Improving environmental sustainability of intensive care units: a mini-review

Kay Choong See

Abstract
The carbon footprint of healthcare is significantly impacted by intensive care units, which has implications for climate change and planetary health. Considering this, it is crucial to implement widespread efforts to promote environmental sustainability in these units. A literature search for publications relevant to environmental sustainability of intensive care units was done using PubMed. This mini-review seeks to equip intensive care unit practitioners and managers with the knowledge necessary to measure and mitigate the carbon cost of healthcare for critically ill patients. It will also provide an overview of the current progress in this field and its future direction.

INTRODUCTION
Slowing down the harmful effects of climate change and improving planetary health are crucial for humankind [1]. Sustainability involves protecting ecosystems and staying within planetary boundaries [2], which are limits that, if exceeded, could lead to catastrophic environmental changes. One of these boundaries relates to climate change and is measured by atmospheric carbon dioxide concentration, with a threshold of 350 ppm proposed, which has already been exceeded [2]. This highlights an urgent need to reduce greenhouse gas emissions.

It is important for healthcare professionals to promote environmental sustainability, with intensive care units (ICUs) being in a unique position to implement solutions due to their intersection with healthcare and high resource use for critically ill
patients. For instance, a life cycle assessment conducted in a US hospital showed that compared to acute care units, an ICU generates 1.3 times more solid waste (7.1 kg vs. 5.5 kg) and 3.1 times more greenhouse gases (138 kg vs. 45 kg CO2-equivalents [CO2e]) per bed day [3]. The major contributors to emissions were consumable goods, building energy consumption, capital equipment purchases, food services, and staff travel.

While ICU staff may be familiar with the need for environmental sustainability, the ability to implement improvements require knowledge regarding measuring and mitigating the carbon cost of healthcare for critically ill patients. To equip ICU practitioners and managers with such knowledge, this mini-review was therefore done to provide an overview of the current progress in this field and its future direction.

METHODS

An updated search on 8 July 2023 of PubMed® (pubmed.ncbi.nlm.nih.gov) using the search term ("environmental sustainability" OR "ecological sustainability" OR "planetary health" OR "waste recycling" OR "recyclable waste" OR "climate change" OR "climate action" OR "carbon footprint" OR "carbon cost" OR "environmental footprint" OR "life cycle assessment" OR "life cycle analysis" OR “plastic waste”) AND ("ICU" OR "intensive care" OR "critical care") yielded 269 publications. This search was done to update the author's personal library of articles. When they were relevant to environmental sustainability of ICUs, articles were included in this narrative review.

IMPACT OF THE ENVIRONMENT ON HEALTH

The burning of fossil fuels results in the release of greenhouse gases, which include carbon dioxide, methane, and nitrous oxides, as well as particulate matter and sulphur dioxides. The accumulation of these gases in the atmosphere contributes to global warming, which is estimated to cause a rise in temperature of 1 degree Celsius per decade. This increase in temperature can lead to heat-related injuries, dehydration, renal dysfunction, skin cancer, mental health issues, pregnancy complications, allergies, cardiorespiratory illnesses, and an elevated risk of death from cardiovascular causes.
such as ischemic heart disease, stroke, and heart failure. Additionally, there may be changes in vector-related diseases, rising sea levels, and an increase in wildfires. Regions that experience warmer climates such as central and south America, central and south Europe, and southeast Asia may experience an increase in mortality. Burning fossil fuels also generate particulate matter, which further damage the respiratory system, worsen respiratory and cardiovascular diseases, have various non-cardiorespiratory health effects, and increase the number of excess deaths.

Plastics, which are widely used in healthcare, are derived from fossil fuels and their extraction, refining, and manufacturing processes contribute to greenhouse gas emissions and global warming. In addition to their impact on global warming, plastics can also harm human health through the presence of microplastics. These are tiny plastic particles with a diameter of less than 5 mm, which can be synthetic or formed from the natural breakdown of larger plastic pieces. Microplastics can be found in air, water, and soil, and can enter plants and animals, including humans, where they have been found in the lungs, blood, stool, and placenta. Per- and polyfluoroalkyl substances (PFAS) are a type of plastic material that is resistant to water, oil, and fire and are commonly used in a wide range of products, including containers, wrapping, and personal protective equipment. However, these chemicals are long-lasting and can accumulate in the blood, brain, liver, and kidneys, leading to adverse health effects. PFAS exposure has been linked to decreased antibody response, dyslipidaemia, decreased growth in infants and foetuses, neurotoxicity in developing brains, and an increased risk of kidney and breast cancer. These chemicals are poorly excreted from the body and can persist for years or decades.

**IMPACT OF HEALTHCARE ON PLANETARY HEALTH**

Health systems are responsible for 1-5% of the world’s carbon footprint. Within health systems, there are several sources of carbon emissions within the ICU. For instance, in patients receiving treatment for septic shock, a carbon footprint evaluation conducted in two ICUs located in Australia and the US found that energy
consumption related to heating, ventilation, and air conditioning accounted for 76-87% of the carbon footprint, while the use of single-use materials and other consumables were less significant contributors.\textsuperscript{[13]}

On a related note, the use of plastic in healthcare has a significant negative impact on the environment, as it contributes to various harmful effects at different stages of the plastic life cycle.\textsuperscript{[11]} These include the extraction of coal, oil, and gas, which are the primary raw materials for plastic production, the energy-intensive manufacturing process, and the inefficient disposal methods, which involve landfilling, controlled burning, and uncontrolled incineration. The use of single-use plastic products, which now make up 35-40% of plastic production, has contributed to the growing plastic use trend. However, the global recovery and recycling rates for plastic are below 10%, which exacerbates the harmful effects of plastic waste. Plastic production is estimated to be responsible for 3.7% of global greenhouse gas emissions, and this figure is projected to increase to 4.5% by 2060 if no action is taken to curb plastic use.

**MEASURING THE ENVIRONMENTAL COST OF HEALTHCARE**

Two complementary methods have been used in the ICU to measure the environmental cost of critical care: life cycle assessment (LCA)\textsuperscript{[13]} and more recently, material flow analysis (MFA)\textsuperscript{[14]}. An LCA involves analysing the environmental impact of products or processes, at every stage of a product or process life cycle.\textsuperscript{[13]} This life cycle includes natural resource extraction, manufacturing, packaging, transport, use/reuse, and recycling/waste disposal. In other words, an LCA is a scientific approach that evaluates the environmental impact of a product or process from the beginning of its life cycle to its disposal.

Two main types of LCAs are relevant to healthcare, namely process-based LCAs and Environmentally Extended Economic Input Output (EEIO) LCAs. Process-based LCAs directly measure the environmental impact of a product or activity by assessing material inputs and emissions. These LCAs are useful for comparing related products
or processes, such as reusable vs disposable equipment. On the other hand, EEIO LCAs are suitable for analysing large data sets where process-based LCA is not feasible. These LCAs rely on nationally reported economic input-output tables and pollution emissions tables to estimate the environmental impact of a system. By assigning an environmental footprint to monetary value spent, approximations of entire healthcare systems’ CO2e emissions are possible. For example, the UK-MRIO (multi-region input-output) model of Greenhouse Gas (GHG) emissions \cite{15} and the Eora multiregional input-output database \cite{12} are commonly used in multiregional input-output analysis. This approach covers the entire supply-chain network underpinning the operation of healthcare services and yields comprehensive estimates for environmental footprints. The use of international input-output tables (MRIO in terms of nations/countries as regional units) in EEIO LCA allows for the expansion of the system boundaries from a single country to surrounding regions.

While LCAs focus on a particular product or patient pathway, MFAs provide a broader perspective on all materials entering and leaving the ICU. MFAs quantify all goods and waste flows, making them useful for waste management and raising awareness among ICU staff. They also identify environmental hotspots, which are areas that cause significant environmental impacts and require urgent attention. These hotspots often include products with the highest mass and environmental footprint assessment. By highlighting these hotspots, ICU personnel can then target areas for improvement. In a 2019 case study of a Dutch ICU, 2839 patients were admitted, with an average stay of 4.6 days and a material mass inflow of 247,000 kg. Of this, 50,000 kg were incinerated as hazardous hospital waste. MFA analysis showed that each patient had an environmental impact of 17 kg of mass, 12 kg CO2e, 300 L of water usage, and 4 m² of agricultural land occupation per day. The five identified hotspots were non-sterile gloves, isolation gowns, bed liners, surgical masks, and syringes (including packaging). \cite{14}. 
PRACTICAL SOLUTIONS FOR IMPROVING ENVIRONMENTAL SUSTAINABILITY IN ICU

REDUCE

Categories of interventions include reduce, reuse, and recycle\textsuperscript{[16]}. The category that has the most significant impact is reduction of waste generation since it prevents the creation of environmental pollution from the outset. A review of 54 studies revealed that there is substantial waste in the US healthcare system, with a cost ranging from USD 760-935 billion, representing 25\% of all spending\textsuperscript{[17]}. Among this waste, USD 75.7-101.2 billion is attributed to overtreatment or low-value care. Efforts to reduce overtreatment or low-value care could save USD 12.8-28.6 billion.

There are various methods to decrease waste generation in the healthcare industry, such as preventing the progression of illnesses and inpatient admissions, avoiding unnecessary ICU admissions through accurate triage and avoiding futile care, reducing overdiagnosis by not detecting harmless conditions that could be safely left undiagnosed and untreated\textsuperscript{[18]}, minimizing over-investigation by avoiding routine blood tests\textsuperscript{[19]}, changing central venous catheter infusion sets not earlier than 7 days\textsuperscript{[20]}, and curtailing overtreatment such as routine use of proton pump inhibitors for low-risk patients or continued thromboprophylaxis in ambulatory patients. Other solutions for reducing healthcare resources include managing the supply chain prudently to reduce unused medical waste, replacing intravenous drug use with oral alternatives, avoiding unnecessary vehicular transport by utilizing telepresence enabled by medical robots\textsuperscript{[21]}, reducing facility energy consumption for HVAC (heating, ventilation, and air conditioning) by setting a moderate room temperature\textsuperscript{[13]}, improving first-pass success of procedures through better training, decarbonizing energy sources by using natural rather than artificial lighting, reducing paper printouts and forms, minimizing plastics use, and reducing healthcare-associated infections and iatrogenic complications.

Another example of reducing waste generation in healthcare involves avoiding the routine use of supplementary oxygen, which can prevent harmful gas emissions during the production of medical oxygen and disposable plastic masks and tubing\textsuperscript{[22]}. 
Although avoiding unnecessary computed tomography (CT) or magnetic resonance imaging (MRI) is ideal [23], when necessary, chest X-ray (CXR) or point-of-care ultrasound could also help reduce the carbon footprint. A study showed that the mean CO2e emissions were much higher for MRI and CT scans compared to CXR and ultrasound (17.5 kg/scan for MRI and 9.2 kg/scan for CT, compared to 0.8 kg/scan for CXR and 0.5 kg/scan for ultrasound [24]). In some paediatric ICUs, isolation rooms contribute to over 75% of unused medical waste, which includes endotracheal tubes, diapers, disposable under pads, and flexible suction catheters [25]. Interventions for reducing this waste include stocking fewer items inside patient rooms and keeping them in supply carts outside patient rooms, protecting bedside resuscitation bags, positive end-expiratory pressure valves, and oropharyngeal airways in plastic bags for re-use. Another interesting intervention is to reduce the use of super-pollutants such as inhalational anaesthetics [26, 27] (e.g., replace with total IV anaesthesia) and hydrofluorocarbon-containing MDI [28] (e.g., replace with mesh nebulizer), which have high global warming potential.

REUSE

If direct reduction of waste generation is not possible, then indirect methods of reusing and recycling are important. Choosing reusable equipment over single-use disposable ones is one such method [29]. Examples of reusable equipment include stethoscopes, procedural kits, laryngoscope blades, bronchoscopes, laryngeal mask airways, and metal scissors [30]. In one hospital, reusable flexible bronchoscopes were preferred over single-use devices due to their lower environmental impact, lower cost, and technical reliability for tracheal intubation. Another approach to reducing waste is single-use device reprocessing, where used single-use devices are sent to a third-party facility for cleaning, sterilization, and sale back to hospitals. Investing in durable equipment with modular components that are repairable and upgradable can also reduce waste. When making procurement decisions, factors such as energy efficiency and equipment quality must be considered. Extending product lifespans through repairing and upgrading equipment as much as possible can also be effective.
RECYCLE

The final approach to reducing waste is recycling used fluid bags and non-sharps, with appropriate segregation of registered medical waste (i.e., biohazard waste, which is expensive to process) and non-medical waste. However, recycling has the lowest impact because most life cycle emissions occur during the upstream manufacturing and distribution of products, and recycling requires additional energy and materials, which can create emissions. While there are many practical solutions for reducing, reusing, and recycling (Table 1), few have been validated and peer-reviewed (Table 2).

IMPLEMENTATION OF ENVIRONMENTAL SUSTAINABILITY IN ICU

The COM-B model of behaviour change identifies three essential conditions: capability, opportunity, and motivation\textsuperscript{[31]}. Education can improve motivation among staff, but simply having the willpower is not sufficient. Health systems must also provide the opportunity (space), logistics (stuff), and capability (system) for sustainability interventions. Battup and colleagues conducted a recent systematic review of behavioural change interventions designed to encourage clinicians to reduce carbon emissions in clinical activity. They analysed six full-text studies and 14 conference abstracts and found that the most common behaviour change techniques used were social support, highlighting the consequences, restructuring the physical environment, using prompts and cues, providing feedback on behaviour outcomes, and sharing information about environmental consequences\textsuperscript{[32]}.

Education has played a significant role in decreasing the usage of inhalational anaesthetics with high global warming potential (GWP). According to the GWP100 (100 year time horizon GWP), which is used as the standard comparison of long-lived effects, carbon dioxide has a GWP of 1, while desflurane has a GWP100 of 2540, sevoflurane 130, isoflurane 510, and nitrous oxide approximately 265 (nitrous oxide also having ozone-depleting potential)\textsuperscript{[33]}. In one example, staff education on desflurane-sparing practices and distribution of posters has allowed for a gradual removal of
desflurane from operating theatres, resulting in a 95.63% reduction in desflurane bottles purchased (from 800 bottles in January 2016 to 35 bottles in December 2021). In contrast, the number of sevoflurane bottles purchased (which has a low global warming potential) increased by 6.13% from 1191 bottles to 1264 bottles, leading to an overall 87.9% decrease in carbon emissions\[34\].

Improving environmental sustainability in critical care involves the concepts of "greening" and environmental stewardship. "Green" teams, made up of critical care leaders and frontline staff, can be formed to undertake these measures \[16, 25\]. Change management is important, which involves convincing others, obtaining leadership support, and acquiring necessary resources, time, and staffing. Audit, feedback, and continuous improvement cycles are also crucial. Multidisciplinary team members can help reduce waste, such as pharmacists who can review drug charts to identify unnecessary medications and implement antimicrobial stewardship. Ultimately, reducing waste in healthcare is crucial for better patient care, improved efficiency, and a healthier planet.

**FUTURE DIRECTION**

Improving environmental sustainability in healthcare is not only good for the planet but may also reduce healthcare costs. However, it is important to validate interventions to ensure their effectiveness and avoid unintended consequences, such as limiting patients' access to necessary products \[35, 36\]. Education on planetary health and sustainability should be included in medical education \[37\] and training for all stakeholders \[38, 39\]. Education platforms include virtual learning spaces like the Virtual Health Academy, which provides lectures and workshops on transformative planetary health education in Germany \[40\]. Education for sustainable healthcare (ESH) should also be included in faculty development to improve knowledge and teach community-building and leadership skills \[41\].

Collaboration between humans and artificial intelligence (AI) \[42\] can contribute to environmental sustainability. Clinicians can input clinical data into electronic health
records, while AI can use big data to accurately triage patients for ICU admission\[43\], potentially reducing unnecessary ICU utilization and healthcare waste. Additionally, ICU staff members can use Radio Frequency Identification (RFID) systems or AI-driven contactless visual systems\[44\] to provide real-time data on consumable and equipment usage. Predictive AI models can then assist with forecasting resource utilization\[45\] and optimizing inventory management, reducing losses from expired consumables and equipment. In other words, AI-enabled effective supply chain management and stocking systems may help minimize overstocking and waste of expired equipment.

Promoting environmental sustainability requires the active participation of stakeholders beyond the ICU, e.g., manufacturers and healthcare regulators. On the one hand, manufacturers should strive to prioritize sustainability in their product designs and production processes, aiming for environmentally friendly alternatives whenever feasible. For non-recyclable products, these should offer substantial advancements in device performance compared to their recyclable counterparts, to justify their purchase. On the other hand, healthcare regulators should preferentially approve products that can be reusable or recycled, lessening waste accumulation and environmental degradation. For instance, the World Health Organization has recommended that when purchasing equipment and supplies, environmentally friendly products should be prioritized, such as those with minimal packaging, reusable and recyclable parts, and minimal hazardous chemicals and non-degradable plastics\[46\].

CONCLUSION

Promoting environmental sustainability in healthcare, specifically in the ICU, is essential for mitigating the environmental impact of critical care and improving planetary health. Sustainability involves staying within planetary boundaries, which if exceeded, could lead to catastrophic environmental changes. One of these boundaries relates to climate change, and the atmospheric carbon dioxide concentration has already exceeded the proposed threshold of 350 ppm. Therefore, reducing greenhouse gas emissions is urgent.
To achieve environmental sustainability in the ICU, healthcare professionals must have the knowledge and tools to measure and mitigate the carbon cost of healthcare for critically ill patients. Two complementary methods have been used in the ICU to measure the environmental cost of critical care: life cycle assessment (LCA) and material flow analysis (MFA). Various methods can decrease waste generation in the healthcare industry, such as preventing the progression of illnesses and inpatient admissions, avoiding unnecessary ICU admissions, minimizing overdiagnosis and over-investigation, and curtailing overtreatment. Interventions can also focus on reducing energy consumption and reusing/recycling products.

ICU staff should take a lead role in implementing solutions due to their intersection with healthcare and high resource use for critically ill patients. However, reducing the environmental footprint of critical care requires a collective effort from healthcare providers, patients, policymakers, and other stakeholders. Collaborative efforts, including those with artificial intelligence, can result in more sustainable healthcare systems and better health outcomes for individuals and the planet.
### PRIMARY SOURCES

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<td>&quot;An integrated environmental, economic, and clinician satisfaction comparison between single-use and reusable flexible bronchoscopes for tracheal intubation&quot;</td>
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