers that implement environmentally responsible manufacturing practices, further reducing the indirect environmental impact of healthcare supplies [79].

For example, choosing medical instruments made from recycled metals or other materials can decrease the carbon emissions associated with producing new materials. Similarly, opting for packaging made from recycled paper and avoiding excessive plastic use can significantly reduce waste [80]. Several healthcare systems, including the UK's National Health Service (NHS), have adopted sustainable procurement frameworks that mandate suppliers to adhere to specific environmental standards. By leveraging their purchasing power, large healthcare systems can influence suppliers to adopt sustainable practices, thus amplifying the impact of individual facilities' sustainability efforts [81, 82].

Sustainable procurement policies are especially effective when combined with environmentally responsible certifications, such as the Forest Stewardship Council (FSC) certification for paper products or the Cradle to Cradle certification for products designed with circular economy (economy designed to reduce waste) principles [83]. These certifications provide hospitals with assurance that the materials used meet certain environmental and ethical standards. Such certifications also enable healthcare providers to easily identify eco-friendly products, making sustainable procurement a more seamless process. By choosing sustainable suppliers, healthcare facilities not only reduce their environmental footprint but also help drive broader industry change toward responsible sourcing and manufacturing [84].

3.3. Green manufacturing

Green manufacturing in the medical supply industry involves manufacturing practices that reduce energy consumption, minimize waste, and source raw materials responsibly [85]. Medical supply manufacturers are increasingly embracing green manufacturing techniques that limit emissions and prioritize renewable energy. In practice, this shift often involves optimizing production processes to use less energy, incorporating recycling programs within factories, and investing in low-emission technologies [86]. A significant focus within green manufacturing is the use of non-toxic, biodegradable materials and reducing reliance on fossil-fuel-based materials. For example, some companies are using bio-based alternatives to traditional petrochemical-based plastics, which have a much smaller carbon footprint and break down more readily after disposal [87]. Additionally, companies are working toward closed-loop systems where waste from the manufacturing process is either reused or recycled, minimizing overall waste. For instance, some factories recycle used water and chemicals within their facilities rather than discharging them as waste, reducing both pollution and resource use [15].

Pharmaceutical packaging is also seeing advancements in green manufacturing, with companies developing eco-friendly packaging that reduces material usage and prioritizes recyclability. This change is particularly important as packaging contributes a significant portion of the waste associated with medical supplies [88]. For example, blister packs traditionally made from plastic and aluminum can be redesigned using recyclable materials that maintain product integrity without contributing to long-term waste. A recently developed biomimetic coating used in such applications demonstrated a 97 % recycling rate and exhibited high durability under a wide range of environmental conditions.

[89]. The impact of green manufacturing extends beyond the immediate reduction in resource use and emissions. By adopting these practices, manufacturers in the medical sector align with broader environmental goals and often gain access to new markets and customers who prioritize sustainability. As hospitals and healthcare systems increasingly adopt sustainable procurement policies, green manufacturing becomes a competitive advantage, encouraging more companies to innovate in this direction [90].

3.4. Benefits and challenges of transitioning to eco-friendly medical supplies

The transition to eco-friendly medical supplies offers both environmental and economic benefits. Environmentally, the shift to biodegradable materials and reusable supplies helps reduce the vast amounts of waste generated by single-use products, thereby easing pressure on landfills and lowering the demand for waste-to-energy incineration, which—while useful for reducing waste volume can contribute to harmful emissions if not properly controlled [91]. Economically, while the initial costs of eco-friendly supplies may be higher, the potential for reuse and the reduced need for waste management services can lead to substantial long-term savings for healthcare facilities [92].

Despite these advantages, the adoption of eco-friendly medical supplies is not without its challenges. Biodegradable materials may not yet meet all the technical and regulatory standards required for certain medical applications, particularly where high durability and sterility are essential. Additionally, the production costs for biodegradable alternatives are often higher, as bio-based materials are still relatively new and less available than traditional plastics [93]. Healthcare organizations may also face logistical hurdles in implementing reusable supplies, as they require facilities and protocols for sterilization and quality control [94]. Moreover, the success of these transitions relies heavily on broader systemic changes, including investment in infrastructure and regulatory frameworks that encourage sustainable practices. Governments and healthcare authorities can play a critical role by incentivizing eco-friendly innovations in medical supplies, supporting research into new materials, and establishing guidelines that make sustainable options more accessible to healthcare providers. For instance, UK health sector businesses prioritize enhancing supplier environmental performance and adherence to voluntary social responsibility standards, whereas Italian organizations emphasize compliance with obligatory rules and regulations [95]. Fig. 2 provides a visual overview of the essential elements involved in the transition to eco-friendly medical supplies within the healthcare sector. Each component of the figure illustrates how these strategies collectively contribute to reducing waste, lowering carbon emissions, and promoting sustainability in healthcare operations. This transition not only addresses environmental challenges but also supports cost-effective solutions for healthcare facilities. It highlights four main categories: Biodegradable Materials, which include plant-based plastics and biodegradable gloves; Reusable Items, such as durable trays and surgical instruments that can withstand sterilization; Sustainable Procurement Practices, focusing on sourcing from environmentally responsible suppliers; and Green Manufacturing Techniques, which emphasize energy-efficient production methods and the use of non-toxic materials.

Fig. 2. Illustration of eco-friendly medical supplies, highlighting its key components.

4. Sustainable waste management

Effective waste management is a crucial component of sustainability in healthcare, as hospitals and healthcare facilities generate large volumes of waste daily [96]. This waste includes hazardous materials like chemicals, infectious agents, and radioactive substances, which require specialized handling to avoid environmental and public health risks. Improper disposal can result in pollution of soil, water, and air, contributing to environmental degradation and increasing the risk of human exposure to toxins and consequently lead to the spread of infectious diseases [97,98]. Sustainable waste management in healthcare, therefore, is not only an environmental responsibility but also a vital aspect of public health. Key strategies in sustainable waste management include waste segregation and recycling, energy recovery from waste, and reducing the use of hazardous materials [99].

4.1. Waste segregation and recycling

Waste segregation is the foundation of sustainable waste management, as it enables the safe handling, disposal, and potential recycling of various types of waste. Segregating waste at the source—separating hazardous from non-hazardous materials and recyclable from non-recyclable items—improves both safety and efficiency in waste management processes [100,101]. For example, in many hospitals, color-coded bins are used to separate infectious, chemical, and non-hazardous waste, reducing the risk of contamination and allowing for appropriate handling of each type of material [102]. Segregation also makes it easier to divert non-hazardous waste, such as paper, plastic, and metal, to recycling facilities rather than landfills. Recycling non-hazardous waste is environmentally beneficial, as it reduces the demand for new raw materials and minimizes the carbon emissions associated with production processes [103]. The World Health Organization (WHO) estimates that >85 % of healthcare waste is non-hazardous, indicating a potential for efficient recycling and waste reduction measures [104]. Some healthcare facilities have also adopted "zero waste" programs, which strive to recycle or repurpose as much waste as possible [105]. For instance, used surgical instruments and other metal waste can be sterilized, melted, and repurposed, contributing to a circular economy approach within the healthcare sector [91].

In addition, the adoption of closed-loop recycling, where specific items such as surgical drapes, gowns, and trays are sent back to the manufacturer to be sterilized, recycled, and reused, further reduces waste. This practice not only diverts waste from landfills but also conserves resources and lowers emissions associated with the production and disposal of new materials [106]. Effective waste segregation practices, combined with strong recycling programs, significantly reduce the environmental impact of healthcare waste and support broader sustainability goals [99].

4.2. Energy recovery from waste

Energy recovery from waste, such as through waste-to-energy (WtE) incineration, is an established method that can reduce landfill burden by converting medical waste into usable energy. However, while it offers waste volume reduction and energy generation benefits, it must be carefully managed due to concerns about air pollution and emissions, particularly when incinerating single-use medical supplies [107]. Waste-to-energy (WtE) technologies like incineration, gasification, and pyrolysis offer viable methods for handling certain types of medical waste, particularly infectious or hazardous materials that cannot be safely recycled. Through these processes, organic material is combusted or thermally decomposed, generating heat and electricity that can be utilized within the facility or redirected to the grid [108].

Incineration, one of the most widely used methods, has become increasingly advanced with modern emissions-control technology that significantly reduces the release of harmful pollutants. For example, some healthcare facilities have installed incinerators equipped with scrubbers and filters to capture and neutralize toxic emissions. While incineration remains controversial due to potential emissions, controlled use with advanced technologies can make it a relatively safe and efficient option for handling infectious waste [109].

Pyrolysis and gasification are alternative WtE technologies that offer more environmentally friendly options by operating in low- or no-oxygen environments, which can reduce harmful emissions [110]. Pyrolysis, for instance, decomposes organic material at high temperatures in an oxygen-free environment, producing synthetic gas and bio-oil, which can be used as alternative energy sources [111]. These processes create an additional energy source for hospitals, decreasing dependence on conventional energy sources and thereby reducing carbon emissions.

Several hospitals globally have successfully integrated WtE systems. For example, Cleveland Clinic uses a waste-to-energy system that converts its medical waste into renewable energy, reducing its waste-to-landfill rate by up to 50 % [112]. Such facilities demonstrate how energy recovery can be a practical component of sustainable waste management in healthcare. However, it is essential for hospitals to use these technologies responsibly, adhering to stringent emissions regulations and monitoring to ensure minimal environmental impact.

4.3. Reducing hazardous waste

Reducing hazardous waste is a crucial step in sustainable healthcare, as hazardous materials pose significant risks to both human health and the environment [113]. Healthcare facilities use various chemicals for cleaning, disinfection, and treatment purposes, many of which are toxic and require specialized disposal. The adoption of less toxic alternatives for these applications can substantially decrease the volume of hazardous waste generated and reduce associated disposal challenges [114].

Hospitals in Malaysia are progressively utilizing "green" cleaning and disinfecting products composed of biodegradable, non-toxic ingredients, which enhance human health and mitigate the environmental repercussions linked to traditional cleaning methods in healthcare settings [115]. For example, using hydrogen peroxide or UV-C disinfection systems as alternatives to harsh chemical disinfectants can achieve the same level of sanitation without producing hazardous byproducts [116]. Additionally, certain pharmaceutical waste, especially unused medications, poses a risk of leaching toxic substances into the environment if disposed of improperly. Implementing pharmaceutical waste take-back programs or adopting closed-loop medication disposal systems helps prevent contamination of water sources and reduces the environmental footprint of pharmaceutical waste [117].

Moreover, some hospitals have adopted practices to minimize the use of hazardous substances in medical procedures. For instance, Choosing mercury-free medical equipment, such as thermometers and sphygmomanometers, mitigates the risk of mercury contamination—an important environmental threat—and these devices are progressively being embraced in numerous nations [118]. The use of digital diagnostic tools that do not rely on toxic chemicals or materials is another growing trend in reducing hazardous waste. These initiatives not only decrease the amount of hazardous waste requiring disposal but also reduce the environmental and health risks associated with chemical exposure [119]. Reducing hazardous waste is aligned with international health and environmental goals, such as the Minamata Convention on Mercury, which calls for the phasing out of mercury-based equipment and encourages the use of safer alternatives [120]. Table 2 highlights sustainable waste management and operational practices that healthcare facilities can implement to reduce their carbon footprint through improved resource efficiency and reduced emissions.

5. Low-Carbon pharmaceutical manufacturing

The pharmaceutical industry is critical to public health, providing life-saving medicines and treatments. However, the environmental impact of pharmaceutical manufacturing has raised concerns due to its heavy reliance on resource-intensive processes and fossil fuels, which contribute significantly to healthcare's overall carbon footprint [127]. The industry's production processes involve high energy consumption, extensive water use, and the generation of waste and emissions that are often challenging to manage [128,129]. As a result, reducing the carbon footprint of pharmaceutical manufacturing is increasingly essential to creating a more sustainable healthcare sector. Achieving this involves strategies like process optimization, green chemistry, and the adoption of renewable energy and carbon offsetting programs [129].

5.1. Process optimization

Process optimization within pharmaceutical manufacturing focuses on enhancing efficiency to reduce both energy and resource consumption, resulting in lower carbon emissions [130]. Many pharmaceutical production processes involve large quantities of water and energy for heating, cooling, and maintaining controlled environments, often resulting in high levels of waste [129]. Optimizing pharmaceutical processes using Life-Cycle Assessment (LCA) can significantly lower the carbon footprint, increase production yield, as well as reduce operational costs [131]. Closed-loop water systems, for instance, are gaining traction in pharmaceutical manufacturing due to their ability to minimize water consumption. These systems recycle and reuse water throughout the production process, reducing the need for fresh water and decreasing the volume of wastewater produced [132]. Implementing closed-loop systems is particularly valuable in water-scarce regions where pharmaceutical production can compete with other essential water needs. Similarly, solvent recycling is an effective way to cut down on waste and emissions, as solvents are commonly used in large quantities during drug formulation and purification stages. Solvent recovery systems allow solvents to be cleaned and reused, thus reducing the need for fresh solvents and minimizing hazardous waste output [133].

Minimizing waste production is another key element of process optimization. In pharmaceutical manufacturing, waste is generated at multiple stages, including chemical reactions, formulation, and packaging [134]. By using lean manufacturing techniques, companies can identify and eliminate inefficiencies in the production process, ultimately producing less waste and requiring less energy [135]. For example, continuous manufacturing—an approach that produces drugs in a continuous flow rather than in batch production—has proven to be more cost-efficient, resource-efficient, offers quality consistency, reducing energy usage and waste compared to traditional batch processes. Through these measures, process optimization allows pharmaceutical companies to maintain production efficacy while significantly reducing their carbon footprint [136].

5.2. Green chemistry

Green chemistry is an approach that emphasizes the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances [137]. In pharmaceutical manufacturing, applying green chemistry principles can help make production processes safer for the environment and reduce resource demand. The concept of green chemistry is gaining attention in the industry as companies recognize the benefits of reducing toxic waste, conserving energy, and using renewable materials in the production process [138]. One of the core goals of green chemistry in pharmaceuticals is to develop compounds that are not only effective but also less

Table 2
Sustainable waste management and operational strategies in healthcare and their estimated impact on carbon emission reduction.

Sustainable Waste Management System	Description	Key Benefits	Reduction in carbon emissions relative to initial emission	Reference
Medical Waste Segregation	Separating recyclable, hazardous, and general waste	Lowers incineration volume, reduces toxic emissions	10–20 %	Cesario et al. [121]
Recycling of Non-Hazardous Waste	Processing plastics, metals, and paper for reuse	Reduces landfill use, conserves raw materials	15–25 %	Dorofeeva et al. [122]
Composting of Organic Waste	Converting food and biodegradable waste into compost	Limits methane emissions, enriches soil	5–10 %	Dietrich et al. [123]
Waste-to-Energy Systems	Converting waste into renewable energy	Reduces reliance on fossil fuels, generates energy	15–30 %	Rasheed et al. [107]
Reusable Medical Supplies	Using durable, sterilizable supplies instead of disposables	Cuts down single-use items, reduces waste generation	20–30 %	Reynier et al. [124]
Electronic Medical Records (EMR)	Digital documentation replacing paper records	Lowers paper waste, saves trees, decreases transport	5–15 %	Bednorz et al. [125]
Green Procurement Practices	Sourcing eco-friendly, minimal-packaging supplies	Decreases packaging waste, promotes sustainable sourcing	10–20 %	Ndua [126]

toxic and resource-intensive to manufacture. For instance, researchers are exploring synthetic pathways that avoid the use of hazardous chemicals, reduce reaction steps, and lower energy requirements [139]. Enzymatic processes, for example, can often replace traditional chemical synthesis, offering a more environmentally friendly alternative with higher specificity and lower energy demands [140]. Biocatalysis, a method that employs natural catalysts such as enzymes to produce desired reactions, can significantly reduce the need for harsh chemicals and solvents, making pharmaceutical synthesis cleaner and safer [141].

Another important aspect of green chemistry is the development of drug formulations that are biodegradable and less likely to persist in the environment after disposal. Many pharmaceuticals, when not completely metabolized by the human body, are excreted and end up in wastewater, contributing to water pollution and harming aquatic life [142]. Developing drugs that break down more easily in the environment can help mitigate this issue, reducing the environmental impact of pharmaceuticals throughout their entire life cycle. Green chemistry also encourages the use of renewable feedstocks, such as bio-based rather than petroleum-based chemicals, further decreasing the dependency on fossil fuels in the pharmaceutical industry [143]. By adhering to green chemistry principles, pharmaceutical companies not only contribute to environmental sustainability but also often improve the efficiency of their production processes. Reduced reliance on toxic substances and streamlined reactions can result in cost savings and a lower carbon footprint, making green chemistry both an ethical and economically sound choice for pharmaceutical manufacturers [144].

5.3. Carbon offsetting and renewable energy in production

As part of their sustainability efforts, many pharmaceutical companies are turning to renewable energy sources to power their manufacturing facilities. Transitioning from fossil fuel-based energy to renewable sources such as solar, wind, and hydropower allows these companies to reduce their carbon emissions significantly [145]. Solar and wind installations are particularly suitable for pharmaceutical plants, as they offer reliable energy sources with minimal environmental impact [146]. In cases where renewable energy cannot fully meet energy needs, companies are increasingly supplementing their energy usage with renewable energy credits or partnerships with local green energy providers to minimize their reliance on non-renewable resources. For example, GlaxoSmithKline (GSK) has pledged to obtain 100 % of its electricity from renewable sources by 2030 and aims to decrease carbon emissions throughout its entire supply chain [147]. Similarly, AstraZeneca has made significant investments in solar and wind power across its facilities globally, contributing to its ambitious goal of reaching zero carbon emissions by 2025 [148]. These companies demonstrate that the integration of renewable energy in pharmaceutical manufacturing is both achievable and effective in reducing the industry's carbon footprint.

A growing number of pharmaceutical businesses are implementing renewable energy sources and carbon offset initiatives to mitigate their carbon footprint and tackle emissions that cannot be reduced just through operational modifications. Carbon offset programs, including reforestation, afforestation, and renewable energy projects in under-resourced areas, are frequently employed to mitigate residual emissions and achieve net-zero objectives [149]. Research indicates that these solutions can facilitate the achievement of overarching environmental objectives by assisting corporations in offsetting unavoidable emissions [150]. Offset schemes can assist the pharmaceutical industry in fulfilling sustainability obligations while facilitating key manufacturing operations. While carbon offsetting cannot substitute for direct emission reductions, its integration with renewable energy adoption offers a pragmatic strategy for firms to diminish their overall carbon footprint [151].

6. Challenges

The attainment of carbon neutrality in healthcare can be realized by concentrating on energy sources, insulation, waste management, water usage, nutrition, transportation, chemicals, medications, climate education, and leadership [152]. The transition to sustainable practices is increasingly recognized as vital for public health; however, several challenges must be addressed, including the absence of standards and regulations, an inadequate legal and regulatory framework, insufficient incentive policies, limited carbon dioxide conversion efficiency, high energy consumption, low return on investments, and a lack of investment enthusiasm [153]. Nevertheless, advancements in technology, growing awareness, and an increasing commitment to sustainability within the healthcare sector are creating new opportunities for sustainable transformation. By fostering collaboration between policymakers, healthcare providers, and industry stakeholders, healthcare can move closer to a carbon-neutral future.

6.1. Funding and investment

The transition to sustainable healthcare is resource-intensive, often requiring large-scale infrastructure changes, investment in renewable energy, and adoption of new technologies [154]. The upfront costs for sustainable initiatives, such as installing renewable energy systems or retrofitting buildings for energy efficiency, can be prohibitive for many healthcare facilities. Smaller or resource-constrained healthcare providers, in particular, may struggle to fund these transitions [155]. However, sustainable practices often lead to long-term savings, as investments in energy efficiency and waste reduction can lower operational costs over time [156]. For example, energy-efficient HVAC systems and renewable energy installations reduce dependency on non-renewable energy sources, which can result in significant cost savings over the lifespan of the system [157].

Government grants and incentives are crucial in helping healthcare organizations overcome these initial financial barriers. Many governments and international organizations have established funding mechanisms to support sustainability initiatives in healthcare, including grants for renewable energy adoption, subsidies for energy-efficient technologies, and tax breaks for green infrastructure projects [158]. In the United States, for instance, programs such as the Energy Efficient Commercial Buildings Deduction provide tax incentives for facilities that implement sustainable building practices, including hospitals [159]. Additionally, public-private partnerships with green technology companies offer healthcare providers access to innovative solutions that may otherwise be financially unattainable. Partnerships with energy companies, for example, can provide hospitals with access to renewable energy solutions through power purchase agreements (PPAs), allowing them to transition to greener energy sources without incurring the full upfront costs [160].

The role of venture capital and impact investment is also growing in sustainable healthcare, as investors increasingly recognize the financial and environmental value of supporting carbon-neutral solutions [161]. By strategically investing in eco-friendly healthcare innovations, investors can help drive forward technologies and practices that improve environmental sustainability while achieving profitable returns. Continued growth in funding sources—ranging from government subsidies to private investments—is essential for enabling healthcare facilities to adopt sustainable practices on a wide scale [162].

6.2. Policy and regulation

Policy and regulatory support are fundamental in driving the healthcare sector's shift toward carbon neutrality [163]. The healthcare industry operates under strict regulatory standards, particularly concerning safety, hygiene, and patient care, which can make the adoption of sustainable practices challenging [79]. However, implementing policies that set clear standards for carbon-neutral practices in healthcare can provide a framework for sustainable operations while maintaining compliance with safety regulations [164]. For instance, setting regulatory standards for energy efficiency in hospital buildings, waste management practices, and sustainable procurement can push healthcare providers to integrate greener practices into their operations [165].

In regions where supportive policies have been implemented, the healthcare sector has shown promising progress toward sustainability. The United Kingdom's National Health Service (NHS) has developed a comprehensive sustainability policy known as the "Greener NHS" initiative, which includes ambitious targets to reduce carbon emissions across its operations. This policy-driven approach has led to significant advancements, such as the NHS's commitment to achieving net-zero carbon emissions by 2040 [166]. By establishing clear benchmarks and providing guidance on sustainable practices, such policies encourage healthcare facilities to prioritize environmental responsibility alongside patient care.

Moreover, international organizations such as the World Health Organization (WHO) and the United Nations (UN) play a critical role in promoting global sustainability standards in healthcare. Initiatives like the WHO's Health in All Policies (HiAP) approach advocate for environmental health considerations to be integrated into healthcare policy at all levels [167]. As climate change poses an increasing risk to public health, healthcare regulations that prioritize environmental sustainability are essential in addressing the root causes of climate-related health issues [168].

Policy and regulatory frameworks not only provide the necessary guidance for healthcare providers but also create accountability within the sector, ensuring that sustainable goals are consistently pursued. However, the success of these policies relies on effective enforcement and continuous evaluation, as well as collaboration between regulators and healthcare providers to adapt practices to evolving environmental challenges [169].

6.3. Education and training

Education and training play a pivotal role in embedding sustainability within healthcare institutions. For sustainable practices to be effectively implemented, healthcare staff at all levels need to understand and prioritize environmental responsibility [170,171]. Training staff on sustainable practices, such as waste segregation, energy conservation, and eco-friendly procurement, not only increases awareness but also empowers employees to take an active role in reducing the environmental impact of their daily activities [172]. In healthcare settings, where patient care is often prioritized over environmental considerations, sustainability training programs can help shift organizational culture toward a more balanced approach. For instance, training programs on waste management can educate staff about the importance of proper waste segregation and recycling, reducing the volume of waste sent to landfills and improving the efficiency of recycling processes [173]. Furthermore, training in energy conservation methods, such as turning off equipment when not in use and optimizing lighting and HVAC systems, can contribute to substantial energy savings as much as 19.82 % annually in hospitals [174]. Fig. 3 illustrates the main components influencing the journey toward carbon neutrality in healthcare. This figure highlights the main challenges to achieving carbon neutrality in healthcare, such as regulatory gaps, high costs, and low investment interest. Enablers include technology, awareness, and sustainability commitment. Collaborative efforts can drive progress toward this goal. It starts with the central goal of achieving carbon neutrality and identifies primary challenges such as the lack of standards and regulations, high initial costs, and low investment enthusiasm.

Sustainability education should also extend to leadership and management, as decision-makers play a crucial role in setting sustainability goals and prioritizing funding for green initiatives [175]. Executive leadership training on the financial, social, and environmental benefits of sustainability can help align organizational objectives with carbon-neutral goals, fostering a top-down commitment to environmentally responsible practices. Additionally, interdisciplinary training that includes insights from environmental science, engineering, and healthcare administration can equip leaders with a comprehensive understanding of the sustainability challenges unique to healthcare [176]. Educational initiatives in sustainability are particularly impactful when they foster collaboration and innovation among healthcare professionals. For instance, the University of California Education for Sustainable Healthcare (UC-ESH) trained >100 faculty members and facilitated the incorporation of Education for Sustainable Healthcare (ESH) into 99 existing and new courses, ultimately impacting over 7000

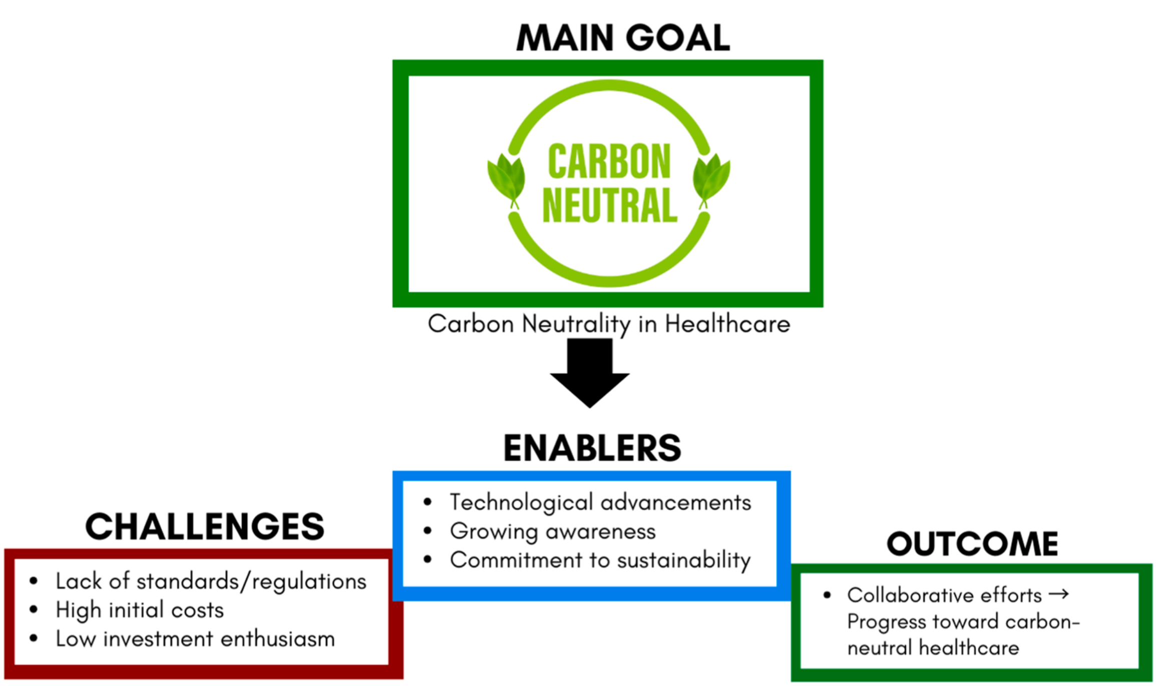

Fig. 3. Key Challenges and Enablers for Carbon Neutrality in Healthcare.

learners. The UC-ESH enhanced empowerment, consciousness, and understanding of the climate catastrophe, while establishing a community of practice focused on ESH [177]. Programs that encourage staff to participate in sustainability projects or propose eco-friendly ideas empower them to contribute to environmental improvements within their facilities [178]. For example, employees may suggest initiatives to reduce water usage, promote recycling, or minimize single-use plastics, directly contributing to the organization's sustainability goals. As sustainability becomes a core aspect of healthcare training and education, a culture of environmental stewardship is more likely to take root, creating lasting change within healthcare institutions [179].

7. Future directions and opportunities for innovation

Despite the challenges, the future of sustainable healthcare offers substantial opportunities for innovation and progress [19]. Advances in green technology, energy efficiency, and waste management hold promise for more environmentally friendly healthcare practices. Emerging technologies, such as AI-driven energy optimization systems and biodegradable medical supplies, offer solutions that address some of the most pressing environmental concerns in healthcare [180]. Smart hospital systems, for example, leverage data analytics to manage energy usage dynamically, reducing waste and improving operational efficiency [181]. Furthermore, collaboration across industries will be essential in driving sustainable healthcare forward. Partnerships with technology companies, environmental organizations, and government agencies can provide healthcare providers with access to resources and expertise needed to implement and scale sustainable solutions [19]. These collaborations can also lead to the development of new products and practices that address the unique needs of healthcare facilities, from eco-friendly sterilization methods to recyclable medical packaging [182].

The healthcare sector's commitment to sustainability must be accompanied by continuous research and adaptation to new environmental challenges. Institutions can play a proactive role by investing in research on eco-friendly practices, exploring sustainable innovations in clinical settings, and contributing to the development of industry-wide best practices [183]. Global health organizations, industry associations, and collaborative healthcare networks can promote the transition to sustainable healthcare by establishing platforms for knowledge exchange and enhancing communication practices that allow providers to learn from successful global sustainability initiatives, thereby supporting accessible and equitable healthcare services [184].

8. Conclusion

The healthcare sector occupies a dual role as a protector of human health and a steward of environmental well-being. While healthcare facilities and practices are essential for treating and preventing illness, they also contribute to significant environmental challenges, from high energy consumption to the generation of hazardous waste. The urgent need to reduce healthcare's carbon footprint has inspired a shift toward more sustainable practices that prioritize both patient care and planetary health. Through the adoption of energy-efficient hospital designs, eco-friendly medical supplies, sustainable waste management, and low-carbon pharmaceutical manufacturing, healthcare can make meaningful progress toward achieving carbon neutrality.

The journey to a sustainable healthcare system is not without its hurdles. Financial costs, regulatory barriers, and the need to maintain stringent safety and hygiene standards all pose obstacles to rapid implementation. However, as advancements in green technology continue and awareness grows, healthcare organizations are increasingly empowered to adopt eco-friendly practices. Support from policymakers, collaboration with industry stakeholders, and education within the healthcare sector are essential for overcoming these challenges and building a culture of sustainability.

Beyond its environmental benefits, sustainable healthcare offers substantial financial advantages. While initial investments in green infrastructure, renewable energy, and waste reduction programs may be considerable, numerous studies demonstrate that these interventions yield significant cost savings in the medium and long term. Energy-efficient hospital operations, improved resource management, and optimized waste disposal systems can reduce operational costs while enhancing resilience to economic and environmental disruptions. By transitioning to more sustainable models, healthcare institutions can strengthen financial sustainability alongside their environmental commitments.

The potential benefits of a sustainable healthcare system are profound. By reducing its environmental impact, healthcare not only aligns itself with global climate goals but also contributes to a healthier, more resilient future for communities around the world. The path to a carbon-neutral healthcare sector may be complex, but through coordinated, dedicated efforts, it is possible to create a system that safeguards both the health of patients and the planet. Moreover, by embracing sustainability as both an environmental and economic opportunity, the healthcare industry reinforces its role as an innovative, forward-thinking sector that prioritizes long-term efficiency, cost-effectiveness, and global health security. In doing so, the healthcare industry affirms its commitment to a holistic approach to health—one that acknowledges the inextricable link between human well-being and the environment.

CRediT authorship contribution statement

David Bamidele Olawade: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Tunbosun Theophilus Popoola:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Eghosasere Egbon:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Aanuoluwapo Clement David-Olawade:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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